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# Resource efficiency and environmental impact assessment

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# Resource efficiency and environmental impact assessment

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POLICY BRIEF
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# Transformation of Resource-Based Cities: The Case of Benxi

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Resource-based cities, which emerge due to the large-scale industrialization of China, mainly rely on local natural resources for industrial layout and economic development. However, resources have been gradually exhausted due to overuse, resulting in a series of negative impacts on the environment and resources. In order to realize long-term sustainable development and avoid falling into the "resource curse," measures such as industrial structure adjustment and technological upgrading to promote the transformation of these cities ought to be implemented. Taking Benxi, one of the most typical mineral resource-based cities in China, as an example, this study discusses the economic and environmental performance and existing problems in the local transformation process, comparing it with successful transformation patterns of global mineral resource-based cities. On this basis, a series of policy suggestions together with possible ways toward sustainable development are put forward and summarized.

**Keywords: resource-based cities, Benxi, transformation, sustainable development, resource curse**

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## INTRODUCTION

Resource-based cities refer to those with mining and natural resources processing as the leading industries (The State Council of the PRC, 2013). The emergence and development of such cities are inseparable from industrialization. Up to now, there are 126 prefecture-level and 120 county-level resource-based cities in China. Relying on rich resources such as energy and minerals, these cities have become China's industrial bases and contributed to China's economic development. In recent years, however, continuous promotion of resource development and gradual depletion of resource reserves have led to severe overcapacity of steel, cement, glass, and other resource products. Many resource-based economies have encountered difficulties or even recession in urban development, manifested as environmental degradation and economic decline. On the one hand, compared with other non-resource-based economies, resource-based economies are facing more severe resource exhaustion and environmental deterioration (Wang and Chen, 2020), such as the increasing shortage of forest resources, land resources, and water resources, as well as excessive emissions of air pollutants. On the other hand, due to their single industrial structure, the economic growth is weak (Auty, 1994; Torvik, 2002), which will push up the poverty rate and unemployment rate. In addition, the excess profits of the resource industry will exacerbate income inequality and lead to some social problems (Ali et al., 2020). Abundant resources are likely to hinder economic growth and lead to the problem of the "resource curse". Once such a problem appears, it will significantly affect the sustainable development of cities and bring high governance costs (Sachs and Warner, 1995). Therefore, resource-based regions must actively promote the industrial structure transformation in order to reduce the over-reliance on resources, seek new growth power, and then in turn fully meet the requirements of sustainable and high-quality development in the new era (Long et al., 2020). In this regard, the consensus has been reached around the world, with a series of transformation means, including innovation orientation, talent attraction, and environment protection having been put forward (Papyrakis and Gerlagh, 2004; Du et al., 2012; Du et al., 2020; Li and Long, 2020).

However, although the problem of the "resource curse" and the solutions to it are heated topics in research on the environment and resources, little attention has been paid to the economic and environmental impact of the "resource curse" at the city level, especially in the conditions of those resource-based cities in China. Also, gaps in the existing research, which mainly concentrates on academic theories of the mechanism of the "resource curse," have limited our understanding of specific city transformation patterns and practical policies.

Benxi, located in the southeast of Liaoning province, is an important industrial city in China, with a population of over 1.3 million and a GDP of 81 billion RMB in 2020. Benxi is rich in mineral resources and takes the iron and steel industry as its pillar industry. During the 1950s–1990s, when China vigorously developed the secondary industry, the social economy of Benxi achieved rapid development. However, due to the overuse of resources, it gradually faced double pressure on the economy and environment after entering the 21st century (Li and Zou, 2018). Though a series of policies have been issued in an attempt to solve the problem of the "resource curse," little progress has been made. Therefore, effective measures to promote the transformation are awaited.

This study chose Benxi as a typical case to study the resource-based cities in China for the following reasons. First, since Benxi was positioned as a mature resource-based city in The National Sustainable Development Plan for Resource-Based Cities (2013-2020) issued by the State Council of the PRC, it is necessary to reveal the environmental performance and economic developments in its transformation process. Second, as Benxi is an important industrial city in Liaoning province, clarifying the focus and direction of transformation is meaningful to the sustainable development of the old industrial bases in Northeast China. Finally, Benxi is a representative of many resource-based cities in China. A feasible transformation path is significant and provides a valuable reference for the high-quality development of all such cities in China.

This study, therefore, analyzes the environmental and economic performance of Benxi, briefly explains the mutual relationship, and summarizes reasonable approaches to promoting its sustainable development through the comparison of successful transformation patterns from resource-based cities across the world, aiming to provide policy implications for the transformation of such cities in China.

## ANALYSIS OF THE ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF BENXI

In the past, resource-based cities and old industrial cities in China, such as Benxi, developed their economies rapidly through the flourishing secondary industry, which caused severe negative impacts on the environment. At the same time, it is accompanied by severe consumption and rapid depletion of resources. Since the secondary industry, especially the mineral resource industry, is the main pollution source, this study analyzes the environmental and economic performance and focuses on the effect generated by the mineral industries and the defects inherent in such industries. Furthermore, governments ought to intervene in developing such industries through policy means, in order to achieve the goal of transformation and sustainable development.

### Economic Performance: The "Steel-Dominated" Economic Model

The economic structure of Benxi is mainly dominated by the secondary industry, especially the iron and steel industry, and the chemical industry. As presented in **Figure 1**, the output value of the iron and steel industry accounts for more than 80% of the city's total industrial output value. As the pillar industry of Benxi, this industry has made significant contributions to the economic and social development of Benxi, which served as the momentum of economic growth and created tens of thousands of jobs for Benxi.

Benxi has implemented policies to boost its economy and reduce its reliance on resources in recent years. First, it emphasizes the development of the tertiary industry. As shown in **Figure 2**, the tertiary industry has gradually occupied the leading position in the industrial structure, with the importance of the service industry becoming increasingly prominent since 2011. In terms of the secondary industry, aiming at changing the situation of "steel dominating," Benxi has established several industrial clusters other than the iron and steel industry successively, including the biomedical industry cluster, advanced material industry cluster, glass product industry cluster, and packaging and printing industry cluster, which support each other and develop in multiple ways.

Although Benxi has taken a series of measures, problems existing in the industrial structure have not been fundamentally changed. Even though the proportion of the tertiary industry exceeded that of the secondary industry for the first time in 2016, the secondary industry regained its advantage over the tertiary industry in 2019, which implies that the service industry of Benxi lacked growth momentum. Moreover, as for the secondary industry, the proportion of the output value of the iron and steel industry in the total industrial output value has even risen to more than 80% (see **Figure 1**). Also, for those not so relevant to mineral resources, the compound annual growth rate (CAGR) from 2016 to 2020 of industries that have already taken shape (e.g., the pharmaceutical manufacturing industry) is significantly lower than the average, while industries with a higher CAGR have suffered from their small scale (**Figure 3**). The reason behind the situation is that *Bensteel Group*, the largest enterprise in Benxi, has been set as the core and leader of Benxi's industry and tilted many resources. Although Benxi has strived to construct several industrial clusters other than the iron and steel industry, it inevitably lays out

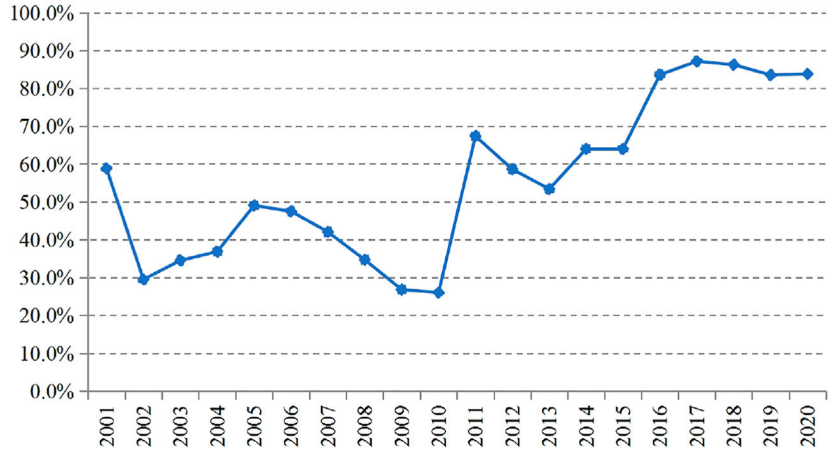


**FIGURE 1 |** Output value of the iron and steel industry. Data source: Benxi Statistical Yearbook, 2001-2020.

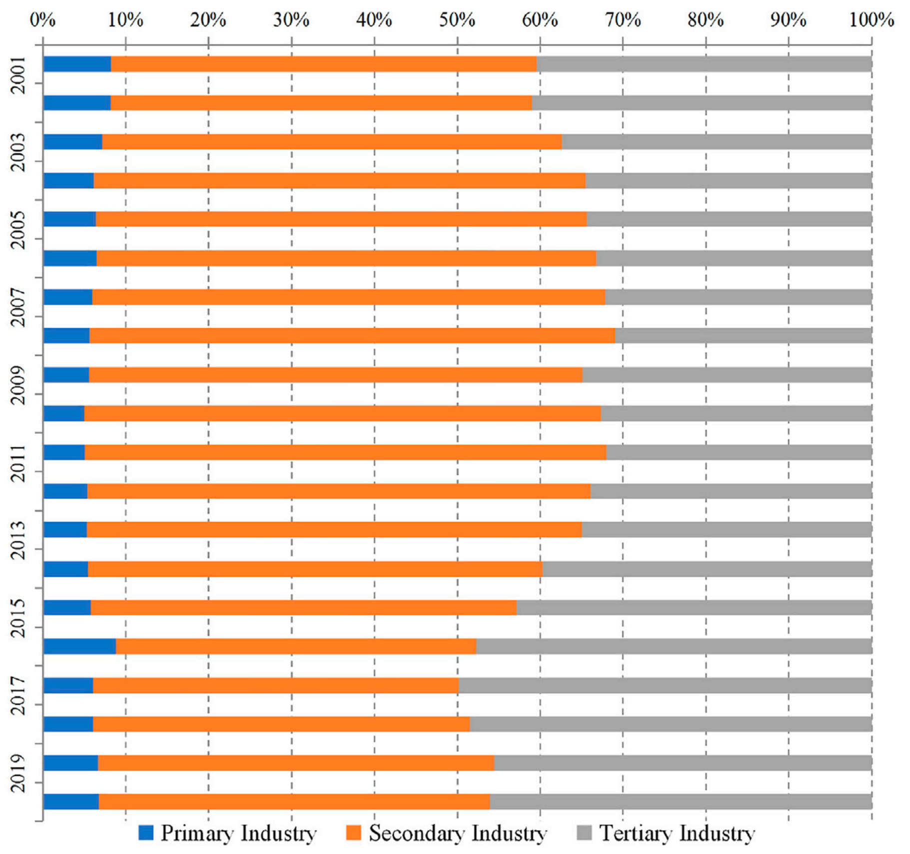


**FIGURE 2 |** Industrial structure, Benxi, 2001-2020. Data source: Benxi Statistical Yearbook, 2001-2020.

industrial clusters around *Bensteel Group* due to the path dependence supporting the development of pillar industries. Therefore, the tertiary industry and other sectors of the secondary industry are facing limited resources, sluggish development, and heavy reliance on resources.

In addition, due to the lack of a fine business environment and educational resources in Northeast China, it is difficult for Benxi to attract and retain professionals. Furthermore, the severe aging population structure also restricts its long-term sustainable development (in 2020, the population over 60 years old in

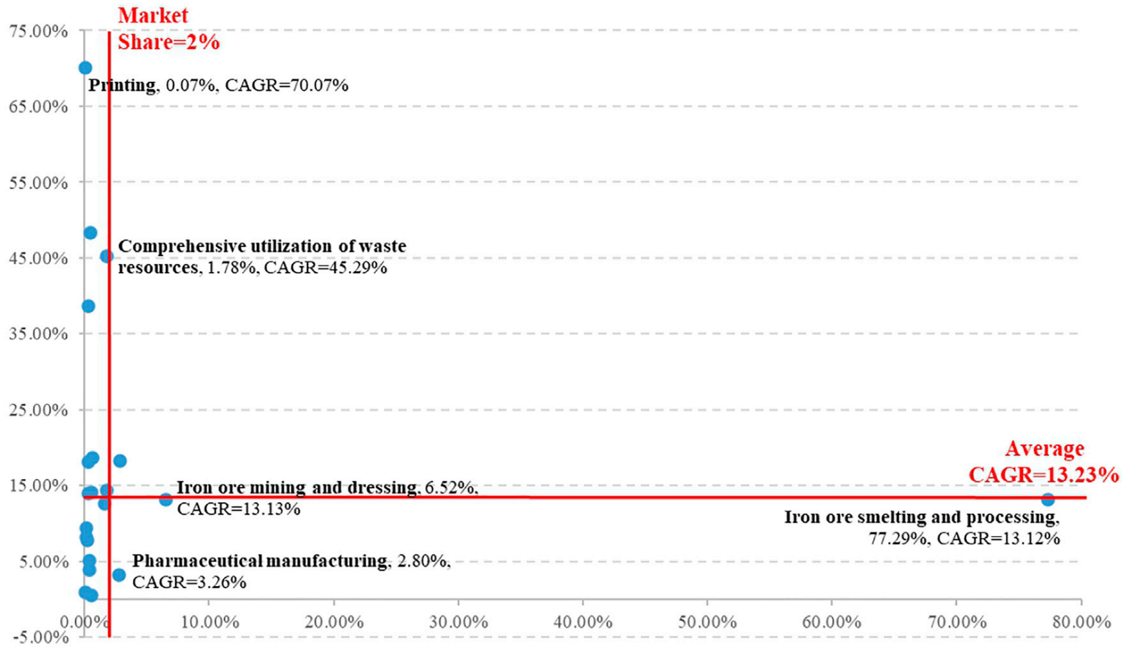


**FIGURE 3 |** Boston matrix of industrial output value, Benxi, 2016-2020. Data source: Benxi Statistical Yearbook, 2001-2020

Benxi accounted for 29.01% (national average 18.7%), and over 65 years old accounted for 19.11% (national average 13.5%)).

## Environmental Performance: Severe Pollution Caused by the Steel Industry

The secondary industry, especially the steel industry, has long been the root cause of the environmental problems of Benxi. For example, the proportion of industrial waste in total waste is around 40%, while the provincial average is around 15%. Over the years, by implementing measures that selected Benxi as a national demonstration city for the construction of ecological civilization and defined this city as an "important water conservation area, the 'hinterland' of ecological security, and the ecological 'barrier'" of Liaoning province, Benxi has made some achievements in environmental protection. For example, in 2020, the number of days above grade II (good) ambient air quality in the city was 319, while 274 in 2015. The total emission of sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) has decreased compared with the situation in the past, the same as the wastewater emission from the iron and steel industry.

Nevertheless, the progress of the transformation is not satisfactory, and the pressure on resources and environmental protection is still severe. As the mineral resources industry is still vital, coupled with the needs for agricultural planting and road construction, the pressure on land and water resources is huge, and the ecological functions such as forest water conservation, hydrological regulation and storage, and biodiversity protection continue to decline. The industrial structure dominated by iron and steel with high energy consumption and high emission will be maintained for a long time. For instance, in 2020, the average dust content in the air was 8.4 t/($km^2$·month), 0.4 t/($km^2$·month) higher than the provincial standard. The energy consumption per unit of GDP did not meet the provincial standard. The total emission of carbon dioxide and major significant pollutants was still high, with *Bensteel Group* accounting for 84.3%. Among them, the emission of $SO_2$ and $NO_x$ is prominent. In 2020, the annual average emission concentrations of $SO_2$ and $NO_x$ were 17 μg/$m^3$ and 30 μg/$m^3$, respectively. Moreover, the PM 2.5 concentration in 2020 was 37 μg/$m^3$. It did not reach the national average level of 30 μg/$m^3$ in that year, and it was also far from that of well-performed industrial cities in China. In addition, as the main source of solid waste (accounting for 19.5% of the city's output), the average utilization rate of the iron and steel industry is only 24%, which is far lower than the national average. Current situations indicate that the mineral industries and products in Benxi can be characterized as inefficient, resource-consuming, and not so environment-friendly. The low level of science and technology in the mineral industries led to such problems. Furthermore, this is why none of plenty of those existing treatments can make a substantial difference to the conditions of the environment and resources.

## Summary

The analysis of the current situation of Benxi shows that the path of giving priority to heavy industries with high resource consumption and high pollution frustrates the development of Benxi, together with its efforts to solve the crux of the "resource curse." More specifically, the deep reliance on *Bensteel Group* and the inability to promote environment-friendly production due to the low level of science and technology cause Benxi's difficulties in both environmental and economic aspects and hinder the

**TABLE 1 |** Three patterns of transformation of mineral resource-based cities.

| | Pattern | Similarities | Difference |
|---|---|---|---|
| **Type I** ***Kawasaki, Japan*** | Transforming to an innovative city based on traditional industries | 1. Form **a diversified industrial structure** integrating manufacturing and services<br>2. Develop **high-tech industries** (new materials, biomedicine, environmental protection, and information technology.) | **Retain** the mineral resource industry |
| **Type II** ***Ruhr Region, Germany*** | Taking the strategy of new industrialization based on traditional industries | 3. Improve **urban service functions** (leisure, entertainment, culture, tourism, medical treatment, and education.)<br>4. Strengthen **environment protection** | **Reduce** the mineral resource industry |
| **Type III** ***Pittsburgh, US*** | Transforming to a city of "green, science, and high-tech" and abandoning traditional industries | 5. Combine **colleges and universities** with the local economy<br>6. Stimulate the development of **small- and medium-sized enterprises** | **Abandon** the mineral resource industry |

*The bold values provided in Table 1 are the things we want to emphasize, i.e., keywords in the similarities and differences.*

transformation process. Therefore, there is still a long way for resource-based cities such as Benxi to fully realize their transformation goals and sustainable development and numerous effective policies on green development, such as giving impetus to clean production and setting more stringent emission standards, are urgently needed.

# COMPARISON OF PATTERNS OF TRANSFORMATION AND POLICY IMPLICATIONS

## Policy Experience From Three Patterns of Transformation

The development of the mineral resources of Benxi has impacted its environment a lot. A series of policies issued by the local government have effectively promoted the city's transformation. However, there is still a big gap between the policy effect of Benxi and the advanced level as optimizing the industrial structure is the fundamental way to form high-quality development. The problems faced by global mineral resource-based cities similar to Benxi have tried to transform. Among them, the transformation of Kawasaki in Japan, Ruhr in Germany, and Pittsburgh in the United States were successful. This study summarizes the policies experienced in the three cities mentioned earlier in their transformation processes (see **Table 1**).

Kawasaki is a representative of "Retaining the mineral resources industry." The city has gradually evolved from a steel manufacturing city to one composed of a highly developed service industry and technology-intensive industries. This city upgraded its technology gradually and made full use of the original market demand, which designed more research and development (R&D) bases for new materials and environmental industries based on retaining the iron and steel industries and chemical industries. By transforming the past manufacturing plants into the core R&D bases of enterprises, Kawasaki constructed high value-added and knowledge-intensive industries, cultivated small- and medium-sized enterprises, and turned the small- and medium-sized enterprises that had originally provided support for transforming large enterprises into enterprises with R&D capabilities.

Ruhr Industrial Zone is a world-famous heavy industry base. Its transformation focused on "Reducing the mineral resources industry" and was committed to implementing "new industrialization." Compared with the pattern of Kawasaki, it emphasized developing and diversifying traditional industries upstream and downstream of them. In this pattern, new technologies comprehensively changed traditional industries, and high-tech industries such as the information technology industry rose. At the same time, the upstream and traditional downstream industries have made significant progress. Industries such as real estate, electronic systems, technical consulting, and service trade developed successively, absorbing the unemployed labor force from the coal and steel industries. It is worth mentioning that higher education in the Ruhr district is closely combined with economic development, industry, university, and research deeply integrated, which has promoted the improvement of technological innovation and further stimulated the transformation of the industrial structure.

Pittsburgh has transformed from "the steel capital of the world" to "the most livable city in the US." This process of "abandoning the mineral resources industry" supported by education is remarkable. Pittsburgh has achieved a comprehensive transformation from a single steel industry to a diversified economy, including biotechnology, computer technology, machine manufacturing, education, medical treatment, tourism, and finance. Relying on two prestigious universities, the University of Pittsburgh and Carnegie Mellon University and their disciplinary advantages in medicine and computers, the city has vigorously developed emerging technology industries such as biomedicine, information communication, and new materials. The city has constructed a complete technology transformation mechanism, and has promoted the financial market represented by venture capital. Also, when having its secondary industry reformed, Pittsburgh attached great importance to education, life, leisure, and infrastructure construction simultaneously to produce more employment opportunities and promote the overall improvement of urban quality.

To summarize, there are many dimensions to the implications of the transformation of resource-based cities according to the three patterns. Measures to adjust the economic structure to avoid a dominant industry, boost innovation and the development of science and technology, promote environment-friendly industries, improve public services in cities, and preserve the environment need to be implemented.

## Actionable Recommendations for Benxi

It is necessary to apply the merits of the three patterns to the transformation of China's mineral resource-based cities. The policy suggestions in terms of the current economic and environmental performance of Benxi to shield the city from being troubled by the "resource curse" and promote its sustainable development are provided as follows.

First of all, Benxi should consider promoting the construction of technology-intensive and environment-friendly industries. The newly arranged industrial clusters in Benxi may be incapable of supporting its sustainable development. For example, the packaging and printing industrial cluster is difficult to contribute to the potential long-term stable growth of Benxi, and this industry will still have a negative impact on the environment. The entry of local high-tech industries can better promote the TFP and economic growth (Barro and Lee, 1994; Yang and Wang, 2004) with greater environmental performance. Therefore, under the goal of sustainable development, Benxi should vigorously promote the construction of technology-intensive and environment-friendly industries, such as new materials, new energy, environmental protection, and other industries (Wei et al., 2022). For the iron and steel industry, Benxi ought to scientifically regulate and control the iron and steel output, focus on reasonably predicting the output in combination with the relevant requirements of waste gas emission and environmental capacity, and pay attention to strengthening energy management and green production research and development (Wei et al., 2021). A gradual reduction in reliance on the steel industry should also be considered.

Second, Benxi should be committed to improving the urban service functions and service attributes. Benxi still retains its obvious characteristics as a traditional industrial city. Although the proportion of the service industry is gradually increasing, the urban service function is still limited, not to mention the underdeveloped higher education. Therefore, Benxi should emphasize improving urban service functions and service attributes, especially the development of scientific research and education, cultivation of research bases, and combination of primary and higher education with local economic development. In addition, environmental renovation can also be used to expand the city's leisure functions, such as constructing landscape parks and developing shopping tourism (e.g., Industrial Heritage Tourism).

Last but not least, Benxi ought to assist in developing small and medium-sized enterprises and provide diversified and efficient supporting policies. The current industrial pattern of Benxi City regards *Bensteel Group* as the core. The leading enterprise has monopolized the input from Benxi, which may erode the growth space of other enterprises and industries. The existence of super-large enterprises may also affect the allocation of labor share (Autor et al., 2020). In this case, Benxi is supposed to support the development of small- and medium-sized enterprises, weaken the financing and policy barriers restricting their development, and focus on cultivating several small- and medium-sized enterprises with R&D capacity to add more vitality to the process of economic development and transformation.

# CONCLUSION

Resource-based cities can often face the "resource curse" after mature development. The transformation of the industrial structure is the only way to realize both economic and ecological benefits and achieve sustainable and high-quality development. As a typical mineral resource-based city, Benxi has further optimized its environment and significantly improved its industrial structure by implementing economic and environmental policies. However, some problems have not been solved yet. Compared with the three successful transformation cases of mineral resource-based cities worldwide, the local transformation effect needs to be improved. Therefore, relevant policies should be upgraded by concentrating on innovation and the high-tech industry's development and deeply combining education with industry in the three cases. As for Benxi's case, its excessive dependence on the iron and steel industry has eroded the development space of emerging industries. The negative impact of high energy consumption and emissions on environmental resources persists and has not been fundamentally improved. Under such circumstances, this study puts forward a series of suggestions, including vigorously building technology-intensive and environment-friendly industries, reasonably regulating the output of iron and steel, focusing on developing science and education, and supporting small- and medium-sized enterprises. This study aims to provide a possible path for Benxi's transformation and the transformation and high-quality development of resource-based cities in China and even the world.

# AUTHOR CONTRIBUTIONS

HL conceived of the idea and outlined the brief. XW collected data and wrote the first draft of the article. HL and ZC made important modifications to the brief. All authors contributed to article revision and have both read and approved of the submitted version.

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# Spatial Differences and Influencing Factors of Urban Water Utilization Efficiency in China

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The purpose of urban water management is to improve urban water utilization efficiency (UWUE), which in turn addresses water shortages in urban areas. The present study aimed to evaluate the UWUE of 284 cities at the prefecture level in China between 2003 and 2018 by the slacks-based measure of super-efficiency, explore its spatial differences through exploratory spatial data analysis, and analyze the influencing factors using the statistical tool Geodetector. The results showed that the average value of UWUE in China was generally low but tended to rise gradually. There were significant spatial differences in UWUE across China, with considerable global and local spatial autocorrelation, and local spatial autocorrelation was characterized primarily by high-high and low-low regions. Industrial structure and urban population were the main influencing factors for UWUE. Finally, based on these findings, we offered policy implications for improving UWUE and coordinated development between cities.

**Keywords: urban water utilization efficiency, spatial difference, influencing factor, slacksbased measure of super-efficiency, exploratory spatial data analysis, geodetector**

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## 1 INTRODUCTION

According to a report by the Food and Agriculture Organization of the United Nations, with the rapid growth of the global population, the per capita supply of freshwater resources has decreased by over 20% in the past 20 years (Cazcarro and Steenge 2021). Global water consumption has increased sixfold in the past 100 years and has grown at an annual rate of about 1%. It is estimated that by 2050, more than half of the world's population will face water shortages (Liao et al., 2021). Affected by natural conditions and continued economic development, China also sustains a severe shortage of water resources (Deng et al., 2021). On the one hand, uneven spatial and temporal distributions, mismatches between supply and demand, the lack of public awareness of water conservation, and extensive use of water resources pose a massive challenge to the "ecological civilization" and sustainable development (Liu et al., 2022). On the other hand, China *per se* is extremely short of urban water resources, as evidenced by water shortages in nearly all provincial capitals. More than 400 out of the 660 cities in China are short of water, of which 110 are facing grievous situations (Huang Y. et al., 2021). Water utilization efficiency (WUE) refers to the ratio of the optimal input of water resources to their actual input required by economic and social demands, namely, the economic value of products manufactured per unit of water consumption (Sileshi et al., 2020). In the situation of water shortage, improving the WUE is of great significance in two aspects. First, the improvement of WUE means improving the intensive and economical utilization of water resources, which helps to reduce the waste of water resources and realize the sustainable utilization of water resources. Second, the improvement of WUE means increasing the economic output per unit of water consumption, which is helpful to further improve economic benefits. Therefore, improving China's urban water utilization efficiency (UWUE) may be a pivotal solution to water shortages in cities.

Most previous studies have focused on WUE, while little attention has been directed to UWUE. These studies favor industry sectors and regions as the object of WUE evaluation, especially agriculture and industry. Since water plays a crucial role in maintaining agricultural security, improving agricultural WUE becomes an important means of promoting sustainable agricultural development (Namaalwa et al., 2020; Liu et al., 2021). The consumption of water resources has been increasing with industrialization, and improving WUE may play an essential part in developing a system of green industrial production. For this reason, researchers have made efforts to find a way to increase industrial WUE (Shang et al., 2017; Liu et al., 2020a; Liu et al., 2020b). Previous studies on the spatial differences in WUE have focused on provincial administrative units or the overall situation across China. In addition, attention has also been paid to the WUE in strategic regions, such as the Yellow River Basin (Guan et al., 2016), the Yangtze River Basin (Pan et al., 2020), and the Tibetan Plateau (Cheng et al., 2021).

Four methods have been used to calculate WUE in previous studies: 1) water footprint (Cao et al., 2021); 2) comprehensive indicator evaluation (Zhang et al., 2019; Song et al., 2020); 3) single factors (Li et al., 2008); and 4) the total factor of WUE (Hu et al., 2006; Shi et al., 2021; Liu et al., 2022), such as stochastic frontier analysis (SFA) and data envelopment analysis (DEA). The first three simple methods cannot reflect the dependency of the output of the production process on multiple factors. It is vital to take into consideration the inputs of factors other than investment in water resources when calculating WUE. Compared with SFA, DEA does not require the basic functional form and gives consideration to a variety of inputs and outputs. It thus has significant advantages in the measurement of efficiency.

WUE is the result of multiple factors. Some researchers have been concerned with single factors, such as environmental regulation (Wang and Wang 2021), the fattening period in animal husbandry (Huong et al., 2020), and national policies on WUE (Zhang et al., 2020; Zhang et al., 2021). Other researchers have examined the effects of multiple factors. According to them, positive factors included dependence on exports (Deng et al., 2016), technical progress and educational value (Wang G. et al., 2018), government behavior (Yang et al., 2020), economic growth, urbanization, and effective irrigation (Lu et al., 2021). Conversely, negative factors were agricultural added value, per capita water consumption, and unit output of sewage (Deng et al., 2016), industrial structure (Wang S. et al., 2018), population pressure (Yang et al., 2021), and per capita water resources (Lu et al., 2021). Some studies focused on the agricultural sector for resources utilization (Elahi et al., 2021a; Elahi et al. 2021b; Elahi et al.2022a; Elahi et al.2022b).

The above-referenced studies contribute knowledge to the spatial pattern and genesis of WUE at the provincial scale and provide a reference for policymaking. However, little attention has been paid to the WUE of cities (UWUE). Cities are highly populated and economically concentrated areas that consume large water volumes for both domestic and industrial purposes. In other words, the research on UWUE is of great significance. In the present study, we evaluated the UWUE of 284 cities at the prefecture level in China using the slacks-based measure (SBM) of super-efficiency based on unexpected output. On this basis, we also explored the spatial differences in UWUE by exploratory spatial data analysis (ESDA) as well as the influencing factors with the statistical tool Geodetector. The contributions of this study to the existing literature include: 1) The research object of cities rather than provinces can enrich the research content of WUE. 2) Cities are smaller than provinces, and the spatial differences in UWUE between them can reflect the spatial pattern of WUE more accurately. 3) The influencing factors of UWUE at the prefecture level can provide more empirical evidence for UWUE and offer a reference for policymaking.

## 2 METHODS AND DATA

### Methods

#### 2.1.1 Slacks-Based Measure of Super-efficiency

Since DEA focuses only on the expected output of economic activities and ignores unexpected output, its results may be biased (Liu et al., 2010). As such, SBM based on unexpected output was used to calculate UWUE in China, which took into consideration the unexpected output in the production process (Tone 2001). The specific procedures are described as follows:

Suppose there are n decision-making units (DMUs) in the production system. Each unit is composed of three input–output vectors: 1) input, 2) an expected output, and 3) an unexpected output. The three input–output vectors can be expressed as:

$$X = [x_1,\ x_2,\ \ldots, x_n] \in R^{m\times n} \tag{1}$$

$$Y^g = \left[y_1^g, y_2^g,\ \ldots, y_n^g\right] \in R^{s_1\times n} \tag{2}$$

$$Y^b = \left[y_1^b, y_2^b,\ \ldots, y_n^b\right] \in R^{s_2\times n} \tag{3}$$

Suppose $X > 0$, $Y^g > 0$, and $Y^b > 0$. Then, the set of possibilities of production can be defined as:

$$P = \left\{\left(x, y^g, y^b\right)\middle| x \geq X\theta,\ y^g \geq Y^g\theta,\ y^b \leq Y^b\theta,\ \theta \geq 0\right\} \tag{4}$$

The actual expected output is lower than the ideal expected output of the frontier, while the actual unexpected output is higher than the unexpected output. Based on the set of production possibilities, the SBM model that considers the unexpected output in the DMU of evaluation ($x_0$, $y_0^g$, $y_0^b$) is as follows:

$$\rho = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} S_i^- / x_{i0}}{1 + \frac{1}{S_1 + S_2}\left(\sum_{r=1}^{S_1} S_r^g / y_{r0}^g + \sum_{r=1}^{S_2} S_r^b / y_{r0}^b\right)}\ s.t. \begin{cases} x_0 = X\theta + S^- \\ y_0^g = Y^g\theta - S^g \\ y_0^b = Y^b\theta - S^b \\ S^- \geq 0,\ S^g \geq 0,\ S^b \geq 0,\ \theta \geq 0 \end{cases} \tag{5}$$

In the formula, $S = (S^-, S^g, S^b)$ = the slacks in input, expected output, and unexpected output, respectively; $\rho$ = the efficiency of the DMU (0-1). For a given DMU $(x_0, y_0^g, y_0^b)$, if and only if $\rho = 1$, that is, when $S^- = S^g = S^b = 0$, it is effective; if $0 \le \rho < 1$, the evaluated unit is inefficient, and the input and output need to be improved. This nonlinear model is not conducive to the calculation of efficiency. Therefore, it was transformed into a linear model by the Charnes-Cooper transformation:

$$\tau = \min t - \frac{1}{m}\sum_{i=1}^{m}\frac{S_i^-}{x_{i0}}, \text{ s.t.} \begin{cases} 1 = t + \dfrac{1}{S_1 + S_2}\left(\sum_{r=1}^{S_1}\dfrac{S_r^g}{y_{r0}^g} + \sum_{r=1}^{S_2}\dfrac{S_r^b}{y_{r0}^b}\right) \\ x_0 t = X\mu + S^- \\ y_0^g t = Y^g\mu - S^g \\ y_0^b t = Y^b\mu - S^b \\ S^- \ge 0,\ S^g \ge 0,\ S^b \ge 0,\ \mu \ge 0,\ t > 0 \end{cases} \tag{6}$$

Most indicators used to assess efficiency involve a common phenomenon that the DMUs have 100% efficiency. It is necessary to distinguish these DMUs and the factors affecting the efficiency ranking. To ensure that the efficiency analysis yields reasonable values, SBM of super-efficiency was used for calculation in the present study:

$$\rho^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\overline{x_i}}{x_{i0}}}{\frac{1}{S_1+S_2}\left(\sum_{r=1}^{S_1}\bar{y}_r^g / y_{r^0}^g + \sum_{r=1}^{S_2}\bar{y}_r^b / y_{r^0}^b\right)}$$

$$s.t. \begin{cases} \bar{x} \ge \sum_{j=1,\ne k}^{n}\theta_j x_j \\ \bar{y}^g \le \sum_{j=1,\ne k}^{n}\theta_j y_j^g \\ \bar{y}^b \ge \sum_{j=1,\ne k}^{n}\theta_j y_j^b \\ \bar{x} \ge x_0,\ \bar{y}^g \le y_0^g,\ \bar{y}^b \ge y_0^b,\ \bar{y}^g \ge 0,\ \theta \ge 0 \end{cases} \tag{7}$$

The value of the objective function $\rho^*$ represents the efficiency of the DMU. The definitions of the other variables are the same as those used in **Eq. 6**. The above models are based on the assumption that the scale is constant.

### 2.1.2 Exploratory Spatial Data Analysis

ESDA is a collection of spatial data analysis techniques used to describe the spatial distribution of data and express it visually. It can explain spatial differences in data and reveal the mechanism of spatial interaction between phenomena (Messner et al., 1999; Dong et al., 2021). ESDA takes use of global Moran's $I$ and local Moran's $I$, and the former can express the spatial distribution of UWUE in an entire region. If global Moran's $I$ is >0, the research object has a positive spatial autocorrelation, and the larger the value, the stronger the spatial agglomeration. It was calculated as follows:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}} \tag{8}$$

$$S = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{9}$$

In the formula, $n$ = the number of units in the research area; $x_i$ and $y_j$ = the UWUEs of units $i$ and $j$; $\bar{x}$ = the average of all units; $Wij$ = the spatial weight matrix of units $i$ and $j$. If $i$ and $j$ have a boundary in common, $Wij = 1$; otherwise, $Wij = 0$. The standardized statistic was used to test the significance as follows:

$$Z(I) = \frac{[1 - E(I)]}{\sqrt{Var(I)}} \tag{10}$$

Wherein, $Z(I)$ = significance; $E(I)$ = mathematical expectation; $Var(I)$ = variance.

Local Moran's $I$ expresses the spatial heterogeneity of UWUE in subregions of a given region. Combined with the scatter diagram and local Moran's $I$, the local indicators of spatial association (LISA) clustering map can directly show the types of clustering and significance levels of different elements, as given in **Eq. 11**:

$$I_i = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{S^2} \tag{11}$$

The significance of local Moran's $I$ is given in **Eq. 11**. By comparing the signs of $Z(I)$ and the significance levels of $I_i$, the research area whose significance levels reach a certain threshold ($p = 0.05$) can be divided into four types of spatial autocorrelation. If $I_i$ is significantly positive and $Z(I) > 0$, it is a "high-high" type, which means that the UWUEs of the given city and its adjacent cities are high, and they are designated as "hot spots". If $I_i$ is significantly positive and $Z(I) < 0$, it is a "low-low" type, which means that the UWUEs of the given city and adjacent cities are low, and they are "cold spots". If $I_i$ is significantly negative and $Z(I) > 0$, it is a "high-low" type, suggesting that cities with high UWUE are surrounded by cities with low UWUE. If $I_i$ is significantly negative and $Z(I) < 0$, it is a "low-high" type, indicating that cities with low UWUE are surrounded by cities with high UWUE. If $I_i$ is significantly positive, this illustrates a significant local spatial positive correlation, reflecting spatial aggregation. If $I_i$ is significantly negative, this indicates a significant local spatial negative correlation, reflecting spatial dispersion.

### 2.1.3 Geodetector

The Geodetector makes no linear hypothesis and has an elegant form and a clear physical meaning (Wang et al., 2010). The q-statistic can be used to measure spatial differentiation, detect explanatory factors, and analyze the interaction between variables. It has been widely used to explore the influencing factors for resources and the environment (Zhou et al., 2019; Huang C. et al., 2021; Wei et al., 2021). In the present study, it was calculated as follows:

$$P_{D,UWUE} = 1 - \frac{1}{n\sigma_{UWUE}^2}\sum_{i=1}^{m}n_{D,i}\sigma_{UWUE_{D,i}}^2 \tag{12}$$

In the formula, $P_{D,UWUE}$ = the driving force of UWUE; D = the factor driving UWUE; $n$ = sample size; $\sigma^2$ = the variance of the research objects; $m$ = the number of categories of a factor; $n_{D,i}$ =

**TABLE 1 |** Descriptive statistics of the indicators of UWUE.

| Indicator | Variable | Units | Sample Size | Mean | Median | Standard Deviation | Maximum | Minimum |
|---|---|---|---|---|---|---|---|---|
| Input | Investment in fixed assets | 10,000 yuan | 4544 | 10,811,319.65 | 5983936 | 14,631,539.37 | 186,614,099 | 165,672 |
| | Total water supply | 10,000 tons | 4544 | 16,227.79 | 7043.5 | 31,166.22 | 320,400 | 349 |
| | Number of employees in urban areas | 10,000 persons | 4544 | 31.93 | 14.135 | 65.90 | 819.3 | 1.02 |
| Expected output | GDP | 10,000 yuan | 4544 | 16,356,025.63 | 8533802.5 | 26,162,615.89 | 326,798,700 | 317,731 |
| Unexpected output | Wastewater discharge | 10,000 tons | 4544 | 7530.26 | 5617.5 | 6552.85 | 30,081 | 88 |

the samples size of indicator $D$ in class $i$. The range of values of $P_{D,UWUE}$ is [0, 1]. The larger the value, the stronger the explanatory power of this factor for UWUE. A value of zero indicates that the given factor has nothing to do with UWUE, and a value of one means that the relevant factor can fully explain UWUE.

## Indicators

Indicators need to be determined to assess UWUE in China from the perspectives of input, expected output, and unexpected output. Capital, resources, and labor force required in economic production yield not only expected outputs such as economic growth and income but also unexpected outputs such as resource consumption and environmental pollution. Some researchers have investigated the characteristics of water resources utilization in economic production (He et al., 2020). In light of the availability and comparability of data, capital, water resource, and labor force were taken into consideration as the input-related indicators of UWUE and were expressed as the investment in fixed assets, total water supply, and the number of employees in urban areas, respectively. Economic growth was regarded as an indicator of the expected output of UWUE and expressed as the gross domestic product (GDP). Wastewater discharge was deemed as an indicator of the undesirable outputs of UWUE and expressed as industrial wastewater discharge. **Table 1** shows the descriptive statistics of the UWUE indicators.

## Source of Data

The data of the five indicators were all derived from China's Economic and Social Big Data Research Platform (https://data.cnki.net/). There are totally 333 cities above the prefecture level in China. Since the data of some cities in central and western China were unavailable, 284 of them were finally included in this study.

# 3 RESULTS

## The Evolution of UWUE in China

SBM of super-efficiency was employed to assess UWUE in China between 2003 and 2018, as shown in **Figure 1**, which showed two prominent characteristics. First, the overall UWUE of Chinese cities during this period was low. As previously described in Wang et al. (2020), 0.6 was used as the standard to gauge efficiency. The year of 2018 saw the maximum number of cities (82) with a UWUE >0.6, accounting for 28.9% of the 284 cities. 2006 and 2007 witnessed the minimum number of cities (10) with a UWUE >0.6, accounting for only 3% of the total. Only a few cities in China had high UWUEs, suggesting that there is considerable room for improvement in UWUE. This result was consistent with the results of other research on WUE efficiency (Liu et al., 2022). The fundamental reason for this is that the long-term rapid economic growth in China depends on the traditional growth model featuring extensive investment of resources, labor, and other factors. This inefficient model consumes huge water resources and produces large volumes of wastewater discharge, thereby resulting in a low overall UWUE in China.

Second, the overall UWUE appeared to be on the rise during the research period. This phenomenon can be described more concisely and directly by dividing the cities into regions and scales. China's regional economic layout can be divided into four regions: eastern China, central China, western China, and Northeastern China (**Table 2**.) (Li and Liu 2020). The evolution of the average UWUEs in China and its four regions is illustrated in **Figure 2**, which shows a fluctuating upward trend from 2003 to 2015, with slight declines in some years. After 2015, UWUE rose significantly, possibly because the government decided to promote the "ecological civilization" ever since for resource conservation and environmental protection. According to the scale type of the resident population, Chinese cities can be divided into five types: super megacity, megacity, large-scale city, medium-scale city, and small-scale city (Qi et al., 2016). The city-size classification standard in China is listed in **Table 3**. The average UWUEs of different scales are illustrated in **Figure 3**, indicating that the UWUEs of different scales tended to increase. Since 2008, the UWUE in super megacities has maintained the highest level for a long time. The possible reasons are as follows: First, the developed technology of super megacities is conducive to improving the level of economical and intensive utilization of water resources; Second, super megacities have a higher degree of population and economic agglomeration, which can bring significant agglomeration benefits in the process of water resources utilization. The UWUE in large-scale cities has remained at the lowest level in recent years. The possible reason is that there is a high demand for water resources due to the large population and economic scale, but the technical level and agglomeration effect have not been brought into play, resulting in the low level of UWUE.

ArcGIS 10.2 was used to test global spatial agglomeration, which demonstrated that global Moran's $I$ was positive and

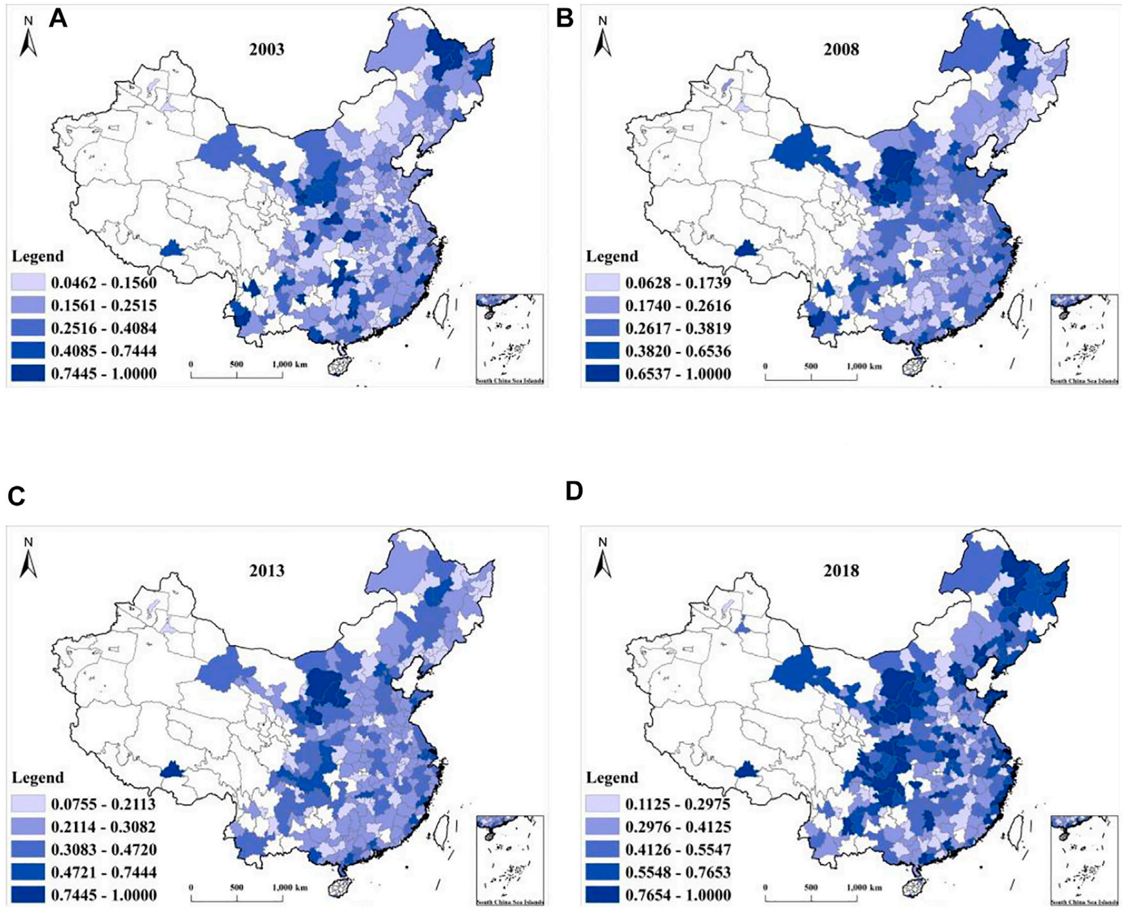


**FIGURE 1 |** China's UWUEs between 2003 and 2018. **(A)** 2003; **(B)** 2008; **(C)** 2013; **(D)** 2018. Note: This figure shows only the results of 4 years, and the others can be seen in **Supplemental Materials**.

**TABLE 2 |** Four regions in China.

| Regions | Provinces (Municipality Directly under the Central Government, Autonomous Region) |
|---|---|
| Eastern China | Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan |
| Central China | Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan |
| Western China | Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang |
| Northeastern China | Liaoning, Jilin, and Heilongjiang |

passed the 1% significance test (**Table 4**). The UWUE across China was similarly characterized by spatial agglomeration, which could be used to identify hot and cold spots. The overall global Moran's I increased, indicating that spatial agglomeration of UWUE in China was becoming increasingly prominent.

ArcGIS 10.2 also demonstrated that UWUE was characterized by remarkable local spatial autocorrelation (**Figure 4**). This result was also consistent with the findings of other research on WUE efficiency (Liu et al., 2022). The relevant regions can be divided into the four types mentioned above. Together, the high-high and low-low regions accounted for more than 60% of all cities in each year and more than 70% throughout the research period. The high-high cities were distributed mainly in northwestern, northeastern, and southwestern China, while the urban agglomerations of Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta were scattered in individual years. The low-low cities were distributed mainly in northeastern and central China. The results of both global and local spatial autocorrelation showed that there were significant spatial differences in UWUE across China.

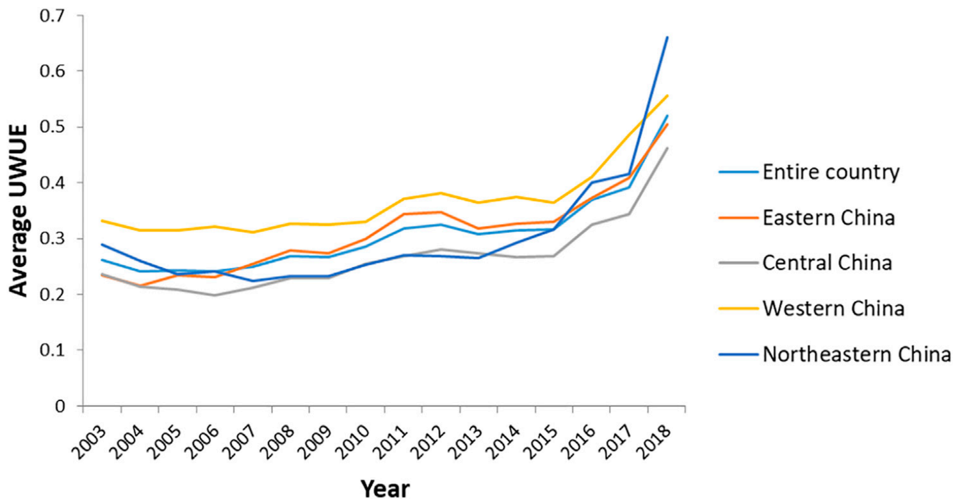


**FIGURE 2 |** Average UWUEs in China and its four regions.

**TABLE 3 |** City-size classification standard in China.

| Type of City | Super Megacity | Megacity | Large-Scale City | Medium-Scale City | Small-Scale City |
|---|---|---|---|---|---|
| Resident population | ≥1 million | (5 million, 10 million) | (1 million, 5 million) | (0.5 million, 1 million) | <0.5 million |

*Spatial Differences in UWUE.*

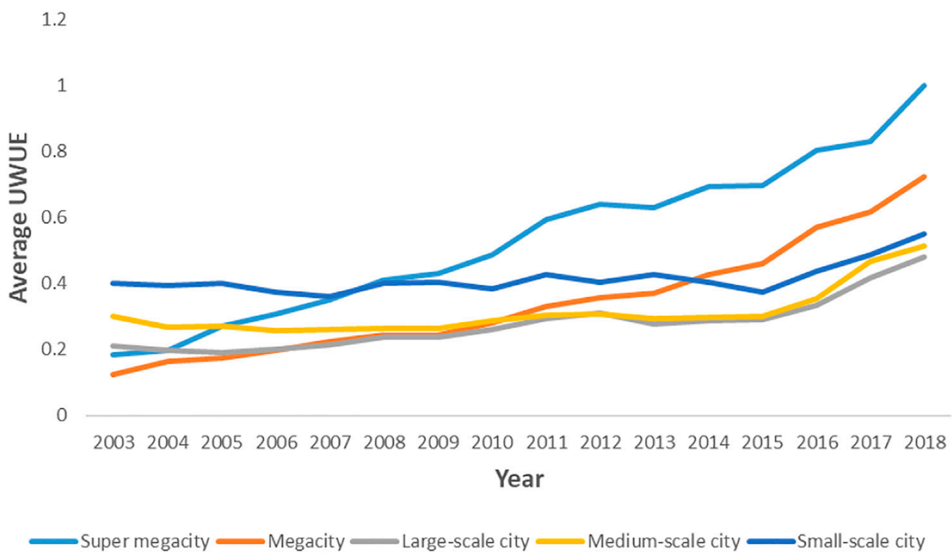


**FIGURE 3 |** Average UWUEs of different scales of cities.

## Influencing Factors for UWUE

WUE is affected by various economic, social, and natural factors. With reference to a previous study (Babuna et al., 2020), in the present study, urban population, industrial structure, resident income, technological progress, the volume of surface water, and environmental regulation were selected as the potential influencing factors for UWUE and justified as follows.

1) Urban population. This is a frequently used indicator of urbanization. The larger the indicator, the higher it can drive the growth of urban consumption, which improves

**TABLE 4 |** Global spatial autocorrelation of UWUE in China.

| Year | Moran's *I* | *Z* | *p* value |
|---|---|---|---|
| 2003 | 0.151 | 6.45 | 0.000000 |
| 2004 | 0.158 | 7.85 | 0.000000 |
| 2005 | 0.146 | 8.59 | 0.000000 |
| 2006 | 0.174 | 8.40 | 0.000000 |
| 2007 | 0.205 | 7.66 | 0.000000 |
| 2008 | 0.226 | 7.87 | 0.000000 |
| 2009 | 0.186 | 9.21 | 0.000000 |
| 2010 | 0.208 | 8.29 | 0.000000 |
| 2011 | 0.301 | 7.55 | 0.000000 |
| 2012 | 0.324 | 8.98 | 0.000000 |
| 2013 | 0.284 | 7.60 | 0.000000 |
| 2014 | 0.255 | 8.94 | 0.000000 |
| 2015 | 0.303 | 7.71 | 0.000000 |
| 2016 | 0.205 | 6.39 | 0.000000 |
| 2017 | 0.234 | 7.47 | 0.000000 |
| 2018 | 0.298 | 6.70 | 0.000000 |

the input and output of the economy. However, a larger urban population also entails excessive consumption of water resources, which in turn affects UWUE (Meng et al., 2021). It is expressed as the number of people residing in a given urban area.

2) Industrial structure. The state of industrial structure is an important indicator of economic growth. Different industrial structures lead to significant differences in economic output, water consumption, and wastewater discharge, which in turn affect UWUE (Zhu and Zhang 2021). It is expressed as the share of the secondary industry.
3) Resident income. Resident income promotes the input and expected output of UWUE but may also impact the unexpected output. With increasing resident income, residents are more aware of the need to save water, which reduces the discharge of industrial wastewater. However, this also increases demand for products, which increases the discharge of industrial wastewater (Liu L. et al., 2020). Resident income is expressed as the per capita disposable income of urban residents.
4) Technological progress. This is not only the result of economic growth but also its cause, and affects the input and expected output of UWUE. Technological progress affects industrial wastewater discharge from two aspects: technological innovation in industrial production can reduce the amount

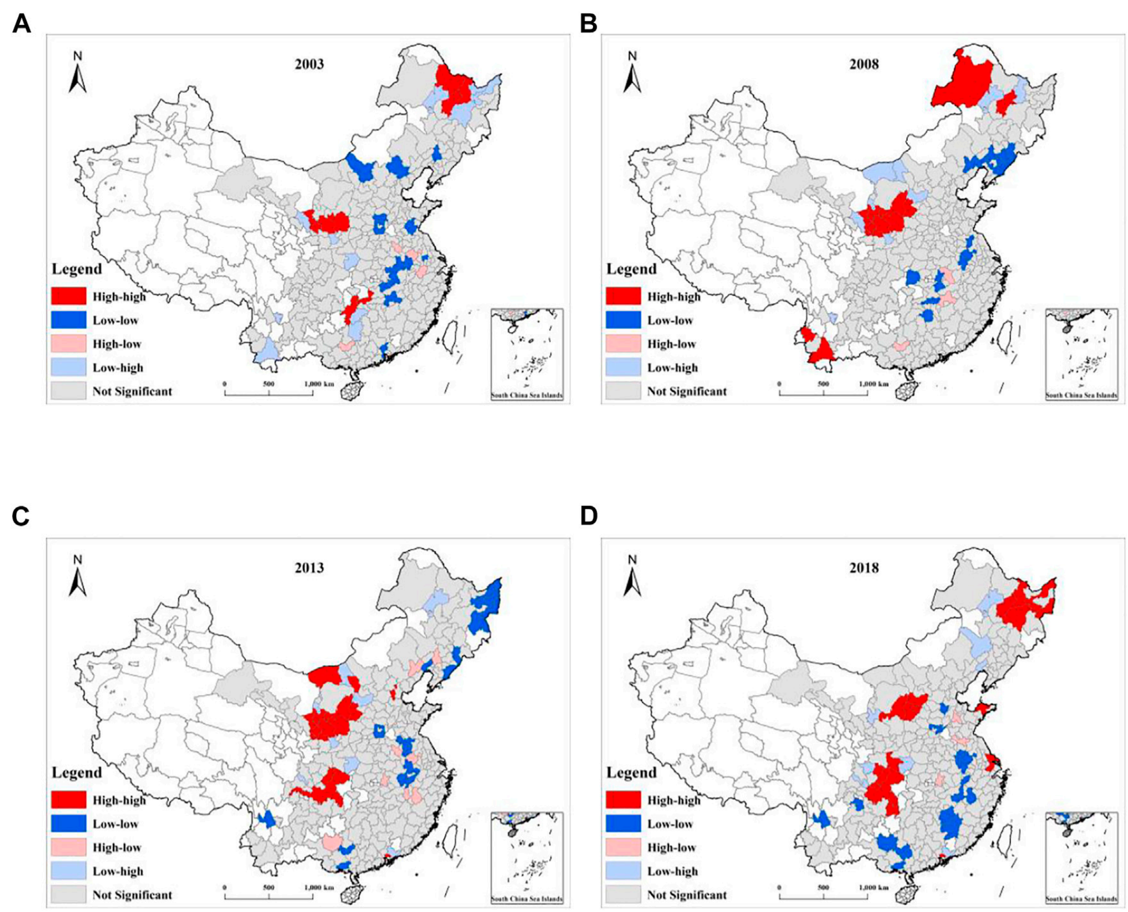


**FIGURE 4 |** Local spatial autocorrelation of UWUE in China between 2003 and 2018. **(A)** 2003; **(B)** 2008; **(C)** 2013; **(D)** 2018. Note: This figure shows only the results of 4 years, and the others can be seen in **Supplemental Materials**.

**TABLE 5 |** Analysis of UWUE using Geodetector.

| Year | Urban Population | Industrial Structure | Resident Income | Technological Progress | Volume of Surface Water | Environmental Regulation |
|---|---|---|---|---|---|---|
| 2003 | 0.2206 | 0.3111 | 0.0017 | 0.1242 | 0.0013 | 0.0022 |
| 2004 | 0.2331 | 0.4662 | 0.0012 | 0.1097 | 0.0012 | 0.0018 |
| 2005 | 0.2192 | 0.4563 | 0.0014** | 0.1052 | 0.0004 | 0.0018 |
| 2006 | 0.2172 | 0.5030 | 0.0013 | 0.1124 | 0.0005 | 0.0012 |
| 2007 | 0.2533 | 0.5617 | 0.0012 | 0.1002 | 0.0003 | 0.0039** |
| 2008 | 0.2512 | 0.5822 | 0.0012 | 0.0935 | 0.0016 | 0.0029 |
| 2009 | 0.2655 | 0.6406 | 0.0019 | 0.1005** | 0.0012 | 0.0033** |
| 2010 | 0.2824 | 0.6011 | 0.0018 | 0.1017** | 0.0014 | 0.0028 |
| 2011 | 0.2811 | 0.6782 | 0.0017 | 0.0958** | 0.0013 | 0.0037 |
| 2012 | 0.2316 | 0.6908 | 0.0004*** | 0.0870 | 0.0015 | 0.0041 |
| 2013 | 0.2582 | 0.7205 | 0.0003 | 0.0807 | 0.0012 | 0.0022 |
| 2014 | 0.2312 | 0.7536 | 0.0004 | 0.0924** | 0.0008 | 0.0027 |
| 2015 | 0.2512 | 0.7779 | 0.0002 | 0.0967** | 0.0013 | 0.0021 |
| 2016 | 0.2880 | 0.7705 | 0.0008 | 0.0877 | 0.0017 | 0.0030** |
| 2017 | 0.2662 | 0.7834 | 0.0007 | 0.0855 | 0.0006 | 0.0034 |
| 2018 | 0.3436 | 0.7991 | 0.0011 | 0.0939 | 0.0011 | 0.0037 |

*Note: ** and ***represent significance at levels of 10 and 5%, respectively; the other values are significant at the 1% level.*

of discharged wastewater, and technological progress may lead to expansion of production and an increase in wastewater discharge (Chen Z. et al., 2021). In this study, the number of patent applications was used to represent technological progress.

5) The volume of surface water. This is a natural factor affecting UWUE. Under the same conditions, the greater the volume of surface water, the greater the total volume of water supply in a city (Song et al., 2021). It is expressed as the volume of surface water in a given urban area.
6) Environmental regulation. The purpose of environmental regulation is to protect the environment, improvements in which can save water and thus improve UWUE (Fu et al., 2021). It is expressed as the amount of investment in environmental pollution control.

**Table 5** shows the analysis results of the six indicators pertaining to UWUE in China with Geodetector. Industrial structure and urban population made significantly greater contributions to UWUE than the other four factors, hence the primary influencing factors for UWUE. Technological progress played a role, while resident income, the volume of surface water, and environmental regulation had little impact on UWUE. This differed from the influencing factors of agricultural WUE, namely, technological progress and farmers' income (Liu et al., 2022).

With respect to urban industrial structure in China, 125 out of the 284 cities studied were dominated by secondary industry in 2018. The structure of urban industry had been dominated by secondary industry for a long time and was in the middle of rapid industrialization. An inverted U-shaped relationship was observed between water consumption and economic growth in different stages of industrialization, where this was commonly known as the environmental Kuznets curve. Rapid industrialization with respect to industrial structure led to increased consumption and rising demand for water resources. Moreover, a large volume of wastewater discharge was inevitably the result of industrial production. Therefore, the industrial structure was the biggest factor affecting UWUE in China.

A clue to the impact of urban population on UWUE could be seen from **Figure 3** mentioned above. UWUE in small-scale cities was highest between 2003 and 2007. This could be attributed to low water consumption and sewage discharge in small-scale cities, and therefore UWUE could be maintained at a high level compared with other types of cities. Since 2008, super megacities enjoyed the highest UWUE instead of small-scale cities. For a long time, there were only six super megacities in China: Beijing, Tianjin, Shanghai, Shenzhen, and Chongqing. The highest UWUE in these six cities could be attributed to the government's promotion of national economic and environmental protection policies as well as the agglomeration effect produced by these huge urban populations. With the gradual agglomeration of populations and economies to form super megacities, in addition to the effect of technological progress improving UWUE, the various elements of agglomeration helped to reduce the consumption and pollution of water resources, thereby improving their utilization efficiency as a result of the building and utilization of water resource infrastructure. Therefore, the agglomeration of large-scale urban populations could improve UWUE.

# 4 CONCLUSIONS AND POLICY IMPLICATIONS

## Conclusions

This study attempted to evaluate UWUE and exploring its spatial differences and influencing factors. We evaluated the UWUE of 284 cities at the prefecture level in China between 2003 and 2018 by SBM of super-efficiency, explored its spatial differences through ESDA, and analyzed the influencing factors using

Geodetector. The findings were as follows: The average value of UWUE in China was generally low but tended to rise gradually. There were significant spatial differences in UWUE across China, with considerable global and local spatial autocorrelation, and local spatial autocorrelation was characterized primarily by high-high and low-low regions. Industrial structure and urban population were the main influencing factors for UWUE. This study has some limitations. We analyzed the spatial differences of UWUE by ESDA, which could reflect the spatial autocorrelation characteristics of UWUE but could not reflect the spatial differences of UWUE comprehensively. In the future, it is necessary to further study the spatial differences of UWUE using Dagum's decomposition of the Gini coefficient and kernel density estimation.

## Policy Implications

In view of the overall low UWUE in China, it is necessary for urban managers to comprehensively understand the nature and dynamics of their water usage, increase investment in water resources in terms of capital, technology, and talent, and reduce wastewater and sewage discharge. It is also important for industrial enterprises to improve water-saving and pollution control technologies for the improvement of UWUE. Citizens are expected to become aware of the importance of saving water and reducing waste. Efforts should also be made to coordinate industrial production, living demands, and ecological water use between all cities and build "green systems" to secure water supplies.

As for the substantial impact of industrial structure on UWUE, it is important for cities to build a modern industrial structure to cater to the use of green water resources. The industrial upgrade is an important means of improving UWUE. It is necessary to transform labor-intensive industries into new industrial clusters based on innovations in capital and technology. Moreover, it is also essential to keep abreast of structural adjustments and technological progress and transform traditional industries that consume large amounts of water.

With regard to the impact of urban population on UWUE, it is crucial to strengthen the effect of the population agglomeration of megacities and large-scale cities. The populations of these two types of cities have accounted for a large proportion but they have yet witnessed an agglomeration effect. In particular, the UWUE of large-scale cities has become the lowest since 2013. It is necessary to make specific action plans to improve UWUE in these cities. In addition, it is also important to give full play to the radiation effect of super megacities, so that medium- and small-scale cities can enjoy the benefits of technology transfer, thereby improving their UWUE.

In terms of the spatial differences in UWUE, it is necessary to establish a coordinated mechanism to strengthen regional technical cooperation and form contiguous, highly efficient regions for water resource use to improve the UWUE of all cities. Regions with high UWUE are expected to rely on their advantages of capital and technology to explore more channels for spillover. Regions with low UWUE are supposed to invest in science and technology and strengthen environmental monitoring and government supervision. This includes a joint supervision system and information sharing mechanism between local tax departments and water conservation departments.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://data.cnki.net/.

## AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Conceptualization, KL and ZC; methodology, WL and JW; software, WL and JW; validation, KL, WZ; formal analysis, KL, WZ; investigation, JW; resources, KL; data curation, JW; writing—original draft preparation, KL; writing—review and editing, ZC, FL; supervision, ZC; project administration, KL, FL. All authors read and approved the final manuscript.

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# Fiscal Pressure and Air Pollution in Resource-Dependent Cities: Evidence From China

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Under the dual pressure of central environmental performance appraisal and fiscal pressure, local Chinese governments, especially those in resource-dependent cities, struggle with reprioritizing environmental protection over economic growth while staying under budget. However, the empirical impact of such endeavors on pollution control remains underexplored. Based on 2003–2018 panel data on resource-dependent cities in China, this paper adopts a dynamic panel model to explore the effect of local government fiscal pressure on air pollution. The results show that (1) due to the effect of path dependency on existing economic development patterns, resource-dependent cities suffer from a vicious circle where fiscal pressure aggravates air pollution emissions. (2) As shown by the heterogeneity test, air pollution emissions increase significantly as financial pressure becomes severe; the situation also worsens in mature-type resource-dependent cities. (3) The increase in the number of years in the office of top local government leaders exacerbates the negative effect of fiscal pressure on air pollution; in contrast, the increase in age of these officials mitigates the negative effect. (4) The results of the mechanism test show that financial pressure mainly aggravates environmental degradation by hindering industrial structure upgrading and inhibiting urban green innovation.

**Keywords: resource-dependent cities, fiscal pressure, air pollution, industrial upgrading, urban green innovation, China**



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## 1 INTRODUCTION

Since the reform and opening up, an extensive growth model has driven the rapid development of China's economy at the expense of environmental quality (Wei et al., 2021a; Wei et al., 2021b; Shen et al., 2021). In recent years, improvements have been made under a series of environmental regulations. According to the 2020 National Overview of Ecological and Environmental Quality, 202 out of 337 cities at or above the prefectural level met the national standards for air quality. The rest of these cities still need to make improvements.

Resource-dependent cities are those with resource exploitation and processing as the leading industry. As suppliers of energy and essential raw materials, these cities contribute to China's long-term economic growth, but the industrial structure based on energy consumption significantly impacts environmental pollution. In China, resource-based cities account for 43% of the total number of cities. As one of the major national strategies for energy development, the transformation of resource-dependent cities is highly related to the country's ability to acquire and utilize natural

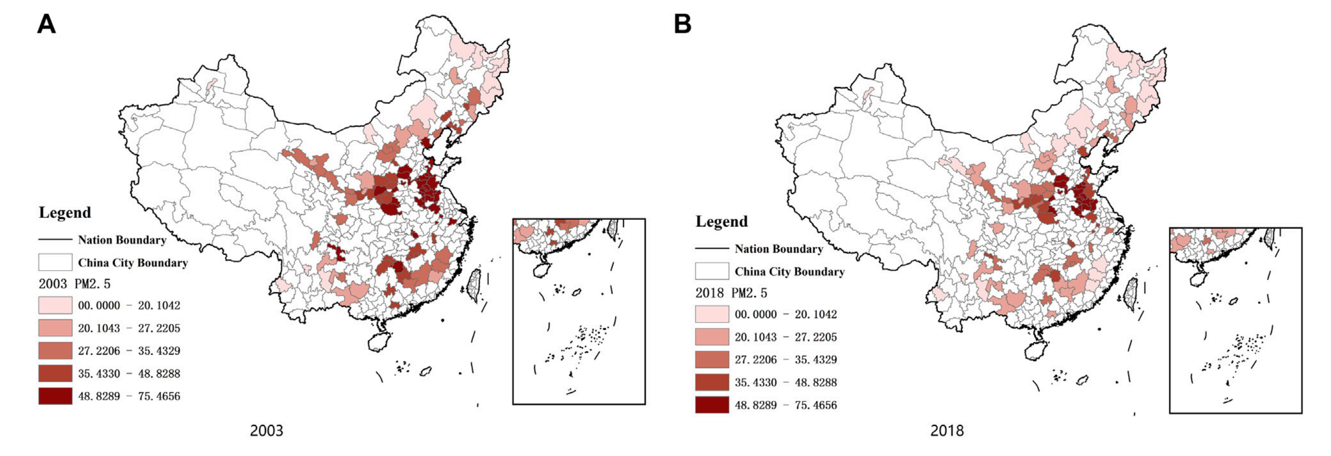


**FIGURE 1 |** Emission concentration of $PM_{2.5}$ in resources-dependent cities in 2003 **(A)** and 2018 **(B)**.

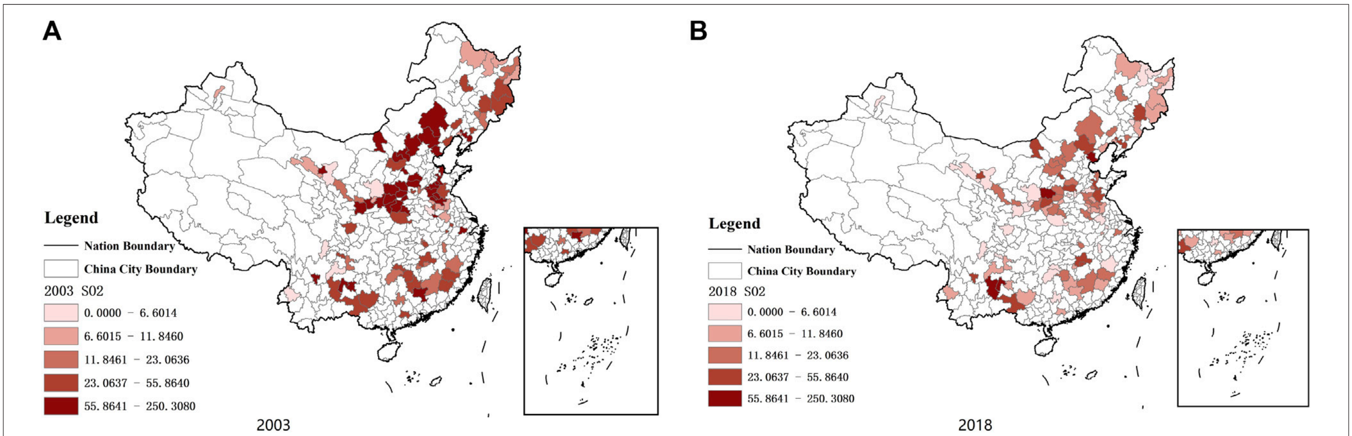


**FIGURE 2 |** Emission concentration of $SO_2$ in resources-dependent cities in 2003 **(A)** and 2018 **(B)**.

resources and has an important impact on the sustainable development of the national economy. Cities with poor ambient air quality are mainly resource-dependent cities. In these cities, the distortion of energy consumption and factor endowment structure has led to a low comprehensive utilization rate of resources, high energy consumption and pollutant emissions, and dependence on resource-based industries that cause severe environmental pollution (Li et al., 2015; Ma et al., 2018; Marais et al., 2018). The country's 14th Five-Year Plan prioritizes the transformation of resource-dependent cities to mitigate the problem. The plan attaches great importance to the imbalance and incongruity between economic development and ecological protection in resource-dependent cities.

Economic growth has reached a plateau in recent years, and fiscal pressure has increased in parallel with stagnation. At the same time, accelerating ecological improvement and maintaining high-quality development has become the national strategy, as stated in a report of the 19th Communist Party of China (CPC) National Congress. Therefore, it is essential to understand how local governments should coordinate and balance economic growth and environmental protection, especially in resource-dependent cities where trade-offs are difficult to make. **Figures 1**, **2** show the $PM_{2.5}$ and industrial SO2 emission concentrations of resource-dependent cities in 2003 and 2018. Over time, air pollution emissions have decreased, but the overall concentration level remains high.

An increase in financial pressure weakens the government's ability to coordinate economic regulation and the public service supply, which is not conducive to the high-quality development of the national economy (Xu et al., 2020). One of the ways that the central government incentivizes local governments and officials is through performance evaluations. Since the tax distribution reform in 1994, the central government has been in charge of distributing fiscal revenue, while local governments control economic development and fiscal expenditure. As a result, local governments rely heavily on transfer payments from the central government, and the vertical imbalance of the fiscal system intensifies local financial pressure. The situation worsened after major fiscal and tax system reforms, such as the agricultural tax reform and value-added tax reform (Xu et al., 2020). **Figure 3** shows China's fiscal revenue and

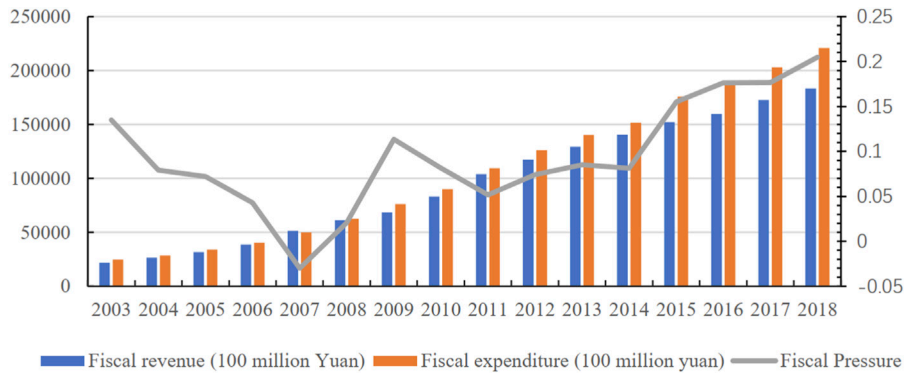


**FIGURE 3 |** China's fiscal revenue and expenditure, 2003–2018.

expenditure. The gap between fiscal revenue and expenditure increases year by year, and fiscal pressure increases year by year. In recent years, since China's implementation of the large-scale "tax and fee reduction" policy, together with the impact of COVID-19, the government's fiscal revenue has decreased while expenditure has increased. As a result, fiscal pressure on governments has significantly increased.

In the transitional stage of economic development, the sources of financial pressure on local governments are even more multifaceted. On the one hand, they face top-down political performance evaluation pressure from the central government; on the other hand, pressure also comes from the bottom-up demand for public infrastructure, environmental health, and peer pressure from other local governments. In other words, the natural endowment fund gap caused by the reform of the financial system and the competitive fund gap caused by the promotion tournament have led to the severe financial pressure faced by local governments.

Resource-dependent cities contribute to China's industrialization by providing sufficient resources for the country's economic growth, but the unsustainable exploitation of resources causes severe ecological and environmental problems. Therefore, the transformation and upgrading of resource-dependent cities are the keys to achieving high-quality development. Under tremendous fiscal pressure, it is essential to understand whether resource-dependent cities can reverse the traditional mentality of development first, save the environment later, and transform the development mode. This paper focuses on the impact of fiscal pressure on air quality and the mechanism of this impact in resource-dependent cities. A total of 114 resource-dependent cities in China were selected to test the environmental effects of fiscal pressure and the mechanism from 2003 to 2018 based on a dynamic panel model. Specifically, the system generalized method of moments (SYS-GMM) and difference generalized method of moments (DIFF-GMM) methods are adopted. The paper has sought to provide an alternative explanation for the *dual dilemma* of economic growth and environmental protection in resource-based cities and identifies the role of fiscal pressure in the transformation and upgrading of resource-based cities.

## 2 THEORETICAL FOUNDATION AND HYPOTHESES

The principal-agent theory is the basis of fiscal decentralization theory. The information asymmetry between the central and local governments is likely to cause a moral hazard in the performance of local government functions. Under vertical fiscal imbalance, local governments face the dilemma of alleviating financial pressure while achieving high-quality development. Kou and Han (2021) explored the relationship between local fiscal pressure and local environmental regulatory behavior based on 2003–2017 Chinese provincial panel data. Their study found that fiscal pressure weakens local environmental regulation. Bai et al. (2018) took tax competition as a strategy for coping with fiscal pressure to explore the environmental effects induced by corporate income tax competition and the value-added tax in 30 provinces in China. Their study found that interregional tax competition not only reduces local environmental quality but also produces spillover effects and worsens the environment of neighboring regions. In contrast, other studies have shown that fiscal decentralization positively impacts environmental quality (Wen and Lee, 2020; Su et al., 2021).

Economic development is highly reliant on resource-dependent industries in resource-dependent areas, and financial pressure may aggravate the imbalance of the industrial structure, forming a resource curse and accelerating pollution emissions. On the one hand, resource-dependent cities have been adopting a high energy consumption and high emission production mode for a long time, and the regional industrial development mode has become path-dependent, posing a great threat to ecology and the environment (Karlsson, 2012; Takatsuka et al., 2015; Jiao et al., 2020). On the other hand, based on officials' promotion incentive theory, financial pressure will force local governments to choose the development mode of emphasizing development and ignoring environmental protection. This incentivization mechanism will relax environmental regulation, accelerate resource industry development, and aggravate environmental pollution. Denise et al. (2017) showed that local governments produce a race-to-the-bottom effect and aggravate environmental degradation under fiscal pressure. Lin and Zhou (2021) studied the environmental performance of fiscal decentralization from the perspective of vertical fiscal imbalance based on 2000–2017 Chinese provincial panel data. The study showed that vertical fiscal imbalance could weaken environmental performance and cause more severe environmental deterioration in eastern China. Local governments tend to support high-tax industries to relieve financial pressure and increase budgetary revenue. Although such industries can relieve financial pressure, local governments in regions with greater financial pressure will relax environmental regulation more and attract large taxpayers by lowering the threshold of environmental protection, causing a substantial negative impact on environmental quality (Cole and Fredriksson, 2009; Dean et al., 2009; Han and Kung, 2015). Therefore, this paper proposes the following hypothesis:

H1: In resource-dependent cities, a high resource endowment leads to serious environmental problems in the region, and financial pressure accelerates air pollution emissions and further aggravates environmental deterioration, leading to the "Matthew effect".

Furthermore, as the government is the leading actor in regional environmental governance, the decision-making behavior of local governments has an essential impact on regional environmental governance. The individual characteristics of officials, such as their age, term of office, and other individual factors, affect their governing philosophy and decision-making behavior (Mccabe et al., 2008). On the one hand, the increasing age of local officials is conducive to improving environmental quality. Based on 2002–2014 panel data on Chinese cities, Yu et al. (2019b) explored the environmental effects of the individual characteristics of government officials. They found that older officials attach more importance to environmental issues. In contrast, young local officials have a strong desire for promotion and ample promotion space. Therefore, they will sacrifice environmental quality to promote economic growth in the short term and introduce high-pollution and high-tax enterprises to drive economic growth.

As officials get senior in age, the probability of promotion decreases. They become more rational in industrial planning and transformation for sustainable urban development and have relatively strong motivation to improve basic public services, such as regional environmental quality (Li and Zhou, 2005). Admittedly, while promotion incentives become relatively low for older officials, the potential cost of the punishment increases due to increased environmental accountability posed by the central government. Hence, the officials are more motivated to implement environmental measures and improve environmental quality to avoid the risk of punishment (Bai and Kung, 2014). In addition, older local officials may have more experience in politics and better coordinate the relationship between regional economic growth and environmental protection.

On the other hand, the longer the tenure of local officials is, the worse the environmental effects of fiscal pressure. Fan and Tian (2013) found that with an increase in the term of office of local officials, the probability that they will be "captured" by current enterprises gradually increases; additionally, the government-enterprise collusion network surrounding officials solidifies gradually. The longer the term of local officials is, the greater the likelihood that government-enterprise collusion will occur. Enterprises rely on the government to provide policy guidance and financial support for their production and operation. In turn, the government relies on the enterprises in its jurisdiction to guarantee employment and economic growth. Therefore, under government-enterprise collusion, local officials with longer terms of office have the incentive to lower regional environmental regulatory standards, thus acquiescing to local enterprises to maintain an extensive development mode and reducing the production costs of enterprises (Wu et al., 2014; Jia, 2017). Such practice leads to an increase in environmental pollution and a decrease in the environmental quality of the jurisdiction. Maintaining an appropriate level of turnover of officials can restrain government-enterprise collusion to a certain extent, which is conducive to environmental governance. Therefore, the following hypothesis is proposed:

H2: In resource-dependent cities, with the increase in the tenure of officials, the air pollution effect of financial pressure intensifies. As local officials become senior in age, the environmental effects of fiscal pressure can be ameliorated.

If financial pressure in resource-dependent cities aggravates regional air pollution, this phenomenon naturally raises the next question. What are the mechanisms of the impact of financial pressure on air quality deterioration? Previous studies show that technological progress, especially green technology innovation, is an important means of achieving green development (Aghion et al., 2016; Acemoglu et al., 2012; Calel and Dechezlepretre, 2016). The choice of technology is not only coupled with the thought, perception, knowledge, and skills of the technology creator but is also subject to the factor endowment characteristics of the technology origin (Basu and Weil, 1998; Antonelli, 2016; Dong and Wang, 2021). For example, if regional capital and skills are relatively abundant and the market size is relatively large, regional technological progress will be characterized by a capital or skill bias (Acemoglu, 2002; Jerzmanowski and Tamura, 2019; Chen, 2020). Therefore, the energy endowment characteristics of resource-dependent cities are likely to lead to a nonclean bias in regional technological progress, further hindering the development of regional low-carbon environmental technologies and forming a pollution "lockin effect" (Balsalobre-Lorente et al., 2018; Unruh, 2002; Unruh and Hermosilla, 2006). According to resource curse theory, the economic development of such regions does not benefit from large-scale resource development and crowds out other types of production activities, forming a resource advantage trap (Gylfason, 2001; Sachs and Warner, 2001; Papyrakis and Gerlagh, 2007), and inhibits green technology innovation (Li and Xu, 2018). In addition, resource-dependent cities in China suffer from other problems, such as unreasonable resource development and lagging industrial structure adjustment (Sun and Ding, 2005; Li and Dewan, 2017; Li et al., 2021), which worsen the situation.

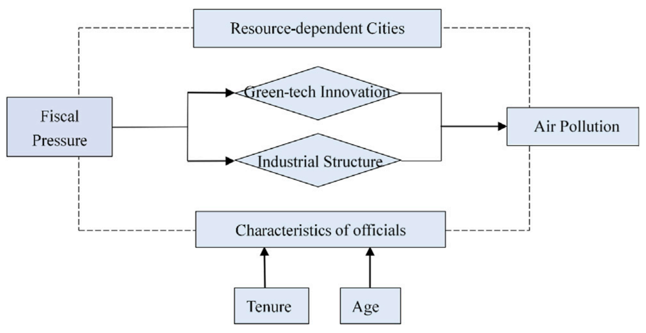


**FIGURE 4 |** Pathways of financial pressure effect.

Regarding the industrial structure, resource-dependent cities are dominated by the secondary industry, and resource-dependent industries with higher pollution emissions have lower resource exploitation and utilization costs. Regional industrial development is gradually prone to path dependency, aggravating regional environmental deterioration (Romanelli and Khessina, 2005). The transformation and upgrading of the economic development mode of resource-dependent cities are imminent (Emrah and Cali, 2018). Therefore, the following hypothesis is proposed:

H3: In resource-dependent cities, financial pressure intensifies environmental degradation mainly by crowding out green technology innovation and hindering the upgrading of industrial structures.

In summary, the mechanism of the impact of financial pressure on air pollution in resource-dependent cities is shown in **Figure 4.** The rest of this paper is structured as follows. **Section 3** describes the econometric models and data sources, **Section 4** shows the empirical results, and **Section 5** includes the conclusion and policy implications.

## 3 ECONOMETRIC MODELS AND DATA SOURCES

The potential path-dependent characteristic of pollution emissions is taken into account to test the environmental effects of fiscal pressure. This characteristic refers to the situation that the environmental situation in the previous year may have an impact on the environmental situation in the next year (Shao et al., 2011). The omission of dynamic characteristics may lead to model bias (Wooldridge, 2001). Therefore, this paper examines the effect of fiscal pressure on pollution emissions in resource-dependent cities through a dynamic panel model, which can reflect the path-dependent characteristic of pollution emissions.

$$pollution_{it} = \delta_0 + \alpha_1 pollution_{it-1} + \beta_0 pressure_{it} + \gamma_x X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where $pollution_{it}$ represents the pollution emissions of resource-based cities. $pollution_{it-1}$ represents the lagged first-order term of pollution emissions in resource-dependent cities, reflecting the path-dependent effect of pollution emissions. $pressure_{it}$ represents fiscal pressure. If the coefficient $\beta_0$ is positive, fiscal pressure exacerbates air pollution in resource-based cities and vice versa. $X_{it}$ represents control variables. $\delta_0$ is the intercept. $\gamma_x$ is the estimated coefficient of each control variable, $\lambda_t$ is the time fixed effect, $\mu_i$ is the individual fixed effect, and $\varepsilon_{it}$ is the error term.

Dependent variables: $pollution_{it}$ represents the pollution emissions of resource-based cities, characterized by PM2.5 concentration (PM2.5) and PM2.5 concentration per unit output (dPM2.5) in this paper. The PM2.5 concentration data are annual averages obtained by optical satellite space remote sensing in the Air Quality Life Index Report (AQLIR) issued by the Energy Policy Institute of the University of Chicago. This data source effectively addresses the lack of monitoring data in specific years and cities (Wang et al., 2022).

Key independent variable: Fiscal stress is caused by fiscal deficits resulting from persistent imbalances between fiscal revenues and fiscal expenditures. Specifically, under the fiscal decentralization system, the persistent imbalance between local government revenues and expenditures or the fiscal gap induced by the imbalance between fiscal revenues and expenditures results in a consolidated fiscal balance (Cai et al., 2022). In this paper, we refer to Bai et al. (2018) and use the gap between fiscal expenditure and fiscal revenue as a proportion of fiscal revenue to characterize fiscal pressure, with large values characterizing high fiscal pressure.

Control variables: Research and development (R&D) investment (Rd): Technological progress is an important factor that affects environmental conditions and depends on regional R&D investment. Thus, this paper uses the share of science expenditure in GDP to characterize R&D investment (Dong and Wang, 2021). Foreign direct investment (Fdi): The impact of foreign direct investment on the environment may lead to the pollution haven effect or the pollution halo effect. This paper uses the product of the actual use of foreign investment and the annual average exchange rate as a proportion of GDP for characterization (Zhang and Zhou, 2016). Governance (Gov): The government is the dominant force in environmental governance. We use the share of government fiscal expenditure in GDP to characterize government dominance (Li and Xu, 2018). The population growth rate (Peo): According to the impact–population–affluence–technology (IPAT) model, population growth is an important factor that affects environmental conditions, for which it is necessary to control the population growth rate (Zhou and Liu, 2016). Based on the segmentation of resource-dependent cities in the Sustainable Development Planning of National Resource-dependent Cities (2003–2020), the study collated data on 114 prefecture-level resource-dependent cities. Data were collected from the *Statistical Yearbook of Chinese Urban Cities* and *Statistical Yearbook of China's Regional Economy*. The descriptive statistics of the variables are presented in **Table 1**.

**TABLE 1 |** Descriptive statistics of variables.

| Variable | N | Mean | Sd | Min | p50 | Max |
|---|---|---|---|---|---|---|
| $\ln PM_{2.5}$ | 1824 | 3.556 | 0.570 | 1.141 | 3.606 | 4.691 |
| $\ln dPM_{2.5}$ | 1824 | −12.100 | 0.937 | −15.057 | −12.097 | −9.647 |
| Pressure | 1824 | 2.002 | 1.745 | 0.0240 | 1.486 | 17.40 |
| Rd | 1824 | 0.001 | 0.001 | 0.000 | 0.001 | 0.011 |
| Gov | 1824 | 0.181 | 0.103 | 0.031 | 0.153 | 1.027 |
| Fdi | 1824 | 0.0140 | 0.016 | 0.000 | 0.009 | 0.115 |
| Peo | 1824 | 0.0050 | 0.033 | -0.433 | 0.005 | 0.840 |

# 4 RESULTS

## 4.1 Baseline Model

**Table 2** shows the regression results of the impact of financial pressure on pollution emissions in resource-dependent cities. Model (1) and model (2) take the $PM_{2.5}$ concentration as the regression result of the explained variable, and model (3) and model (4) take the $PM_{2.5}$ concentration per unit of output as the regression result of the explained variable. In addition, the SYS-GMM and DIFF-GMM regression methods are used to estimate the dynamic panel model, which can effectively alleviate problems of endogeneity and reduce bias in the empirical results.

The results show that regardless of whether the $PM_{2.5}$ concentration or the $PM_{2.5}$ concentration per unit of output is the explained variable, the coefficient of financial pressure on resource-dependent cities remains positive and significant at the 1% level under different regression models. This indicates that financial pressure on resource-dependent cities will accelerate pollution emissions and lead to environmental deterioration. The result shows that governments will take extensive measures to stimulate production at the cost of sacrificing the environment when dealing with fiscal pressure in resource-dependent cities. H1 is proven to be valid. Regarding the control variables, the coefficient of the first-order lag term of pollution emissions remains positive and significant at the 1% level, indicating that pollution emissions have strong path-dependent characteristics. The impact of R&D investment (Rd) on pollution emissions remains negative and significant at the 1% level, indicating that increasing R&D investment can restrain pollution emissions and improve environmental quality by promoting technological progress. The influence of government leadership (Gov) on pollution emissions is negative and significant at the 1% level, indicating that the government, as the main body of environmental governance, plays a vital role in improving environmental quality. The influence of foreign direct investment (Fdi) on pollution emissions is positive and significant at the 1% level, indicating that foreign direct investment aggravates environmental pollution and that the pollution haven effect is established in China's resource-dependent cities. The impact of population growth (Peo) on pollution emissions is significantly negative, indicating that the current slowdown in population growth in China is conducive to reducing pollution emissions and improving environmental quality to a certain extent.

**TABLE 2 |** Baseline test of the impact of financial pressure on pollution emission of resource-dependent cities.

| Variable | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | **SYS-GMM** | **DIFF-GMM** | **SYS-GMM** | **DIFF-GMM** |
| | **$LnPM_{2.5}$** | **$LnPM_{2.5}$** | **$LndPM_{2.5}$** | **$LndPM_{2.5}$** |
| $L.\ln PM_{2.5}$ | 0.8513*** | 0.6151*** | | |
| | (0.0016) | (0.0016) | | |
| $L.\ln dPM_{2.5}$ | | | 0.8469*** | 0.8336*** |
| | | | (0.0014) | (0.0017) |
| Pressure | 0.0091*** | 0.0082*** | 0.0480*** | 0.0540*** |
| | (0.0005) | (0.0005) | (0.0006) | (0.0009) |
| Rd | −13.7369*** | −20.0847*** | −54.7797*** | −56.2772*** |
| | (0.6421) | (0.4526) | (1.1569) | (1.1705) |
| Gov | −0.2152*** | −0.1397*** | −0.5631*** | −0.7023*** |
| | (0.0076) | (0.0066) | (0.0148) | (0.0217) |
| Fdi | 1.8281*** | 1.4307*** | 2.8771*** | 1.1298*** |
| | (0.0949) | (0.1112) | (0.1837) | (0.3358) |
| Peo | −0.1766*** | −0.0382*** | −0.1257*** | −0.1118*** |
| | (0.0179) | (0.0108) | (0.0221) | (0.0163) |
| _cons | 0.5346*** | 1.3802*** | −1.9292*** | −2.0482*** |
| | (0.0052) | (0.0069) | (0.0158) | (0.0205) |

*Note: ***, ** and * represent the significance level of 1, 5 and 10% respectively. The numbers in brackets are the corresponding standard errors. The Sargan test and AR (2) test have been carried out in this paper, both accepting the null hypothesis, the same as below.*

**TABLE 3 |** Robustness test of the impact of financial pressure on pollution emission of resource-dependent cities.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Variable | SYS-GMM $LnSO_2$ | DIFF-GMM $LnSO_2$ | SYS-GMM $LndSO_2$ | DIFF-GMM $LndSO_2$ |
| L. $LnSO_2$ | 1.1312*** | 1.1339*** | | |
| | (0.0036) | (0.0026) | | |
| L. $LndSO_2$ | | | 1.1207*** | 1.1331*** |
| | | | (0.0022) | (0.0025) |
| Pressure | 0.1011*** | 0.0638*** | 0.0380*** | 0.0147*** |
| | (0.0015) | (0.0011) | (0.0016) | (0.0010) |
| Control var | YES | YES | YES | YES |
| _cons | −0.3065*** | −0.2591*** | 1.3147*** | 1.4179*** |
| | (0.0126) | (0.0100) | (0.0255) | (0.0306) |

Robustness tests are conducted by replacing the explanatory variables; that is, $PM_{2.5}$ emissions are replaced by $SO_2$ emissions. The regression results are shown in **Table 3**. In models (1) and (2), the regression results are based on using the $SO_2$ concentration as the explanatory variable, while in models (3) and (4), the $SO_2$ concentration per unit of output is used. The dynamic panel models are estimated using the SYS-GMM and DIFF-GMM regression methods. The results show that regardless of whether the explanatory variable is the $SO_2$ concentration or the $SO_2$ concentration per unit of output and regardless of the regression method that is used, the regression coefficient of fiscal pressure (Pressure) remains positive and significant at the 1% level, which further confirms that fiscal pressure has a positive effect on air pollution emissions and induces pollution effects that are detrimental to environmental quality improvement.

**TABLE 4 |** Influence of different financial pressure intensities on air pollution emissions in resource-dependent cities.

| | First 1/2 | Last 1/2 | First 1/2 | Last 1/2 | First 1/2 | Last 1/2 | First 1/2 | Last 1/2 |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| | SYS-GMM | SYS-GMM | DIFF-GMM | DIFF-GMM | SYS-GMM | SYS-GMM | DIFF-GMM | DIFF-GMM |
| | $LndPM_{2.5}$ | $LndPM_{2.5}$ | $LndPM_{2.5}$ | $LndPM_{2.5}$ | $LndSO_2$ | $LndSO_2$ | $LndSO_2$ | $LndSO_2$ |
| $L.lndPM_{2.5}$ | 0.8792*** | 0.8174*** | 0.7994*** | 0.7166*** | | | | |
| | (0.0033) | (0.0026) | (0.0059) | (0.0042) | | | | |
| $L.LndSO_2$ | | | | | 1.0705*** | 1.0846*** | 1.0547*** | 1.0750*** |
| | | | | | (0.0036) | (0.0022) | (0.0065) | (0.0050) |
| Pressure | 0.0600*** | 0.0759*** | 0.0540*** | 0.0982*** | -0.2014*** | 0.0551*** | -0.1517*** | 0.0363*** |
| | (0.0101) | (0.0010) | (0.0083) | (0.0010) | (0.0136) | (0.0010) | (0.0132) | (0.0016) |
| Control var. | YES | YES | YES | YES | YES | YES | YES | YES |
| _cons | -1.6576*** | -2.2890*** | -2.4732*** | -3.4204*** | 0.8073*** | 0.9045*** | 0.5891*** | 0.7601*** |
| | (0.0383) | (0.0272) | (0.0718) | (0.0483) | (0.0405) | (0.0342) | (0.0692) | (0.0622) |

*Notes: The test for differences between groups was passed.*

## 4.2 Heterogeneity Analysis

The entire sample is divided into two parts for grouped regressions: cities with financial pressure at the first 50% median and those with financial pressure at the last 50% median. The regression results are presented in **Table 4**. In models (1)–(4), the regression results are based on using the $PM_{2.5}$ concentration per unit of output as the explanatory variable, and in models (5)–(8), the regression results are based on using the $SO_2$ concentration per unit of output for the robustness test. Models (1), (3), (5), and (7) show the regression results for cities with fiscal pressure in the first 50% median; models (2), (4), (6), and (8) show the regression results for cities with fiscal pressure in the last 50% median. Models (1), (2), (5), and (6) are regressed using the SYS-GMM method; models (3), (4), (7), and (8) are regressed using the DIFF-GMM method. The empirical results show that the regression coefficients of fiscal pressure in the high median group are larger than those in the low median group regardless of whether the $PM_{2.5}$ concentration per unit of output or the $SO_2$ concentration per unit of output is chosen as the explanatory variable. The results indicate that environmental pollution is more severe in resource-based cities with higher fiscal pressure. In such cities, the government actively develops the advantages of resource industries. It accelerates the development of resource industries to relieve fiscal pressure, squeezing out environmental protection expenditures and relaxing environmental controls. This means that in resource-based cities with higher fiscal pressure, local government behavior may be distorted, and some behaviors incentivize production through various sacrifices to the environment.

Additionally, based on the classification method for resource-based cities in the Sustainable Development Planning of National Resource-based Cities (2003–2020), we divide these cities into four categories: the growth type, mature type, decline type, and regenerative type. Based on this division, the impact of fiscal pressure on pollution emissions in different types of resource-based cities is further examined in a disaggregated manner. The regression results are presented in **Table 5.** Models (1)–(4) show the regression results when the $PM_{2.5}$ concentration per unit of output is the explanatory variable; models (5)–(8) show the regression results when the $SO_2$ concentration per unit of output is the explanatory variable. Models (1) and (5) show the regression results for growth-type resource-based cities; models (2) and (6) show the regression results for mature-type cities; models (3) and (7) show the regression results for decline-type resource-based cities; and models (4) and (8) show the regression results for regenerative-type resource-based cities. The results show that the coefficient of fiscal pressure remains positive and significant at the 1% level only for mature-type resource-based cities regardless of whether the $PM_{2.5}$ concentration per unit of output or the $SO_2$ concentration per unit of output is the explanatory variable. The results suggest that fiscal pressure is more likely to induce environmental degradation in mature-type resource-based cities than in other types of resource-based cities.

The possible reason for this result is that there are differences in the government's development patterns and development priorities for the four types of resource-based cities. Growing cities mainly promote their regulated and orderly development, raise the access threshold for resource development, and reasonably determine the development intensity. Mature cities should promote their leapfrog development, lengthen the industrial chain, and cultivate resource deep-processing enterprises. Declining cities vigorously develop the succession of alternative industries and solve the most prominent historical legacy problems to accelerate their transformation and development. Regenerative cities guide their innovative development, improve the quality and efficiency of development, and establish a long-term mechanism for sustainable development.

For this reason, the fiscal pressure of mature resource cities is more likely to induce environmental degradation than that of other types of resource-based cities. Mature resource cities have a large scale of resource industries, and resource development has reached a stable stage. However, the government's leapfrog development model for mature cities and higher dependence on resource industries make the regional development more likely to expose disadvantages such as a single resource industry structure as financial

**TABLE 5 |** Impact of financial pressure on air pollution emissions in different resource-dependent cities.

| Variable | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| | SYS-GMM | SYS-GMM | SYS-GMM | SYS-GMM | SYS-GMM | SYS-GMM | SYS-GMM | SYS-GMM |
| | $LndPM_{2.5}$ | $LndPM_{2.5}$ | $LndPM_{2.5}$ | $LndPM_{2.5}$ | $LndSO_2$ | $LndSO_2$ | $LndSO_2$ | $LndSO_2$ |
| L. $LndPM_{2.5}$ | 0.8804*** | 0.8788*** | 0.7529*** | 0.8864*** | | | | |
| | (0.1956) | (0.0030) | (0.0184) | (0.0506) | | | | |
| L. $LndSO_2$ | | | | | 1.0010*** | 1.1168*** | 1.0113*** | 1.0726*** |
| | | | | | (0.0813) | (0.0055) | (0.0355) | (0.0540) |
| Pressure | −0.0361 | 0.0430*** | 0.0245 | 0.0419 | 0.1057 | 0.0221*** | −0.0084 | 0.0461 |
| | (0.1323) | (0.0028) | (0.0155) | (0.0374) | (0.0787) | (0.0048) | (0.0383) | (0.1123) |
| Control var | YES | YES | YES | YES | YES | YES | YES | YES |
| _cons | −2.0737 | −1.5404*** | −2.8836*** | −1.4793** | 0.1268 | 1.2860*** | 0.3286 | 0.6189 |
| | (1.4491) | (0.0319) | (0.1803) | (0.5704) | (1.1364) | (0.0599) | (0.2960) | (0.5366) |

**TABLE 6 |** The role of age of officials in the environmental effects of financial pressure.

| Variable | Municipal party secretary | | | | Mayor | | | |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| | $LndPM_{2.5}$ | $LnPM_{2.5}$ | $LndSO_2$ | $LnSO_2$ | $LndPM_{2.5}$ | $LnPM_{2.5}$ | $LndSO_2$ | $LnSO_2$ |
| Lagged var | 0.8333*** | 0.8296*** | 1.1071*** | 1.0516*** | 0.8145*** | 0.8401*** | 1.0991*** | 1.0527*** |
| | (0.0019) | (0.0017) | (0.0032) | (0.0045) | (0.0012) | (0.0022) | (0.0018) | (0.0046) |
| Pressure*age1 | −0.0014*** | −0.0024*** | −0.0013*** | −0.0027*** | | | | |
| | (0.0001) | (0.0001) | (0.0002) | (0.0002) | | | | |
| Pressure*age2 | | | | | −0.0057*** | −0.0022*** | −0.0056*** | −0.0075*** |
| | | | | | (0.0001) | (0.0001) | (0.0001) | (0.0001) |
| Control var | YES | YES | YES | YES | YES | YES | YES | YES |
| _cons | −2.0945*** | 0.6008*** | 1.1459*** | −0.1078*** | −2.3212*** | 0.5607*** | 1.0428*** | −0.1188*** |
| | (0.0218) | (0.0047) | (0.0356) | (0.0172) | (0.0122) | (0.0073) | (0.0219) | (0.0166) |

pressure increases. The high resource endowment leads to the environmental pollution "lockin" effect, and the environmental deterioration becomes evident.

## 4.3 Individual Characteristics of Officials

To verify H2 and test the influence of the age and tenure of officials on the environmental effect of fiscal pressure, this paper constructs an interaction term between fiscal pressure and the individual characteristics of officials to explore their effect on the environmental effect of fiscal pressure. With reference to the method of Yu et al. (2019a), the following model is proposed:

$$pollution_{it} = \alpha_0 + \alpha_1 pollution_{it-1} + \beta_0 pressure_{it} + \beta_1 pressure_{it} * age + \sum \gamma_i X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$pollution_{it} = \alpha_0 + \alpha_1 pollution_{it-1} + \beta_0 pressure_{it} + \beta_2 pressure_{it} * tenure + \sum \gamma_i X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

**Equation 2** tests the moderating effect of officials' age on fiscal pressure, while **Eq. 3** tests the moderating effect of officials' tenure on fiscal pressure. We expect the result that β_1 < 0, β_2 > 0. Regarding the method used by Yao and Zhang (2013), the age of an official is measured by subtracting the birth year of the official from the age of the official during his or her term of office, while the term of an official is represented by the time from when the official takes office to when he or she leaves office. In this paper, officials are local party secretaries and mayors, and the data come from the official websites of governments at all levels (Yu et al., 2019b).

**Table 6** shows the regression results of the effect of officials' age on the environmental effect of financial pressure. Models (1)–(4) show the regression results of the interaction term between the age of municipal party secretaries and financial pressure; models (5)–(8) show the regression results of the interaction term between mayors' age and financial pressure. Models (1) and (5) show the regression results when the $PM_{2.5}$ concentration per unit of output is the explained variable; models (3) and (7) show the regression results when the $SO_2$ concentration per unit of output is the explained variable; models (2) and (6) show the regression results when the $PM_{2.5}$ concentration is the explained variable; and models (4) and (8) show the regression results when the $SO_2$ concentration is the explained variable. The regression results show that the coefficient of the interaction term between the age of either party secretaries or mayors and financial pressure is negative and significant at the 1% level. The results show that the increase in the age of local officials is conducive to weakening the positive impact of financial pressure on pollution emissions and promoting an improvement in regional environmental quality.

**Table 7** shows the regression results of the impact of officials' tenure on the environmental effect under fiscal pressure. Models

**TABLE 7 |** The role of official tenure in the environmental effects of fiscal pressure.

| Variable | Municipal party secretary | | | | Mayor | | | |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| | $LndPM_{2.5}$ | $LnPM_{2.5}$ | $LndSO_2$ | $LnSO_2$ | $LndPM_{2.5}$ | $LnPM_{2.5}$ | $LndSO_2$ | $LnSO_2$ |
| Lagged var | 0.7944*** | 0.8201*** | 1.0782*** | 1.0561*** | 0.7929*** | 0.8345*** | 1.0384*** | 1.0112*** |
| | (0.0026) | (0.0023) | (0.0017) | (0.0048) | (0.0021) | (0.0023) | (0.0017) | (0.0016) |
| Pressure*tenure1 | 0.0041*** | 0.0087*** | 0.0026*** | 0.0057*** | | | | |
| | (0.0002) | (0.0002) | (0.0002) | (0.0003) | | | | |
| Pressure*tenure2 | | | | | 0.0026*** | 0.0038*** | 0.0169*** | 0.0211*** |
| | | | | | (0.0001) | (0.0001) | (0.0002) | (0.0002) |
| Control var | YES | YES | YES | YES | YES | YES | YES | YES |
| _cons | −2.5235*** | 0.6413*** | 0.8117*** | −0.0858*** | −2.5626*** | 0.5651*** | 0.3768*** | 0.0747*** |
| | (0.0279) | (0.0074) | (0.0192) | (0.0167) | (0.0254) | (0.0078) | (0.0220) | (0.0080) |

(1)–(4) show the regression results of the interaction term between municipal secretaries' tenure and fiscal pressure; models (5)–(8) show the regression results of the interaction term between mayors' tenure and fiscal pressure. Models (1) and (5) show the regression results when the $PM_{2.5}$ concentration per unit of output is the explanatory variable. In contrast, models (3) and (7) show the regression results when the $SO_2$ concentration per unit of output is the explanatory variable. Models (2) and (6) show the regression results when the $PM_{2.5}$ concentration is the explanatory variable, and models (4) and (8) show the regression results when the $SO_2$ concentration is the explanatory variable. The regression results show that the coefficients of the interaction term between the tenure of either municipal party secretaries or mayors and fiscal pressure remain positive and significant at the 1% level. The results indicate that as local officials' tenure in office increases, it exacerbates the positive effect of fiscal pressure on pollution emissions, which is not conducive to improving environmental quality. Therefore, H2 is valid.

## 4.4 Test of the Transmission Mechanism

The results above show that fiscal pressure in resource-based cities exacerbates pollution emissions and is not conducive to improving environmental quality. The question naturally arises regarding the mechanism through which fiscal pressure in resource-based cities affects pollution emissions. Empirical studies show that the regional industrial structure is an important factor that affects regional environmental conditions. If the dominant industry in a region is environmentally friendly, then the environmental conditions are good; otherwise, they deteriorate. As regional fiscal pressure increases, local governments tend to loosen environmental controls in exchange for economic growth. They also accelerate the development of pillar industries, which in resource-based cities are often not environmentally friendly, hindering industrial structure optimization and accelerating environmental pollution (Ebenstein, 2012). In addition, green technology innovation has become an important tool for improving environmental quality, and the academic community has reached a consensus on this point (Acemoglu et al., 2012; Shen et al., 2021). Therefore, an increase in government fiscal pressure may have a crowding-out effect on green technology innovation. Therefore, to test H3, this paper employs the method used by Gelbach (2016) to test the transmission role of the industrial structure and green technology innovation in the pollution effect of fiscal pressure. The following regression equation is established:

$$Med_{it} = \delta_0 + \alpha_1 med_{it-1} + \beta_0 pressure_{it} + \beta_i X_{it} + \vartheta_t + \mu_i + \varepsilon_{it} \quad (4)$$

$$pollution_{it} = \delta_0 + \gamma_1 pollution_{it-1} + \theta_i Med_{it} + \gamma_0 pressure_{it} + \beta_i X_{it} + \vartheta_t + \mu_i + \varepsilon_{it} \quad (5)$$

where $i$ represents the region, $t$ represents time, $Med_{it}$ is the mechanism variable, **Equation 4** is the mediation model represented by the industrial structure and green technology innovation, and $\beta_0$ is the partial effect parameter of regional financial pressure on the mechanism variable. **Equation 5** is a comprehensive model, $\theta_i$ is the partial effect parameter of the influence of mechanism variables on pollution emissions, and $\gamma_0$ is the effect of financial pressure on pollution emissions after introducing the mechanism variables. The industrial structure (Jg) is represented by the proportion of the added value of the secondary industry in GDP. With reference to Shen et al. (2021), green technology innovation (Ginvo) is represented by the proportion of green invention patents in the total number of patents granted in the region annually.

**Table 8** shows the regression results of the industrial structure transmission mechanism of the impact of financial pressure on pollution emissions. DIFF-GMM regression is used for models (1), (3), and (5), and SYS-GMM regression is used for models (2), (4), and (6). Models (1) and (2) show the regression results of the mediation model, and models (3)–(6) show the regression results of the comprehensive model. Models (3)–(4) show the regression results when the $PM_{2.5}$ concentration is the explained variable, and models (5)–(6) show the regression results when the $PM_{2.5}$ concentration per unit of output is the explained variable. The results of models (1) and (2) show that financial pressure has a positive effect on upgrading an industrial structure dominated by the secondary industry; that is, financial pressure will hinder industrial structure upgrading. The results of models (3)–(6) show that regardless of whether the $PM_{2.5}$ concentration or the $PM_{2.5}$ concentration per unit of output is the explained variable, an industrial structure dominated by the secondary industry aggravates environmental pollution, indicating that the financial pressure of resource-dependent cities will hinder

TABLE 8 | Transmission mechanism of financial pressure pollution effect in resource-dependent cities -industrial structure effect.

| Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | DIFF-GMM | SYS-GMM | DIFF-GMM | SYS-GMM | DIFF-GMM | SYS-GMM |
| | Jg | Jg | $LnPM_{2.5}$ | $LnPM_{2.5}$ | $LndPM_{2.5}$ | $LndPM_{2.5}$ |
| L.Jg | 0.9722*** | 0.9984*** | | | | |
| | (0.0030) | (0.0039) | | | | |
| L. $LnPM_{2.5}$ | | | 0.5482*** | 0.7673*** | | |
| | | | (0.0029) | (0.0036) | | |
| L. $LndPM_{2.5}$ | | | | | 0.8193*** | 0.8081*** |
| | | | | | (0.0032) | (0.0029) |
| Jg | | | 0.0100*** | 0.0088*** | 0.0022*** | 0.0050*** |
| | | | (0.0001) | (0.0001) | (0.0002) | (0.0002) |
| Pressure | 0.3472*** | 0.6234*** | 0.0249*** | 0.0112*** | 0.0391*** | 0.0273*** |
| | (0.0384) | (0.0256) | (0.0012) | (0.0009) | (0.0012) | (0.0014) |
| Control var | YES | YES | YES | YES | YES | YES |
| _cons | 3.2766*** | 1.2624*** | 1.0847*** | 0.3501*** | −2.2978*** | −2.6069*** |
| | (0.1662) | (0.2091) | (0.0133) | (0.0122) | (0.0393) | (0.0380) |

TABLE 9 | Transmission mechanism of fiscal pressure pollution effect in resource-dependent cities - green technology innovation effect.

| Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | DIFF-GMM | SYS-GMM | DIFF-GMM | SYS-GMM | DIFF-GMM | SYS-GMM |
| | Ginvo | Ginvo | $LnPM_{2.5}$ | $LnPM_{2.5}$ | $LndPM_{2.5}$ | $LndPM_2$ |
| L Ginvo | 0.0404*** | 0.0465*** | | | | |
| | (0.0028) | (0.0037) | | | | |
| L. $LnPM_{2.5}$ | | | 0.6349*** | 0.8522*** | | |
| | | | (0.0024) | (0.0031) | | |
| L.$LndPM_{2.5}$ | | | | | 0.8439*** | 0.8435*** |
| | | | | | (0.0039) | (0.0051) |
| Ginvo | | | −0.3261*** | −0.1350*** | −0.4811*** | −0.1616*** |
| | | | (0.0114) | (0.0218) | (0.0259) | (0.0253) |
| Pressure | −0.0292*** | −0.0234*** | 0.0205*** | 0.0006 | 0.0251*** | 0.0031 |
| | (0.0005) | (0.0004) | (0.0017) | (0.0015) | (0.0021) | (0.0038) |
| Control var | YES | YES | YES | YES | YES | YES |
| _cons | 0.0985*** | 0.1011*** | 1.4151*** | 0.6036*** | −1.8496*** | −1.9065*** |
| | (0.0019) | (0.0021) | (0.0089) | (0.0134) | (0.0444) | (0.0579) |

industrial structure upgrading. A high degree of dependence on resource endowment leads to a lack of freedom in economic development. Therefore, rapid economic development can be achieved by accelerating the development of the secondary industry, forming a "resource gospel" for economic growth, and helping to relieve financial pressure to a certain extent. However, accelerating secondary industry development can also aggravate environmental pollution.

**Table 9** shows the regression results of the green technology innovation transmission mechanism of the effect of fiscal pressure on pollution emissions. Models (1), (3), and (5) are regressed through the DIFF-GMM method, and models (2), (4), and (6) are regressed through the SYS-GMM method. Models (1) and (2) show the regression results of the mediated model. Models (3)–(6) show the regression results of the integrated model, where models (3)–(4) show the regression results when the $PM_{2.5}$ concentration is the explanatory variable, and models (5)–(6) show the regression results when the $PM_{2.5}$ concentration per unit of output is the explanatory variable. The results of models (1) and (2) show that fiscal pressure has a negative effect on green technology innovation, meaning that fiscal pressure crowds out green technology innovation in the region. Furthermore, the results of models (3)–(6) show that the effect of green technology innovation on pollution emissions is negative regardless of whether the $PM_{2.5}$ concentration or $PM_{2.5}$ concentration per unit of output is the explanatory variable. These results indicate that fiscal pressure in resource-based cities will force local governments to squeeze out investment in green technology innovation, weaken the green technology innovation capacity of the region, enhance economic development at the expense of the environment, and gain an economic growth advantage. For this reason, H3 is proven to be valid.

## 5 CONCLUSIONS AND POLICY IMPLICATIONS

This paper explores the environmental effects of governmental fiscal pressure and use a dynamic panel model based on 2003-

2018 panel data on resource-based cities in China. The findings show that (1) fiscal pressure has a significant air pollution effect in resource-based cities, and environmental deterioration becomes more pronounced as the intensity of fiscal pressure increases. Comparing different types of resource-based cities, we find that the air pollution effect of fiscal pressure is most significant in mature-type resource-based cities. (2) As the tenure of officials increases, the air pollution effect of fiscal pressure intensifies; in contrast, as the age of local officials increases, it facilitates an improvement in the air pollution effect of fiscal pressure. (3) Fiscal pressure exacerbates environmental degradation mainly by impeding industrial structure upgrading and crowding out urban green innovation. Based on the conclusions above, we propose the following suggestions for the economic transformation and upgrading of resource-based cities. Following suggestions for the economic transformation and upgrading of resource-based cities are proposed.

First, multichannel transfer payment mechanisms should be established to improve the efficiency of local government fiscal expenditures and to relieve fiscal pressure in resource-based regions. Finances are a key factor in the government's environmental governance, and fiscal pressure aggravates environmental pollution. Thus, fiscal pressure can be eased by accelerating the optimization and transformation of the fiscal expenditure structure and establishing horizontal transfer payments between regions. Additionally, by improving the fiscal expenditure evaluation system, we can achieve the goals of economical, efficient, and effective fiscal expenditure, coordinating the development of regions, and promoting the construction of ecological civilization to realize the high-quality development of resource-based regions.

Second, green development should be incorporated into the promotion assessment mechanism for government officials, and the role of the individual characteristics of officials in the environmental governance of resource-based regions should be fully considered. For example, the empirical results show that older local officials have a catalytic effect on improving regional environmental quality. For this reason, the appointment of local officials should not blindly emphasize youthfulness; instead, officials should be scientifically judged based on their contribution to high-quality urban development. Additionally, longer tenures of officials do not effectively improve regional environmental quality. Therefore, a reasonable assessment and tenure system should be established to promote environmental quality improvement through appropriate changes in officials while ensuring policy stability and the continuity of officials' appointments.

Third, it is essential to stimulate regional green technology innovation through policies to ensure that we can give full play to the leading role of green technology innovation in the transformation and upgrading of resource-based cities. The transformation and upgrading of resource-based cities is a gradual process. Full consideration can be given to promoting the derivation, extension, and replacement of the industrial chain of resource-based cities through green technology innovation to realize the green development of the industrial chain. The government should also actively promote the transformation of resource industries. We can optimize the industrial structure and crack the pollution lockin effect formed by dependence on resource industries through technological progress, promoting the leapfrog development of mature-type resource-based cities. Improving the diversified industrial system and comprehensively promoting the transformation and upgrading of resource-based cities are also necessary.

This paper focuses on the macro-level analysis of the cities. However, with the development of more energy-intensive, high-emission industries and the disclosure of more corporate environmental information, future research will be able to look into micro-level enterprise data. This will help to identify the impact of financial pressure on pollution with new evidence of the environmental effects of large-scale firms. In addition, with the advent of a new round of the scientific and technological revolution, follow-up research will further focus on the crucial role of artificial intelligence and big data technology in the transformation of resource-dependent cities.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, ZJ, upon reasonable request.

## AUTHOR CONTRIBUTIONS

CH: software, methodology, writing original draft, and project. BL: software, methodology, investigation, writing original draft. LT: Investigation, visualization. JZ: conceptualization, writing- review and editing, funding acquisition, supervision. FS: data curation, methodology, formal analysis, writing original draft.

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POLICY BRIEF
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# Improving China's Global Lithium Resource Development Capacity

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Flourishing sales of new electric vehicles have led to a considerable surge in demand for the vital, upstream raw material, lithium (Li). As an essential energy metal and raw material for the production of batteries, lithium has become indispensable to the electric vehicle industry. It has been identified as a strategic, emerging industrial mineral in China. Based on a literature review and qualitative analysis of the imbalance between the supply and demand of lithium raw materials in China, this paper analyzes the current challenges of China's lithium supply chain, especially mining, pricing and recycling, that are obstructing the realization of China's carbon neutrality. On this basis, relevant policy suggestions are proposed from three perspectives: strengthening lithium resource development and reserve capacity, promoting international cooperation for lithium supply, and properly regulating the circular economy of domestic lithium resources.

**Keywords: lithium, supply and demand imbalance, new energy, electric vehicle industry, carbon neutrality, policy implications**

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## INTRODUCTION

As climate change has an increasingly negative impact on the living environment, it is urgent to mitigate carbon dioxide emissions. As the main sources of carbon emissions, buildings, energy, transportation and industry have become the main focus of China's emission reduction efforts. For example, many previous studies have investigated the low-carbon roadmap or carbon-neutral pathway of the building sector (Li et al., 2022; Sun et al., 2022; Xiang et al., 2022). This paper, however, focus on another sector with vast potential for carbon emission reduction: transportation.

According to the International Energy Agency (IEA), global electric vehicle sales reached 6.6 million in 2021, more than double the 2020 level of three million. By the close of 2020, more than 20 countries/regions had either announced plans to ban the sale of conventional cars or mandated that all newly sold vehicles must be zero-emissions. Many governments have further stimulated consumer demand for electric vehicles through incentives such as subsidies. Moreover, many large automobile manufacturers worldwide have announced plans to expand the scale of electric vehicle production. Therefore, because lithium-ion technology is the most widely used path for powering electric vehicles, the most critical resource, lithium (Li), has been listed as a strategic resource in many countries, such as the United States and China.

Lithium has the strongest charge mobility among the metals and the highest electrical storage density of known elements and, therefore, is an essential mineral for new electric technologies. Lithium has the highest standard oxidation potential among all elements. It can be easily used in various battery sizes and configurations for energy storage and, thus, is called the "energy metal for the 21st century".

Lithium resources are primarily stored in hard rock and brines. Mined materials are processed to capture lithium compounds, including lithium carbonate, lithium hydroxide, lithium halide, etc. Finally, the concentrated lithium products are used in downstream industrial production in the form of energy storage compounds. As a vital raw material for batteries, lithium is indispensable in the new energy automobile industry.

According to the United States Geological Survey (USGS), there are 89 million tons of identified lithium resources worldwide. However, due to insufficient exploitation, the available reserves are only 22 million tons, of which China accounts for approximately 6.8% with 1.5 million tons. As suggested by Wei et al. (2022), the current capacity for supplying critical minerals in China cannot satisfy the demand, especially under carbon neutrality-focused plans.

Although it is among the major suppliers of lithium, China's lithium resources are still highly dependent on foreign entities due to insufficient national development of its exploitation potential and the poor quality of its mineral resources, leaving a large gap between supply and demand. This intensified import-dependent situation is risky to the domestic market (Guo et al., 2021). For example, the production of downstream lithium batteries for electric automobiles is restricted by international resource development, which restricts the development of essential industries in China. Based on the available literature and the current supply-demand situation, this policy brief analyzes the current challenges facing China's lithium resource supply chain from the aspects of supply, distribution, and the circular economy.

Previous studies on lithium have focused on three aspects. First, the supply-demand situation of lithium resources has been investigated (Tabelin et al., 2021). For example, debate persists about whether the supply is adequate to meet demand (Gruber et al., 2011). Second, the recycling of lithium resources, including the effects of the recycling of lithium resources on lithium supply and the environment, the efficient methods for recycling, and so on, have been studied (Oliveira et al., 2015; Tabelin et al., 2021). Finally, researchers have explored the usage of lithium resources in electric vehicles and some new technologies (Laadjal and Cardoso, 2021; Wang and Yu, 2021). However, a systematic analysis of the current challenges in China's lithium supply chain, including mining, pricing and recycling, as well as the proposition of related policy suggestions, remain to be done. Our paper is intended to fill this gap. Furthermore, based on China's actual situation, this paper clarifies the problems China faces in its lithium resources reserves, which involve energy security and the realization of China's goal of carbon neutrality. Our policy suggestions provide a useful reference for policymakers around the world to improve the capacity to development lithium resources. *Introduction* of this paper describes the current demand for lithium resources. *Introduction* identifies the challenges regarding lithium resources at all stages of China's the supply chain. Relevant policy recommendations are proposed in *Introduction*. Finally, we conclude our paper in *Introduction*.

## PRESENT SITUATION OF LITHIUM RESOURCE DEMAND IN CHINA

In recent years, booming production of electric vehicles has led to a surge in demand for the primary upstream raw material, lithium. According to SNE Research, a South Korean market research institution, the total battery energy requirement for electric vehicles (EVs) reached 53.5 GWh globally in the first 2 months of 2022, more than double the figure from the same period in 2021. Among suppliers, Contemporary Amperex Technology Co., Ltd. (CATL), and BYD shipments ranked first and third globally, with market shares of 34.4 and 11.9%, respectively. Due to the sharp increase in demand, China's lithium resource enterprises have increased their production to varying degrees. For example, the industry leader Tianqi Lithium Corporation's production of lithium concentrates increased by 39% and sales volume increased by 56% in the first 2 months of 2022 years-on-year. The rapid growth in demand has correspondingly escalated the price of lithium resources. According to the Shanghai Metals Market (SMM), the price of lithium carbonate, which is the primary battery material, rose from 53,000 yuan/ton in January 2021 to 525,000 yuan/ton on 1 April 2022, representing a year-on-year increase of 487.72%, including an increase of 52.88% between January and the end of March 2022 (as shown in **Figure 1**).

As many countries, such as China and the United States, shift toward low-carbon and new energy technologies, the demand for lithium will continue to increase (Tabelin et al., 2021). China has committed to capping its peak carbon dioxide emissions by 2030 and reaching carbon neutralization before 2060 (UNFCC, 2015; Xi, 2020). Substituting electric vehicles for traditional energy vehicles is critical to achieving this plan.

According to the IEA, in 2021, global electric car sales reached 6.6 million, a year-on-year increase of 120% (as shown in **Figure 2**). The IEA expects global new energy vehicle yearly sales to reach 13 million in 2025 and 25.8 million by 2030, maintaining an annual growth rate of approximately 30%. China is the world's largest consumer of new energy lithium resources.

According to **Figure 2**, the sales volume of electric vehicles was 3.4 million units in China in 2021, up 183.33% year-on-year, accounting for 51.5% of the global electric vehicle market. China also drove the consumption of lithium resources (calculated as lithium carbonate) to 303,400 tons in 2021, up 61.7% year on year. *Statista* predicts that the growth of battery demand for electric vehicles will continue to be a strong driving force for lithium consumption over the next 10 years. The global demand for lithium carbonate will exceed two million tons in 2030, more than twice the predicted demand in 2025. Sun et al. (2019) also predict that the flow of lithium resources in 2050 will be 13-20 times that in 2015. Beginning in 2022, lithium for electric vehicles will account for the largest proportion of lithium usage.

## CURRENT CHALLENGES IN LITHIUM RESOURCES

The scarcity of lithium resources and the rapid growth of demand lead to an imbalance between supply and demand in China. At

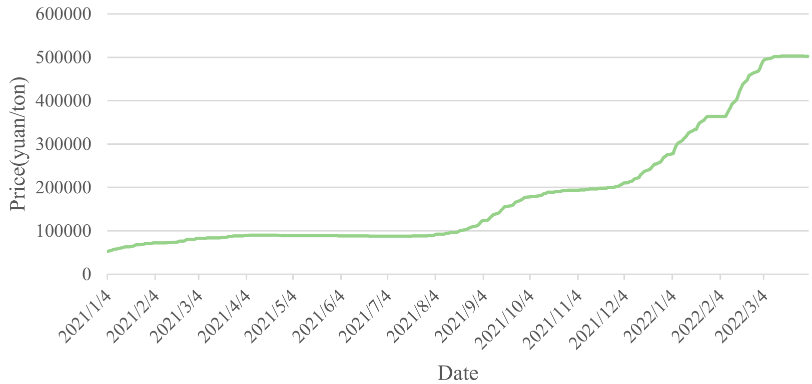


**FIGURE 1 |** The price of lithium carbonate in China. Data Source: SMM.

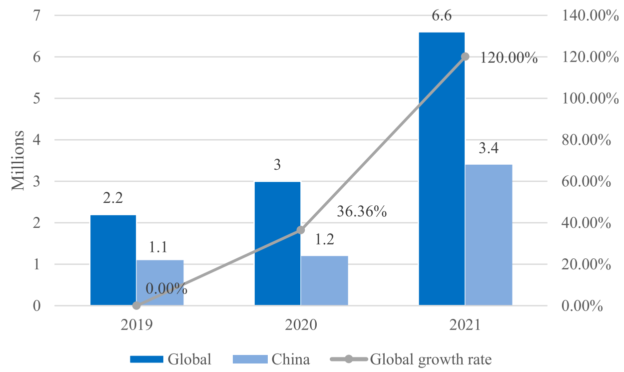


**FIGURE 2 |** Global and Chinese EV sales, 2019-2021. Data Source: IEA.

present, China is confronted with three main challenges in lithium resources: insufficient resource endowment and exploitation, insufficient ability to participate in the formulation of lithium resource prices, and realization of its aspirations regarding the circular economy of lithium resources. Therefore, China's related industries are constrained by foreign development and supply of lithium resources.

First, China's identified lithium resources are insufficient. Lithium resources are primarily embodied in natural mineral reserves. The USGS reports that the globally identified lithium resources are 89 million tons. Identified resources are defined as "Resources for which location, grade, quality, and quantity are known or estimated from specific geologic evidence". **Figure 3A** shows the global distribution of identified lithium resources, chiefly distributed in South America and Australia, with the top four countries being Bolivia, Argentina, Chile, Australia, and China, accounting for 23.6, 21.3, 11, 8.2, and 5.7%, respectively. In addition, the USGS also reported that global lithium reserves in 2021 were approximately 22 million tons. Relative to the identified lithium resources, the USGS defined reserves as "that part of the reserve base that could be economically extracted or produced at determination". The global distribution of lithium reserves is shown in **Figure 3B**. Compared with the amount of identified lithium resources, the available lithium reserves are minuscule, making the identification of new lithium resources a top global priority.

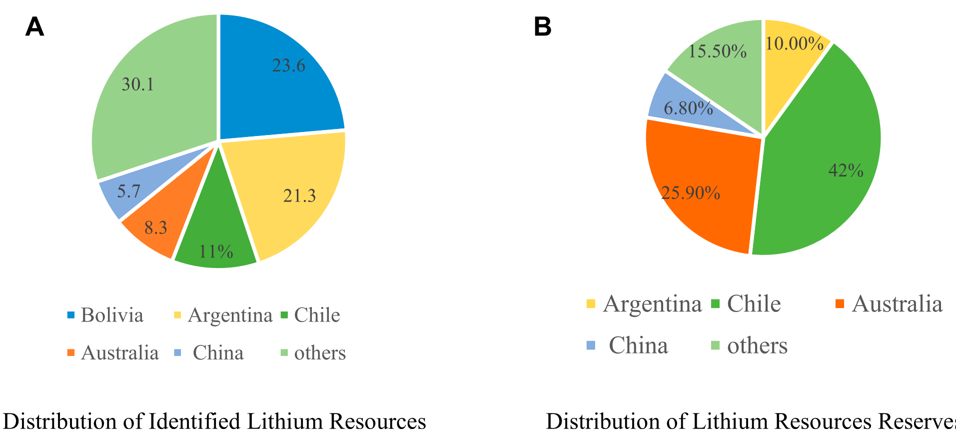


**FIGURE 3 |** Distribution of lithium resources. Data Source: UGSG.

China's lithium resources are characterized by a scattered distribution and inferior quality. Lithium is mainly stored in brines, lithium spodumene hard rock, and lepidolite. Brines in China are mainly distributed in salt lakes in Qinghai and Tibet. Lithium spodumene hard rock is mainly distributed in Sichuan, and Jiangxi also has significant lepidolite resources. Seventy-five percent of China's lithium resources are stored in salt lakes in Qinghai and Tibet. However, due to a low lithium-ion concentration and relatively elevated levels of impurities, while salt lakes are rich in lithium and magnesium it is challenging to extract lithium from such brines. In addition, Sichuan Province is also rich in lithium spodumene hard rock. However, most of the spodumene mines are located in high-altitude areas with poor vegetation coverage and severe soil and water loss. Moreover, due to the influence of harsh natural conditions and inadequate mine infrastructure in these areas, the development potential is low. Therefore, the exploitation of lithium resources in China is limited by natural conditions, cost, and technology. As a result, the production capacity for exploiting lithium resources has not yet been fully realized.

Second, because China is highly dependent on imported lithium raw materials it is not able to participate in the formulation of lithium resource prices. From the perspective of the supply structure, the global development of lithium resources is unbalanced and inadequate. The global output of lithium mines is mainly concentrated in Australia, Chile, and China, accounting for 55, 26, and 14%, respectively, in 2021. Although Argentina and Bolivia have resource advantages, they are limited by a challenging geographical environment, development technology, etc., leaving only a small number of available sources. With its remarkable output advantage, Australia dominates the current supply of lithium mineral resources globally. As China's domestic supply of lithium resources cannot meet the rapidly growing demand, dependence on foreign lithium resources remains at a prominent level, requiring the importation of 86.5% of China's current lithium demand (Song et al., 2019). Although the statistics[1]are incomplete, nearly 90% of lithium imports in 2021 came from Australia. The key to improving China's domestic lithium security is to reduce the excessive dependence on foreign resources. Although Chinese enterprises such as Zijin Mining and Ganfeng Lithium have begun to invest in lithium resource development projects in many countries around the world, most of the projects are still in early development, which cannot ease China's high dependence on foreign lithium resources in the short term.

Third, China's lithium recycling economy has not yet formed a complete chain. Recycling lithium resources is generally considered an effective way to reduce the demand for primary raw materials supply and to mitigate the potential risks of spent lithium disposal (Sun et al., 2019; Guo, Zhang, and Tian, 2021). Therefore, to achieve a balanced supply and demand for lithium resources, the well-established recycling systems is necessary. Gruber et al. (2011) suggested that if the recovery rate of lithium were 90–100%, the recovered lithium could meet 50–63% of the cumulative demand for lithium for 2010 to 2,100 worldwide.

The service life of lithium-ion batteries is generally 5–8 years, and the practical life is 4–6 years. When the battery capacity drops to 80% of the rated capacity, it will not meet the needs of electric vehicles and will be scrapped (Olivetti et al., 2017). Approximately 200,000 tons of power batteries were retired in China in 2020, according to data from the China Automotive Technology Research Center (CATARC). As the rapid growth of the electric vehicle market in recent years has significantly increased the use of lithium batteries, China will face a rapidly increasing battery retirement situation in the next few years and become one of the largest markets for lithium-ion battery recycling. The lithium concentration in waste batteries is 3–7% of their weight, much higher than the lithium concentration in natural ore (Barik et al., 2016). Sun et al. (2019) predicted that by 2050, the total amount of lithium in end-of-life products will reach 45-121 kt, which will represent half of the chemical consumption. The comprehensive utilization and recycling of waste power batteries plays an essential role in protecting the ecological environment and ensuring the safety of resources. However, the recycling economy of lithium resources has not been properly guided in China.

The infrastructure for recycling spent lithium batteries is still in the development stage, far from meeting the requirements of battery recycling technology. The recycling of lithium batteries includes collection and classification, discharge, disassembly, separation of active substances, metallurgy, etc. and is a complicated process with high costs and a low rate of recovery. In addition, with an increasing number of batteries being scrapped, a certain chaos is emerging in the battery recycling marketplace. Many recycling enterprises lacking professional qualifications are already crowding out the profitability of qualified enterprises. This situation has created escalating problems in the battery recycling process due to the unregulated participation of unqualified enterprises, which reduces economic benefits, increases environmental pollution, and creates potential safety hazards from unprofessional dismantling practices.

The three main challenges confronted by China in the lithium resources supply chain make it difficult for domestic supply to meet demand, leading to high dependence on foreign supplies of lithium raw materials and threatening the security of China's related industries. To solve this problem, we present the following policy suggestions.

First, since the exploitation of lithium resources in China is limited mainly by technology, it is essential to upgrade the technical requirements and professionalize the technical capacity of lithium resource recycling and development. China still faces many technical challenges in developing lithium resources from high-altitude ores and low-concentration brines. For example, high-altitude areas are often accompanied by a fragile ecological environment, increasing the difficulty of realizing green development. Further, the currently poor recovery rate of using low-concentration brine lithium resources must be improved. Addressing these core issues will require a unified, multi-department response including the resources,

[1]Part of the data comes from Chinese Customs Statistics.

environment, science and technology, industry, and other departments to formulate achievable technology development plans. Furthermore, the government should coordinate the use of natural science funds, venture capital, and other diversified tools to promote breakthroughs in required technologies as soon as possible to allow the effective realization of adequate resource development.

In addition, China should strengthen cooperation with other countries to increase the quality and quantity of global lithium resource supplies. At present, although several countries, such as Bolivia and Chile, have identified abundant lithium resources, resource nationalization, technology limitations, and other problems thwart the development of adequate lithium resources, leaving the global lithium resource supply far from meeting the present and increasing global demand. China should engage in building a community with a shared future through cooperative development with the countries where resources are located, using multiple channels to ensure adequate progress toward global peak carbon dioxide emissions and carbon neutrality.

Finally, the government should further perfect laws and regulations to improve domestic capacity for lithium resource recycling. For example, the government could create a qualified resource cycling enterprise list and impose measures to require a high quality, professional business environment for compliant enterprises to avoid risks in safety and environmental protection. Simultaneously, according to the endowment characteristics of each province and their various advantages of energy, technology talent, capital, and market factors, the provinces should be encouraged to form a strong, closed-loop, green recycling industrial chain of lithium resources and to realize the "green" in the process of industrial upgrading.

## CONCLUSION

Carbon neutrality is an important goal for China in the coming decades, and substituting electric vehicles for traditional energy vehicles is critical to achieving this goal. In recent years, as sales in new electric vehicles have flourished, the upstream raw material, lithium, has been in short supply relative to its demand in China. Furthermore, China's related industries are constrained by foreign development and supply of lithium resources because of China's insufficient resource endowment and exploitation, insufficient ability to participate in the formulation of lithium resource prices, and immature circular economy of lithium resources. Therefore, we propose that related policy-making focus on the following issues: (i) upgrading the technical requirements and professionalizing the technical capacity of lithium resource recycling and development, (ii) strengthening cooperation with other countries to increase the quality and quantity of global lithium resource supplies, and (iii) updating laws and regulations to improve domestic capacity for lithium resource recycling.

## AUTHOR CONTRIBUTIONS

HLiu conceived of the idea, outlined and made important modifications to the brief. HLi collected data and wrote the first draft ofthe article. TZ, XC, and GH made important modifications and provided data support for the brief. All authors contributed to article revisionand have both read and approved of the submitted version.

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# Utilization of Straw Resources May Affect the Speciation of Cd and Its Solubility in Cd-Contaminated Paddy Soil

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Rice-wheat rotation has long been the most typical cropping system along the mid-lower reaches of the Yangtse River in China, and the full amount returning of wheat straw before rice season is widely practiced in the rotation system. However, massive incorporation of fresh wheat straw may activate Cd in the soil solid phase and cause more labile Cd entering soil solution in Cd-contaminated soil during the flooded rice season. An incubation experiment was conducted under flooded conditions to investigate the solubility and speciation of Cd and its variation and driving factors with an ongoing decomposition phase in simulated Cd-contaminated paddy soil treated with wheat straw addition. The results indicated that wheat straw addition enhanced Cd solubility, and soluble Cd concentration increased with the ongoing decomposition phase. The observed significant positive correlation (r = 0.648, $p < 0.01$, n = 77) between soluble Cd concentration and DOC content in soil leachate was gradually strengthened with ongoing decomposition. Wheat straw addition decreased the exchangeable fraction of Cd and increased the residual fraction during the first 5 days of decomposition, while the exchangeable Cd increased and the residual Cd decreased after 10 days of decomposition. The exchangeable Cd increased and the residual Cd decreased gradually with ongoing decomposition. Correlation analysis showed that the exchangeable and residual fractions were sensitive to DOC content. Nitrogen fertilizer input further activated Cd by promoting wheat straw decomposition. In summary, wheat straw addition would activate Cd by increasing Cd solubility and promoting the translation from immobile fraction to labile fraction in Cd-contaminated paddy soil under flooded conditions.

**Keywords: straw resources, Cd contamination, paddy soil, DOC, Cd solubility**

## INTRODUCTION

Soil heavy metal contamination can deteriorate the quality of water bodies and crop products and has become a great threat to the health of animals and human beings (Nabulo et al., 2010; Li et al., 2014; Kumar et al., 2019). In China, fast industrialization, urbanization, and intensive agriculture over the past several decades have caused wide and serious heavy metal pollution in agricultural soil (Dong et al., 2010; Yang et al., 2018). According to the National Soil Pollution Survey Bulletin (2014), the exceedance rate of sample points surveyed on a national scale was 16.1%, among which cadmium (Cd) was the prominent contaminant, and the exceedance rate of sample points reached 7.0% (Sun et al., 2021). Compared with other heavy metals, Cd can transfer and accumulate in the soil-plant system more easily, and its hazard in contaminated soil mainly depends on its mobility and availability (Khodaverdiloo et al., 2020; Yuan et al., 2021), which in turn is significantly influenced by organic matter (Antoniadis and Alloway, 2002; Strobel et al., 2005). Organic matter itself can effectively adsorb Cd due to its strong sorption ability of functional groups on heavy metals (Weng et al., 2002; Gao et al., 2018) or be regarded as a carrier for Cd, thereby enhancing its migration and transformation in soil (Richard et al., 2008; Spaccini et al., 2008). Moreover, organic matter addition can indirectly influence Cd activity by altering soil pH and DOC (Yuan et al., 2019; Yuan et al., 2021).

High-yielding crop production has led to an enormous generation of crop straw in China (Xia et al., 2014). In order to recycle the straw resources and reduce its adverse effects (e.g., open-field burning of crop straw) on the environment, the Ministry of Agriculture and Rural Affairs of China proposed the "*Fertilizer Use Zero-Growth Action Plan by 2020*" in 2015, in which further increase of the nationwide proportion of crop straw incorporation to 60% by 2020 was required. Currently, the full amount returning of crop straw is practiced in the areas with a higher level of mechanization. Straw returning can elevate soil fertility by improving soil structure, returning considerable nutrients to the soil, and increasing soil organic matter (Yan and Gong, 2010; Sharma and Garg, 2018). Nevertheless, straw returning in large amounts would inevitably affect the mobility and availability of Cd in Cd-contaminated soil. Although there have been many studies that provided general information on the mobility and availability of Cd in straw-treated contaminated soil, their results are inconsistent or even contrasting. For example, some studies show that crop straw addition can reduce Cd mobility and availability via enhancing the Cd adsorption in the soil solid phase by the organic matter ligands (Mohamed et al., 2010; Yuan et al., 2019). In contrast, some studies reported that the mobility and availability of Cd increased in straw-treated soil owing to the release of low-molecular-weight organic matter (mainly DOC), as it can complex metals previously bound to soil particles (Khan et al., 2006; Bai et al., 2013; Wang et al., 2015). In addition, some studies show that straw incorporation has an insignificant influence on Cd mobility or availability (Feng et al., 2018; Nie et al., 2019). The inconsistent results were mainly attributed to the difference in crop straw materials and straw decomposing environment.

Rice-wheat rotation has long been the most typical cropping system along the mid-lower reaches of the Yangtse River in China, and the full amount returning of wheat straw before rice season is widely practiced in the rotation system. The area under rice cultivation in this region accounts for about half of the total in China. Nearly 1/3 of the surveyed 187 administrative regions with rice cultivation in China had Cd contamination (Liu et al., 2016). More importantly, the hazard of Cd might be more prominent in paddy soil as rice can accumulate Cd from contaminated soil more efficiently than other crops (Maret and Moulis, 2013). Studies carried out in 2008 and 2018 showed that 10% of the rice samples collected from Chinese rice markets contained >200 μg $kg^{-1}$ Cd (Zhen et al., 2008; Chen et al., 2018). In addition, long-term flooding and nitrogen fertilizer input in rice season will inevitably affect the decomposition of preceding wheat straw and further complicate the migration and transformation of Cd in Cd-contaminated paddy soil. However, the temporal variation of mobility, availability, and speciation of Cd influenced by wheat straw incorporation and its driving factors during the wheat straw decomposition phase remains unclear in Cd-contaminated paddy soil.

In this study, simulated Cd-contaminated paddy soil was treated with different wheat straw addition rates that were cultured under different decomposition periods. The main objectives of this study were to 1) evaluate the mobility and speciation distribution of Cd under different straw addition rates in Cd-contaminated soil under flooded conditions; 2) investigate the variation of the above Cd properties during the straw decomposition phase; and 3) explore the driving factors closely related to the migration and transformation of Cd in Cd-contaminated soil treated with wheat straw.

# MATERIALS AND METHODS

## Experimental Materials

The soil used was sampled from the upper layer of the soil (0–20 cm) in the experimental field of Yangzhou University (32°20′33″ N, 119°23′43″ E), Jiangsu Province, China, and belongs to Xiashu Loess. The soil was crushed and sieved (2 mm) after naturally air-dried. The straw used was collected from the wheat plant experimental field of Yangzhou University. The fresh wheat plant was dried at 105 C for 15 min and then oven-dried at 80 C. The oven-dried wheat plant was comminuted and then passed through 2 mm mesh. The initial pH, total Cd concentration of soil, and Cd concentration of wheat straw are 7.50, 4.74 mg $kg^{-1}$, and 0.24 mg $kg^{-1}$, respectively.

## Experimental Design

The sieved soil was evenly mixed with $CdCl_2$ solution and aged stably at room temperature (about 25°C) for 3 months to simulate Cd-contaminated soil. Deionized water was replenished by weighing every 3 days during the aging stabilization period to maintain a 40% field saturation in the soil. Total and available Cd concentrations in this Cd-contaminated soil were 78.63 mg $kg^{-1}$ and 31.12 mg $kg^{-1}$. Then, one hundred grams of Cd-contaminated soil was put into a 300-ml plastic cup. The treatments of wheat straw addition were conducted by mixing the sieved wheat straw uniformly with soils in plastic cups at the dry weight rates of 0, 2.5, 5, 10, and 20 g $kg^{-1}$ (defined as S0, S1, S2, S3, and S4), respectively. In order to investigate the effect of nitrogen fertilizer input on Cd dissolution in Cd-contaminated soil treated with wheat straw, additional treatment with 10 g $kg^{-1}$ wheat straw addition rate and 0.06 g ammonium nitrate was set and defined as SN. Eighteen plastic cups were set up for each

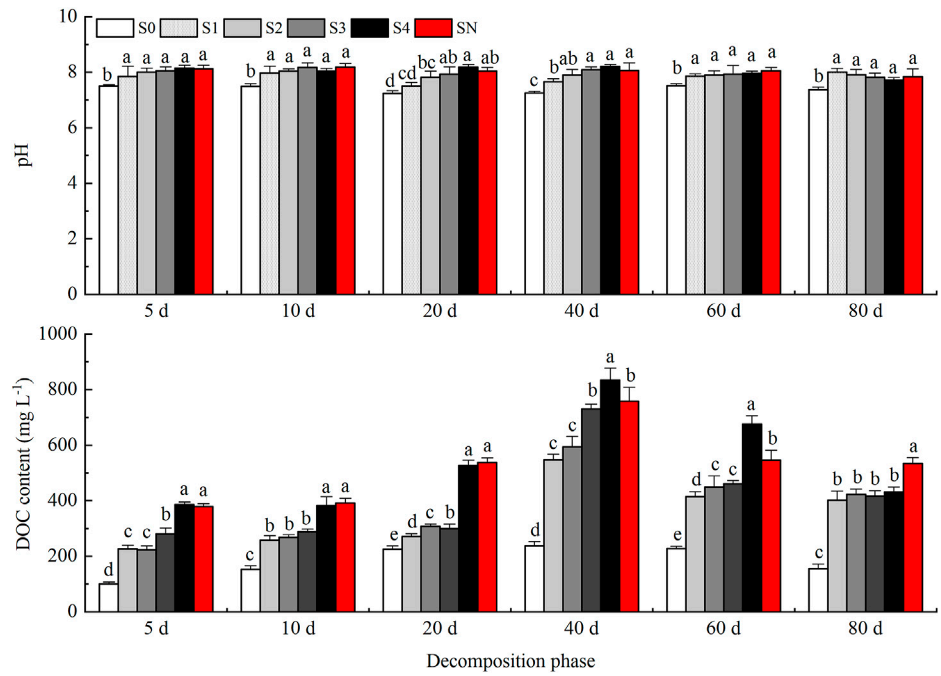


**FIGURE 1 |** pH and DOC content in soil leachate in response to wheat straw addition. The vertical bars denote standard errors. Columns with different letters represent significant difference ($p < 0.05$).

treatment to ensure three replicates per sampling period. Then 150 ml deionized water was added to the plastic cup to simulate the flooding condition of paddy soil. The plastic cups were incubated in a constant temperature incubator with temperature controlled at 25–28°C. During the incubation period, the mixture of Cd-contaminated soil and wheat straw was stirred irregularly, and the lost water was replenished according to the change in the weight of the plastic cup.

## Soil Analysis

The mixture in the plastic cup was collected by destructive sampling and placed in a centrifuge tube at 5, 10, 20, 40, 60, and 80 days, respectively and centrifuged for 10 min (3,000 rpm). The supernatant in the centrifuge tube passed through a 0.45 μm filter membrane for soluble Cd, pH, and DOC analysis. The remaining soil in the centrifuge tube was naturally air-dried, crushed, and sieved (1 mm) for Cd fraction analysis. Soluble Cd, pH, and DOC in soil leachate were detected by ICP-AES (Model iCAP 6300, Thermo Fisher Scientific Inc., United States), pH meter (Model IQ150, Spectrum, United States), and total organic carbon (TOC) analyzer (Model TOC-L, Shimadzu, Japan), respectively. Soil available Cd concentration was analyzed by the DTPA extraction method (Bao 2000). Geochemical fractions of Cd in the remaining soil were divided into four parts: exchangeable fraction (EX), reducible fraction (RG), oxidizable fraction (OXI), and residual fraction (RES). Sequential extraction for Cd fractions was described in our previous study (Bai et al., 2016). Furthermore, certified reference materials (CRMs) were used to ensure the reliability and accuracy of test results.

## Statistical Analysis

SPSS 13.0 software (SPSS Inc., United States) was used to analyze the data using analysis of variance (ANOVA). The differences between treatments were detected by the least significant difference (LSD) method at the 5% level. The relationships between pH, DOC, and soluble Cd and geochemical fractions of Cd were established through regression analysis, and the significance of the regression was judged according to the probability (p) value for the corresponding linear model.

# RESULTS

## pH and DOC in Soil Leachate

Wheat straw addition significantly increased pH in soil leachate in all treatments (**Figure 1**). With increasing wheat straw addition rates, the pH in soil leachate increased during the initial 60 days of decomposition, followed by a gradual decrease during the subsequent 20 days of decomposition (at 80 days). Compared with S0 (without wheat straw addition), the average increase of pH units in 20 g $kg^{-1}$ treatment (S4) was 0.64, 0.55, 0.94, 0.96, 0.44, and 0.35 at 5, 10, 20, 40, 60, and 80 days, respectively. The pH in soil leachate collected from soils treated with high straw inputs (S3 and S4) remained relatively stable during the first 40 days and then slightly decreased during the subsequent 40 days of decomposition. There was no significant change in pH under nitrogen addition.

Additions of wheat straw significantly increased DOC content in soil leachate and its concentration increased with increasing wheat straw addition rates (**Figure 1**). The maximum increments in DOC contents were 283.0% (5 days), 150.3% (10 days), 134.2% (20 days),

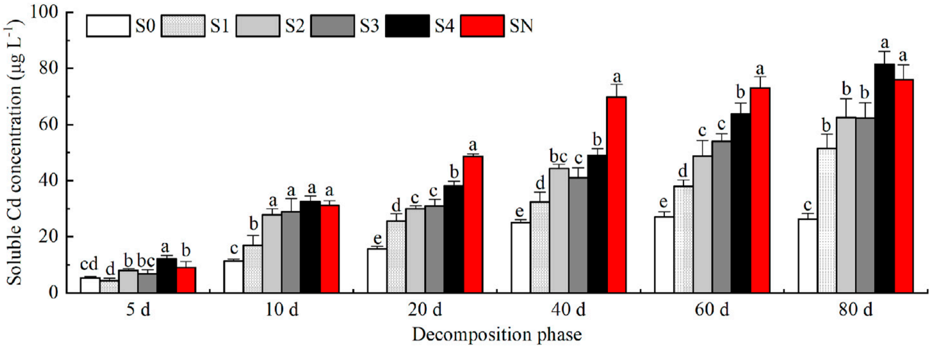


**FIGURE 2 |** Soluble Cd concentration in soil leachate in response to wheat straw addition. The vertical bars denote standard errors. Columns with different letters represent significant difference ($p$ < 0.05).

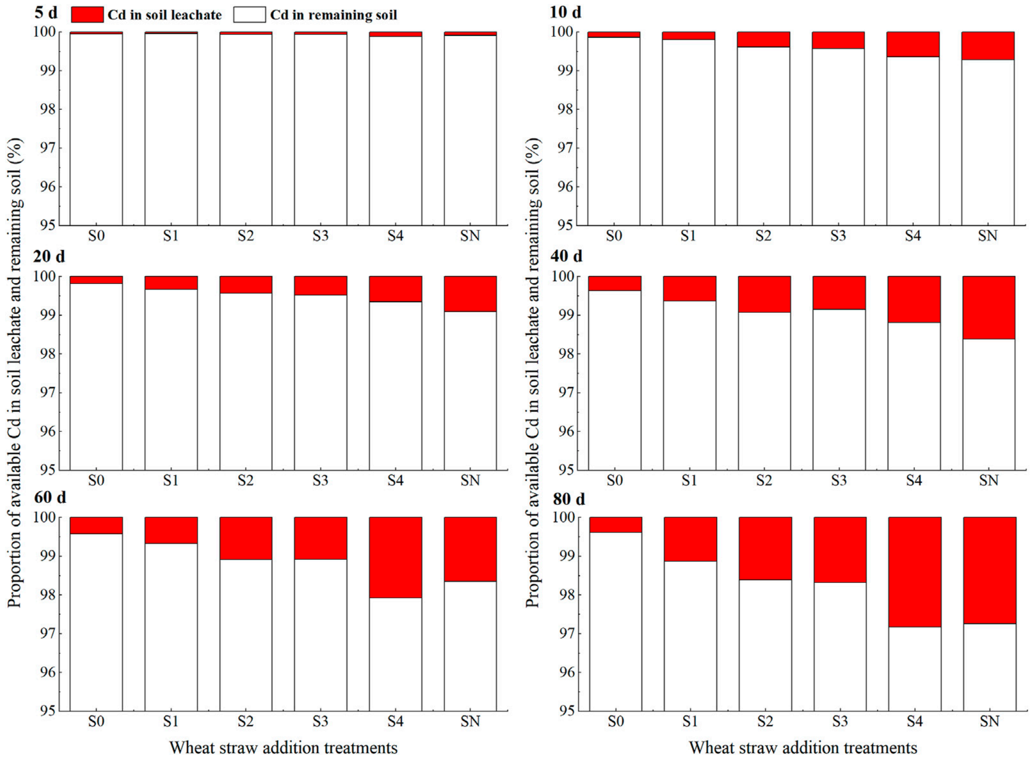


**FIGURE 3 |** Effect of wheat straw addition on the distribution of available Cd in soil leachate and remaining soil.

251.9% (40 days), 197.0% (60 days), and 178.1% (80 days), respectively, compared with S0. DOC contents in all treatments increased substantially to the maximum value after flooding for 40 days, followed by a gradual decrease during the subsequent 40 days of decomposition. DOC contents at 40 days decomposition were 135.9% (for S0), 141.3% (for S1), 165.5% (for S2), 160.3% (for S3), and 116.7% (for S4) higher than those at the first 5 days of decomposition phase. Wheat straw addition combined with nitrogen fertilizer (SN) further elevated DOC content in soil leachate. Compared with S3, the average increment in DOC content in SN reached 33.2% during wheat straw decomposition.

## Distribution of Available Cd in Soil Leachate and Remaining Soil

With increasing rates of wheat straw added, Cd concentrations in soil leachate increased as a whole (**Figure 2**). Soluble Cd in treatments with wheat straw added was significantly higher than those in soil without wheat straw addition except for S1 and S3 treatments at the first 5 days of the decomposition phase. Soluble Cd concentration in S4 were 124.1% (5 days), 187.6% (10 days), 140.8% (20 days), 94.8% (40 days), 135.2% (60 days), and 209.1% (80 days) higher than those in S0. Soluble Cd concentrations in S0 rose

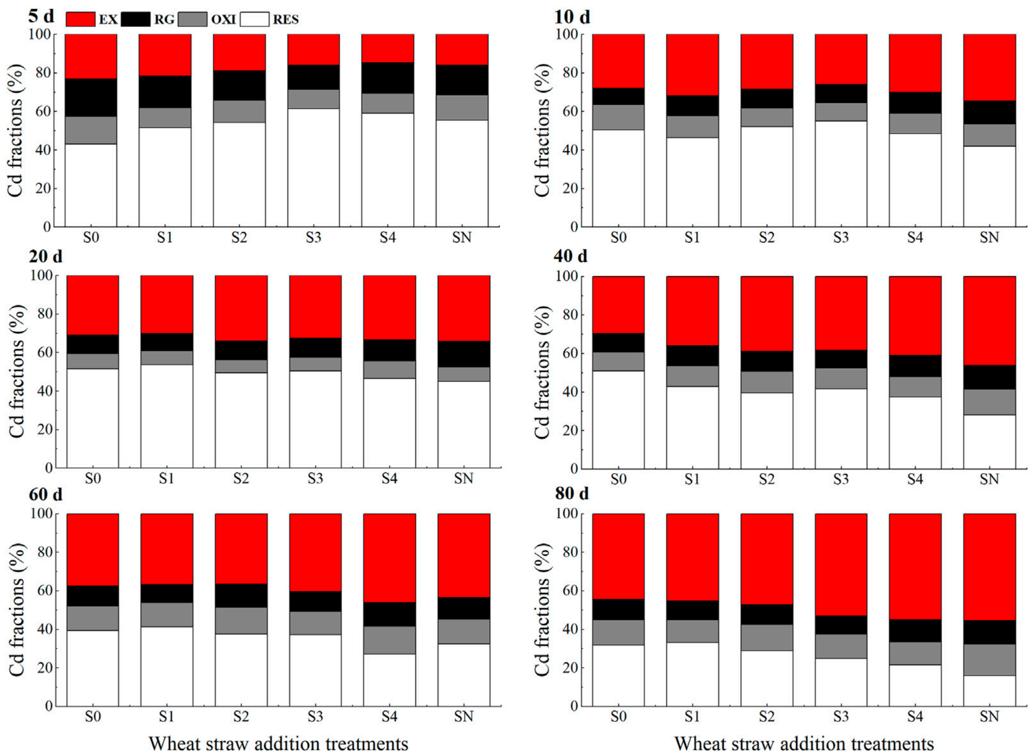


**FIGURE 4 |** Effect of wheat straw addition on geochemical fractions of Cd in remaining soil. EX, exchangeable fraction; RG, reducible fraction; OXI, oxidizable fraction; RES, residual fraction.

gradually to the maximum value after flooding for 59 days (at 60 days) and then decreased during the subsequent 20 days of decomposition. While soluble Cd concentrations in straw-treated treatments increased substantially with ongoing decomposition, the maximum values in soluble Cd concentration after 80 days of decomposition for S1, S2, S3, and S4 reached 51.5, 62.5, 62.2, and 81.28 $\mu g\ L^{-1}$, respectively. Compared with S3, SN further elevated soluble Cd concentration in soil leachate, and the increases were 32.4%, 7.5%, 57.3%, 70.0%, 35.2%, and 22.2% at 5, 10, 20, 40, 60, and 80 days, respectively.

**Figure 3** shows soluble Cd in soil leachate in S0 accounted for only 0.05%, 0.13%, 0.18%, 0.37%, 0.43%, and 0.38% of available Cd in the mixture at 5, 10, 20, 40, 60, and 80 days, respectively. While wheat straw addition significantly increased the proportion of soluble Cd in soil leachate, the proportion increased substantially with ongoing decomposition (**Figure 3**). The maximum proportions of soluble Cd reached 0.12% (5 days), 0.64% (10 days), 0.66% (20 days), 1.18% (40 days), 2.07% (60 days), and 2.82% (80 days), respectively. Compared with S3, the average increment in the proportion of soluble Cd in soil leachate in SN reached 70.0% during wheat straw decomposition.

## Cd Speciation in Remaining Soil

Wheat straw addition initially decreased the exchangeable fraction during the first 5 days of decomposition and then increased the exchangeable fraction after 10 days of decomposition compared to S0 (**Figure 4**). The proportion of exchangeable fraction at 10, 20, 40, 60, and 80 days increased from 28.0%, 30.8%, 29.5%, 37.6%, and 44.4% in S0 to 30.1%, 33.3%, 41.0%, 46.0%, and 54.8% in S4, respectively. In contrast to exchangeable fraction, wheat straw addition initially increased the residual fraction during the early decomposition phase (5 and 10 days) and then decreased the residual fraction after 20 days of decomposition. Compared with S0, the proportion of residual fraction in S4 decreased by 9.7% (20 days), 26.6% (40 days), 30.9% (60 days), and 32.5% (80 days), respectively. The fractions of reducible and oxidizable showed no significant change in response to wheat straw addition. Compared with S3, SN further increased the proportions of exchangeable, reducible, and oxidizable fractions by 11.7%, 26.1%, and 19.7% and decreased the proportion of residual fraction by 21.0% throughout the decomposition phase, respectively.

The exchangeable fraction increased gradually with ongoing decomposition (**Figure 4**). Compared with the first 5 days of decomposition, the proportion of exchangeable fraction at 80 days increased by 91.8% (S0), 109.9% (S1), 150.2% (S2), 231.6% (S3), and 273.4% (S4), respectively. By contrast, the residual Cd decreased gradually with ongoing decomposition. The decrements in the proportion of residual fraction for S1, S2, S3, and S4 reached 35.5%, 46.7%, 59.8%, and 63.7% from 5 days to 80 days of decomposition, respectively, which were higher than 26.2% in control soil. The reducible fraction decreased markedly during the first 10 days of decomposition and then remained

**TABLE 1 |** Correlations between pH, DOC, and soluble Cd concentrations in soil leachate and Cd speciation in remaining soil.

| | pH | DOC ($mg L^{-1}$) | Soluble Cd ($\mu g L^{-1}$) | Exchangeable Cd (%) | Reducible Cd (%) | Oxidizable Cd (%) | Residual Cd (%) |
|---|---|---|---|---|---|---|---|
| pH | 1 | 0.537** | $0.217^{ns}$ | $-0.081^{ns}$ | $0.081^{ns}$ | $-0.042^{ns}$ | $0.067^{ns}$ |
| DOC ($mg L^{-1}$) | | 1 | 0.643** | 0.464** | $-0.215^{ns}$ | $0.109^{ns}$ | -0.421* |
| Soluble Cd ($\mu g L^{-1}$) | | | 1 | 0.892** | -0.393* | $0.319^{ns}$ | -0.838** |
| Exchangeable Cd (%) | | | | 1 | -0.473** | 0.378* | -0.935** |
| Reducible Cd (%) | | | | | 1 | $0.257^{ns}$ | $0.165^{ns}$ |
| Oxidizable Cd (%) | | | | | | 1 | -0.635** |
| Residual Cd (%) | | | | | | | 1 |

$^{ns}$ $p > 0.05$; *$p < 0.05$; **$p < 0.01$.

relatively stable. The oxidizable fraction decreased over the first 20 days of decomposition and then rose gradually to the initial values during the subsequent 60 days of decomposition.

## DISCUSSIONS

Wheat straw addition increased DOC in soil leachate, and its content increased with increasing straw addition rates. This result indicated the dissolution and decomposition of organic matter in wheat straw (Bai et al., 2013). A similar result was reported that straw addition led to an increase in DOC content (Kalbitz et al., 2000; Kalbitz, 2003). In this study, DOC content increased substantially after flooding for 40 days, followed by a gradual decrease during the subsequent 40 days of decomposition, which is consistent with the study that DOC content in wheat straw-treated soil nearly linearly increased (0–30 days) and decreased during the subsequent decomposition phase (30–90 days) (Gao et al., 2018). This result is mainly because the rapid decomposition of wheat straw released a large amount of DOC in the early and middle stages, which was consumed by microorganisms as a preferential substrate with ongoing decomposition (Chen et al., 2010). The pH in soil leachate increased after wheat straw addition, which might be attributed to the degradation and ammonification of organic nitrogen and the proton consumption caused by the decarboxylation of organic anions during straw decomposition (Yan et al., 1996). With ongoing decomposition, the accumulation of various organic acids released by cellulose degradation under flooded conditions and the nitrification might result in a pH decrease in soil leachate (Yan et al., 1996; Shan et al., 2008).

The addition of wheat straw in Cd-contaminated soil elevated soluble Cd concentration in soil leachate, and its concentration increased with ongoing decomposition. Although organic matter itself can directly influence Cd mobility through its higher adsorption capacity for heavy metals (Yuan et al., 2021), the adsorption capacity of fresh wheat straw which is mainly composed of cellulose is very weak for metals (Bai et al., 2013). Therefore, the increase in soluble Cd concentration in soil leachate might be attributed to the indirect effects of wheat straw addition on DOC content and soil pH (Gao et al., 2018; Yuan et al., 2019). In this study, the soluble Cd concentration correlated positively with DOC content (**Table 1**), with a linear equation of $y = 0.065x + 6.7178$ ($r = 0.537$, $p < 0.01$), which indicated that soluble Cd concentration could be increased by about 6.5 $\mu g L^{-1}$ for each 100 $mg L^{-1}$ increase in DOC content. Correlation between soluble Cd concentration and DOC content in soil leachate were all significant and positive in each decomposition period and were gradually strengthened with ongoing decomposition (**Figure 5**). The previous results indicated that DOC might be the driving factor influencing Cd solubility in Cd-contaminated soil treated with wheat straw under flooded conditions. Some studies also reported that DOC plays a significant role in mediating metal's solubility and mobility due to its stronger complexation ability (Weng et al., 2002; Gao et al., 2018). The release of low-molecular-weight organic matter (a major constituent of DOC) from biodegradation of wheat straw increased DOC content in soil leachate, which combined Cd and reduced the previously adsorption of Cd on soil surfaces, thus enhancing Cd solubility (Antoniadis and Alloway, 2002; Bai et al., 2018). This conclusion was further supported by the data obtained in which the proportion of available Cd decreased in the remaining soil treated with wheat straw in this study. Although there was no significant correlation between pH and soluble Cd concentration in this study mainly because pH remained relatively stable during the first 40 days (**Figure 1**), pH is still an important factor affecting Cd activity in Cd-contaminated soil. Some studies reported that one unit increase of soil pH can lead to 3–5 times elevation of Cd adsorption by soils (Sauvé et al., 2000; Degryse et al., 2009). In contrast, the decrease in pH will activate the insoluble Cd in soil, resulting in an increase in Cd mobility and availability (Alvarenga et al., 2009; Laird et al., 2010). Therefore, facing the decreasing trend of DOC after 40 days of decomposition, the continuous increase in soluble Cd concentration in soil leachate might be partly due to the decrease in pH during this period.

The distribution of Cd speciation can reflect its mobility and availability more effectively (Kidd et al., 2007). In this study, wheat straw addition led to the redistribution of exchangeable, reducible, oxidizable, and residual fractions in soil. Studies have found that crop straw incorporation reduced metals' mobility by transforming them from the easily accessible fraction into less mobile fractions (Ok et al., 2011; Xu et al., 2016). For example, Xiao et al. (2019) reported that crop straw reduced the proportion of metals in acid-soluble and reducible fractions and increased their persistence in oxidizable fraction. Similar results were found in this study that wheat straw addition decreased the

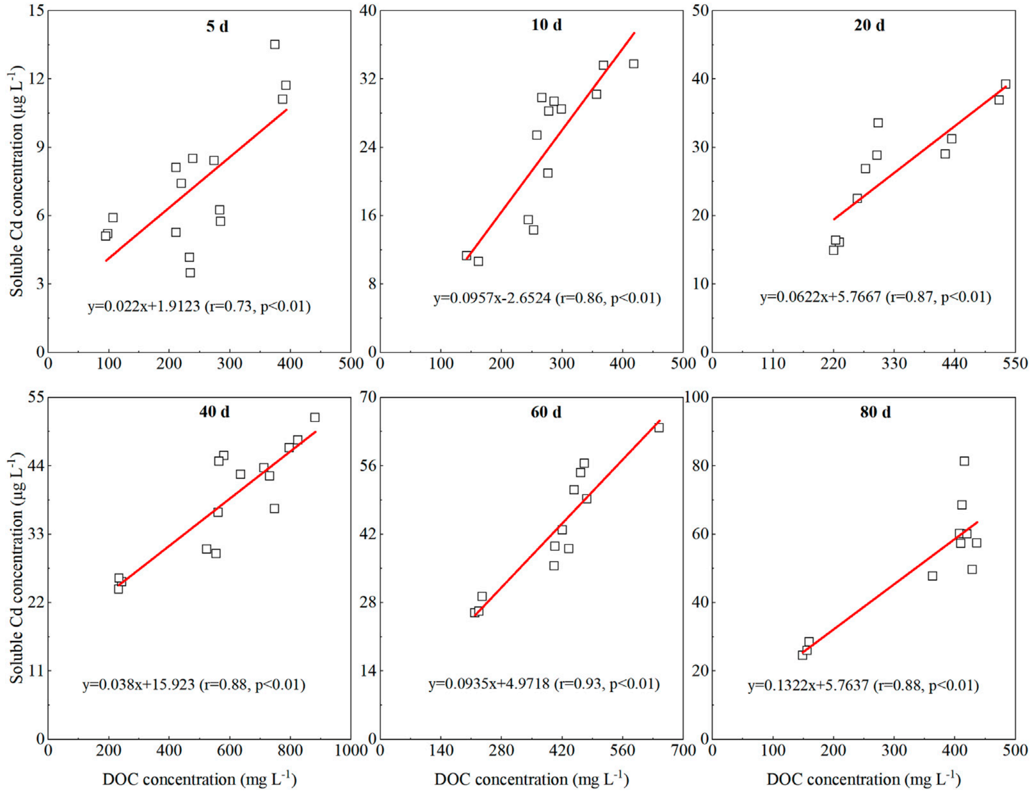


**FIGURE 5 |** Correlations between soluble Cd concentration and DOC content in soil leachate at different decomposition phases of wheat straw (5, 10, 20, 40, 60, and 80 days).

exchangeable and reducible fractions of Cd, while increasing the residual fraction during the beginning of the decomposition phase (5 days). Crop straw incorporation rapidly reduces soil redox potential under flooded soil, which leads to the rapid dissolution and activation of iron oxide closely related to Cd activity (Mukwaturi and Lin, 2015), resulting in stronger adsorption of exchangeable Cd on the soil surface (Hu et al., 2004). Therefore, the weakly adsorbed Cd rapidly transformed into strongly adsorbed Cd through reabsorption or co-precipitation at the early decomposition phase of straw incorporation (Chefetz et al., 1998; Kashem and Singh, 2006). However, the soluble organic matter (mainly DOC) released with the ongoing decomposition of wheat straw has more active sites than soil and solid organic matter (Chefetz et al., 1998; Lu et al., 2000). The hydrophilic component or low molecular weight component of soluble organic matter in flooded soil has a strong complexation ability with Cd, which can form a chelate with Cd and lead to the increase of Cd solubility, and also reduce the adsorption of Cd (Hesterberg et al., 1993; Maes et al., 2003). Therefore, the exchangeable fraction increased and the residual fraction decreased in Cd-contaminated soil after 10 days of decomposition in this study. Furthermore, the increase in exchangeable fraction and the decrease in residual fraction were observed with ongoing decomposition in this study, and the highest increment or decrement in corresponding fractions were all observed in the highest wheat straw addition rate. Correlation analysis shows that DOC content correlated positively with exchangeable Cd (r = 0.464, $p < 0.01$) and negatively with residual Cd (r = -0.421, $p < 0.05$) and had no significant correlation with reducible and oxidizable fractions (**Table 1**). This result further indicates that the redistribution of Cd fractions was mainly attributed to the increase in DOC content, which activates Cd through promoting the release of strongly adsorbed Cd (residual fraction of Cd) in Cd-contaminated soil. However, further experimental studies are required to explore the interaction mechanism between DOC and a residual fraction of Cd in Cd-contaminated soil.

Wheat straw addition combined with nitrogen fertilizer further elevated soluble Cd concentration in soil leachate and promoted the transformation from residual fraction to exchangeable fraction in Cd-contaminated soil under flooded conditions. This result indicates that nitrogen fertilizer input might further amplify the environmental hazard of Cd by promoting the decomposition of returned wheat straw to release more DOC in Cd-contaminated soil, which further confirmed the significant role of DOC in mediating Cd solubility and mobility. Therefore, the current measures of the full amount returning of wheat straw in the mid-lower reaches of the Yangtse River in China should be adjusted to appropriately reduce the proportion of wheat straw incorporation in order to reduce Cd hazard in Cd-contaminated paddy soil. In addition, either wheat straw addition or nitrogen fertilizer input can promote the solubility of Cd and increase soluble Cd concentration in soil leachate, thus increasing the Cd hazard in Cd-contaminated soil under flooded conditions. Therefore, appropriate water management measures, such as intermittent irrigation and shallow irrigation, can be considered in the early stage of the rice growth season to prevent the dissolution of Cd in the soil solid phase from affecting the surrounding environment of Cd-contaminated paddy soil with wheat straw incorporation.

## CONCLUSION

Wheat straw addition increased pH and DOC content in soil leachate. With the ongoing decomposition of wheat straw, pH remained relatively stable and DOC content increased substantially during the first 40 days, and then pH and DOC all decreased during the subsequent 40 days of decomposition. The soluble Cd concentration in soil leachate was elevated by wheat straw addition, and its concentration was correlated positively with DOC content. The exchangeable fraction of Cd decreased during the first 5 days of decomposition and increased after 10 days of decomposition in Cd-contaminated soil treated with wheat straw. By contrast, wheat straw addition increased the residual fraction of Cd at the first 5 days of decomposition and decreased its proportion after 10 days of decomposition. The exchangeable fraction increased gradually and the residual fraction decreased gradually with ongoing decomposition, and these two fractions were significantly positively correlated and negatively correlated with DOC content, respectively. Wheat straw addition combined with nitrogen fertilizer further elevated soluble Cd concentration and promoted the transformation from residual fraction to exchangeable fraction (National Soil Pollution Survey Bulletin, 2014).

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article are available upon request from the corresponding author.

## AUTHOR CONTRIBUTIONS

WZ: Writing original draft. SY and YC: Data and Methodology. GH and XZ: Investigation. YL, CG, and YB: Methodology. YS: Review and Editing. All authors read and approved the final manuscript.

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# Study of the Effect of China's Emissions Trading Scheme on Promoting Regional Industrial Carbon Emission Reduction

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The creation of carbon emissions trading markets is a core policy for realizing China's twin objectives of reaching a peak in $CO_2$ emissions before 2030 and achieving carbon neutrality by 2060. Given that industry is the most significant energy consumer and $CO_2$ emitter, it is imperative to implement carbon reducing initiatives to attain these goals. Following the implementation of carbon emissions trading pilots in China, this article theoretically analyzes the mechanisms of action and paths of influence of China's carbon trading policies on regional industrial carbon emissions. Then, regarding the trading rights policies launched in 2013 as a quasi-natural experiment, this study uses provincial panel data and industry data from 2003 to 2016 to empirically test the effect of carbon trading on industrial emissions by employing the difference-in-difference and difference-in-difference-in-difference methods. It was found that carbon emissions trading can promote a reduction in regional industrial carbon emissions, achieving the dual aims of reducing total emissions and reducing emission intensity. The reduction effect occurs after the implementation of the carbon trading market policies. The carbon trading policies reduced regional industrial emissions by optimizing regional industrial structures and increasing regional technological innovation. It was also found that reductions in carbon emissions were heterogeneous among industries. These research conclusions will help to improve the top-level design of China's industrial energy saving and carbon reduction policies and to achieve low-carbon and green industrial development.

**Keywords: carbon emissions trading policies, industrial carbon emission reduction, global climate governance, function mechanism, difference-in-difference**

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## INTRODUCTION

Climate change is a global issue that presents a significant challenge to human survival and development. China has emerged as the largest greenhouse gas (GHG) emitter in total annual emissions, to accelerate the pace of GHG emission reduction in China is important to the success of global efforts in addressing climate change (Yang et al., 2022). As an important participant, contributor, and leader in promoting global ecological conservation efforts, China has worked tirelessly to build a "community of human and natural life" through practical action. In 2020, Chinese President Xi Jinping gave an important speech during the general debate of the 75th Session of the United Nations General Assembly in which he emphasized that China will scale up its Intended Nationally Determined Contributions by adopting more effective policies and measures and strive to reach a peak in $CO_2$ emission by 2030 and achieve carbon neutrality by 2060. This This would represent the highest reduction in carbon emission intensity globally and the shortest transition from peak $CO_2$ emission to carbon neutrality in global history. China will need to work very hard to transform its socioeconomic system to achieve these goals. As the most significant contributor to China's carbon emissions, the industry must fully implement low-carbon and decarbonization strategies, which are key measures of China's climate governance. Amid this struggle to achieve ambitious emission reductions and reach a peak in $CO_2$ emissions in key industrial sectors as soon as possible, market-based environmental policy tools, such as emissions trading have gained unprecedented importance, especially since China set up carbon emissions trading markets in 2013. The European carbon emission trading system is the largest carbon emission trading market in the world, and the carbon emission trading market based on China, the world's largest carbon emitter, has great development potential. Therefore, the research on China's carbon emission trading market is of global significance.

The markets are a major part of a modern environmental governance system. China's early environmental governance was based on command-and-control environmental policies, but it is widely felt among economists that market-based tools can achieve the internalization of externalities through market transactions and economic incentives. Unlike the existing literature on market-based environmental policies, which mostly looks at emissions trading policies and traditional industrial pollutants, this article focuses more on market-oriented carbon emissions trading policies and industrial carbon emissions reduction, to supplement existing research on market-based tools and emissions reduction. A review of the current literature on market-based environmental policies and carbon emission reduction shows that domestic and foreign scholars have mainly conducted theoretical studies on market-based policies, empirical studies on the effectiveness of carbon emissions trading policies in reducing pollution, and research on the impact of environmental policies on carbon emissions reduction.

Among the theoretical studies on market-based environmental policies, Hahn and Stavins (2011) pointed out that the emissions reduction cost effectiveness of a cap-and-trade system is not impacted by initial allowable allocations, emission source production technology, or the heterogeneity of emission reduction costs, and that it is relatively strong compared to traditional command-and-control environmental policy tools led by the government. Looking at the effectiveness of market-based policies, Schmalensee and Stavins (2019) pointed out that pollution regulation has evolved from sole reliance on command-and-control policies to greater use of emissions trading. Allen et al. (2018). found that market-based environmental policies have significant theoretical advantages, but due to a late start, the current environmental policies of most countries in the world are still command-and-control-based and only supplemented by economic incentive policies. They also note that deficiencies in the economic system and regulatory constraints on enforcement also affect the effectiveness of market-based policy tools in developing countries. Studies, such as those by Bell and Russell (2002) and Kathuria (2006), have pointed out that the effectiveness of economic-incentive environmental regulations is mainly dependent on having a sound market environment and forcibly promoting incentive policies in developing countries may not have the predicted results. Hu et al. (2020) pointed out that China's relatively weak institutional environment makes the implementation of market-based environmental supervision particularly challenging.

In terms of empirical research on the effectiveness of carbon emissions trading in reducing pollution, Schmalensee and Stavins (2017) pointed out that economic incentives, such as carbon emissions trading, are more effective and economical at controlling pollution than traditional command-and-control methods because of their implementation is more flexible which can encourage enterprises to create innovative emission reduction technologies and processes. Carbon pricing has been hailed as an essential component of any sensible climate policy (Kanamura, 2019). Internalize the externalities, the logic goes, and polluters will change their behavior. Mackellar (2015) suggested that carbon pricing should be a key measure in slowing global warming. Research by Chinese scholars on carbon emissions trading has mainly focused on China's 2011 proposal to develop carbon markets. According to Tang et al. (2020), the most researched topics in carbon trading literature are the European Union's Emissions Trading System, the world's largest carbon market, and China's regional carbon markets. Most quantitative research on carbon markets discusses price discovery and the effectiveness of carbon markets as financial markets (Joyeux and Milunovich, 2010), price formation and influencing factors (Hammoudeh et al., 2015), and methods of measuring market and policy risk (Blyth and Bunn, 2011), with only a few studies on the effectiveness of carbon trading, as an environmental rights market, at reducing emissions. For example, Anderson and Di Maria (2011) found that the EU's carbon emissions trading plan reduced emissions by almost 3%, with the majority of the reduction occurring in 15 EU countries. Many empirical analysis results based on G6 countries, BRICs countries and other countries have confirmed that green investment, green technology innovation and renewable energy usage can play a significant role in reducing carbon dioxide emissions (Jia et al., 2021; Su et al., 2021; Xin et al., 2022). Other studies have also focused on the carbon trading market (Ren et al., 2022a; Ren et al., 2022b; Liu et al., 2022; Shi and Xu, 2022).

In contrast, current Chinese literature on the effectiveness of carbon emissions trading in reducing emissions is still relatively small. Most consist of qualitative discussions, empirical discussions, model predictions and simulations, or research on specific industries or regions (Jeris and Nath, 2020; Xu et al., 2022). There are relatively few empirical studies on carbon emissions trading at the national level, but one such study by Li and Lin (2020) pointed out that carbon emissions trading can effectively promote a reduction in carbon emissions as well as reductions in traditional industrial pollutants, such as sulfur dioxide, industrial wastewater, and solid waste, in pilot areas with spillover effects. A study by Cui et al. (2018) found that carbon emissions trading significantly promoted technological innovation among enterprises, especially applications for green patents. Hu et al. (2020) found that compared with other areas, $CO_2$ emissions in carbon trading pilot areas declined by 15.5%, and energy consumption by regulated industries declined by 22.8%.

Regarding research on the impact of environmental policies on carbon emission reduction, because the issue of climate change did not receive widespread attention until the 1990s and because carbon emissions data involves complex calculations (and such data is provided by different international organizations and institutions), many scholars have only begun to pay attention to the role of environmental policies in reducing carbon emissions in recent years. The lack of data means that most existing literature estimates the impact of environmental policies on emissions through models and data simulations. For example, Weng et al. (2018) simulated the impact of different carbon intensity targets on total carbon emissions and economic output. Lin and Jia (2019) established a recursive-dynamic computable general equilibrium (CGE) model to simulate the carbon emission reduction effect of China's power generation industry emissions trading system.

Very few studies have used carbon emissions data to empirically test the effectiveness of environmental policies in reducing emissions. Zhang et al. (2017) used per capita carbon emissions to measure carbon reduction and found that despite them being relatively new and market mechanisms being imperfect, carbon emissions trading policies are more effective than government command-and-control tools. Other studies have used methods such as decomposition and attribution and scenario simulation to determine the driving factors of carbon intensity, which mainly include energy intensity, emission factors, R&D intensity, and investment intensity.

In summary, Chinese and overseas scholars have conducted many valuable studies on the effectiveness of various environmental policy tools in reducing emissions. However, this author believes that the following two aspects are still urgently in need of research. First, more studies based on the real-life situation in China are required to investigate the effects of China's carbon trading policies on regional industrial carbon emissions. Much literature ignores the significant differences between China's emissions trading and its carbon emissions trading policy design. They equate the two and put them both in the basket of market-based environmental policies without distinguishing and analyzing them. In addition, the implementation of market-based environmental policies relies on a sound market environment and incentive mechanisms. In the early stage of using market-based tools in China, the market was not at the level of developed countries, so the results of targeted analysis today may be different from the past. Second, the empirical research on the impact of China's environmental policies on carbon emission reduction based on scenario simulation and prediction needs to be improved. Due to the lack of official carbon emissions data, simulations and predictions based on theoretical models are more sensitive to minor changes in parameters, which can cause different or even contrary conclusions. Moreover, the economy and government policies are both dynamic, but parameters in simulation models do not capture their dynamism, resulting in model conclusions that do not directly apply to real-life decisions.

Following the research of previous scholars, this article attempts to develop three elements: First is a theoretical and empirical analysis of carbon emissions trading policies, including a summary of the trading policy context, analysis of the role and mechanisms of carbon emissions trading policies in promoting regional industrial carbon emission reductions, and particularly the structural and technical means of reducing emissions. The second is empirical research to identify changes in the regulatory intensity of carbon emissions trading policies and distinguish between the planning and construction period and the formal trading period of the market. This will be more in-depth and specific than previous studies that only looked at regions and years with and without pilot projects. Third, this study uses China's Carbon Emission Accounts and Datasets (CEADs), which has relatively accurate and up-to-date data on China but which has seldom been used in other studies, to empirically test the effect of carbon emissions trading policies in promoting regional industrial carbon emission reduction and to more comprehensively reflect the level of, and principles behind, carbon emission reduction in China. Analysis in this study covers different provinces and industries and includes the two indicators of total carbon emission reduction and carbon emission intensity reduction. These innovations allow this study to reach conclusions that differ from the existing literature, contributing knowledge to this field. This study uses the most common quasi-natural experiment methods to identify causal effects in evaluating current environmental regulation policies. Therefore, this paper regards China's carbon emission trading policy launched in 2013 as a quasi-natural experiment to evaluate the effect of environmental regulation policy. In order to comprehensively test the effect of China's carbon emission trading policy on promoting regional industrial carbon emission reduction, this paper establishes a two-way fixed effect model that uses (DID), difference-in-difference-in-difference (DDD), and other methods to test the impact of carbon emissions trading policies on promoting regional industrial carbon emission reductions, with robustness tests to ensure the reliability of the conclusions.

# POLICY BACKGROUND AND MECHANISMS OF ACTION OF CARBON TRADING PILOTS

## Policy Background

China began considering establishing carbon emissions trading markets and announced that pilot carbon emissions trading platforms were Shenzhen, Beijing, Tianjin, Shanghai, Chongqing, Guangdong, and Hubei in 2011. Transactions were launched in 2013. According to the China Carbon Emissions Trading Network, the seven provinces and cities involved in the pilot schemes traded 172 million tons of $CO_2$

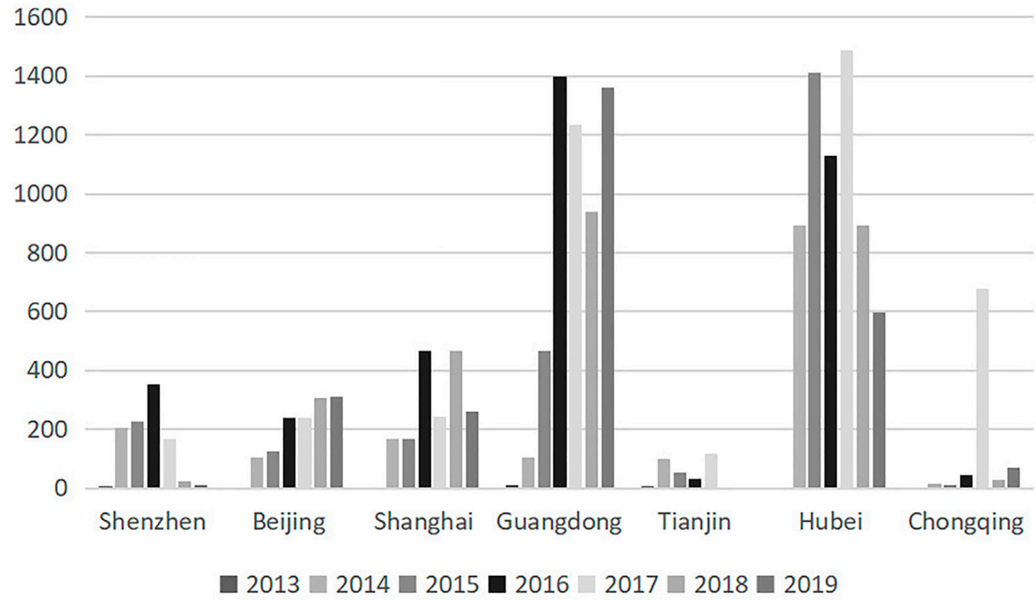


**FIGURE 1 |** Trading Volume of Carbon emission rights in the seven Pilots 2013–2019. Notes: (unit: 10,000 tons of $CO_2$ equivalent). Source: China Carbon Emissions Trading Network.

equivalent between 2013 and 2019, worth a total of 4.3 billion yuan, with both the transaction volume and transaction value increasing year on year. It can be seen from **Figure 1** that the trading volume of carbon emission rights in the different cities and provinces was very uneven. As of 2019, most transactions were concentrated in Guangdong (40%) and Hubei (47%). Tianjin and Chongqing, which have the lowest trading volume, only traded 305 and 840 tons of carbon emission rights.

The total transaction volume across the seven pilot schemes during the first three quarters of 2020 was 23.3 million tons, an increase of 5.77% over the same period the previous year (22.03 million tons). The transaction value was 679 million yuan, a slight decrease (−2.97%) compared to the previous year (700 million yuan). The coronavirus pandemic affected all the pilot schemes, especially in Hubei Province, which resumed trading more than a month (23 March ) after the others. Nevertheless, due to its relatively high daily average transaction volume (9.1 million tons) and value of transactions (250 million yuan), the Hubei pilot scheme retained its leading position among the seven pilot regions, accounting for 38.90% of the total transaction volume and 36.85% of the transaction value. In general, China's carbon emissions trading markets have not been significantly affected by coronavirus, and they are operating steadily. With the launch of the national carbon market for the power generation industry in June 2021, carbon emissions trading is on the brink of extraordinarily rapid growth.

## Analysis and Hypotheses

This paper begins with a statistical analysis of industrial carbon emissions and carbon intensity in pilot and non-pilot areas. The results show that total industrial carbon emissions were higher in both pilot and non-pilot areas during the pilot period (2003–2012) than during the non-pilot period (2013–2016), indicating that economic expansion led to increases in energy consumption and carbon emissions. However, emissions in pilot areas were lower than in non-pilot areas during both the non-pilot period and the pilot period, with a multiplicative relationship between them that expanded from 1.4 times before the pilot to 1.7 times after the pilot. Economic growth in the pilot areas did not bring about a sharp increase in industrial carbon emissions, and industrial carbon intensity in pilot areas declined much faster than non-pilot areas during the pilot period. This tentatively shows that the pilot carbon emissions trading policies may have been effective in reducing regional industrial carbon emissions.

In addition, looking at features and administrative levels of policies and regulations, there are differences in regulatory intensity in different areas. At present, only Beijing, Shenzhen, and Chongqing have formulated local regulations on carbon trading. Other areas mainly manage their carbon markets based on government regulations or departmental documents. This difference in regulatory intensity is transmitted through policies and reflected in the prices and quota-turnover ratio of carbon markets, as shown in **Figures 2**, **3**. The quota-turnover ratio is the ratio of the annual transaction volume of a carbon market to the quota issued for a specific year. It can be seen from the figures that there is a correlation between carbon prices and the quota-turnover ratio. Cities such as Beijing and Shenzhen have relatively high carbon prices and relatively high quota-turnover ratios. According to a 2016 report from the Green Finance Committee's Carbon Finance Working Group, the criteria for evaluating carbon market development includes resource allocation efficiency (carbon pricing effectiveness) and

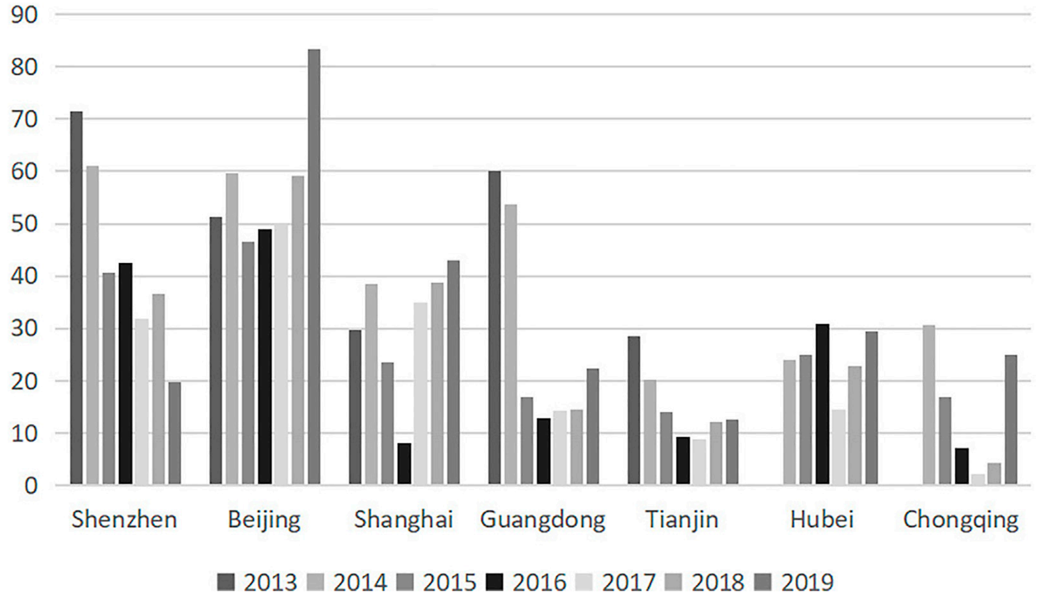


**FIGURE 2 |** Carbon emissions trading prices of the seven pilots 2013–2020. Source: china carbon emissions trading network.

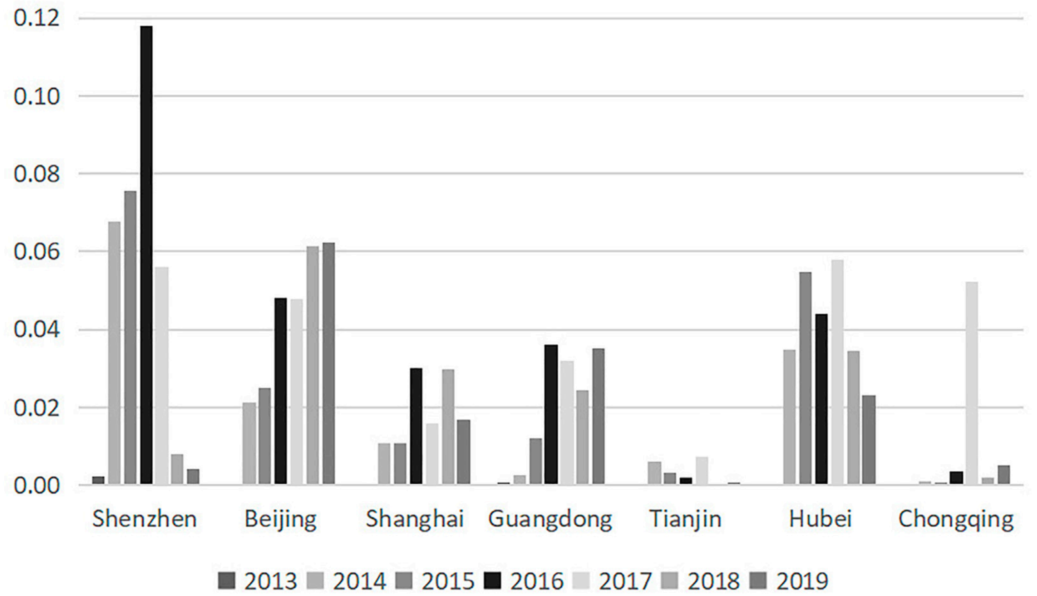


**FIGURE 3 |** Carbon emissions trading quota-turnover ratios of the seven pilots 2013–2019. Source: china carbon emissions trading network.

market operation efficiency (market liquidity) (Yang et al., 2021a; Balezentis et al., 2021; Song et al., 2021; Yao et al., 2021; Zhao et al., 2022).

Based on the previous, this study proposes the following hypotheses.

**Hypothesis 1:** Trading carbon emissions rights promotes a reduction in the volume and intensity of regional carbon emissions, and the greater the regulatory intensity, the greater the effectiveness.

China's carbon emissions trading policies can be divided into two time periods: the first is the period of policy planning and local market preparation from 2011 to 2012; the second is the period of formal implementation of the policy from 2013, when trading began. Based on information transmission analysis, it can be inferred that the information received and the expectations formed by the enterprises in these two periods were completely different, and the resulting decisions and behaviors of the enterprises were also different. In the first period, due to China being a large developing country, the value of foreign experience in developing carbon markets was very limited, and policy evolution was relatively slow. As for regulatory intensity, after transactions officially started, companies had to rely on extremely limited information to make judgments and decisions. Some companies adopted a wait-and-see approach and took no action to prevent losses. In the second period, electronic bidding was introduced, which provided real-time changes and announcements of carbon pricing. Companies could obtain timely market supply and demand information such as pricing and transaction volumes in a relatively liquid market. As a result, this study proposes Hypothesis 2.

**Hypothesis 2:** Carbon emissions trading only reduced industrial carbon emissions following the start of formal market transactions, and reductions increased year on year.

The mechanism of action whereby carbon emissions trading policies reduce regional industrial carbon emissions is primarily based on the structural and technical effects of market-based environmental policies.

In terms of structural effects, the existence and fluctuation of the market price of carbon emissions trading cause changes in enterprises' cost-benefit structure, affecting polluters' behavior. Increases in emission reduction benefits and pollution costs create economic incentives or cost pressures for enterprises. Companies that are expected to emit more than the government quota can choose to purchase the quotas of other companies or seek to limit their emissions through structural adjustments, optimization, and technological innovation. Due to the increased certainty over future costs and benefits, it is possible for companies to conduct effective long-term planning. When companies know that pollution control costs and production costs will rise due to carbon emissions trading policies, they will adjust factors of production based on economic performance and long-term development plans to reduce investment in high-carbon sectors and products while increasing investment in low-carbon sectors and products. This optimizes the efficiency of enterprise resource allocation and the industrial structure of the entire region. The industrial output of pilot industries increases while the output of non-pilot industries decreases, and the output ratio of non-pilot and pilot industries increases. Thus, the industrial structure optimization effect of carbon emissions trading policies promotes a reduction in regional industrial carbon emissions.

In terms of technological effects, carbon emissions trading policies enable companies to achieve more effective expectations of the benefits of reducing carbon emissions through green technological innovation and strengthen the economic incentives for enterprises to make technological innovations. Companies can calculate the cost and benefits of reducing emissions and the impact on future economic performance based on their production and operation conditions and the trading volume and price trends of carbon emission rights in the marketplace, which improves the efficiency of corporate decision-making. Therefore, the carbon market encourages enterprises to invest in emission reduction technologies and energy use technologies to achieve technological innovations and low-carbon production and reduce energy consumption and carbon emissions per unit of output value. Moreover, the law of market value plays a fundamental and decisive role in the carbon trading market, which means mandatory supervision by the government is significantly reduced, and the autonomy and flexibility of enterprises in technological innovation are enhanced. Enterprises will also be more willing and motivated to improve production technology and create green innovations to reduce emissions. If the carbon emission rights market operates continuously, effectively, and stably, companies will continue to create technological innovation and achieve regional carbon emission reductions. The mechanisms by which carbon emissions trading policies promote reduced regional industrial carbon emissions are shown in **Figure 4**.

**Hypothesis 3:** Carbon emissions trading policies reduce regional industrial carbon emissions by optimizing regional industrial structures and promoting regional technological innovation.

In the mechanism of action analysis above, it is stated that carbon emissions trading will optimize local industrial structures, and companies may reduce their investment and production scale in high-carbon industries, investing instead in low-carbon industries, leading to an increase in the output value of low-carbon industries and a decrease in the output value of high-carbon industries. As well as changes to the structures of different industrial sectors, this study also looks at the heterogeneity of reactions to carbon emissions trading policies by industries with different features. In the mechanism of action analysis above, it is stated that carbon emissions trading will optimize local industrial structures, and companies may reduce their investment and production scale in high-carbon industries, investing instead in low-carbon industries, leading to an increase in the output value of low-carbon industries and a decrease in the output value of high-carbon industries. As well as changes to the structures of different industrial sectors, this study also looks at the heterogeneity of reactions to carbon emissions trading policies by industries with different features.

Based on this, we propose Hypothesis 4.

**Hypothesis 4:** The effect of carbon emission rights trading policies in reducing carbon emissions differs by industry, and the effect on high-carbon intensity industries is significantly more significant than for low-carbon intensity industries.

## RESEARCH DESIGN

This article regards the carbon emissions trading policy launched in 2013 as a quasi-natural experiment and defines the six provinces (Shenzhen is included in Guangdong Province) in the carbon emission rights pilots as the experiment group, with the non-pilot area as the control group. It uses the difference-in-difference (DID) method to examine the impact of carbon emissions trading in reducing regional industrial

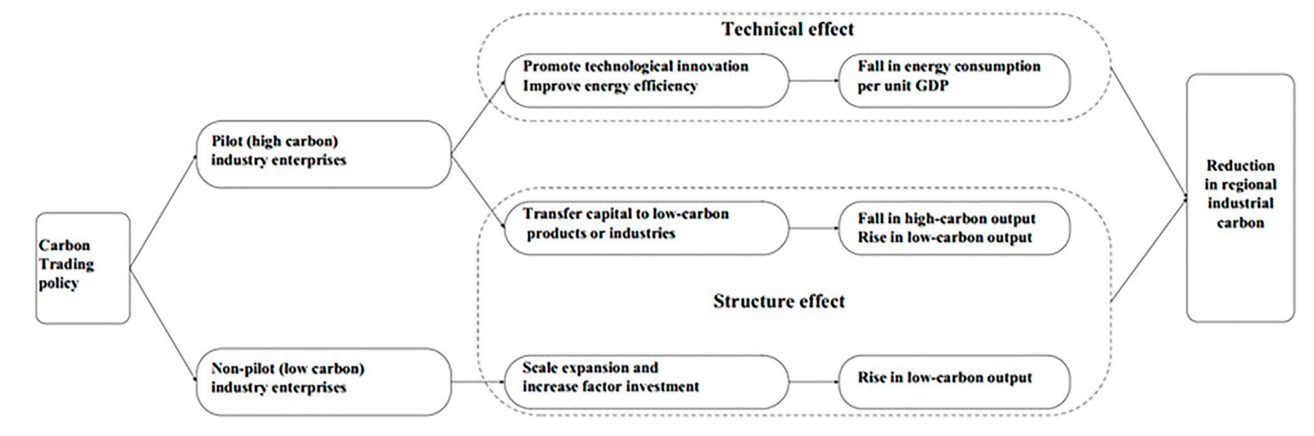


**FIGURE 4 |** The mechanisms by which carbon emissions trading policies promote reduced regional industrial carbon emissions. This leads to Hypothesis 3.

carbon emissions. Hu et al. (2020) pointed out that carbon emissions trading pilot areas are geographically spread out in eastern, central, and western regions of China, so they have different economic environments. As the central government determines the pilot areas, they have a top-down nature, so the pilot carbon emissions trading scheme can be regarded as a relatively good quasi-natural experiment.

Based on the above analysis, we constructed a DID two-way fixed effects model:

$$emission_{it} = \alpha_0 + \alpha_1 co2t2013_{it} + \sum_j \alpha_j control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \tag{1}$$

Where i represents the region, t represents the year, γt represents the fixed effect of the year, μi represents the fixed effect of the area, and εit is the random disturbance term. The explained variable emissionit is the reduction in regional industrial carbon emissions, covering the two indicators of industrial carbon emissions volume and carbon intensity. The key explanatory variable co2t2013 is the DID term. If the coefficient $\alpha_1$ is significantly negative, the pilot carbon trading scheme effectively reduces regional industrial carbon emissions. Control is a series of other control variables, including the level of economic development, openness to the outside world, industrial structure, government investment in industrial pollution control, and economic fluctuations.

During the planning and construction period from 2011 to 2012 and the formal implementation period after 2013, there were differences in the regulatory intensity of the carbon emissions trading policies, and there may also have been differences in their effectiveness. To test the impact of different stages and different regulatory intensities, this study identified two stages and selected the annual average carbon trading price indicators and quota-turnover ratio indicators to construct **Eq. 2** and **Eq. 3**.

$$emission_{it} = \delta_0 + \delta_1 co2t1112_{it} + \delta_2 co2t2013p_{it} + \sum_j \delta_j control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \tag{2}$$

$$emission_{it} = \theta_0 + \theta_1 co2t1112_{it} + \theta_2 co2t2013t_{it} + \sum_j \theta_j control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \tag{3}$$

The data used in this article comes from China Statistical Yearbook and China Statistical Yearbook on Industrial Economy. Carbon emission data comes from China's Carbon Emission Accounts and Datasets (CEADs). Due to a lack of certain data, industrial sector data runs only to 2016, and data for Tibet is missing. **Table 1** shows the descriptive statistics of the main variables. In addition to the variables in the benchmarking and regression, it also shows the descriptive statistics of the two intermediary variables of structural and technical effects in the mechanism verification.

# EMPIRICAL ANALYSIS

## Testing the Effectiveness of Carbon Emissions Trading Pilots

This study used the DID method to establish a two-way fixed effects model for testing the impact of carbon emissions trading policies on regional industrial carbon emissions. The results in **Table 2** show that carbon emissions trading led to a significant decrease in regional industrial carbon emissions, simultaneously achieving the dual objectives of reducing carbon volume and carbon intensity. In addition, annual average carbon trading price and allowance turnover are the two indicators of the liquidity and effectiveness of different pilot carbon market The cross-product coefficients of carbon trading, carbon pricing, and the quota-turnover ratio are all significantly negative, which means that the effect of carbon emissions trading is more significant in years when annual average carbon trading prices and the quota-turnover ratio are higher, indicating the importance of increasing regulatory intensity. The coefficients of economic fluctuations indicate that, areas which have higher economic stability enjoy lower carbon intensity while the impact of GDP

**TABLE 1 |** Variable explanations and descriptive statistics.

| Variable | Variable explanation | Sample | Mean | St. Dev. | Min. | Max. |
|---|---|---|---|---|---|---|
| lnco2emi | Regional industrial carbon emissions (10,000 tons) logarithm | 420 | 9.681 | 0.848 | 7.039 | 11.208 |
| co2inten | Regional industrial carbon intensity (tons/10,000 yuan of industrial output value) | 420 | 2.042 | 1.729 | 0.207 | 14.887 |
| lnpergdp | Per capita GDP (yuan) logarithm | 420 | 10.178 | 0.720 | 8.190 | 11.680 |
| lntrade | Traded goods (100 million yuan) logarithm | 420 | 7.465 | 1.638 | 3.345 | 11.282 |
| secind | Percentage of secondary industry | 420 | 0.471 | 0.079 | 0.193 | 0.615 |
| lnpoinvest | Investment in industrial pollution control (10,000 yuan) logarithm | 420 | 11.676 | 1.060 | 7.561 | 14.164 |
| gdpgrowth | GDP growth rate | 420 | 0.115 | 0.029 | −0.025 | 0.238 |
| struc | Output value of non-pilot industries/output value of pilot industries | 420 | 1.663 | 0.803 | 0.307 | 4.010 |
| tech | Regional industrial energy consumption/Gross industrial output value (tons of standard coal/10,000 yuan) | 420 | 0.218 | 0.262 | 0.006 | 3.774 |

**TABLE 2 |** Impact of carbon trading on regional industrial carbon emissions: Benchmarking and regression.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Regional industrial carbon emissions | | | Regional industrial carbon intensity | | |
| Carbon trading | −0.239*** | | | −0.387** | | |
| | (−2.872) | | | (−2.199) | | |
| Carbon trading x carbon pricing | | −0.070** | | | −0.125** | |
| | | (−2.621) | | | (−2.400) | |
| Carbon trading × quota-turnover ratio | | | −10.154*** | | | −10.818 |
| | | | (−3.307) | | | (−1.647) |
| lnpergdp | −0.030 | 0.038 | 0.133 | −14.831*** | −14.830*** | −14.265*** |
| | (−0.041) | (0.052) | (0.190) | (−5.716) | (−5.778) | (−5.500) |
| lnpergdp2 | 0.021 | 0.016 | 0.013 | 0.562*** | 0.559*** | 0.534*** |
| | (0.614) | (0.486) | (0.400) | (4.026) | (4.095) | (3.794) |
| lntrade | 0.001 | −0.011 | −0.024 | 0.185 | 0.168 | 0.144 |
| | (0.019) | (−0.243) | (−0.560) | (0.903) | (0.856) | (0.796) |
| gdpgrowth | 0.685 | 0.641 | 0.608 | 11.790*** | 11.813*** | 11.380*** |
| | (0.790) | (0.738) | (0.721) | (3.181) | (3.179) | (3.058) |
| lnpoinvest | 0.075*** | 0.074*** | 0.086*** | −0.092 | −0.094 | −0.075 |
| | (2.988) | (2.987) | (3.229) | (−0.936) | (−0.952) | (−0.774) |
| secind | 0.627 | 0.676* | 0.791* | 1.832 | 1.900 | 2.069 |
| | (1.572) | (1.701) | (1.941) | (1.003) | (1.049) | (1.131) |
| Year effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Province effect | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 420 | 420 | 420 | 420 | 420 | 420 |
| r2 | 0.854 | 0.853 | 0.858 | 0.800 | 0.801 | 0.799 |

*Notes: ① t-values are in parentheses, using province clustered standard errors; ② significance levels are ***p < 0.01, **p < 0.05, *p < 0.1.*

growth on total emissions are insignificant. This verifies Hypothesis 1.

## Parallel Trend Test

We conducted a dynamic effect test to reflect differences in the effects of pilot carbon emissions trading policies in different years. Following the event analysis method framework, a two-way fixed effects model was used in **Eq. 4**.

$$emission_{it} = \alpha_0 + \sum_{\tau=2010}^{2016} \alpha_\tau treat_i \times D_\tau + \sum_j \alpha_j control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (4)$$

Where Dτ is the year dummy variable, ατ is the coefficient being focused on, and the meanings of the other letters are the same as **Eq. 1**. It can be seen that **Eq. 4** sets 2009 as the base year for event analysis, so the specific meaning of the coefficient ατ is whether there is a significant reduction in carbon emissions between pilot provinces and non-pilot provinces in $\tau$ compared with 2009. Specifically, if ατ is not significant (the 95% confidence interval includes the null value) before the launch of carbon emissions trading in 2013, a parallel trend is established.

Based on the regression results of **Eq. 4** and **Figure 5** shows the estimated values of the coefficient ατ from 2010 to 2016 and the 95% confidence intervals. It can be seen that, in the first 3 years of the carbon emissions trading policy, although there were differences in industrial carbon emissions and industrial carbon intensity between pilot and non-pilot areas, these differences are not significant once regional economic factors are controlled, so the parallel trend assumption in the DID method is satisfied. This means that if carbon emissions trading had not started, the carbon emission reduction trends of the two groups (pilot provinces and non-pilot provinces) would be parallel. Moreover, after the launch of carbon

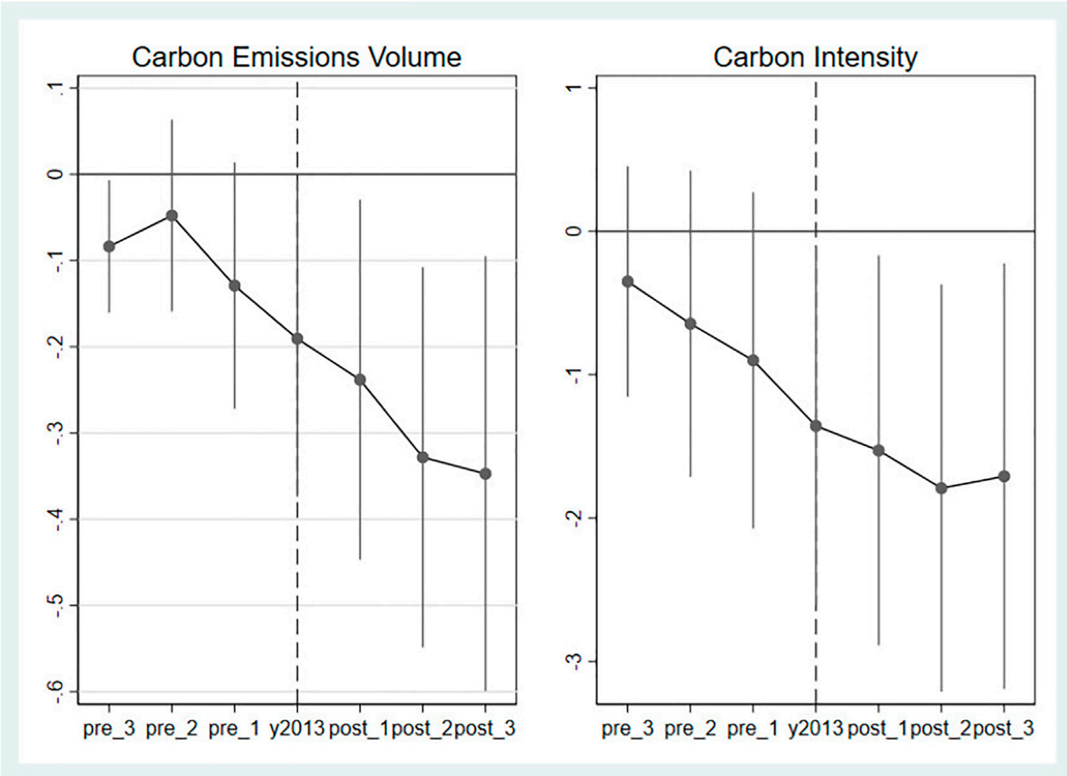


**FIGURE 5 |** The Impact of Carbon Trading on Regional Industrial Carbon Emissions: Dynamic Effect. Note: The vertical lines in the graphs represent the 95% confidence interval of the estimated regression coefficient.

emissions trading, reductions in regional industrial carbon emissions grew year on year.

## Predicted Efficacy and Impacts at Different Stages

To ensure the reliability of the research results, this paper distinguished between the planning and construction period (2011–2012) and the formal trading period (2013–2016) when examining the impact of the predicted efficacy on the regression results. Prior to the pilot provinces launching formal carbon emissions trading in 2013, the National Development and Reform Commission issued a document in 2011 specifying the seven pilot provinces and cities. This may have enabled companies to form expectations before the official launch of carbon emissions trading and adjust their production and investment behavior accordingly. If there were a systematic difference in their adjusted behavior in pilot provinces and non-pilot provinces, it would lead to bias in the estimation results. To control the impact of enterprise expectations on the research results, this study established **Eq. 2** and **Eq. 3**, and in regression **Eq. 1**, an interaction term between the pilot provinces and the planning and construction period (2011–2012) is added. The corresponding regression results are shown in **Table 3**.

**Table 3** shows that the regression coefficient of carbon emissions trading barely changed after adding the expectation term during the planned construction period. In addition, the planned construction period coefficient was not significant. This indicates that although the carbon market was in the planning and construction stage in 2011 and 2012, because there were no substantial transactions at this stage and the pilot areas did not issue management documents on the carbon market, it remained unclear which industries and companies would be included in the carbon market and which methods would be used to issue allowances. As a result, at that stage, carbon emissions trading policies did not substantially impact the carbon emissions behavior of companies that adopted a wait-and-see attitude. In 2013, after the carbon emissions trading market was officially launched, relevant policy documents in pilot areas gradually improved. Only then did companies receive information on carbon market pricing and quota-turnover ratios, which they used to adjust their carbon emissions decision-making and behavior accordingly, which led to a reduction in regional industrial carbon emissions. This verifies Hypothesis 2.

## Mechanism Verification of Carbon Trading Reducing Regional Industrial Carbon Emissions

In our analysis of the mechanism of action, we stated that carbon emissions trading policies could optimize regional industrial structures (structural effect) and give rise to new

**TABLE 3 |** Impact of carbon emissions trading on regional industrial emissions at different stages.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Regional industrial carbon emissions | | | Regional industrial carbon intensity | | |
| Carbon trading 2011–12 | −0.077 | −0.065 | −0.027 | −0.139 | −0.136 | −0.024 |
| | (−1.360) | (−1.019) | (−0.620) | (−0.722) | (−0.700) | (−0.178) |
| Carbon trading 2013 | −0.261** | | | −0.427* | | |
| | (−2.715) | | | (−1.902) | | |
| Carbon trading × Carbon price | | −0.075** | | | −0.136* | |
| | | (−2.427) | | | (−2.043) | |
| Carbon trading × Quota-turn-over ratio | | | −10.297*** | | | −10.945 |
| | | | (−3.143) | | | (−1.579) |
| lnpergdp | −0.124 | −0.034 | 0.116 | −15.000*** | −14.981*** | −14.280*** |
| | (−0.169) | (−0.047) | (0.167) | (−5.655) | (−5.728) | (−5.460) |
| lnpergdp2 | 0.025 | 0.019 | 0.013 | 0.569*** | 0.565*** | 0.534*** |
| | (0.741) | (0.582) | (0.421) | (4.049) | (4.126) | (3.788) |
| lntrade | 0.004 | −0.010 | −0.024 | 0.191 | 0.171 | 0.145 |
| | (0.074) | (−0.207) | (−0.557) | (0.901) | (0.853) | (0.794) |
| gdpgrowth | 0.708 | 0.655 | 0.604 | 11.830*** | 11.842*** | 11.377*** |
| | (0.818) | (0.755) | (0.716) | (3.188) | (3.184) | (3.054) |
| lnpoinvest | 0.071*** | 0.071*** | 0.085*** | −0.099 | −0.101 | −0.076 |
| | (3.032) | (3.045) | (3.305) | (−0.978) | (−0.990) | (−0.774) |
| secind | 0.628 | 0.681* | 0.796* | 1.834 | 1.910 | 2.074 |
| | (1.567) | (1.702) | (1.936) | (1.006) | (1.055) | (1.127) |
| Year effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Province effect | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 420 | 420 | 420 | 420 | 420 | 420 |
| r2 | 0.855 | 0.853 | 0.858 | 0.801 | 0.801 | 0.799 |

*Notes: ① t-values are in parentheses, using province clustered standard errors; ② significance levels are ***p < 0.01, **p < 0.05, *p < 0.1.*

**TABLE 4 |** Mechanism verification of the impact of carbon trading on regional industrial carbon emissions.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Regional industrial | Carbon emissions | Structural effect | Technological effect |
| Carbon trading | −0.239*** | −0.191** | 0.314** | −0.097** |
| | (−2.872) | (−2.333) | (2.119) | (−2.527) |
| Structural effect | | −0.099 | | |
| | | (−1.633) | | |
| Technological effect | | 0.168* | | |
| | | (1.782) | | |
| lnpergdp | −0.030 | 0.671 | 2.502** | −2.700*** |
| | (−0.041) | (0.940) | (2.507) | (−3.701) |
| lnpergdp2 | 0.021 | −0.006 | −0.096* | 0.102*** |
| | (0.614) | (−0.179) | (−1.771) | (3.349) |
| lntrade | 0.001 | 0.004 | 0.065 | 0.023 |
| | (0.019) | (0.077) | (0.502) | (0.624) |
| gdpgrowth | 0.685 | 0.217 | −2.117 | 1.541* |
| | (0.790) | (0.282) | (−1.512) | (1.976) |
| lnpoinvest | 0.075*** | 0.068*** | −0.122* | −0.032 |
| | (2.988) | (3.205) | (−1.983) | (−1.249) |
| secind | 0.627 | 0.568 | 0.326 | 0.540 |
| | (1.572) | (1.670) | (0.340) | (0.951) |
| Year effect | Yes | Yes | Yes | Yes |
| Province effect | Yes | Yes | Yes | Yes |
| N | 420 | 420 | 420 | 420 |
| r2 | 0.854 | 0.867 | 0.323 | 0.543 |

*Notes: ① t-values are in parentheses, using province clustered standard errors; ② significance levels are ***p < 0.01, **p < 0.05, *p < 0.1.*

energy technologies (technological effect), resulting in a reduction in regional industrial carbon emissions and carbon intensity (Yang et al., 2021b). It can be seen from the results of the benchmarking and regression that carbon emissions trading can significantly reduce regional industrial carbon emissions, but the mechanism of action has not yet

**TABLE 5 |** Mechanism verification of the impact of carbon trading on regional industrial carbon intensity.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Regional industrial | Carbon intensity | Structural effect | Technological effect |
| Carbon trading | −0.387** | 0.018 | 0.314** | −0.236** |
| | (−2.199) | (0.118) | (2.119) | (−2.500) |
| Structural effect | | −0.524*** | | |
| | | (−3.693) | | |
| Technological effect | | 1.016*** | | |
| | | (9.819) | | |
| lnpergdp | −14.831*** | −8.602*** | 2.502** | −4.840*** |
| | (−5.716) | (−4.846) | (2.507) | (−2.796) |
| lnpergdp2 | 0.562*** | 0.343*** | −0.096* | 0.166** |
| | (4.026) | (3.119) | (−1.771) | (2.441) |
| lntrade | 0.185 | 0.125 | 0.065 | 0.093 |
| | (0.903) | (0.886) | (0.502) | (1.054) |
| gdpgrowth | 11.790*** | 7.583** | −2.117 | 3.049 |
| | (3.181) | (2.197) | (−1.512) | (1.696) |
| lnpoinvest | −0.092 | −0.088 | −0.122* | −0.067 |
| | (−0.936) | (−1.274) | (−1.983) | (−1.147) |
| secind | 1.832 | 0.804 | 0.326 | 1.180 |
| | (1.003) | (0.777) | (0.340) | (0.795) |
| Year effect | Yes | Yes | Yes | Yes |
| Province effect | Yes | Yes | Yes | Yes |
| N | 420 | 420 | 420 | 420 |
| r2 | 0.800 | 0.909 | 0.323 | 0.454 |

*Notes: ① t-values are in parentheses, using province clustered standard errors; ② significance levels are ***p < 0.01, **p < 0.05, *p < 0.1.*

been empirically verified. According to Li et al. (2022), there exists some problems in using mediating-effects analysis in causal relationships analysis, however, according to Jiang (2022), we could still use mediating-effects analysis based on the characteristics of our sample and objective of our analysis. Using the intermediary effect method, consisting of a three-step process, this study empirically verified how carbon emissions trading reduces regional industrial carbon emissions.

**Tables 4**, **5** show the results of the intermediary effect tests. They show that carbon emissions trading can reduce regional industrial carbon emissions by increasing the ratio of the output of non-pilot industries and pilot industries in a region, optimizing the regional industrial structure, and promoting the creation of energy use technologies by industries, thereby reducing energy consumption per unit of output value. Regardless of whether one takes regional industrial carbon emissions or regional industrial carbon intensity as the explanatory variable, after adding the two intermediary variables of structural effect and technological effect, the absolute value and significance of the carbon trading policy coefficient are reduced. The difference is that for the reduction of regional industrial carbon intensity, the structural effect and technological effect both play a role, but for the reduction of regional industrial carbon emissions, the structural effect is not significant. This shows that if the goal is to reduce total regional industrial carbon emissions, the key is to utilize the role of carbon emissions trading to promote regional technological innovation to improve energy efficiency and reduce energy consumption per unit of industrial output value. The result is consistent with Hu et al. (2020). It verifies Hypothesis 3.

## Analysis of Industry Heterogeneity of the Effect of Carbon Trading on Carbon Emissions

This study used panel data for 35 industries in 30 regions from 2003 to 2016 to analyze industry heterogeneity more accurately to establish a difference-in-difference-in-difference (DDD) fixed effects model.

$$\begin{aligned} emission_{itj} = {} & \alpha_0 + \alpha_1 carbontrading \times pilotindustry \\ & + \alpha_2 carbontrading \\ & + \alpha_3 pilotindustry \times policydate \\ & + \alpha_4 pilotprovince \times pilotindustry \\ & + \alpha_5 policydate + \alpha_6 pilotprovince \\ & + \alpha_7 pilotindustry \\ & + \sum_j \alpha_j control_{it} + \gamma_t + \mu_i + \delta_j + \varepsilon_{it} \end{aligned} \tag{5}$$

We first established a DDD model to analyze the impact of carbon emissions trading on industrial carbon emissions and carbon intensity. α1 is the coefficient of the DDD term that this article focused on. If α1 is significantly negative, it means that carbon emission rights trading has effectively promoted a reduction in carbon emissions among industries in pilot provinces. The seven industries covered by the carbon trading pilot are traditional high-energy-consuming and low-efficiency industries in China. Those industries have far more significant difficulties reducing carbon emissions and achieving decarbonization than other industries,

**TABLE 6 |** DDD analysis of the impact of carbon trading on regional industrial carbon emissions.

| Logarithmic model | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Industrial carbon emissions | | Industrial carbon intensity | |
| Carbon trading × Pilot industries | −0.139 | | −0.061 | |
| | (−0.809) | | (−0.367) | |
| Carbon trading ×High-carbon industries | | −0.288* | | −0.281* |
| | | (−1.840) | | (−1.681) |
| Carbon trading | −0.059 | 0.068 | 0.026 | 0.197 |
| | (−0.440) | (0.436) | (0.123) | (0.786) |
| Pilot industries × Policy date | 0.348*** | | 0.398*** | |
| | (5.482) | | (5.876) | |
| Pilot provinces ×Pilot industries | −0.242* | | −0.115 | |
| | (−1.732) | | (−1.008) | |
| High-carbon industries ×Policy date | | 0.274*** | | 0.427*** |
| | | (3.662) | | (4.946) |
| Pilot provinces × High-carbon industries | | −0.399*** | | 0.344** |
| | | (−2.622) | | (2.557) |
| Policy date | −0.166 | −0.220 | −1.936*** | −2.083*** |
| | (−0.503) | (−0.652) | (−4.344) | (−4.561) |
| Pilot provinces | 0.106 | 0.274** | 0.165 | −0.077 |
| | (0.827) | (1.979) | (1.447) | (−0.525) |
| Pilot industries | 3.092*** | | 1.841*** | |
| | (10.881) | | (8.663) | |
| High-carbon industries | | 4.326*** | | 1.700*** |
| | | (10.977) | | (4.358) |
| lnpergdp | 1.415 | 1.492 | 1.449 | 1.336 |
| | (1.139) | (1.200) | (0.853) | (0.799) |
| lnpergdp2 | −0.089 | −0.094 | −0.075 | −0.070 |
| | (−1.458) | (−1.526) | (−0.924) | (−0.872) |
| lntrade | 0.240*** | 0.240*** | −0.273*** | −0.273*** |
| | (5.058) | (5.019) | (−5.305) | (−5.371) |
| gdpgrowth | −1.875 | −1.816 | −6.159*** | −6.119*** |
| | (−1.005) | (−0.971) | (−2.790) | (−2.760) |
| lnpoinvest | 0.236*** | 0.238*** | −0.026 | −0.028 |
| | (3.295) | (3.275) | (−0.330) | (−0.353) |
| secind | 2.139*** | 2.177*** | 0.173 | 0.146 |
| | (2.793) | (2.846) | (0.158) | (0.133) |
| Industry effect | Yes | Yes | Yes | Yes |
| Time effect | Yes | Yes | Yes | Yes |
| N | 9901 | 9901 | 9888 | 9888 |
| Number of industries | 35 | 35 | 35 | 35 |
| Number of provinces | 30 | 30 | 30 | 30 |
| r2_w | 0.791 | 0.792 | 0.774 | 0.774 |

*Notes: ① t-values are in parentheses, using province clustered standard errors; ② significance levels are ***p < 0.01, **p < 0.05, *p < 0.1.*

which may mean that carbon emissions trading is less effective at reducing carbon emissions in the pilot industries than in average high-carbon industries. Therefore, this article identified two DDD terms: the interaction term of carbon trading DID and pilot industry and the interaction term of carbon trading and high-carbon industry (an industry with carbon intensity above the median). In addition, this study added the individual terms and paired interaction terms of pilot provinces, policy date, and pilot industries/high-carbon industries to the model to control the fixed effects of provinces, industries, and years.

The results of the DDD regression in **Table 6** show that carbon emissions trading is significantly more effective at reducing industrial carbon emissions in high-carbon industries than in low-carbon industries. However, there is no evidence that carbon emissions trading reduces carbon emissions more in pilot industries than in other industries.

Could the reason that carbon emissions trading policies had less effect in reducing carbon emissions among pilot industries than among high-carbon industries be because it is easier for non-pilot industries that are high-carbon to reduce their total carbon emissions and carbon intensity? To further analyze the heterogeneity between industries, this study distinguished industries in the carbon trading pilot, high-carbon emitting industries not in the carbon trading pilot, and low-carbon emitting industries and ran a sub-sample regression. The results are shown in **Table 7**.

**Table 7** shows that carbon emissions trading is ineffective at reducing carbon emissions among low-carbon industries. The coefficient is insignificant for reducing the total emission volume of emission intensity. Carbon emissions trading effectively reduced emissions among industries in the carbon trading pilots and high-carbon industries which not in the pilots, but the reduction in

**TABLE 7 |** Impact of carbon trading on carbon emissions in different industries.

| Logarithmic model | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Industrial carbon emissions | | | Industrial carbon intensity | | |
| | Pilot industries | Non-pilot high-carbon industries | Low-carbon industries | Pilot industries | Non-pilot high-carbon industries | Low-carbon industries |
| Carbon trading | −0.338** | −0.391*** | −0.141 | −0.228* | −0.336** | 0.047 |
| | (−2.165) | (−3.298) | (−0.908) | (−1.722) | (−2.539) | (0.236) |
| lnpergdp | 0.192 | 0.352 | −1.922 | 0.118 | −2.659 | −2.115 |
| | (0.161) | (0.251) | (−1.642) | (0.108) | (−1.493) | (−1.461) |
| lnpergdp2 | −0.005 | −0.002 | 0.102* | −0.040 | 0.087 | 0.073 |
| | (−0.092) | (−0.028) | (1.670) | (−0.742) | (0.951) | (0.994) |
| lntrade | 0.165 | −0.068 | 0.099 | 0.018 | −0.089 | −0.271** |
| | (1.486) | (−0.684) | (1.265) | (0.169) | (−0.498) | (−2.165) |
| gdpgrowth | 2.062** | 0.819 | 0.403 | 1.132 | −0.155 | −2.690 |
| | (2.067) | (0.781) | (0.248) | (1.250) | (−0.081) | (−1.322) |
| lnpoinvest | 0.082** | −0.066 | 0.011 | 0.023 | 0.033 | 0.019 |
| | (2.036) | (−1.292) | (0.202) | (0.662) | (0.458) | (0.276) |
| secind | 0.879 | 1.013 | 2.226*** | −0.794 | −0.814 | 1.114 |
| | (1.108) | (1.186) | (3.740) | (−1.193) | (−0.587) | (1.414) |
| Province effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Industry effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Time effect | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 2871 | 3341 | 3689 | 2869 | 3333 | 3686 |
| Number of industries | 7 | 11 | 17 | 7 | 11 | 17 |
| Number of provinces | 30 | 30 | 30 | 30 | 30 | 30 |
| r2_w | 0.782 | 0.481 | 0.464 | 0.772 | 0.630 | 0.631 |

*Notes: ① t-values are in parentheses, using province clustered standard errors; ② significance levels are ***p < 0.01, **p < 0.05, *p < 0.1.*

industrial carbon emissions among the latter was more significant than among the former. This is consistent with this study's analysis and the DDD result. During the mechanism verification, we found that both the structural effect and technological effect played a role in reducing industrial carbon intensity, but the structural effect was not significant in reducing the volume of industrial carbon emissions. The structure effect variable in this article is the ratio of the output value of non-pilot industries to the output value of pilot industries. The results of our analysis of industry heterogeneity in this section indicate that carbon emissions trading has a more significant impact on high-carbon industries than low-carbon industries, but the impact on pilot industries is not the most significant among all industries. This verifies Hypothesis 4.

# ROBUSTNESS TESTING

## Eliminating Interference From Other Environmental Policies

To control environmental pollution, countries use a variety of policy measures in addition to carbon emissions trading. In the benchmarking and regression, this study controlled the influence of government investment in controlling industrial pollution, but the parallel "environmental rights trading" scheme may still influence the estimated results. This study added various regional economic characteristics and the 2007 Chinese government's policy of expanding pollution trading pilots as a proxy variable for other market-based environmental policies to eliminate the impact of pollution trading on the estimation results. The regression results are shown in columns (1) and (3) of **Table 8**. It can be seen that after controlling the impact of pollution trading, the carbon emissions trading policy coefficient is still significant, and the absolute value is close to the benchmarking and regression. The impact of pollution trading on reducing regional industrial carbon emissions is insignificant.

During its 12th Five-Year Plan period (2011–2015), China set a national carbon emission reduction target and assigned carbon intensity reduction targets to 31 regions across the country, and these were continued during the 13th Five-Year Plan period (2016–2020). It should be noted that, in order not to affect overall economic development, China did not set regional targets on total carbon emissions reductions. There were significant differences in carbon intensity reduction targets between regions, ranging from 10% to 19.5% (during the 12th Five-Year Plan period) and 12%–20.5% (during the 13th Five-Year Plan period). Not only did carbon intensity reduction targets become more stringent, but the number of provinces and cities in the highest target level also increased. To control the impact of carbon intensity reduction targets in various regions, this study controlled the reduction target (%) of $CO_2$ emissions per unit of GDP in each region from 2011 to 2016 and regressed the benchmark **Eq. 1**. The results are shown in columns (2) and (4) of **Table 8**. They show that after adding carbon intensity reduction targets as a control variable, the absolute value of the carbon emission coefficient does indeed decrease, but it is still significantly negative. In addition, carbon intensity reduction targets significantly reduce regional industrial carbon intensity, but because the targets are mainly aimed at carbon intensity rather than the total volume of regional carbon emissions, the coefficient of the impact of targets on regional industrial carbon emissions is negative with no statistical significance.

**TABLE 8 |** Impact of carbon trading on carbon emissions excluding interference from other environmental policies.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Regional Industrial Carbon Emissions | | Regional Industrial Carbon Intensity | |
| Carbon trading | −0.239*** | −0.171*** | −0.386** | −0.187*** |
| | (−2.862) | (−3.762) | (−2.173) | (−3.579) |
| Emission rights trading | 0.002 | | −0.070 | |
| | (0.052) | | (−0.234) | |
| Carbon intensity reduction targets | | −0.008 | | −0.052* |
| | | (−0.331) | | (−1.880) |
| Control variable | Yes | Yes | Yes | Yes |
| Year effect | Yes | Yes | Yes | Yes |
| Province effect | Yes | Yes | Yes | Yes |
| N | 420 | 180 | 420 | 180 |
| r2 | 0.854 | 0.220 | 0.801 | 0.744 |

*Notes: ① t-values are in parentheses, using province clustered standard errors; ② significance levels are ***p < 0.01, **p < 0.05, *p < 0.1.*

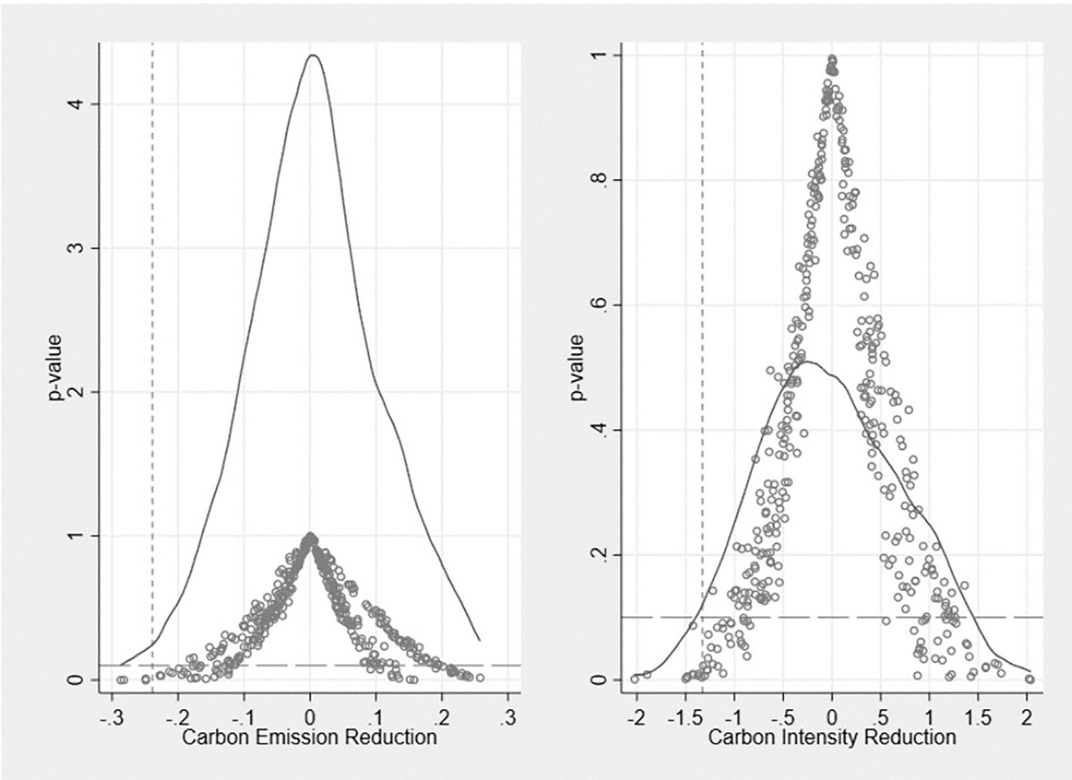


**FIGURE 6 |** Placebo Test of the Impact of Carbon Trading on Carbon Emissions Excluding Interference. Notes: The *X*-axis represents the estimated coefficients from 400 randomly assigned carbon trading DID items. The curve is the kernel density distribution of the estimated coefficients. The points are the *p*-values of the estimated coefficient. The vertical dashed lines are the true estimates, and the horizontal dashed lines represent the 10% significance level.

## Placebo Testing the Experiment Group

To test whether the results of this study are driven by unobservable factors at the province or year level, based on the study by Hu et al. (2020), we conducted a placebo test by randomly assigning provinces as provinces involved in the carbon trading pilots. Specifically, six provinces from 30 were randomly selected as the experimental group. It was assumed that these six provinces implemented the carbon trading pilot and the others were the control group. We performed 400 random samplings, and benchmarking regression was conducted according to **Eq. 1**. **Figure 6** reports the mean value of regression estimates after 400 random allocations. It was found that most estimated coefficients are concentrated near the zero point, the *p*-values are mostly greater than 0.1, and the regression coefficients are not statistically significant. The true estimated coefficient of the carbon emissions trading policy was an obvious outlier in the placebo test. These results indicate that the probability that the previous estimation results are caused by unobservable province or year factors is very low, so the conclusions of this study are robust.

This study also conducted propensity score matching (PSM)-DID estimation and robustness tests involving a virtual official launch date of carbon emissions trading, the influence of the length of sample interval, the use of substitute variables for industrial carbon emission reduction, the impact of an economic crisis, lagged control variables by one period, DID estimates for two periods, and the influence of space-related factors. The results of all these tests indicate that the conclusions of this study are robust.

## CONCLUSION AND POLICY RECOMMENDATIONS

This study has produced four main conclusions. First is that carbon emissions trading can significantly promote a reduction in industrial carbon emissions, including the total volume of carbon emissions and carbon emissions per unit of industrial output value (carbon intensity). The empirical results from introducing the annual average price of carbon trading and the quota-turnover ratio show that the higher the intensity of regulation in a given year, the greater the effect of carbon emissions trading policies. Second, during the planning and preparation stage from 2011 to 2012, carbon emissions trading was ineffective, and only after formal trading started in 2013 did regional industrial carbon emissions decline, with reductions growing year on year. Third, carbon emissions trading achieves both environmental and economic benefits by increasing the ratio of the industrial output of non-pilot industries to pilot industries, promoting regional industrial restructuring and energy-related technological innovation, and reducing energy consumption per unit of output value. Moreover, it was found that the structural effect is not statistically significant in reducing regional industrial carbon emissions. Fourth, the effect of carbon emissions trading policies in promoting a reduction in industrial carbon emissions is heterogeneous across industries, as industries with different carbon intensities have different sensitivity to carbon emissions trading policies.

Based on the research conclusions of this study, we propose the following policy recommendations to better utilize the advantages and functions of the market and improve modern environmental governance systems to achieve green, low-carbon development. First, it is recommended to carry out policy innovations in the areas of trading rules, transaction types, participants, and thresholds. This will continuously improve carbon emissions trading policies and create truly effective carbon pricing that will increase the enthusiasm and motivation of enterprises to participate in the market. Our research also shows that ensuring primary market quotas are not exceeded, secondary market prices are effectively transmitted, and there is clear adherence to rules and dispute resolution mechanisms will maximize the efficacy of carbon emissions trading policies. Given the reality that China's carbon market pricing is far lower than other major international and regional carbon markets, it has a low quota-turnover ratio, and it lacks liquidity, it is important to increase the effectiveness of the carbon market and accelerate the transition from the pilot market to the national unified carbon market by expanding the industry coverage of the national carbon market, formulating a unified system, introducing higher-level and more innovative policies and regulations. The second is to utilize the role of local governments in promoting reductions in regional industrial carbon emissions, particularly focusing on their key role in reducing regional industrial carbon intensity. This study indicates that the structural effect of carbon emissions trading policies is not significant in promoting a reduction in regional industrial carbon emissions and that the reduction effect of carbon trading is slightly greater among high-carbon non-pilot industries than among pilot industries. Therefore, it is even more important to use the power of local governments to introduce supporting systems to maximize the structural effect (structural optimization) and technological effect (energy technology innovations) of carbon emissions trading policies. For example, governments could provide the industries with high carbon intensity and have difficulty decarbonizing with preferential policies, tax incentives, and financial subsidies to guide them to save energy and produce technological innovations. This would fully utilize the government's synergistic role in reducing industrial carbon emissions. Our third policy recommendation is to use the experience of carbon emissions trading policies to establish an environmental rights trading market. Although emissions trading was introduced relatively early in China, excessive government intervention, strict access, and long compliance periods have meant that companies are not incentivized, so emission reduction effects have been unsatisfactory. Carbon emissions trading policies are based on an independent, enterprise-driven market model with low transaction costs, so to achieve a long-term reduction in regional industrial carbon emissions, government intervention must be gradually reduced, various investment entities should be allowed to participate in transactions, and companies should have clear expectations and economic incentives when joining a carbon emissions trading market. This will ultimately lead to the construction of an environmental rights trading market with a unified framework covering pollution rights and carbon emission rights.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

RF, PN, CH, and SJ contributed to conception and design of the study. RF and PN organized the database. CH and SJ performed the statistical analysis. RF, PN, CH, and SJ wrote the first draft of the manuscript. RF, PN, CH, and SJ wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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# Spatial-temporal evolution characteristics and drivers of carbon emission intensity of resource-based cities in china

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As the key object of carbon emission reduction, resource-based cities' carbon emission problems are related to the achievement of China's goals to peak carbon emission and achieve carbon neutrality. In this paper, 115 resource-based cities with abundant natural resources in China were studied, and spatial analysis techniques such as LISA (Local Indicators of Spatial Association) time path and spatial-temporal transition were used to explore their spatial divergence pattern and spatio-temporal evolution characteristics of carbon emission intensity from 2000 to 2019, while geodetector model was used further to reveal their drivers and impacts on the environment. It is found that 1) the carbon emission intensity of resource-based cities shows a significant decreasing trend, with significant differences in carbon emission intensity and its decreasing rate in different development stages and resource-type cities. The overall trend of growing cities, declining cities, mature cities and regenerating cities decreases in order. The carbon emission intensity of cities in the energy, forest industry, general, metal and non-metal categories gradually decrease. The spatial pattern of carbon emission intensity has strong stability, with an overall spatial distribution of high in the north and low in the south. 2) The spatial structure of carbon emission intensity in resource-based cities has strong stability, dependence and integration, with the stability gradually increasing from north to south and the path dependence and locking characteristics of the carbon emission intensity pattern slightly weakened. 3) The spatial divergence of carbon emission intensity in resource-based cities is the result of the action of multiple factors, among which the level of financial investment, urban economic density, urban population density, urban investment intensity and energy use efficiency are the dominant factors. 4) The leading drivers of carbon emission intensity are different in cities at different development stages and with various resources, and grasping the characteristics of carbon emission intensity changes and drivers of various resource-based cities can better provide targeted countermeasures for resource-based cities to achieve carbon emission reduction targets and sustainable development.

KEYWORDS

resource-based cities, carbon emission intensity, carbon neutrality, spatial-temporal evolution, sustainable development

## 1 Introduction

Since the 21st century, China's economy has maintained rapid development, and by 2010, China's GDP surpassed Japan to become the world's second largest economy, while as early as 2006, China's carbon emissions surpassed the United States to become the world's largest carbon emitter (Dong, 2017; Zhang W et al., 2020). While China's GDP accounted for about 16.34% of the world economy in 2019, its carbon emissions occupied 28.76%[1], reflecting the grim reality that China's carbon emissions per unit of GDP are much higher than the world average. At the 75th session of the UN General Assembly in September 2020, China proposed that $CO_2$ emissions strive to peak by 2030 and work towards carbon neutrality by 2060 and at the Climate Ambition Summit in December 2020, it proposed that carbon emissions per unit of GDP decreased by more than 65% compared with the 2005 target (Jiang et al., 2022; Sun et al., 2022). As China's economy enters a stage of high-quality development, how to maintain sustained economic growth while reducing carbon emissions is a critical issue for the future, and may affect the sustainable development of China's economy and society in the 14th Five-Year Plan and beyond.

Resource-based cities are cities with the mining and processing of natural resources such as minerals and forests in the region as their leading industry. The development of these cities is mainly dependent on resource-based industries such as natural resource extraction and processing, which are typically high-energy-consuming, high-polluting and high-emission industries, and they have serious impacts on China's carbon emission reduction process (Wang W et al., 2022). There are 262 resource-based cities in China, accounting for 40% of the total number of cities in China (Hui et al., 2022), and these resource-based cities play important roles in the implementation of the national climate change strategy (Jia et al., 2021). Whether resource-based cities can achieve a low-carbon development transition is crucial to the process of China's carbon emissions and the goal of peak carbon dioxide emissions and carbon neutrality. Therefore, exploring the spatial-temporal evolution characteristics of carbon emission intensity in resource-based cities and analyzing the drivers of their carbon emission intensity can not only provide a basis for resource-based cities to formulate scientific and reasonable emission reduction policies, but also offer theoretical and practical guidance to promote the low-carbon transition of cities, peak carbon dioxide emissions, and carbon neutrality.

Carbon emission intensity is the carbon dioxide emissions per unit of GDP, which is mainly used to measure the relationship between regional economic development and carbon emissions. The research on carbon emission intensity has attracted the attention of many scholars, and the research results are abundant, mainly focusing on the spatial distribution pattern of carbon emission intensity (Bai et al., 2020a; Liu et al., 2021; Liang et al., 2019; Wei et al., 2021; Wang et al., 2017), spatial correlation characteristics of carbon emission intensity (Liang et al., 2019; Song et al., 2020; Wang et al., 2019), the convergence of carbon emission intensity (Bai et al., 2020b; Huang et al., 2019; Yu et al., 2018), factors influencing carbon emission intensity (Shen et al., 2018; Wang et al., 2017; Wei et al., 2020; Zhou et al., 2019), and other aspects. In terms of the distribution pattern and correlation characteristics of carbon emission intensity, spatial autocorrelation and Markov chain are mainly used to analyze the spatial characteristics of carbon emission intensity (Wang et al., 2019; Wang et al., 2020), and Thiel index and coefficient of variation are used to explore the regional differences of carbon emission intensity (Zheng et al., 2018; Shi et al., 2022). For example, Bai et al. used social network analysis to explore the spatial structure characteristics of inter-provincial transportation carbon emissions in China from 2005 to 2015 (Bai et al., 2020a); Zhou et al. combined spatial econometrics to construct a Geo-tree model to reveal the evolution pattern of carbon emission intensity in China from 1990 to 2016 (Zhou et al., 2021).

In terms of the factors influencing carbon emission intensity, the structural decomposition method is used to decompose the factors influencing the change in carbon emission intensity (Dong et al., 2018; Fang and Yang., 2021), and the spatial econometric model is used to explore the effect of different factors on carbon emission intensity (Liang et al., 2019; Huang et al., 2020) with geodetector to identify the dominant drivers of carbon emission intensity (Jiang et al., 2018), etc. For example, Dong et al. used structural decomposition and quantile regression to explore the influencing factors of carbon emission intensity in China (Dong et al., 2018); Liu et al. used STIRPAT and GTWR models to reveal the influence of individual drivers on carbon emission intensity from a spatial-temporal perspective (Liu et al., 2021). At the scale of China's carbon emission studies, due to the difficulty of obtaining and extrapolating carbon emission data at the urban scale in the early years, most of the existing studies have focused on the provincial scale, mainly exploring the provincial differences in carbon emissions at the national level or the evolution pattern of carbon emissions in individual provinces (Bai et al., 2020b; Liang et al., 2019; Wang

1 Data from Statistical Review of World Energy, which is available at: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

and Zheng, 2021; Zhang Y et al. et al., 2020), and with the development of big data technology and the improvement of analysis techniques, the focus of carbon emission research gradually shifts to the municipal scale, analyzing the distribution characteristics and regional differences of carbon emissions at the national level or at the municipal scale in hotspot regions (Chen et al., 2019; Chuai and Feng., 2019; Ren et al., 2019; Wang et al., 2020).

The main shortcomings of the existing studies are as follows: 1) The existing studies mainly focus on the investigation of carbon emission intensity patterns in specific regional cities, and there are few studies focus on the carbon emission intensity of resource-based cities. However, as resource-based cities are the important targets of carbon emission reduction in China, it is necessary to deeply analyze the patterns and influencing factors of carbon emission in these cities. 2) There are many existing studies focus on the evolution of carbon emission intensity patterns. However, few studies focus on the spatial and temporal evolution of carbon emission intensity in resource-based cities from the perspective of specific city types in China. 3) Among the existing studies on the carbon emission intensity of resource-based cities, there are few studies that compare the two types of resource-based cities, namely comprehensive planning classification and resource type classification, and further investigate the factors influencing the carbon emission intensity of resource-based cities.

Based on this, this paper will expand the existing studies from the following aspects: first, the key area of carbon emission reduction, i.e., resource-based cities, is selected as the study area, and resource-based cities are studied separately according to two classification methods, namely, comprehensive planning classification and resource type classification, in order to investigate the evolution of carbon emission intensity in resource-based cities in depth. Second, on the basis of exploring the characteristics of carbon emission intensity of resource-based cities in time and space, exploratory spatial-temporal data analysis techniques are used to reveal the spatial-temporal evolution of carbon emission intensity of resource-based cities, which expands the research tools of carbon emission intensity. Third, on the basis of exploring the factors influencing the carbon emission intensity of resource-based cities, the differences in the influencing factors of carbon emission intensity in different types of resource-based cities are investigated from the perspective of comprehensive planning classification and resource type classification respectively. Fourth, this paper proposes more targeted policy implications based on the carbon emission intensity and influencing factors of different types of resource-based cities, respectively.

The chapters of this paper are organized as follows: Part 2 presents the data sources and related research methods of this paper, Part 3 analyzes the temporal-spatial variation patterns of carbon emission intensity in resource-based cities in China, Part 4 explores the drivers of intensity in resource-based cities in China, and Part 5 concludes the whole paper and presents the policies and insights of the study.

# 2 Data sources and research methods

## 2.1 Data sources

### 2.1.1 Data sources on resource-based cities and carbon emission intensity

By the planning scope of 262 resource-based cities in the National Sustainable Development Plan for Resource-based Cities (2013–2020), including 126 prefecture-level administrative regions, 62 county-level cities, 58 counties, and 16 municipal districts, this paper takes prefecture-level cities in prefecture-level administrative regions as the research objects (excluding prefecture-level cities established after 2000), i.e., 115 research units (as shown in Figure 1). The plan classifies resource-based cities into four categories: mature, growing, declining, and regenerating and the 115 prefecture-level cities include 63 mature cities, 14 growing cities, 23 declining cities, and 15 regenerating cities (hereinafter referred to as "comprehensive planning classification"). With reference to the existing literature (Li et al., 2017; Yan et al., 2019), the resource-based cities are classified into five categories: comprehensive, energy, metal, non-metal, and forest industry, including 24 comprehensive cities, 54 energy cities, 21 metal cities, 10 non-metal cities, and six forest industry cities.

The research period of the paper is 2000–2019, and the city carbon emission data are obtained from the research results (Chen et al., 2020), which uses the particle swarm optimization back propagation (PSO-BP) algorithm to invert the DMSP/OLS and NPP/VIIRS two sets of nighttime lighting data to accurately estimate the county carbon emission data. The carbon emission data of prefecture-level cities were obtained by combining the carbon emissions of counties. The socio-economic data of cities were obtained from the 2001–2020 provincial and municipal statistical yearbooks, the China City Statistical Yearbook, the China Regional Economic Statistical Yearbook and the China Urban Construction Statistical Yearbook.

### 2.1.2 Drivers of carbon emission intensity in resource-based cities and data sources

Based on the theories related to regional economics and urban geography, combined with the studies of many scholars (Wang et al., 2018; Wang et al., 2019; Wang X et al., 2022; Yin et al., 2022), it is found that economic and social development indicators play a major role in influencing carbon emissions. Therefore, based on the principles of objectivity, scientificity and accessibility of the index factors, we selected ten indicators, namely, urban economic density, industrial development level,

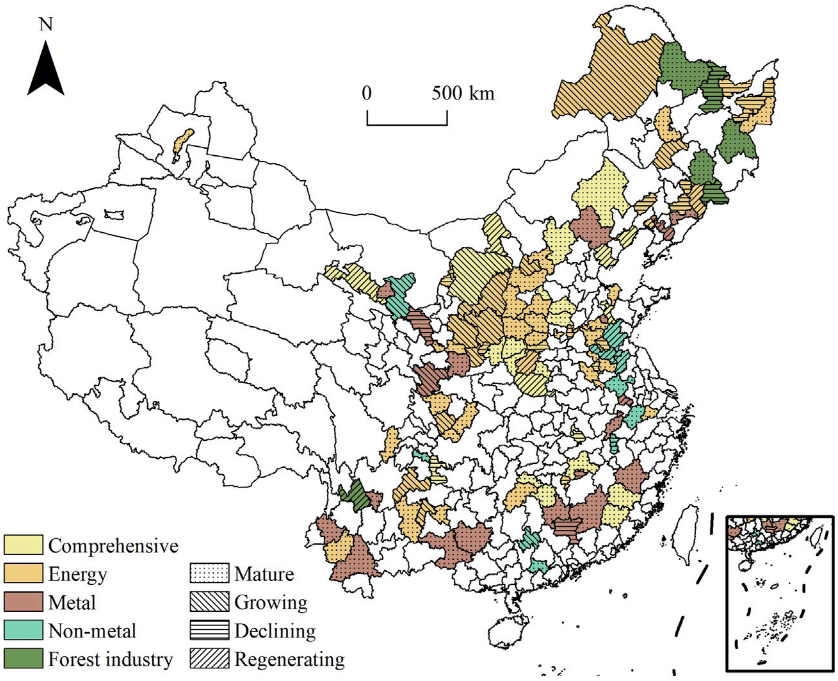


FIGURE 1
Spatial distribution of resource-based cities and their types.

TABLE 1 Driving factors of carbon emission intensity in resource-based cities.

| Drivers factors | Specific indicators | Calculation method | Unit | References |
|---|---|---|---|---|
| Urban economic density (*X1*) | Local average GDP | GDP/area of the administrative district | yuan/person | Bai et al. (2020a) |
| Level of industrial development (*X2*) | Industrial value-added ratio | Industrial value-added/GDP | % | Wang et al. (2018) |
| Financial investment level (*X3*) | Local average fiscal expenditure | Local financial expenditure/GDP | % | Li (2022) |
| Urban investment intensity (*X4*) | Local average fixed asset capital investment | Fixed asset investment/area of the administrative district | % | Dong et al. (2022) |
| Technology development level (*X5*) | Number of patents granted per 10,000 people | Total number of patents granted/resident population | pc/10,000 persons | Huang et al. (2021) |
| Urban development level (*X6*) | Urbanization rate of resident population | Urban population/resident population | % | Wang et al. (2019) |
| Urban population density (*X7*) | Population per unit land area | Resident population/area of the administrative district | % | Yin et al. (2022) |
| Transportation development level (*X8*) | Number of cars per 1,000 people | Private car ownership/resident population | vehicle/ 1,000 persons | Bai et al. (2019) |
| Openness to the outside world (*X9*) | Ratio of foreign capital used | Amount of actual foreign capital used/GDP | % | Ren et al. (2021) |
| Energy utilization efficiency (*X10*) | Electricity consumption per unit of GDP | Social electricity consumption/GDP | kwh/10,000 yuan | Miller et al. (2022) |

financial investment level, urban investment intensity, science and technology development level, town development level, urban population density, transportation development level, openness level and energy utilization efficiency, to construct a system of drivers for carbon emission intensity in resource-based cities (as shown in Table 1).

## 2.2 Research method

### 2.2.1 Exploratory spatial-temporal data analysis

Exploratory Spatial Data Analysis (ESDA) is a collection of techniques and methods for spatial data analysis. It is used to describe and visualize the spatial distribution patterns of data, explore the spatial structure of data, and explore spatial interaction mechanisms. ESTDA (Exploratory Spatial Temporal Data Analysis) was further introduced to reveal the spatial-temporal structural characteristics of carbon emission intensity in resource-based cities, and to systematically analyze spatial interaction characteristics and temporal evolution patterns of carbon emission intensity during the spatial and temporal evolution. ESTDA effectively bridges the shortage of ESDA (Exploratory Spatial Data Analysis) detection in the temporal dimension and realizes the benign coupling of temporal-spatial measures (Zhang et al., 2021), which mainly includes analysis techniques such as LISA time path and LISA spatial-temporal transition.

1) LISA time path. The evolution characteristics of LISA in the Moran scatter plot were observed for each cell in the time dimension to make the static LISA more dynamic (Munibah and Widiatmaka, 2018). By visualizing the pairwise movement of carbon emission intensity and its spatial lag term in resource-based cities, the spatio-temporal synergistic evolution of carbon emission intensity in resource-based cities can be explained and the spatio-temporal dynamics of local spatial differences and carbon emission intensity changes can be reflected. The indicators of the LISA time path include path relative length, curvature and transition direction, etc. LISA time path relative length can reflect the dynamic characteristics of the local spatial structure of carbon emission intensity, curvature reflects the fluctuation characteristics of the local spatial structure of carbon emission intensity, and transition direction reflects the integration characteristics of the evolution of the local spatial structure of carbon emission intensity. The expressions are as follows (Murray et al., 2012):

$$d_i = \frac{N \sum_{t=1}^{T-1} d\left(L_{i,t}, L_{i,t+1}\right)}{\sum_{i=1}^{N} \sum_{t=1}^{T-1} d\left(L_{i,t}, L_{i,t+1}\right)} \quad (1)$$

$$\varepsilon_i = \frac{\sum_{t=1}^{T-1} d\left(L_{i,t}, L_{i,t+1}\right)}{d\left(L_{i,t}, L_{i,T}\right)} \quad (2)$$

$$\theta_i = \arctan \frac{\prod_j \sin \theta_j}{\prod_j \cos \theta_j} \quad (3)$$

Where: $d_i$ and $\varepsilon_i$ are the path relative length and curvature of city $i$, respectively, $N$ is the number of study units. $T$ is the length of study time, $L_{i,t}$ is the LISA coordinates of city $i$ at time $t$, $d\left(L_{i,t}, L_{i,t+1}\right)$ is the distance city $i$ moves from time $t$ to $t+1$. $\theta_i$ denotes the average moving direction of city $i$.

2) LISA spatial-temporal transition, which can reveal the spatial relationship between local neighborhoods of spatial units in terms of temporal changes (Rey et al., 2011), is divided into four types (as shown in Table 2): Type I indicates that transitions of the city itself and the neighboring cities are stable; Type II indicates that the city itself is stable and transitions of the neighboring cities. Type III indicates that both the city itself and the neighboring city transition; it is Type IIIA if the city itself and the neighboring cities transition in the same direction, and it is type IIIB if the city itself and the neighboring cities transition in opposite directions. Type IV indicates that both the city itself and the neighboring cities are stable (Rey and Janikas, 2010). define the spatio-temporal flow and convergence in a regional system as the ratio of the number of a certain type of transition to the total number of transitions in the study time period, i.e., it can be expressed as follows:

Spatio-temporal flow ($SF$):

$$SF = \frac{F_1 + F_2}{m} \quad (4)$$

Spatio-temporal convergence ($SC$):

$$SC = \frac{F_{3A} + F_4}{m} \quad (5)$$

Where: $F_1$, $F_2$, $F_{3A}$ and $F_4$ are the number of transitions of I, II, IIIA and IV, respectively; $m$ is the total number of transitions.

### 2.2.2 Geodetector

Geodetector is a statistical analysis method to identify geospatial heterogeneity and reveal the influence of driving forces behind it (Zhang and Zhoa, 2018), and it can effectively detect the consistency and causality of the spatial distribution of two variables independently (Wang et al., 2010). The core idea is that the relevant characteristic factors affecting the change of carbon emission intensity are spatially heterogeneous, and if the intensity of a factor is significantly consistent or similar to the carbon emission intensity in spatial distribution, it can indicate that this characteristic factor has a decisive role in carbon emission intensity. Geodetectors can detect both numerical and qualitative data and can also perform two-factor interaction detection. The Geodetector principle ensures that it avoids the problem of multiple independent variable covariance. So, the Geodetector requires fewer assumptions and does not need to consider multiple covariances in multiple independent variables, which can effectively overcome the limitations of traditional econometric models. The geographic detector model equation is (Gao et al., 2021):

$$q_{D,U} = 1 - \frac{1}{n\sigma_U^2} \sum_{i=1}^{m} n_{D,i} \sigma_{U_{D,i}}^2 \quad (6)$$

TABLE 2 Type of spatial-temporal transition.

| Type | Form of spatial-temporal transition | Symbol expression |
|---|---|---|
| Type I | Self-transition-neighborhood stabilization | $HH_t \to LH_{t+1}$、 $LH_t \to HH_{t+1}$、 $LL_t \to HL_{t+1}$、 $HL_t \to LL_{t+1}$ |
| Type II | Self-stabilization-neighborhood transition | $HH_t \to HL_{t+1}$、 $LH_t \to LL_{t+1}$、 $LL_t \to LH_{t+1}$、 $HL_t \to HH_{t+1}$ |
| Type III | Self-transition- neighborhood transition | $HH_t \to LL_{t+1}$、 $LL_t \to HH_{t+1}$、 $LH_t \to HL_{t+1}$、 $HL_t \to LH_{t+1}$ |
| Type IV | Self-stabilization-neighborhood stabilization | $HH_t \to HH_{t+1}$、 $LH_t \to LH_{t+1}$、 $LL_t \to LL_{t+1}$、 $HL_t \to HL_{t+1}$ |

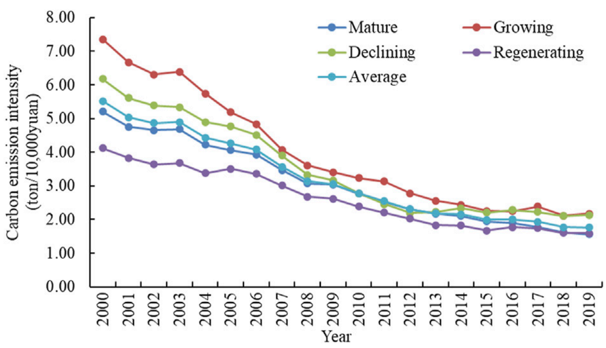


FIGURE 2
Temporal change of carbon emission intensity of resource-based cities during 2000–2019 (Group division based on comprehensive planning classification).

Where: $q_{D,U}$ is the index of the explanatory power of the influence factor $D$ of carbon emission intensity; $n$ is the number of cities in the study area; $m$ is the number of types of each influence factor; $n_{D,i}$ is the number of cities within type $i$ of the influence factor $D$; $\sigma_U^2$ is the variance of carbon emission intensity of all cities in the study area; $\sigma_{U_{D,i}}^2$ is the variance of carbon emission intensity of cities within type $i$; the value range of $q_{D,U}$ is [0,1], the larger the $q_{D,U}$ value is, the stronger the explanatory power of factor $D$ on the spatial distribution of carbon emission intensity is.

# 3 Spatial-temporal evolution characteristics of carbon emission intensity in resource-based cities

## 3.1 Temporal change characteristics of carbon emission intensity in resource-based cities

1) The changes of carbon emission intensity of mature, growing, declining and regenerating cities are counted separately (as shown in Figure 2), and the carbon emission intensity of all types of resource-based cities has decreased significantly, and the carbon emission intensity decreased faster before 2009, and the carbon emission intensity changed more steadily and decreased relatively less after 2009. Before 2009, the proportion of industrial added value to GDP in resource-based cities was on an upward trend, but after 2009, it was on a downward trend. Industry is an important area of carbon emissions, and as the green and low-carbon transformation of China's industrial structure and production methods has achieved remarkable results, carbon emissions intensity has gradually shown a decreasing trend. After 2009, the proportion of industrial added value declined, so the growth rate of total carbon emissions slowed down. In addition, the gradual completion of industrial transformation and upgrading in resource-based cities led to a gradual slowdown in carbon emissions intensity. From the average value of resource-based cities, carbon emission intensity declined from 5.52 t/10,000 yuan in 2000 to 1.76 t/10,000 yuan in 2019, a decrease of 68.06%, including a decrease of 44.71% from 2000 to 2009 and a decrease of 36.50% from 2010 to 2019. In terms of each type of cities, the carbon emission intensity of mature, growing, declining and regenerating cities dropped from 5.21 t/10,000 yuan, 7.36 t/10,000 yuan, 6.17 t/10,000 yuan and 4.12 t/10,000 yuan in 2000 to 1.56 t/10,000 yuan, 2.18 t/10,000 yuan, 2.14 t/10,000 yuan and 1.59 t/10,000 yuan in 2019, respectively, with a decrease of 70.03, 70.38, 65.34 and 61.31%. The overall carbon emission intensity of growing and declining cities is higher than the average value of resource-based cities, while the overall carbon emission intensity of mature and regenerating cities is lower than the average value of resource-based cities, and the decrease of carbon emission intensity of growing and mature cities is higher than that of resource-based cities as a whole, while the decrease of carbon emission intensity of regenerating and declining cities is lower than that of resource-based cities as a whole. Overall, the carbon emission intensity of growing cities is the highest and decreases the most, the carbon emission intensity of declining cities is higher and decreases less, the carbon emission intensity of mature cities is lower and decreases more, and the carbon emission intensity of regenerating cities is the lowest and decreases the least.

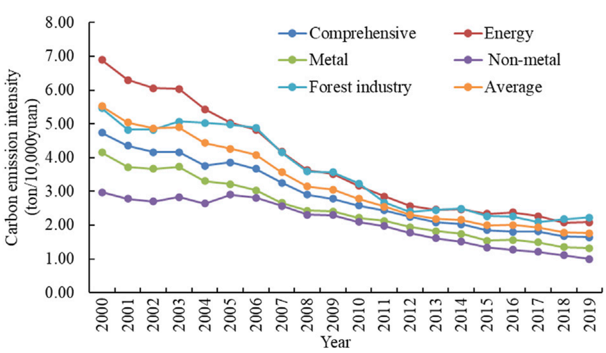


FIGURE 3
Temporal change of carbon emission intensity of resource-based cities during 2000–2019 (Group division based on resource types).

2) The changes of carbon emission intensity in cities of comprehensive, energy, metal, non-metal and forest industry categories (as shown in Figure 3), respectively, show a significant decrease in carbon emission intensity in cities of each resource type. The carbon emission intensity of comprehensive, energy and metal cities decrease faster before 2009 and decrease relatively less after 2009, while the carbon emission intensity of non-metal and forest industry cities changes more steadily and decrease slowly before 2006 and decrease relatively faster after 2006. Specifically, the carbon emission intensity of comprehensive, energy, metal, non-metal and forest industry cities declined from 4.73 t/10,000 yuan, 6.89 t/10,000 yuan, 4.15 t/10,000 yuan, 2.97 t/10,000 yuan and 5.47 t/10,000 yuan to 1.64 t/10,000 yuan, 2.08 t/10,000 yuan, 1.32 t/10,000 yuan, 0.99 t/10,000 yuan and 2.23 t/10,000 yuan in 2019, a decrease of 65.29, 69.75, 68.27, 66.56 and 59.28%, respectively. The overall carbon emission intensity of energy and forest industry cities is higher than the average value of resource-based cities, while the carbon emission intensity of comprehensive, metal and non-metal cities is lower than the average value of resource-based cities, and the decrease of carbon emission intensity of comprehensive, non-metal and forest industry cities is lower than that of resource-based cities as a whole, while the decrease of carbon emission intensity of energy and metal cities is higher than that of resource-based cities as a whole. In general, the carbon emission intensity of energy cities is the highest with the biggest decrease, the carbon emission intensity of forest industry cities is higher with the smallest decrease. The carbon emission intensity of comprehensive cities is lower with the smaller decrease, the carbon emission intensity of metal cities is lower with the larger decrease and the carbon emission intensity of non-metal cities is the lowest with the smaller decrease.

## 3.2 Spatial distribution pattern of carbon emission intensity in resource-based cities

According to the temporal variation characteristics of carbon emission intensity, carbon emission intensity of various types of resource-based cities and the resource-baced cities as whole changed significantly before and after 2009, so the spatial distribution of carbon emission intensity in 2009 is extracted separately. The spatial visualization of carbon emission intensity of resource-based cities in China in 2000, 2009 and 2019 was carried out using the natural intermittent point grading method (Jenks) of ArcGIS software (as shown in Figure 4).

In 2000, the high carbon emission intensity area is "locally concentrated, but overall scattered", i.e., mainly concentrated in Shanxi and northern Shaanxi, such as Lvliang, Linfen, Xinzhou, Yulin, etc., but also scattered in Fuxin, Wuhai and Liupanshui, etc. The development stages are mostly mature, growing and declining, and the resource types are all energy-based. Coal is the main resource in these places, and coal, with its low calorific value and high carbon emissions per unit, is the fossil energy source with the highest carbon content. In 2000, the low carbon emission intensity areas are more numerous and widely distributed, mainly concentrated in the southern regions and Henan and Shandong, etc. The development stages are mostly mature, regenerating and declining, and the resource types are mostly energy, metal and non-metal (Yan et al., 2019). In 2009, the high carbon emission intensity areas were concentrated in Xinzhou, Linfen, Lvliang and Datong in Shanxi, and scattered in Hulun Buir, Wuhai, Fuxin, Liupanshui and Anshun, etc. The secondary high-value areas were mainly distributed in Shanxi and Heilongjiang, etc. The development stages of the high and secondary high-value areas were mostly mature and declining, and the resource types were mainly energy. The low-value areas of carbon emission intensity were mainly distributed in Fujian, Sichuan, Shandong and other regions. The development stage was mainly mature, and the resource type was mostly energy and metal. High-value areas of carbon emission intensity were significantly reduced in 2019, only distributed in Hulun Buir, Wuhai and Shizuishan, and the secondary high-value areas were mainly distributed in Shanxi, Heilongjiang and Liaoning, etc. The development stage of high-value areas and secondary high-value areas were mostly regenerating and mature type, and the resource type was mainly energy. The low-value carbon emission intensity areas are mainly distributed in southern regions, mostly concentrated in Fujian, Anhui, Jiangxi, Sichuan and Yunnan, etc. The development stage is mainly mature, and the resource types are mostly energy, metal and non-metal.

In general, the spatial pattern of carbon emission intensity has strong stability. That is, with the gradual decline of the absolute value of carbon emission intensity, the distribution pattern of carbon emission intensity is high in the north and low in the south. From the development stage, the high value

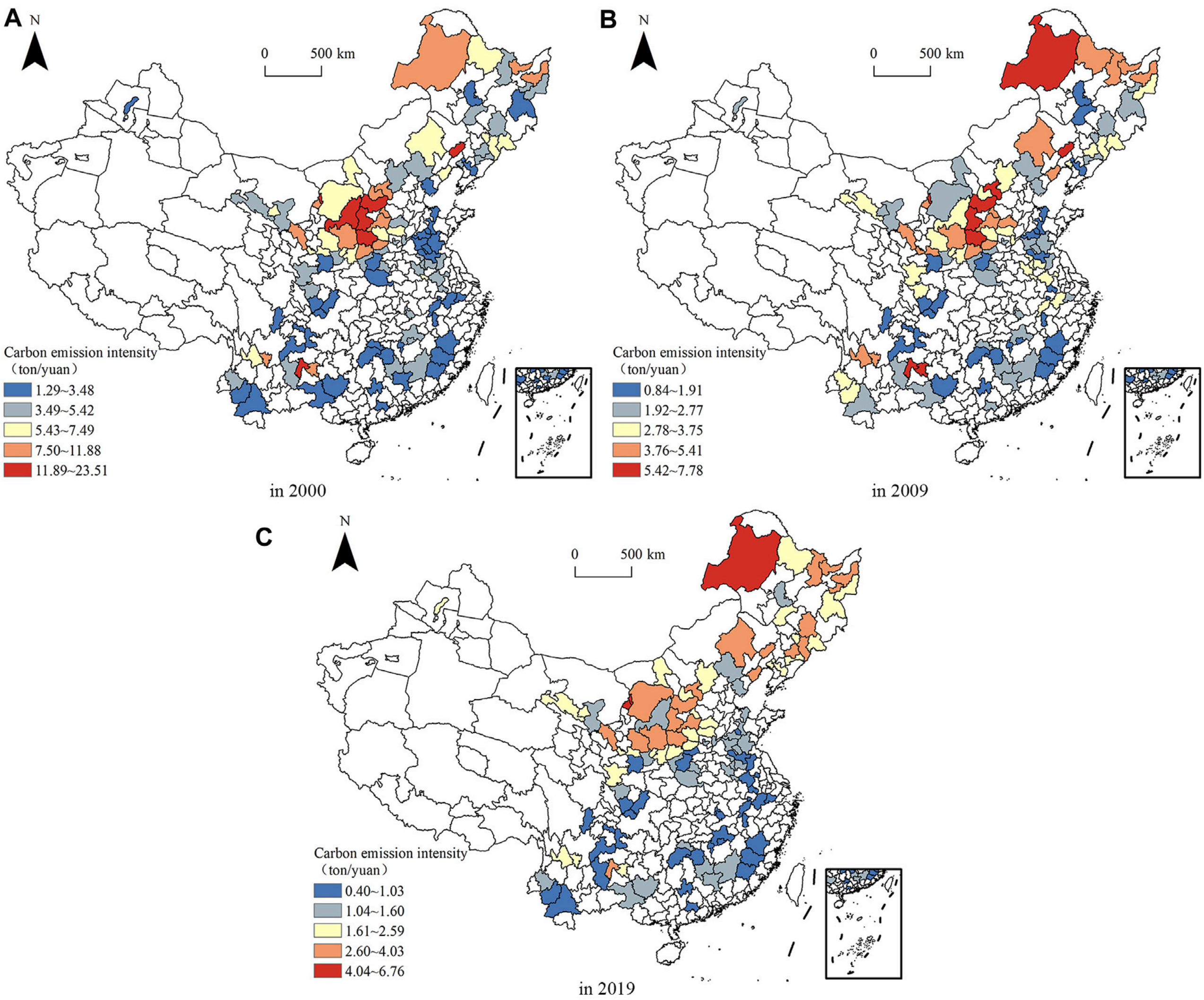


FIGURE 4
Space distribution pattern of carbon emission intensity of resource-based cities during 2000–2019. **(A)** in 2000. **(B)** in 2009. **(C)** in 2019.

areas of carbon emission intensity are concentrated in mature and declining type, and the low value areas are mostly mature and regenerating type. From the resource type, the high-value areas of carbon emission intensity are mostly energy, and the low-value areas are mainly energy, metal and comprehensive type. The above analysis shows that the high carbon emission intensity area is dominated by energy cities, and most of them are coal cities, and there are more cities in the mature and declining stage of resource development, and fewer regenerating and growing cities, reflecting that coal-based energy cities have a greater impact on the ecological environment in the economic development, which affects the sustainable development of the economy. The problem of resource depletion will become a serious challenge for most resource-based cities, and exploring transformation and urban regeneration development is the necessary path for the high-quality development of resource-based cities.

## 3.3 Local indicators of spatial association time path analysis of carbon emission intensity in resource-based cities

The relative length, curvature and movement direction of the LISA time path of carbon emission intensity in resource-based cities are calculated and spatially visualized using ArcGIS software (as shown in Figure 5).

The regions with a higher relative length of LISA time path are distributed in northern Heilongjiang, eastern Inner Mongolia, western Shanxi, and northern Shaanxi, which are

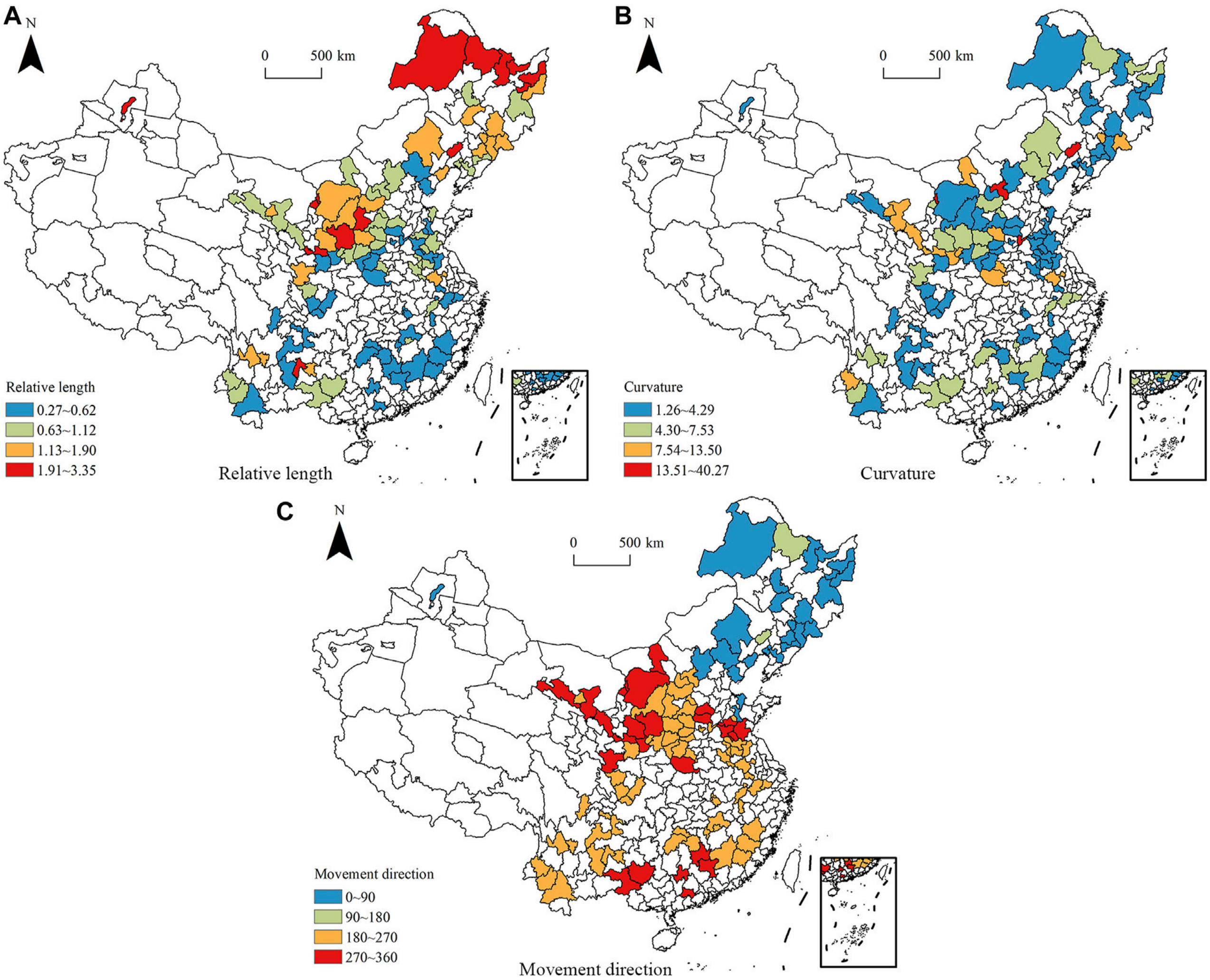


FIGURE 5
The spatial distribution of LISA time path of carbon emission intensity in resource-based cities. **(A)** Relative length. **(B)** Curvature. **(C)** Movement direction.

basically consistent with the distribution of high-value areas of carbon emission intensity, indicating that the change of carbon emission intensity in these regions is larger, i.e., the decrease of carbon emission intensity is more. The regions with lower relative lengths are distributed in western Fujian, south-central Hunan, eastern Sichuan, and western Henan, indicating that the carbon emission intensity changes less in these regions. The relative length of the LISA time path of carbon emission intensity in resource-based cities is lower than the average in 75 cities, accounting for 65.22% of the study area, reflecting that the spatial structure of carbon emission intensity in resource-based cities has strong stability, and the stability gradually increases from north to south.

The number of cities with a high value of LISA time path curvature is small and scattered, such as Datong, Wuhai, Puyang, Fuxin, etc. The curvature of these cities exceeds 20, among which Datong has the highest curvature of 40.27. In addition, Jinchang, Pingliang, Pingdingshan, Tongchuan and Liaoyuan have curvature over 10, which reflects the strong variability of local spatial dependence direction of carbon emission intensity in these regions. The cities with lower curvatures are more numerous and widely distributed in Fujian, Jiangxi, Hunan, Sichuan, Shandong, and Liaoning, where the fluctuation of carbon emission intensity is smaller. Overall, the overall low curvature of carbon emission intensity in resource-based cities indicates that the evolution of carbon emission intensity in resource-based cities shows a more stable spatial dependence, i.e., a strong spatial locking effect.

In the direction of movement, 88 cities of resource-based cities with synergistic growth of carbon emission intensity (0°–90°

TABLE 3 Local Moran's *I* transition probability matrix of carbon emission intensity in resource-based cities.

| Period | t/t+1 | HH | LH | LL | HL | Type | Quantity | Ratio | SF | SC |
|---|---|---|---|---|---|---|---|---|---|---|
| 2000–2009 | HH | 0.8832 | 0.0365 | 0.0000 | 0.0803 | Type I | 39 | 0.0377 | 0.0918 | 0.9072 |
| | LH | 0.0180 | 0.8378 | 0.1396 | 0.0045 | Type II | 56 | 0.0541 | | |
| | LL | 0.0000 | 0.0200 | 0.9422 | 0.0378 | Type III | 1 | 0.0010 | | |
| | HL | 0.0221 | 0.0000 | 0.0575 | 0.9204 | Type IV | 939 | 0.9072 | | |
| 2009–2019 | HH | 0.8750 | 0.0263 | 0.0000 | 0.0987 | Type I | 39 | 0.0339 | 0.0983 | 0.9017 |
| | LH | 0.0814 | 0.7849 | 0.1337 | 0.0000 | Type II | 74 | 0.0643 | | |
| | LL | 0.0056 | 0.0414 | 0.9380 | 0.0150 | Type III | 3 | 0.0026 | | |
| | HL | 0.0476 | 0.0000 | 0.0442 | 0.9082 | Type IV | 1,034 | 0.8991 | | |
| 2000–2019 | HH | 0.8789 | 0.0311 | 0.0000 | 0.0900 | Type I | 78 | 0.0357 | 0.0952 | 0.9043 |
| | LH | 0.0457 | 0.8147 | 0.1371 | 0.0025 | Type II | 130 | 0.0595 | | |
| | LL | 0.0031 | 0.0316 | 0.9399 | 0.0255 | Type III | 4 | 0.0018 | | |
| | HL | 0.0365 | 0.0000 | 0.0500 | 0.9135 | Type IV | 1973 | 0.9030 | | |

and 180°–270°) occupy 76.52% of the study area, reflecting a strong spatial integration of the spatial evolution of carbon emission intensity in resource-based cities. The 25 cities with positive synergistic growth (0°–90°) are concentrated in northern Hebei, Liaoning, Jilin and Heilongjiang, and the carbon emission intensity in these areas shows a synergistic low rate of decline. There are 63 cities with negative synergistic growth (180°–270°), mainly in Anhui, Jiangxi, western Fujian, eastern Sichuan, Yunnan, northwestern Henan, and Shanxi, and the carbon emission intensity in these regions shows a synergistic high-speed decline.

## 3.4 Local indicators of spatial association spatial-temporal transition analysis of carbon emission intensity in resource-based cities

The LISA time path reveals the trend of each city in the Moran scatter plot, and the probability shift matrix and spatial-temporal transition proposed by Rey are used to explore the shift characteristics and evolution process of local spatial association types of carbon emission intensity in resource-based cities (as shown in Table 3).

The probability of *Moran's I* scatter plot staying in the same quadrant (type IV) for the three time periods of 2000–2009, 2009–2019 and 2000–2019 are all around 90%, indicating that there is a strong transfer inertia of carbon emission intensity in resource-based cities, and it is more difficult to change the type of carbon emission intensity in each city, and the pattern of carbon emission intensity has a strong path-dependent and spatially locked characteristics. The probability of type I is less than 4%, type II is less than 7%, and type III is less than 1% in the above three time periods, which indicates that the possibility of transferring carbon emission intensity between local spatial and temporal correlation categories in resource-based cities is low. In type I, the probability of $HL_t \rightarrow LL_{t+1}$and $LH_t \rightarrow HH_{t+1}$ migration is below 4%, and the probability of $HL_t \rightarrow LL_{t+1}$ and $LH_t \rightarrow HH_{t+1}$ migration is mostly below 6% (except for $LH_t \rightarrow HH_{t+1}$ type 8.14% in 2009–2019). In type II, the migration probability of $LH_t \rightarrow LL_{t+1}$ is high, over 13%, $HH_t \rightarrow HL_{t+1}$ migration probability is around 9%, and the migration probability of $HL_t \rightarrow HH_{t+1}$ and $LL_t \rightarrow LH_{t+1}$ is low, not exceeding 5%. In type III, both $LL_t \rightarrow HH_{t+1}$ and $LH_t \rightarrow HL_{t+1}$ migration probabilities are less than 1%, and there are no $HH_t \rightarrow LL_{t+1}$ nor $HL_t \rightarrow LH_{t+1}$ migration types, indicating that the probability of carbon emission intensity jump migration in resource-based cities is extremely low.

As shown in Table 3, the spatio-temporal flow values are lower than 0.1 and the spatio-temporal convergence values are higher than 0.9 in the foresaid three time periods, further indicating that the carbon emission intensity of resource-based cities is all in a strong transfer inertia. 2009–2019 spatio-temporal flow values are higher than that in 2000–2009, and spatio-temporal convergence values are lower than that of 2000–2009, i.e., the path dependence and lock-in characteristics of carbon emission intensity in resource-based cities have weakened over time.

# 4 Analysis of the drivers of carbon emission intensity in resource-based cities

## 4.1 Overall factor detection results for resource-based cities

Using the geographical detector model factor detection tool, the degree of influence of each driver on the carbon emission

TABLE 4 Detection results of drivers of carbon emission intensity in resource-based cities.

| Driver factors | 2000 | | 2009 | | 2019 | |
|---|---|---|---|---|---|---|
| | $q_{D,U}$ | *p value* | $q_{D,U}$ | *p value* | $q_{D,U}$ | *p value* |
| *X*1 | 0.1416*** | 0.0052 | 0.1126** | 0.0189 | 0.1667*** | 0.0000 |
| *X*2 | 0.0813* | 0.0721 | 0.0374 | 0.3993 | 0.0479 | 0.2722 |
| *X*3 | 0.2587*** | 0.0000 | 0.2257*** | 0.0000 | 0.0989** | 0.0342 |
| *X*4 | 0.0592 | 0.1763 | 0.1381*** | 0.0061 | 0.2007*** | 0.0000 |
| *X*5 | 0.0597 | 0.1729 | 0.1129** | 0.0187 | 0.1201** | 0.0136 |
| *X*6 | 0.1107** | 0.0206 | 0.0635 | 0.1483 | 0.1255** | 0.0107 |
| *X*7 | 0.0976** | 0.0362 | 0.1029** | 0.0289 | 0.2151*** | 0.0000 |
| *X*8 | 0.0877* | 0.0551 | 0.0547 | 0.2103 | 0.1429*** | 0.0049 |
| *X*9 | 0.0778* | 0.0832 | 0.0280 | 0.5495 | 0.0366 | 0.4106 |
| *X*10 | 0.1176** | 0.0152 | 0.0068 | 0.9445 | 0.1799*** | 0.0000 |

Note: ***, **, * indicate significant at 1, 5 and 10% confidence levels, respectively.

intensity in resource-based cities in 2000, 2009 and 2019 was explored (as shown in Table 4).

As can be seen from Table 4, the influence of urban economic density on carbon emission intensity tends to increase in general, and passes the significance test in all 3 years. The urban economic density characterizes the efficiency of economic activities and the intensity of land use, and the higher value reflects the higher level of urban development. Therefore, the influence on carbon emission intensity tends to strengthen. The influence of industrial development level on carbon emission intensity is decreasing and then increasing, and only in 2000, it passed the significance test, mainly because the proportion of industrial value-added in resource-based cities increases and then decreases, i.e., the higher the industrial development level, the weaker the influence on carbon emission intensity. The influence of financial investment level on carbon emission intensity is decreasing, and all 3 years are significant at 1% confidence level, that is, the influence of financial investment level on carbon emission intensity is maintained at a high level, and this influence tends to weaken over time. Investment in fixed assets is the primary means of reproducing fixed assets in society. Through the construction and acquisition of fixed assets, cities continuously adopt advanced technology and equipment in the national economy, thus further adjusting and optimizing the economic structure and enhancing the strength of urban economic development. The impact of the level of scientific and technological development on carbon emission intensity is on the rise, and the improvement of the level of scientific and technological development promotes the transformation of the economic development model, the transformation of growth momentum and the optimization of economic structure, and the development of innovative low-carbon technologies to better promote green development.

The influence of urban development level on carbon emission intensity first decreases and then increases, and gradually increases in general. Urbanization and industrialization go hand in hand and develop together, and the agglomeration effect generated by urbanization will promote industrialization, which in turn promotes economic development, and its influence on carbon emission intensity strengthens as the urbanization process steadily advances. The influence of urban population density on carbon emission intensity gradually increases, and the significance level also gradually increases, i.e., the influence of increasing population density on carbon emission intensity is getting stronger. The impact of transportation development level on carbon emission intensity first decreases and then increases. The increase in car ownership, on the one hand, reflects the faster development of the automobile industry and the higher income level of residents, which also indicates the rapid economic development from the side, and on the other hand, the carbon emissions from car exhaust aggravate the deterioration of regional air quality and cause damage to the ecological environment. The impact of openness to the outside world on carbon emission intensity is decreasing and then increasing. The level of openness to the outside world reflects a city's openness to the outside world and its ability to absorb foreign capital, which can promote the improvement of technology and industrial structure, increase jobs and residents' income, and improve the quality of urban economic development. The influence of energy utilization efficiency on carbon emission intensity decreases first and then rises, the current economic development of resource-based cities mainly relies on resource-consuming production, which needs to consume a large amount of electricity and other energy, and a large amount of energy consumption also brings more serious environmental pollution (such as water pollution, air pollution, soil pollution, etc.) and a large amount of carbon

TABLE 5 Detection results of drivers of carbon emission intensity in different resource-based cities (Group division based on comprehensive planning classification).

| Type | 2000 | 2009 | 2019 | Mean value |
|---|---|---|---|---|
| Mature | X3、X9、X2、X8、X4 | X5、X3、X1、X7、X8 | X8、X10、X5、X3、X1 | X8、X3、X5、X10、X1 |
| Growing | X10、X2、X6、X9、X3 | X3、X2、X6、X8、X4 | X6、X2、X8、X7、X3 | X2、X3、X6、X8、X10 |
| Declining | X3、X8、X10、X6、X4 | X4、X6、X7、X2、X10 | X10、X7、X6、X9、X8 | X10、X4、X6、X8、X3 |
| Regenerating | X7、X3、X1、X10、X8 | X10、X4、X7、X2、X5 | X7、X2、X5、X4、X1 | X7、X4、X10、X3、X1 |

emission, while the gradual improvement of energy utilization efficiency (the gradual decrease of electricity consumption per unit of GDP) reflects the decrease of carbon emission intensity.

Comparing the differences in the influence of each driver in 2000, 2009 and 2019, the influence of urban economic density, industrial development level, urban development level, transportation development level, openness level and energy utilization efficiency on carbon emission intensity first decreases and then increases, the influence of financial investment level on carbon emission intensity gradually weakens, and the influence of urban investment intensity, science and technology development level and urban population density on carbon emission gradually increases. In the ranking of the influence intensity of each factor, the level of financial investment, urban economic density, urban population density, urban investment intensity, and energy utilization efficiency rank in the top five in terms of the 3-year average explanatory power, i.e., these factors are the dominant factors affecting carbon emission intensity.

## 4.2 Planning a comprehensive classification of drivers and emission reduction initiatives for each city

The drivers of carbon emission intensity of mature, growing, declining and regenerating cities are detected, respectively, and the top five drivers of explanatory power in 2000, 2009, 2019 and the mean values of the 3 years are counted (as shown in Table 5).

As can be seen from Table 5, mature cities have a high level of economic and social development and relatively low carbon emission intensity because they are in the stable period of resource exploitation, which is mainly influenced by factors such as transportation development level, financial investment level, science and technology development level, energy utilization efficiency and urban economic density. Hence, mature cities should increase investment in science and technology innovation, promote the optimization and upgrading of industrial structure, improve resource utilization efficiency, establish a green and low-carbon industrial system, and advance the green transformation of economy and society.

Growing cities are in the rising period of resource development and rapid industrialization. Therefore, their carbon emission intensity is higher, which is mainly influenced by factors such as industrial development level, financial investment level, urban development level, transportation development level and energy utilization efficiency. Growing cities should pay attention to the protection of the ecological environment in resource development, improve the level of resource processing and utilization, coordinate the relationship between resource development and urban development, and promote the synergistic development of new industrialization and new urbanization.

Declining cities are at the end of resource development, with resources tending to be exhausted, relatively lagging economic development and high carbon emission intensity, which are mainly influenced by factors such as energy utilization efficiency, urban investment intensity, urban development level, transportation development level and financial investment level. The declining cities should timely change their economic development model, seek new economic growth points, strengthen policy support, cultivate new industries, improve the level of basic public services, actively promote ecological environment restoration, and improve the quality of urban development.

Regenerating cities have basically gotten rid of resource dependence and their economic development has gradually entered a healthy development track, so their carbon emission intensity is the lowest among the four types of cities, and is mainly influenced by factors such as urban population density, urban investment intensity, energy utilization efficiency, financial investment level and urban economic density. Regenerating cities should further optimize their economic structure, rely on scientific and technological innovation to promote industrial restructuring, actively cultivate green and low-carbon strategic emerging industries, and improve the quality and efficiency of urban economic development.

In addition, different types of resource-based cities should actively learn from and introduce advanced technologies and successful experiences in energy conservation and emission reduction both in and outside of China, strengthen cooperation and exchange in key areas and industries such as

TABLE 6 Detection results of drivers of carbon emission intensity in different resource-based cities (Group division based on resource types).

| Type | 2000 | 2009 | 2019 | Mean value |
|---|---|---|---|---|
| Comprehensive | *X*5、*X*3、*X*1、*X*10、*X*7 | *X*3、*X*8、*X*5、*X*9、*X*10 | *X*10、*X*8、*X*5、*X*4、*X*1 | *X*10、*X*3、*X*5、*X*8、*X*7 |
| Energy | *X*3、*X*1、*X*6、*X*2、*X*4 | *X*3、*X*4、*X*1、*X*7、*X*5 | *X*7、*X*4、*X*6、*X*1、*X*10 | *X*3、*X*4、*X*1、*X*7、*X*6 |
| Metal | *X*6、*X*10、*X*1、*X*9、*X*3 | *X*3、*X*4、*X*1、*X*6、*X*7 | *X*10、*X*4、*X*9、*X*7、*X*1 | *X*10、*X*3、*X*6、*X*1、*X*4 |
| Non-metal | *X*3、*X*8、*X*4、*X*1、*X*6 | *X*2、*X*6、*X*3、*X*1、*X*7 | *X*10、*X*7、*X*1、*X*2、*X*4 | *X*2、*X*3、*X*1、*X*6、*X*10 |
| Forest industry | *X*8、*X*9、*X*5、*X*10、*X*1 | *X*9、*X*8、*X*3、*X*2、*X*7 | *X*5、*X*4、*X*6、*X*3、*X*10 | *X*5、*X*8、*X*9、*X*10、*X*4 |

efficient utilization of resources, development and utilization of new energy, and low-carbon transformation of traditional industries, and establish cooperation mechanisms for low-carbon development.

## 4.3 Resource type classification of each city's drivers and development path

The drivers of carbon emission intensity in cities of comprehensive, energy, metal, non-metal and forest industry categories are detected, respectively, and the top five drivers in terms of explanatory power in 2000, 2009, and 2019, and the mean values of the 3 years are counted (as shown in Table 6).

As can be seen from Table 6, integrated cities are mostly mature and regenerating cities due to the more balanced resources of each type, and such cities are either in the stable stage of resource development or basically free from resource dependence, and their economic development level is relatively high. Therefore, their carbon emission intensity is low, and is mainly affected by factors such as energy utilization efficiency, financial investment level, science and technology development level, transportation development level and urban population density. Comprehensive cities should adhere to the drive of scientific and technological innovation, transform and upgrade traditional industries, promote the optimization and upgrading of industrial structure, and actively cultivate new industries with high technological content, high added value and strong driving effect; implement green development strategies, strengthen ecological restoration and treatment of mining areas, explore the establishment of market-oriented and diversified ecological compensation mechanisms, enhance urban environmental protection and pollution control, and improve the sustainable development and utilization of resources.

Energy cities mainly focus on coal, oil and gas and other fossil energy extraction, and most of them are mature and declining cities. These cities are mostly in the stable or end-stage of resource development, and their economic and social development levels are relatively lagging behind, and their carbon emission intensity is the highest, which is mainly influenced by the level of financial investment, urban investment intensity, urban economic density, urban population density and urban development level. Energy cities take the energy revolution as an opportunity to promote the coordinated development of energy development and utilization and ecological environment, support the green and sustainable development of the city and even the regional economy and society, improve the added value of the energy industry, enhance the efficiency of the energy system, and reduce the pressure on the environment and other systems; they should also increase financial investment and technology research and development, develop multi-energy complementary technologies, promote clean energy consumption, and promote the diversified development of urban energy.

Metal cities mainly focus on ferrous and nonferrous metal mining and metal cities are mostly mature resource cities; most of these cities are in the stable period of resource development, with relatively high level of economic and social development and low carbon emission intensity, and are mainly influenced by factors such as energy utilization efficiency, financial investment level, urban development level, urban economic density and urban investment intensity. Metal cities should accelerate the formation of the clustering effect of subsequent alternative industrial clusters with characteristics and cultivate and grow new economic growth points according to the characteristics and advantageous combinations of urban industries and national development goals (Yan et al., 2019); continue to increase investment in scientific research and innovation, drive the upstream and downstream extension of industrial chains through technology integration and innovation, make up the shortcomings of industrial chains, gather industrial development elements, and form a whole industrial chain competitive advantage.

Non-metal cities are mainly based on non-metallic mineral resources, and non-metal cities are mostly mature and regenerating cities, which are mostly in the stable period of resource development or basically free from resource dependence, and maintain good development momentum in economic and social development, with the lowest carbon emission intensity, and are mainly influenced by factors such as industrial development level, financial investment level, urban economic density, town development level and energy utilization efficiency. The impact of non-metal cities should promote the development of the non-metal mining industry toward intensification and scale through market-oriented means, establish a perfect R&D system around key minerals, products and application fields, build industrial clusters based on the development and utilization of non-metal minerals according to resource characteristics, and form a more comprehensive industrial chain; increase the management of environmental pollution in mineral development, comprehensively improve the ecological environment, and strive to achieve “Green Mine Construction”.

Forest industry cities mainly focus on developing and processing natural resources such as forests. Most of the cities in the forest industry category are mature and declining cities, which are mostly in the stabilization period or the end of resource development, facing severe challenges in economic and social development and high carbon emission intensity, mainly influenced by factors such as the level of scientific and technological development, the level of transportation development, the level of opening to the outside world, energy utilization efficiency and urban investment intensity. Cities in the forest industry category should strengthen forest management and protection in key forest areas of cities, completely ban commercial logging of natural forests, comprehensively improve the quantity and quality of forest resources, enhance the supply capacity of timber production, and build a national reserve base of strategic timber resources; in addition, cities should explore leading industries suitable for their own development, accelerate the cultivation of successive alternative industries, extend industrial chains, increase innovation investment, and provide new impetus for industrial diversification.

# 5 Conclusions and implications

## 5.1 Conclusion

This paper explores the spatial and temporal evolution characteristics of carbon emission intensity in resource-based cities in China, using panel data of prefecture-level cities from 2000–2019, and analyzes the drivers of spatial divergence in carbon emission intensity the geographic detector model to obtain the following main conclusions.

1) The carbon emission intensity of resource-based cities in China shows an obvious decreasing trend overall, but there are some differences between different types of resource-based cities. The overall trend of growth, decline, maturity and regeneration of cities in order on the comprehensive planning classification, and the classification of resource types basically shows a gradually decreasing trend of energy, forest industry, comprehensive, metal and non-metal cities, and the decrease of carbon emission intensity of each type of cities is negatively correlated with carbon emission intensity. In terms of spatial distribution, the high-value areas of carbon emission intensity are mainly concentrated in energy cities in Shanxi, Shaanxi and Heilongjiang, while the low-value areas are located in Fujian, Sichuan and Shandong, showing a spatial trend of high in the north and low in the south, and the spatial pattern has strong stability.
2) The spatial structure of carbon emission intensity of resource-based cities in China has strong stability, dependence and integration. Stability gradually increases from north to south, and dependency reflects a strong spatial locking effect, with positive synergistic growth cities concentrated in northern Hebei and northeastern provinces, and negative synergistic growth cities are more numerous and scattered. There is strong transfer inertia of carbon emission intensity in resource-based cities, with a low probability of transfer between local spatial and temporal correlation categories and a very low probability of jump migration, and the path dependence and locking characteristics of carbon emission intensity patterns slightly weaken over time.
3) There are significant temporal differences in the drivers of carbon emission intensity in resource-based cities. The impact of urban economic density, industrial development level, urban development level, transportation development level, openness level and energy utilization efficiency on resource-based cities first decreases and then increases, while the impact of financial input level gradually decreases, and the impact of urban investment intensity, science and technology development level and urban population density gradually increases. The level of financial investment, urban economic density, urban population density, urban investment intensity and energy utilization efficiency is the dominant factors influencing the carbon emission intensity of resource-based cities.
4) There are significant differences in the drivers of different types of resource-based cities. Mature, growing, declining and regenerating cities have different dominant factors affecting their carbon emission intensity because they are in different resource development periods and have large differences in their economic and social development levels. Comprehensive, energy, metal, non-metal and forest industry cities have different carbon emissions in the process of resource utilization and development due to the differences in the dominant resource types, and there are large differences in the degree of impact on the ecological environment. Therefore, the dominant drivers of their carbon emission intensity are different.

## 5.2 Policy implications

As China’s economic growth gradually changes from a high growth rate to high quality, the contradiction between economic development and carbon emissions still exists and affects sustainable development of the economy and society. The problem of "one industry only" or "one mine only" and the deformed industrial structure of resource-based cities have squeezed the development of other industries and restricted the sustainable development of cities, which seriously impacts the goals of peaking carbon dioxide emissions, and carbon neutrality. In view of the above situation, this paper draws the following policy inspirations.

Firstly, get rid of "one industry alone", strengthen technological innovation and promote industrial upgrading. Resource-based cities must get rid of the development pattern of "one industry only" or "one mine only" in the process of development in order to effectively reduce carbon emissions and attain sustainable development. This requires resource-based cities to actively strengthen the research and development and utilization of renewable energy technologies, build a diversified and clean energy supply system, and promote changes in energy consumption patterns, so as to accelerate the industrial transformation and upgrading of resource-based cities and improve their energy utilization efficiency.

Secondly, for different types of resource-based cities, carbon emission reduction strategies should be formulated according to local conditions to promote sustainable development. As for mature, growing, declining and regenerating cities, mature cities are in the stable stage of resource development, so they should pay more attention to the optimization of industrial structure and invest more in green technology innovation; growing cities are in the rising stage of carbon emission, so they should pay more attention to the protection of the ecological environment and improve energy utilization efficiency; declining cities are at the end of resource development, so they need to strengthen ecological restoration and cultivate new industries; while for regenerating cities, they need to further take advantage of their technology and industrial structure to expand the proportion of green industries. In addition, for comprehensive energy, metal, non-metal and forest industry resource cities, comprehensive cities should insist on science and technology innovation to transform and upgrade traditional industries, improve energy utilization efficiency, and develop green and sustainable industries at multiple levels; energy cities are constrained by the "one industry only" and need to get rid of reliance on fossil energy and open up the new green industry to lighten the pressure from carbon emissions. For metal and non-metal cities, the situation is similar, and both need to increase investment in scientific research, extend the industrial chain, make up the short board of the industrial chain, and promote industrial gathering; for forest industry cities, it is necessary to strengthen forest management and protection in key forest areas to ensure the quantity and quality of forest resources.

Thirdly, the government needs to optimise top-level design, and regional and society cooperation needs to be strengthened. In terms of top-level design, the government level should formulate carbon emission reduction plans, policies and regulations, coordinate the relationship between sustainable economic and social development and carbon emission reduction, systematically coordinate carbon emission reduction efforts in various regions and industries, and establish a sound carbon emission monitoring, reporting and accounting system. With regard to regional and society cooperation, resource-based cities are characterized by strong path dependence and spatial locking. In order to break this path of dependence, it is necessary to rely on industrial assistance from neighboring regions, the support of international and domestic innovative technologies, and national, regional and society cooperation and support to promote green growth in the economy, and upgrade the transformation of resource-based cities into low-carbon sustainable cities.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

WS, SY, and XY conceived the ideas and designed the research framework; WS performed the literature research; SY, YZ, and XY performed the data collection and result calculation; WS, YZ, and LQ led the writing of the manuscript; All authors read and approved the final manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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# Towards carbon neutrality: Improving resource efficiency of the rare earth elements in China

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Rare earth elements (REEs) are essential for promoting clean energy technologies and making high-performance materials because of their unique physical and chemical properties. In order to respond to climate change, the Chinese government has promised to achieve carbon neutrality before 2060. Under such a circumstance, the demand for REEs will increase significantly. However, several challenges exist in current REEs supply chain management in China. This policy brief discusses these challenges from a life cycle perspective, covering REEs mining, smelting, manufacturing, waste management, and recycling. Policy recommendations on future REEs supply chain management are then proposed, including adequate mining quota, a strategic REEs list, innovative high-tech applications, and circular economy.

KEYWORDS

**rare earth elements, supply chain management, carbon neutrality, policy implication, high-tech industry**

## 1 Introduction

Rare earth elements (REEs) include scandium (Sc), yttrium (Y), and 15 kinds of lanthanide elements, including lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) (Zeng et al., 2020). These rare earth elements have outstanding optical, electrical, magnetic, and nuclear characteristics and can be composed with other materials to improve the quality and performance of various products. Currently, rare earth elements are mainly used in chemical, metallurgical, military, clean energy, and other high-tech industries (Wang X et al., 2017; LeeJason and Wen, 2018). The global rare earth reserves reached 0.13 Gt (gigatons) in 2017, among which China accounted for about 30% with a figure of 44 million tons (Das et al., 2018). Due to its rich reserve, China has become the largest REEs supplier in the world, supplying more than 60% of the global REEs production (Du and Graedel, 2011). However, with

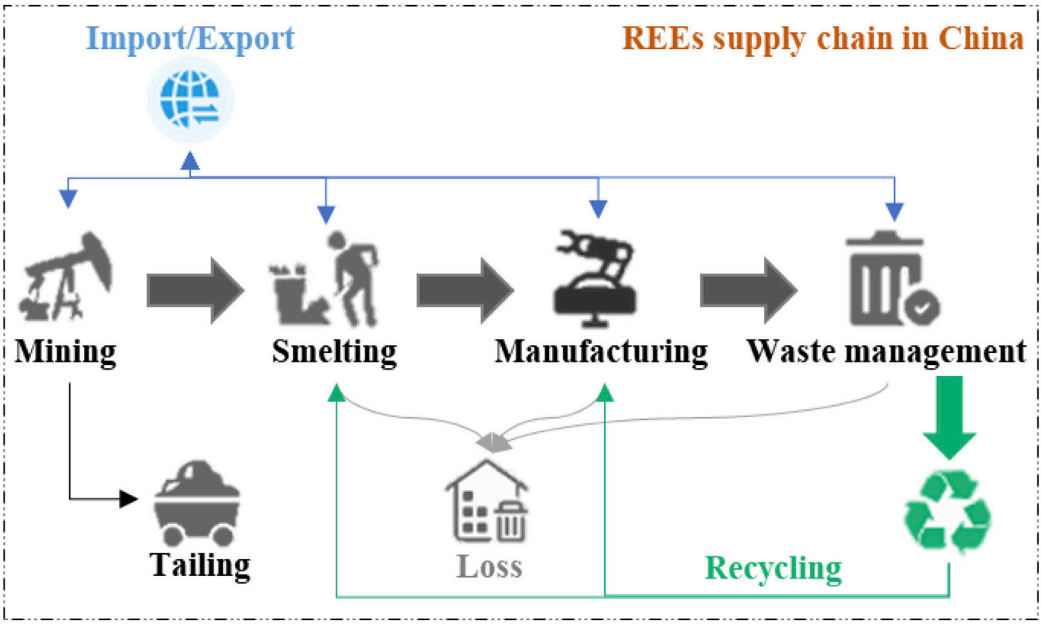


FIGURE 1
Rare earth elements supply chain in China.

unsustainable and extensive mining activities during the past few decades, both the amount and the grade of rare earth ores have gradually reduced in China. As a result, rare earth elements were listed as strategic mineral resources by the Ministry of Natural Resources in 2016 (Ministry of Natural Resources, 2016). Meanwhile, in order to respond to climate change, many countries proposed to achieve carbon neutrality before 2050 and have begun their efforts to transit their energy systems towards renewable and clean energy systems, as well as through the rapid development of high-tech industry (Wei et al., 2021). With the future expansion on these emerging industries, the demand for rare earth elements will continue to increase, indicating new challenges to the global rare earth elements supply chain. Under such a circumstance, it would be urgent for China to manage its rare earth elements supply chain by considering these complicated realities. Based on the literature review and site investigations, this policy brief discusses the whole rare earth elements supply chain from a life cycle perspective so that valuable policy insights can be obtained. In the remaining part of this paper, Section 2 identifies the associated supply chain challenges in each life cycle stage; Section 3 proposes policy recommendations. Finally, Section 4 draws research conclusions.

## 2 Current challenges on rare earth elements supply chain in China

From a life cycle perspective, the rare earth elements supply chain can be divided into five stages in China, covering mining, smelting, manufacturing, waste management, and recycling (Figure 1). There are three major types of rare earth ores in China, including mixed monazite and bastnaesite in Bayan Obo ores of Inner Mongolia, bastnaesite ores in Sichuan and Shandong, and ionic clays in seven southern provinces. In particular, more than 80% of domestic rare earth elements were mined from Bayan Obo ores, the largest rare earth elements reserve in China (LeeJason and Wen, 2018). In the mining process. Rare earth elements are extracted from these natural reserves and beneficiated into high-grade concentrates through gravity separation, magnetic separation, electrostatic separation, and froth flotation. These concentrates are then refined and separated into rare earth oxides and other compounds by leaching, extraction, and precipitation in the smelting stage. During the manufacturing process, final REEs-containing products are produced. These final products will be consumed and become stocks serving the whole society. When these products reach the end of their life spans, they become scraps and will be recycled in the waste treatment plants or landfilled. To date, China has already built such a complete rare earth elements supply chain. But several challenges exist and should be identified for further improvement. We discuss these challenges along this supply chain.

### 2.1 Mining

Firstly, the production capacity of rare earth elements is far higher than the mining quota in China. Although China has rich rare

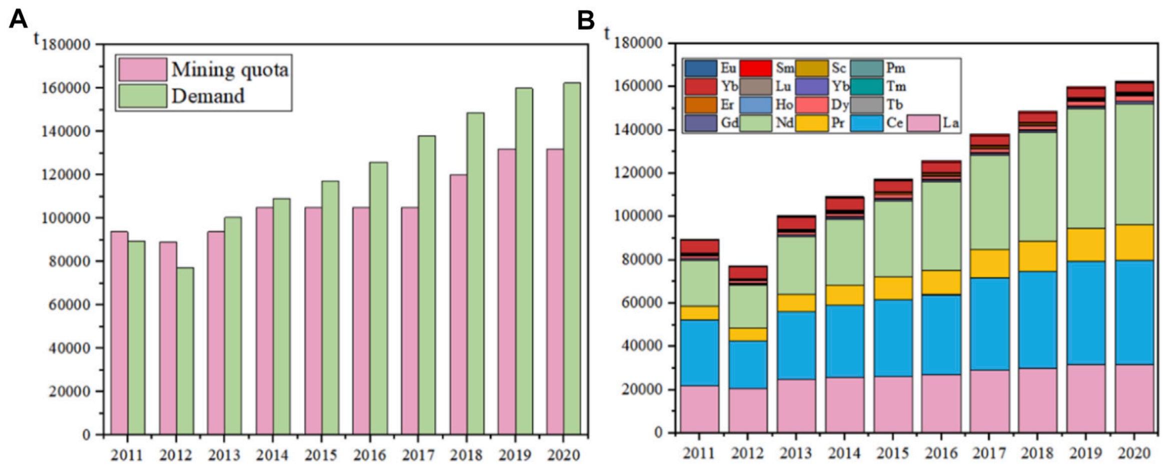


FIGURE 2
Annual mining quota and demand of rare earth elements in China from 2011 to 2020 **(A)**; Annual demand for different rare earth elements in China from 2011 to 2020 **(B)**. Data source: Chinese Society of Rare Earths Yearbooks.

earth elements reserves, the large export amount with lower economic values will deplete such reserves shortly. Therefore, in order to protect the domestic rare earth elements supply chain and control the total mining amount, the Ministry of Natural Resources and the Ministry of the Industry and Information Technology jointly released annual quota for such rare earth elements in different provinces. Figure 2 shows the annual quotas and demands of rare earth elements in China from 2011 to 2020. However, with rapid technological development, such quota is very limited and cannot meet with the soaring demand from those downstream companies. For example, the mining and smelting quota for Inner Mongolia was 73,550 and 63,784 tons in 2020, respectively. However, such mining and smelting production capacity was 125,000 and 100,000 tons in Inner Mongolia in 2020, respectively (Chinese Society of Rare Earths, 2011). Several relevant studies found that the demands for several rare earth elements, such as Nd, exceeded the official supply with the development of the emerging clean technologies (Packey and Kingsnorth, 2016; LeeJason and Wen, 2018; Geng et al., 2021). In order to achieve carbon neutrality before 2060, the demands for such rare earth elements will continuously increase (Wang, 2018). Thus, it is necessary to set adequate mining quotas to satisfy these companies' production capacities and meet with the increasing demands for rare earth elements. Additionally, such mining process results in various environmental damages, such as radioactive contamination, soil and water contamination, and eutrophication (Wang L et al., 2017). Also, many suppliers of rare earth elements paid less attention on such environmental impacts due to their backward awareness, higher treatment costs, and ineffective enforcement of relevant regulations by local governments. From a legal point of view, current regulations on rare earth mining do not address such environmental impacts efficiently. As such, stricter and more suitable environmental standards are still lacking.

## 2.2 Smelting and manufacturing

In the smelting process, the production amounts for different rare earth elements are significantly different. The amounts of several bulk rare earth elements, such as Nd, La, and Y, are hundreds of times that of other elements, such as Lu, Tm, and Er (Goodenough et al., 2018). Such differences are attributed by different applications of different rare earth elements (Figure 3). Renewable energy sector has a high demand for several rare earth elements (such as Nd, Y) since such elements are indispensable for making magnets. The annual demands for such rare earth elements always exceed their official supplies (Gong et al., 2017; Chen et al., 2018). However, the demands for rare earth elements in traditional industries (such as optical material) are lower, leading to oversupply, such as Eu (Wang L et al., 2020). In addition, since many rare earth elements are mined together, it is not easy to separate one specific rare earth element from the entire ore. For example, light rare earth elements are mainly extracted from iron tailings in Bayan Obo ores and become concentrates. It is extremely difficult to separate different elements from such concentrates. Also, since it is difficult for those companies to sell their rare earth elements surplus, they have to reserve such surplus by themselves, which increased their storage costs and influenced their monetary flows. Additionally, due to the lack of advanced technologies, several rare earth elements are mainly used for making primary products in China, such as rare earth-related oxides and compounds. For several heavy rare earth elements such as Tm, Yb, and Er, only their oxides are being circulated in the market. Their final products are mainly used as additives (Li et al., 2012). As such, Pm and Sc are the scarcest rare earth elements, but have not been applied in China (Wang L et al., 2020). However, these rare earth elements are key in several high-tech industries, especially under China's ambitious carbon neutrality targets (Fishman and

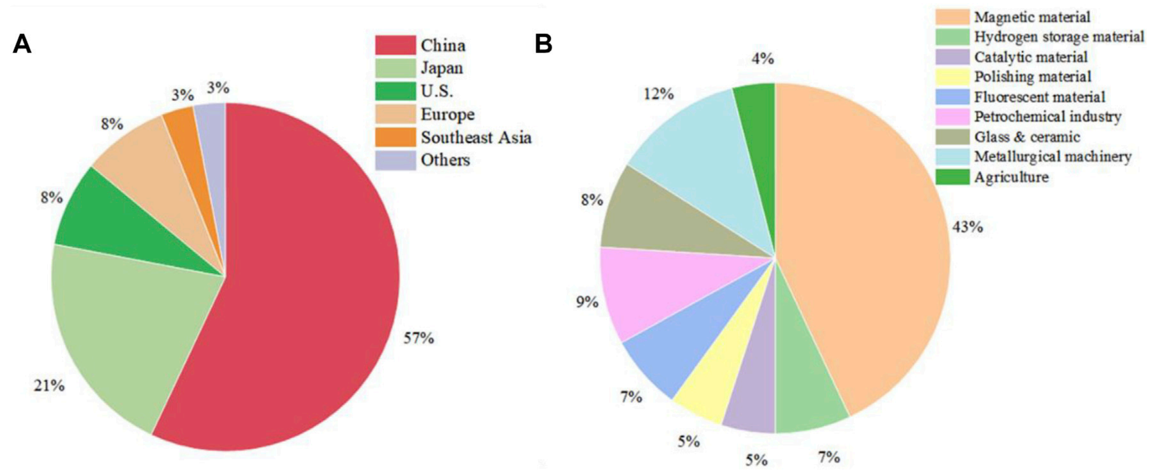


FIGURE 3
Leading suppliers of rare earth elements around the world **(A)**; Main applications of rare earth elements in China **(B)**. Data source: Chinese Society of Rare Earths Yearbooks

Graedel, 2019; Li et al., 2020; Wei et al., 2022). Thus, with the rapid development of emerging technologies, the demands for these REEs will grow.

## 2.3 Waste management and recycling

When the REEs-containing final products reach the ends of their life spans, these products should be further treated before being discarded into the environment. It is rational to extend their life spans through repair, refurbish, remanufacturing, recycling, and reuse. However, waste collection and recycling system for rare earth elements is still ineffective in China, resulting in that most end-of-life REEs-containing final products flow into landfills directly without any treatment, especially for several light rare earth elements such as Eu, Gd, Sm. Currently, only Nd-Fe-B permanent magnet has been widely recycled in China because it has the highest demand and value among all the REEs (Jo, 2015). Theoretically, it is feasible to recycle such rare earth elements from these end-of-life REEs-containing final products (Rollat et al., 2016; Qiu and Suh, 2019). For example, by adding hydrochloric acid and oxalic acid, samarium can be recycled from Sm-Co magnet (Onoda and Kurioka, 2015). However, the recovery rate of Sm is still less than 1% in China due to the lack of policy support, backward awareness, a lack of economic incentives, and a lack of advanced recycling technologies (Xiao et al., 2022a; Ge et al., 2022).

# 3 Policy recommendations

First, since annual quota determines the real rare earth elements mining amount in China, it is essential to reallocate such annual quotas by considering the real needs from those downstream companies. This requires scientific evaluation on the real demands for various rare earth elements. Such evaluation should consider both domestic and international demands and avoid irrational allocation to those firms without reasonable production plans. Several studies have already been carried out in this field to evaluate the real demands for different rare earth elements in China. For example, Wang Q et al. (2020) and Xiao et al. (2022a) found the real demands for Eu and Y in China are less than their official supply, leading to enormous surplus. Ge et al. (2022) and Xiao et al. (2022b) found the real demands for Sm and Dy are gradually increasing in China, which may exceed their official supply in the future. Also, the Chinese government should set up appropriate environmental standards for rare earth mining. For example, heavy rare earth mining can lead to severe water pollution with a feature of excessive ammonium nitrogen, which is difficult to be removed for a long time (Packey and Kingsnorth, 2016). In order to mitigate such pollution, the Chinese government has updated national sewage treatment standards and installed on site detectors to measure mining waste water since 2019. Such standards should be updated regularly so that more parameters can be included. In addition, such environmental standards should be updated with the rapid development of innovative technologies so that these technologies can be promoted quickly. For example, ammonium-free mining technology has emerged and can replace the traditional mining process since it avoids using ammonium sulfate. Unfortunately, such ammonium-free process may result in adverse effects on human health since it uses highly concentrated magnesium (Schulze et al., 2017). Consequently, it is urgent for the Chinese government to prepare corresponding regulations to address this public health concern.

Second, rare earth element-specific management should be initiated since different rare earth elements have different features and application fields. Several countries only listed several key rare earth elements in their strategic mineral resource plans. For example, in 2022, the United States updated its strategic mineral resource plan (USDI, 2022), in which 15 kinds of key rare earth elements were listed (except Pm and Sc). However, China listed all the rare earth elements as strategic mineral resources. It would be crucial to further highlight several key rare earth elements in the national strategic mineral plan, such as Nd, Dy, Pm and Sc. These elements can play a key role in promoting renewable energy development and other emerging sectors. Future demands for these key rare earth elements may rise very quickly and should be carefully managed so that sustainable supply can be achieved. For those rare earth elements with surplus, since the demands for such elements are still low, they should be stored with careful plan, rather than relying on those firms. The Chinese government may establish several regional storage centers for such rare earth elements by collecting them from those firms. Such a measure can also help stabilize the prices of such rare earth elements.

In addition, since most of rare earth elements are mainly used for making primary products in China, it is important to encourage research and development (R&D) activities, especially under the ambitious 2060 carbon neutrality target. These activities can help incubate more advanced technologies so that more value-added products can be manufactured within China, such as permanent magnets, hydrogen storage materials. A government-industrial partnership should be created to facilitate such R&D efforts so that adequate funds can be received. Both universities and research institutes should actively engage in such R&D efforts so that they can understand the real industrial needs and focus on seeking potential solutions. Moreover, intellectual rights should be seriously protected so that the promotion of such innovative technologies can be achieved smoothly.

Finally, it is essential to improve the overall resource efficiency of rare earth elements by promoting circular economy. The total recycling rate of such rare earth elements-containing end-of-life products is less than 1% in China (Sprecher et al., 2015; Morimoto et al., 2021). Recently, Ge et al. (2022) found that if the recycling rate reaches 40% in China, approximately 1728 tons of Sm can be recovered from in-use stocks, which can meet domestic demand for 2 years. However, several barriers exist for the implementation of circular economy in these REEs-related businesses, such as the lack of recycling awareness, backward recycling technologies, ineffective collection system for such REEs-containing end-of-life products, and a lack of economic incentives. Therefore, more efforts should be made to solve these problems. For instance, the Chinese government may establish a national information center on rare earth elements products so that information and data on these end-of-life products can be shared by more stakeholders. Similarly, recycling technologies can be shared through this information center so that technology transfer can be achieved quickly. In addition, the Chinese government may provide financial subsides for such recycling activities so that more firms would like to engage in such efforts. As such, capacity-building activities should be initiated so that more stakeholders can improve their recycling awareness and actively participate in such recycling efforts.

## 4 Conclusion

Rare earth elements are essential to help China achieve its ambitious carbon neutrality target. However, several challenges exist. This study discusses these challenges along REEs supply chain, including mining, smelting, manufacturing, waste management, and recycling. The first challenge is that mining quota is not adequate in China, which cannot meet with the soaring demands. The second challenge is that each rare earth element has different features, resulting in various supply problems, including both supply shortage and surplus problem. The third challenge is that current applications of most rare earth elements are mainly used to make primary products, instead of high-tech products. Finally, the recycling system of rare earth elements is ineffective, leading to that the current recycling rate of rare earth elements is still below 1%. By considering the Chinese realities, several policy recommendations are proposed to improve the overall rare earth resource efficiency, especially under the consideration of achieving carbon neutrality, including adequate mining quota, appropriate strategic rare earth elements list, the application of circular economy.

## Author contributions

ZG designed this study and other authors jointly wrote this paper.

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## Conflict of interest

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# Estimation of critical metal stock and recycling potential in China's automobile industry

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The rapid expansion of electric vehicles (EVs) in China will induce a potential imbalance in the demand and supply of critical metals, which emphasized the importance of recycling critical metals. Evaluating their stock and recycling potential is essential to the electrification transformation in the automobile industry and provides references to the overall national resource strategy. In this study, we identified the critical metals in the electrification transformation of the automobile industry, estimated the stock of critical metals from 2022 to 2050 under multiple scenarios in China, and assessed the recycling potential of critical metals in EVs as well as their economic value. The results show that China's passenger vehicles will reach 547.5–623.8 million in 2050. According to China's current energy conservation and emission reduction policies, fuel vehicle (FV) ownership will peak in 2042, at 488.2 million. If strict energy conservation and emission reduction policies are adopted, electric vehicle ownership will increase from 148.3 million to 293.9 million by 2050, leading to a rapid increase in the stock of critical metals. The total stock of key critical metals under the scenario with stringent policies will be 29.27 million tons in 2050, 10.55 million higher compared to the scenario with no ban on fuel vehicles. Based on our results, the recycling of critical metals can be an effective option for the inadequate critical metal supply, especially given the policy context of increasingly expanding EV ownership in the near-term future.

KEYWORDS

**critical metals, passenger vehicle, electric vehicle (EV), recycling potential, scenario analysis**

## 1 Introduction

China remains the largest automobile manufacturing country and automobile market in the world since 2009. China's annual vehicle production has accounted for over 30% percent of global vehicle production. In 2021, China's vehicle production and sales reached 26.08 million and 26.28 million, with a year-on-year increase of 3.4 and 3.8%, respectively. The production and sales of new energy vehicles (NEVs) were 3.55 million and 3.52 million, respectively, with a year-on-year increase of 160%. The NEV market has a great potential for development in the future. The automobile industry is one of the world's largest consumers of raw materials (Serrenho et al., 2017). In recent years, more

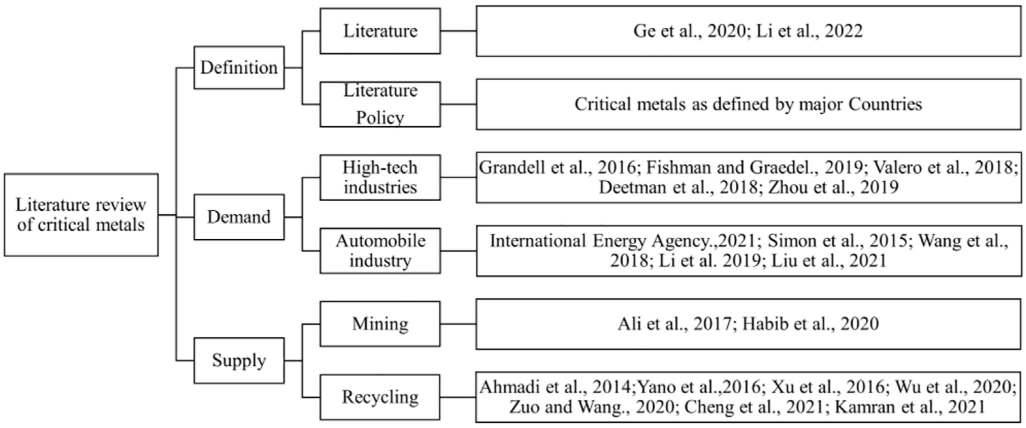


FIGURE 1
Literature review of critical metals.

TABLE 1 Critical metals as defined by major Countries.

| Country | Major critical metals | References |
|---|---|---|
| Japan | Li, Be, Rb, Cs, Nb, Ta, Zr, Hf, W, rare earth, Ga, Ge, In, Te, Re, Tl, Pt, Pd, Cr, Co, Ni, Mo, Mn, V, Sb, Ti, Bi, Sr, Ba | Ministry of economy and industry of Japan (2009) |
| China | Li, Zr, W, Sn, rare earth, Cr, Co, Fe, Cu, Al, Au, Ni, Mo, Sb | Ministry of Land and Resources of the People's Republic of China (2016) |
| India | Re, Be, rare earth, Ge, Ta, Zr, Cr, Sr | Council on Energy, Environment and Water (2016) |
| America | Li, Be, Rb, Cs, Nb, Ta, Zr, Hf, W, Sn, rare earth, Sc, Ga, Ge, In, Te, Re, Pt, Cr, Co, Mn, V, Ti, Sb, Bi, Mg, Al | US Department of Commerce (2019) |
| Australia | Li, Be, Nb, Ta, Zr, Hf, W, rare earth, Sc, Ga, Ge, In, Re, Pt, Cr, Co, Mn, V, Ti, Sb, Bi, Mg | Australian Department of Industry, Science, Energy and Resources (2019) |
| European Union | Li, Be, Nb, Hf, Ta, W, rare earth, Sc, Ga, Ge, In, Pt, Co, V, Sb, Ti, Bi, Sr, Mg | European Union (2018) |

Note: This table selects major critical metals from critical materials of the above countries.

and more new materials have been used for automobile components such as engines, sensors, and electronic equipment to make safer, more complex vehicles (Ortego et al., 2020; Sharma and Pandey, 2020). The manufacturing of NEVs consumes many critical metals, including scarce supplies of Li, Co, rare earth, and others. Specifically in China, serious resource shortages may occur for several key minerals given the carbon neutrality goal by 2050, such as Cr, Cu, Mn, Ag, Te, Ga, and Co (Wei et al., 2022). The possible imbalances in the supply and demand of those critical metals call for a more detailed assessment in the near and long run.

The definition, demand, and supply of critical metals (as shown in Figure 1) in the automobile industry, especially NEVs should be clarified first. The critical metals refer to those metal resources or raw materials that have a high supply risk and an important impact on the national economy, social welfare, and the ecological environment and development strategies (Ge and Liu, 2020; Li et al., 2022). They are of great significance to national security and the development of emerging industries. However, regarding the boundary, it differs among countries. Table 1 summarized critical metal development strategies in different countries in recent years and shows the differences in the definition boundaries.

Regarding the demand of critical metals, in the context of an accelerating sustainable transformation, the development of relevant strategic industries such as NEVs, high-end equipment, next-generation information technology, and energy conservation and environmental protection would induce great demand for the critical metals (Grandell et al., 2016; Fishman and Graedel, 2019). For example, Valero et al. (2018) pointed out that the development of global wind energy, solar photovoltaic, solar thermal energy, and other industries from 2016 to 2050 will increase the demand for 31 critical minerals. Deetman et al. (2018) pointed out that the development of power production and electronic equipment will increase the global total demand for Nd and Ta by about

2–3.2 times in 2050. Zhou et al. (2019) assessed the increase in demand for 12 critical metals caused by the development of solar and wind energy in China.

Moreover, the transformation from fuel vehicles (FVs) to electric vehicles (EVs) has led to great changes in the demand for critical metals (International Energy Agency, 2021). Scholars have discussed critical metals for the development of automobile electrification in many aspects. Simon et al. (2015) analyzed EVs in Europe and pointed out that they are continuously increasing, the shortage of Li and Ni reserves could intensify around 2025, and the demand for Co and Mn will be far lower than the current level. Liu et al. (2021) analyzed the material flow changes of Li batteries in China and found the development of EVs after 2015 is the main reason for the increase in Li-battery consumption. Wang et al. (2018) assessed the global supply risk of 23 critical raw materials required by NEVs. Li X. Y.et al. (2019) based on the sales data of China's NEVs, pointed out that from 2018 to 2030, the maximum total demand for rare earth will reach 315,000 tons, accounting for 22% of the world output in the same period, while the demand for the commonly used elements (Nd, Dy, Ce, Pr, and La) will account for 99% of the total demand.

The large demand for critical metals has brought supply pressure. Habib et al. (2020) pointed out that with the development of electrification in the future, the reserves of Co, Li, and Ni will face great pressure. As critical metals are mostly mined in the form of symbiotic or associated ore, the capacity expansion is slow and the development cost is too high (Ali et al., 2017). Recycling is regarded as a powerful measure to relieve the supply pressure of critical metals (Zuo and Wang., 2020). Many scholars analyzed the recycling potential of critical metals in vehicles (Yano et al., 2016; Xu et al., 2016). Xu et al. (2016) pointed out that recycling Nd and Dy could meet 23% of the production need for EV batteries in Japan. In addition, Ahmadi et al. (2014) also pointed out that by recycling Li batteries, carbon dioxide can be reduced by 56%. Critical metals recycling can reduce the pressure on resources and the environment, which is conducive to sustainable development and carbon emission reduction (Cheng et al., 2021). To sum up, most of the existing studies focus on developed countries to analyze the definition, demand, and supply risks of critical metals. The analysis of medium and long-term stock and recovery potential of Critical metals in the process of automobile electrification transformation in developing countries is not sufficient.

The acceleration of automobile electrification transformation has led to the rapid growth of the consumption of critical metals. EV is an important dimension of green development and low-carbon transformation in the global automobile industry, however, with huge consumption of critical metals. As the world's largest automobile market, China's rapid expansion of EVs in the short term will bring great pressure on the demand for critical metals and provide great recycling potential. Accurately evaluating the change and recovery potential of medium and long-term critical metal inventory is of great significance to the sustainable development of the automobile industry. Therefore, the objective of this study is to clarify the relationship between electrification transformation, fuel ban policy, and critical metal supply risk in China's automobile industry, predict the trend of medium and long-term critical metal inventory and recovery potential, and put forward policy suggestions to reduce the imbalance between supply and demand of Critical metal minerals. This study provides a reference for the sustainable supply of critical metals required for the electrification transformation and sustainable development of the automobile industry.

The methodologies for evaluating the passenger vehicle ownership (Section 2.1), critical metal stock (Section 2.2), recycled critical metals from FVs and EVs (Section 2.3), together with the scenario designs (Section 2.4) are listed in Chapter 2, followed with the corresponding results in Chapter 3. We also discussed the strategic risk, resource governance, and uncertainties in Chapter 4. The conclusions are listed in Chapter 5.

## 2 Methodology

Long-term predictions of stock and flows can effectively reveal the maximum recycling potential and supply risk of critical metals. This study identified the critical metals in the electrification transformation of the automobile industry, estimated the stock of critical metals from vehicles from 2022 to 2050 under multiple scenarios, and discussed the economic value and maximum recycling potential of critical metals in EVs. The critical metal stock model constructed in this paper can be applied to the stock analysis of other industries and different materials. The estimation results obtained based on the model can provide a scientific basis for promoting the recycling of material resources. The steps of this study are shown in Figure 2.

Specifically, 1) combined with literature and policy analysis, this study selects the critical metals in the electrification transformation of China's automobile industry as the research object. 2) Referring to the experience of developed countries and the actual situation of China, setting four scenarios: the saturation value of passenger vehicle ownership per thousand people (high or low) and fuel ban policy (planned or unplanned), using the Gompertz function to predict passenger vehicle ownership. 3) Combined the above four scenarios, predicting the stock changes of critical metal stocks of different vehicles (FV and EV) from 2022 to 2050 in China's automobile industry. 4) Combined with the previous research results (Li et al., 2021), the economic value and maximum recovery potential of critical metals in EV under different recovery levels (high and low) are discussed.

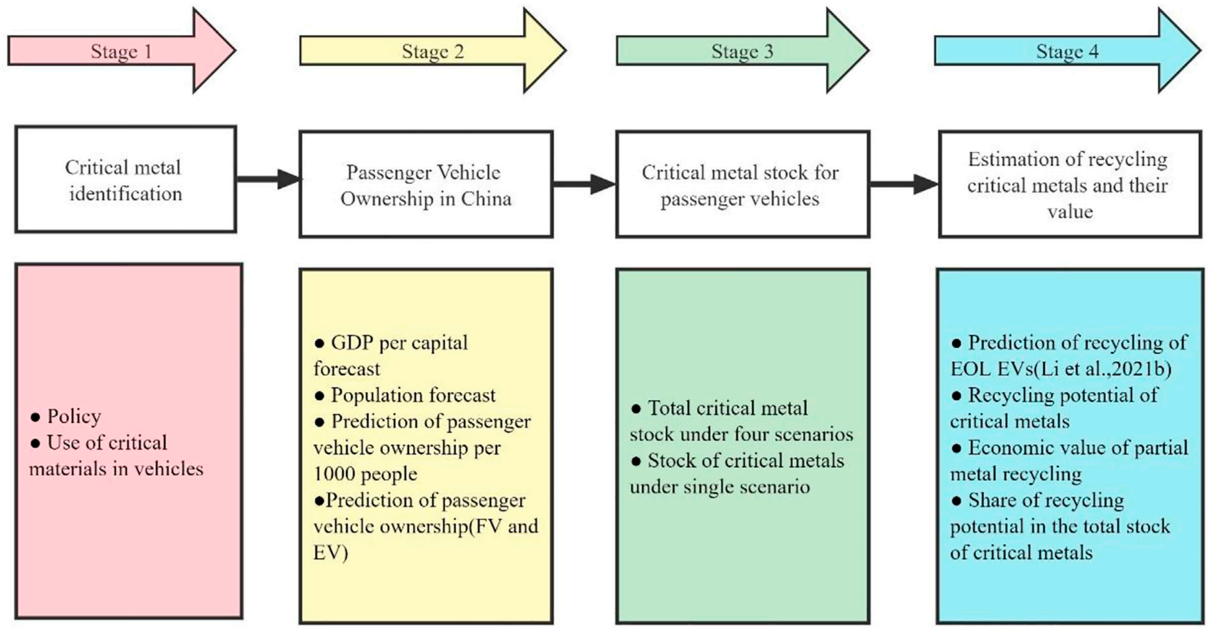


FIGURE 2
Research steps of this paper.

## 2.1 Passenger vehicle ownership prediction model

The number of passenger vehicles owned is jointly determined by the population and the passenger vehicle ownership per thousand people. It can be formulated as:

$$S_t = H_t \times P_t \tag{1}$$

where $S_t$ represents passenger vehicles owned in year $t$, $H_t$ represents passenger vehicle ownership per thousand people in year $t$, and $P_t$ represents the population in year $t$.

The critical metal stock is closely related to the number of vehicle ownership. The methods for estimating the critical metal stock based on vehicle ownership are numerous. For the long-term prediction of regional vehicle ownership, saturation level modeling, such as regression models is usually used. The correlation between vehicle ownership and main driving factors is established by the regression model. Compared with developed countries, China is in the primary stage of automobile popularization. In the initial stage, income growth is one of the most important driving forces for the growth of vehicle ownership (Dargay et al., 2007; Li Y. et al., 2019). According to the experience of developed countries (Huo & Wang, 2012), the development trend of vehicle ownership per thousand people can be an S-shaped "slow–urgent–slow" development process, namely the slow growth in the initial stage, rapid growth in the medium term, slow growth in the later stage, and entering the saturation stage. Therefore, according to the characteristics of changes in vehicle ownership, we used the S-curve model to predict passenger vehicle ownership. Commonly used S-shaped curves include the Richards, logistic, and Gompertz functions (Weiner, 1990). Due to the short development time of China's automobile industry, the availability of data should be considered in the selection of methods. The Richards function involves many parameters, and the logistic function is most suitable for an S-shaped curve with a symmetrical inflection point, while an S-shaped curve with right deflection is well fitted by the Gompertz model (Lee & Shaw, 1996). Compared with the Richards function, the Gompertz function uses simple data and is more suitable for predicting the growth of vehicle ownership in developing countries such as China. Compared with the logistic function, the Gompertz model shows an upward state in the later stage of growth, and other explanatory variables can be added to the model to integrate the development of the automobile industry into the national macroeconomic development system, which is more in line with the changes in China's passenger vehicle ownership. The forecast of the Gompertz curve is flexible and the parameter and saturation value can be adjusted according to the policies, which can be more suitable for medium and long-term prediction at the national level. Therefore, this paper uses the Gompertz model to predict the number of passenger vehicles per thousand people in China in the future. The formula is as follows:

$$H_t = R \times e^{\alpha e^{\beta g_t}} \tag{2}$$

where $H_t$ represents passenger vehicle ownership per thousand people in year $t$; R represents the upper limit of $H_t$, that is, the saturation value of passenger vehicle ownership per thousand people; $g_t$ represents the GDP per capita in year $t$; and $\alpha$, $\beta$ are parameters that determine the shape of the S-curve and the relationship between vehicle ownership and economic growth. The forecast of Gompertz curve is flexible and the parameter and saturation value can be adjusted according to the policies.

Regarding the Estimation of population, the incidence rate is a virtual variable in population prediction, such as survival and mortality rates, incidence and non-incidence rates, and gender ratio. At this time, it is no longer feasible to study such problems with a linear regression model; a logistic regression model can analyze multiple independent variables, including discrete and continuous variables, at the same time, and can effectively analyze the interactions between independent variables, providing a quantitative description of the relationships between multiple independent and dependent variables. The logistic model has the characteristics of limited growth and monotonic increase, which is in line with the population growth model. However, the defect of this model is that population growth generally shows an upward trend in the short term (30–50 years). This study assumes that China's population growth will continue to grow from 2020 to 2050, so it can be predicted by logistic regression model.

According to the research needs, combined with the logistic curve model equation, the following population prediction formula can be obtained:

$$P_t = \frac{p_m}{1 + \left(\frac{p_m}{p_0} - 1\right) \times e^{-r_0 t}} \tag{3}$$

where $P_t$ represents the population in year $t$, $p_m$ is the maximum population that the environment can accommodate, $p_0$ is the initial population, and $r_0$ represents the inherent growth rate of the population under unrestricted conditions.

## 2.2 Critical metal stock model for passenger vehicles

In this paper, the bottom-up method is used to calculate the material stock of passenger vehicles, which is determined according to the weight of each critical metal per vehicle. The formula is as follows:

$$M_t = \sum_{i=1}^{n} S_t \times W_i \tag{4}$$

where $M_t$ represents the material stock of passenger vehicles in year $t$, and there are n types of critical metals; $S_t$ represents passenger vehicle ownership in year $t$; and $W_i$ represents the weight of the $i$ th type of critical metal per passenger vehicle. In this paper, the stock of critical metals for FVs and EVs is calculated.

## 2.3 Estimation of recycled critical metals and their economic value

The total weight of recycled critical metals from end-of-life passenger vehicles, $Q_t$, can be formulated as:

$$Q_t = \sum_{i=1}^{n} B_t \times W_i \times C_i \tag{5}$$

where $B_t$ represents end-of-life passenger vehicles; $W_i$ represents the weight of the $i$ th type of critical metal per passenger vehicle, and there are $n$ types of critical metal; and $C_i$ represents the recycling rate of the $i$ th type of critical metal in passenger vehicles.

The estimation of the economic value of the $i$ th type of critical metal from end-of-life passenger vehicles in year t, $V_{it}$, can be formulated as:

$$V_{it} = Q_{it} \times U_i \tag{6}$$

where $Q_{it}$ is the weight of the $i$ th type of recycled critical metal from end-of-life passenger vehicles in year $t$ and $U_i$ represents the average unit price of the $i$ th type critical metal.

## 2.4 Scenario design

### 2.4.1 Total passenger vehicle ownership

This paper refers to passenger vehicle ownership per thousand people in countries with a developed automobile industry when setting the saturation value. Taking the US, United Kingdom, France, and Japan as reference objects, the average value of the growth rate of passenger vehicle ownership per thousand people fluctuated by within 2% (±) for more than four consecutive years, and this is taken as the saturation value of the country. Calculating the data from 1960 to 2012, the following saturation values can be obtained: 513 vehicles per thousand people in the US, 472 vehicles per thousand people in the United Kingdom, 433 vehicles per thousand people in France, and 446 vehicles per thousand people in Japan, with an average value of the four countries of 466 vehicles per thousand people (Li et al., 2021). As China's auto market has not yet entered the saturation stage and the level of domestic economic development is uneven, referring to the historical data of the above countries and combined with the characteristics of China, this paper sets the saturation value of passenger vehicle ownership in two scenarios: 1) under the low saturation (LS) level of passenger vehicle ownership, the saturation value per thousand people is 350, and 2) under the high saturation (HS) level of passenger vehicle ownership, the saturation value is 400.

### 2.4.2 Ownership of EVs

In recent years, in order to reduce carbon emissions, some countries began to vigorously promote vehicle electrification

TABLE 2 Timeline for countries to ban the sales of FVs.

| Region | Proposed time (Year) | Implementation time(Year) |
|---|---|---|
| Netherlands | 2016 | 2030 |
| Norway | 2016 | 2025 |
| Germany | 2016 | 2030 |
| France | 2017 | 2040 |
| Scotland, United Kingdom | 2017 | 2032 |
| California, USA | 2018 | 2029 |
| United Kingdom | 2018 | 2040 |
| Rome, Italy | 2018 | 2024 |
| Hainan, China | 2018 | 2030 |

Note: data from iCET (Energy and transportation innovation center, 2019).

(Kromer and Heywood, 2007) and proposed banning the sale of new FVs. Table 2 shows the timeline for the implementation of bans on the sale of FVs.

During 2016–2018, many countries proposed a ban on FV sales. The earliest implementation time was in Rome, Italy, in 2024. Other countries focus on the period from 2030 to 2040. In China, Hainan first proposed to ban the sale of FVs from 2030 at a press conference for the Information Office of the State Council. Banning the sale of FVs will inevitably change the proportion of BEVs. To better understand the impact of these bans, this paper analyzes the potential outcomes in terms of changes in material stocks and carbon emissions, with 2035 taken as the time point for the implementation of bans.

As the ratio of EV ownership to vehicle ownership and the ratio of new energy passenger vehicle ownership to passenger vehicle ownership are similar (China Automobile Industry Association, 2021), in this paper we estimate the proportion of EV ownership to obtain the proportion of new energy passenger vehicle ownership. According to the predictions of the China Automobile Association, the sales volume of EVs in China will reach 50% in 2035. By considering the relationship between the proportions of EV sales and EV ownership from 2015 to 2020, this paper infers such a relationship for the future. It is found that the average ratio of the proportion of EV ownership to the proportion of sales in the past 6 years is 0.27. Based on this, two scenarios are set: 1) In the case of NBS (no plan to ban sales of FVs), the proportion of EVs in 2035 will be 13.7%, and 2) in the case of SBS (plan to ban sales of FVs), the proportion of EVs in 2035 will be 27.39%. The proportion of EV ownership from 2021 to 2050 was fitted by a logarithmic function.

Thus, the overall situation can be divided into four scenarios:

1) HS-NBS: high saturation of passenger vehicle ownership and no plan to ban sales of FVs
2) HS-SBS: low saturation of passenger vehicle ownership and plan to ban sales of FVs
3) LS-NBS: low saturation of passenger vehicle ownership and no plan to ban sales of FVs
4) LS-SBS: low saturation of passenger vehicle ownership and plan to ban sales of FVs

When analyzing the recycling potential, we also adopted 2 levels of recycling rate (high recycling rate for HR and low for LR) from Li et al. (2021).

## 2.5 Data source

The population, per capita GDP, and passenger vehicle ownership data in China from 1990 to 2020 used in this paper are from the China Statistical Yearbook (2021). The data of EV ownership and sales volume from 2015 to 2020 are from the public data of the Ministry of Public Security (Ministry of Public Security of the People's Republic of China, 2016) and the China Automobile Industry Yearbook (2021).

According to the research, among the critical minerals specified by the state, Ni, Cr, Co, Li, and REE are very important metals in the development of EVs (Wang et al., 2018; Zhou, et al., 2019). In addition, Mn is often studied as a critical material for automobiles (Olivetti et al., 2017). Among rare earth elements, Ce, Eu, La, Nd, PR, Dy, Gd, TB, and Y are commonly used in EVs (Field et al., 2017). Among them, Ni, Co, Li, and REE are the critical metals in great demand in the development of EVs, while Mn and Cr are the critical metals in great demand in both EVs and FV. At the same time, Ni, Co, Li, Cr, and Mn are characterized by low reserves and high external dependence in China (Ministry of Land and Resources of the People's Republic of China, 2016). Therefore, Ni, Cr, Co, Li, Pt, Mn, and rare earth elements (Ce, Eu, La, Nd, Pr, Dy, Gd, Tb, and Y) were selected as the critical metals in this paper. The specific parameters and sources are shown in Table 3.

TABLE 3 Metal composition of each type of vehicle and potential recycling rate.

| Critical metals | | Metal composition (g) | | Potential recycling rate (%) |
|---|---|---|---|---|
| | | FV | EV | |
| REE | Ce | 0.37 | 0.15 | 35 |
| | Eu | 0.0001 | 0.23 | 51 |
| | La | 0.4 | 7.38 | 17 |
| | Nd | 18.84 | 749.3 | 79 |
| | Pr | 0.08 | 98 | 75 |
| | Dy | 0.48 | 18.73 | 100 |
| | Gd | 0.0005 | 0.17 | 10 |
| | Tb | 0.02 | 26.93 | 56 |
| | Y | 0.13 | 0.41 | 18 |
| | Li | 4.63 | 7709 | 95 |
| | Co | 8.06 | 9330 | 94 |
| | Ni | 2,993 | 55,724 | 99 |
| | Mn | 4,211 | 5,530 | 95 |
| | Cr | 5,566 | 6,031 | 90 |

Source: The metal composition comes from Ortego et al. (2020); the potential recycling rate: REE and Cr from Zuo and Wang. (2020), Co and Ni from Mashael et al. (2021), Mn from Chen and Zhou (2014), and Li from Greim et al. (2020).

Regarding the representative type of EV, at present, BEV and HEV are the main EVs in China. According to the current development of these two vehicles, BEV ownership has accounted for more than 80% of EV ownership in the past 6 years (China Automobile Industry Association, 2021). In addition, according to national policies, at the end of 2018, the China Development and Reform Commission issued the regulations on investment management in the automotive industry, which mentioned that future PHEV investment projects will be approved and filed in accordance with the requirements of FV projects (National Development and Reform Commission, 2018). In addition, relevant subsidy policies for PHEV have been gradually abolished. It can be seen that HEV, as a transitional product, will gradually withdraw from the market, and BEV will further expand in the future. In addition, in terms of the selection of critical metals. This paper selects metals that are indispensable in the development of EV and are currently highly dependent on imports from China, such as Li, Ni, Co. According to the research of Ortego et al. (2020), the single-vehicle metal composition of Li, Ni, and Co in PHEV is 2,242g, 16,049.57g, and 2,712g, which is far lower than 7,709g, 55,724g and 9,330 g of BEV. With the further increase of BEV's market share in EV, the demand for these critical metals will further expand. In order to cover such critical metals, BEV is selected as the representative type of EV in this paper.

Regarding the unit price of recycled resources, we considered the unit price of both primary resource market and secondary resource market from Shanghai Nonferrous Metals Industry Association (2022).

# 3 Result

## 3.1 Passenger vehicle ownership in China

### 3.1.1 GDP per capital forecast

This paper posits that China's economy will grow steadily up to 2050. By fitting the time series data from 1978 to 2020 (constant prices in 1978), the prediction function of GDP per capita in the future is as follows:

$$\boldsymbol{y = 8.1608x^2 - 125.62x + 955.85\ (R^2 = 0.9949)} \quad (7)$$

where variable x ranges from 1 to 73, representing the years 1978–2050.

Figure 3 shows China's GDP per capita from 2021 to 2050 predicted according to GDP per capita from 1978 to 2020.

According to the forecast, the GDP per capita in 2035 will be 17,222 yuan. In 2050, it will be 35,274 yuan, which is almost three times the value in 2020.

### 3.1.2 Population forecast

This paper uses the actual population data of China from 1949 to 2020 by MATLAB programming fitting and predicts the population from 2021 to 2050. The fitting between predicted and actual data is better. According to the fitting data, $r_0$ is 0.035 2, $p_m$ is 166.36 million, and $p_0$ is 54.17 million under unrestricted conditions. Substituting these into Formula 3, we obtain a logistic model of the Chinese population, as follows:

$$P_t = \frac{166362.71}{1 + 2.0713 \times e^{-0.0352t}} \quad (8)$$

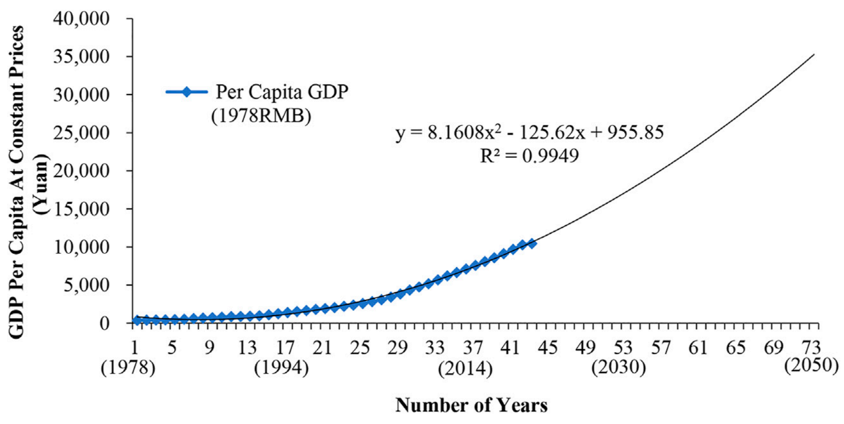


FIGURE 3
Prediction of China's GDP per capita (constant prices in 1978). This study assumes that the GDP per capita will continue to grow within the forecast range.

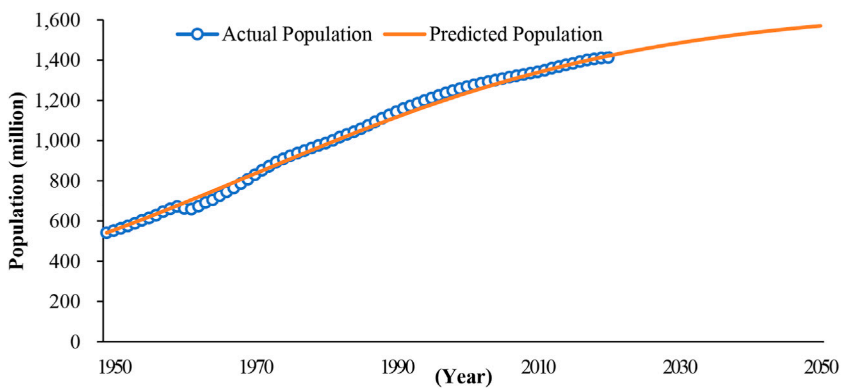


FIGURE 4
Population trends in China. This study will predict that China's population will continue to grow.

The fitting result of Equation 8 is shown in Figure 4.

The population in 2035 and 2050 will be 1,511.45 million and 1,570.32 million, and the growth rates from 2021 to 2035 and 2036 to 2050 will be 5.82 and 3.57%, respectively. Although China's population will continue to grow in the future, the rate will slow down.

### 3.1.3 Prediction of passenger vehicle ownership per thousand people

This paper considers the ownership of passenger vehicles by setting LS and HS scenarios. Table 4 shows the estimation of passenger vehicle ownership per thousand people from 2025 to 2050 under LS and HS scenarios.

### 3.1.4 Prediction of passenger vehicle ownership

Table 5 shows the overall change in passenger vehicle ownership under LS and HS scenarios from 2025 to 2050.

Under the LS scenario, China's passenger vehicle ownership will reach 436.03 million in 2030, increase by 84.53 million in 2040 to reach 520.56 million, and reach 547.50 million in 2050, an increase of 2.05 times compared with 2021. The number of passenger vehicles will reach 623.77 million under the HS scenario in 2050, which is 76.27 million more than that of the LS scenario.

Based on two ownership scenarios, HS and LS, and adding the plan to ban sales of FVs for analysis, four EV and FV ownership scenarios of HS-NBS, HS-SBS, LS-NBS, and LS-SBS can be obtained. Figure 5 shows the changes in EV and FV ownership from 2022 to 2050 under the four scenarios.

Under the HS-NBS scenario, EV ownership will reach 46.48 million, 98.53 million, and 148.27 million in 2030, 2040, and 2050, respectively, while FV ownership will also increase, reaching 475.50 million in 2050. Under HS-SBS, the growth rate of EV ownership is 16.79%, higher than the 13.30% for HS-NBS.

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TABLE 4 Estimation of passenger vehicle ownership per thousand people in China.

| Year | Passenger vehicle ownership per thousand people | |
|---|---|---|
| | LS | HS |
| 2025 | 242 | 254 |
| 2030 | 294 | 318 |
| 2035 | 324 | 359 |
| 2040 | 339 | 382 |
| 2045 | 346 | 393 |
| 2050 | 349 | 397 |
| Parameter/Feature | LS | HS |
| $\alpha$ | 0.0012 | 0.0015 |
| $\beta$ | 0.1205 | 0.1438 |
| $R$ | 0.9990 | 0.9993 |

Under LS and HS scenarios, the number will reach 349 and 397 per thousand people, respectively, in 2050, which is close to the saturation suggested by the two scenarios.

TABLE 5 Estimation of passenger vehicle ownership in China (million).

| Year | LS | HS |
|---|---|---|
| 2025 | 352.45 | 369.56 |
| 2030 | 436.03 | 471.68 |
| 2035 | 489.78 | 542.51 |
| 2040 | 520.56 | 585.47 |
| 2045 | 537.58 | 609.85 |
| 2050 | 547.50 | 623.77 |

Moreover, the peak value of FV advances from 2042 to 2035 for HS-NBS, and peak ownership is reduced from 488.17 million to 402.65 million. EV and FV ownership are slightly lower in the LS scenario than the HS scenario, but the FV peak value will be reached sooner: 364 million in 2034 under LS-SBS vs 432.96 million in 2040 under LS-NBS.

## 3.2 Critical metal stock for passenger vehicles

Table 6 shows the changes in total stocks of critical metals under the four scenarios from 2022 to 2050.

Under the HS-NBS scenario, the total stock of critical metals will reach 18.72 million tons in 2050. Under HS-SBS, the total stock of critical metals will increase rapidly, reaching 29.27 million tons in 2050, showing banning FV sales has a great impact on the stock of critical metals.

The change of a single metal under the four scenarios is similar to that of the total stock. Next, we take a single scenario as an example to analyze the stock of each critical metal. Figure 6 shows the changes in the stock of critical metals under the HS-NBS scenario from 2022 to 2050.

The stock of Li will reach 360.27 thousand, 761.81 thousand, and 1,145.20 thousand tons in 2030, 2040, and 2050, respectively. Similarly, the stock of Co will increase by 76.80 thousand, 161.38 thousand, and 241.97 thousand tons, respectively, compared with 2021, reaching 437.07 thousand, 923.19 thousand, and 1,387.17 thousand tons. The stocks of Mn and Cr will be larger than those of Li and Co, reaching 2,822.26 thousand and 3,540.85 thousand tons, respectively in 2050. Ni is the critical metal with the largest stock. Its stock will be greater in 2030 than in 2050, reaching 9,685.26 thousand tons which is 8.46 times the amount of Li in that year. Due to the diversity and small stock of REEs, nine REEs are analyzed separately. The total stock of REE will be 50.53 thousand, 98.70 thousand, and 143.30 thousand tons in 2030, 2040, and 2050 respectively. Among them, Nd will account for the largest proportion, at 84.77, 84.10, and 83.78% of total REE in 2030, 2040, and 2050, respectively. Next are Dy and Tb, with stocks of 3.01 thousand and 4.00 thousand tons, respectively, in 2050. Eu and Gd account for very little REE, with a stock of only 34.15 and 25.44 tons in 2050.

## 3.3 Estimation of recycling critical metals and their economic value

According to the above analysis, EVs will be widely used in the future, and the supply pressure on critical metals will be huge. On the other hand, EVs will become one of the largest consumers of critical metals, and recycling can be an important source of those critical metals. Therefore, we analyzed the recycling

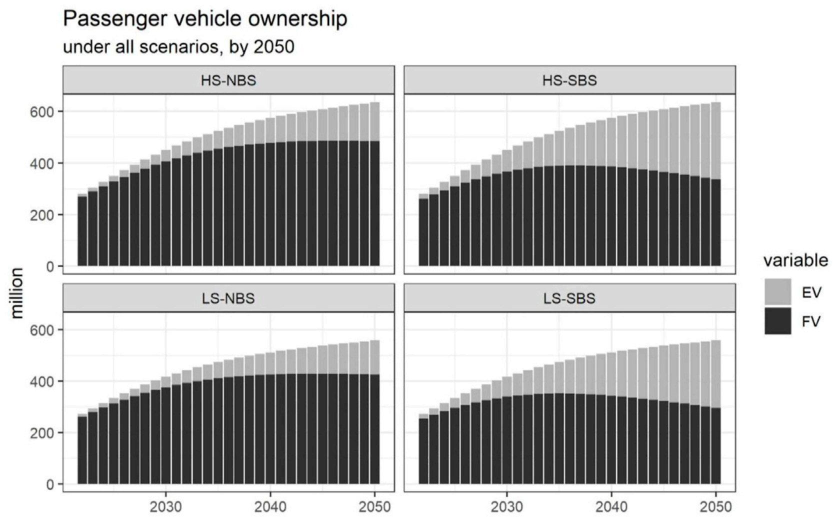


FIGURE 5
Estimation of EV and FV ownership under four scenarios from 2022 to 2050 in China. Under the four scenarios, passenger vehicle ownership continued to rise. The growth rate of the two scenarios under HS is higher than that under LS. FV ownership will reach its peak at different time points under the four scenarios.

TABLE 6 Critical metal stocks under four scenarios from 2022 to 2050 in China (million tons).

| Year | LS-NBS | LS-SBS | HS-NBS | HS-SBS |
|---|---|---|---|---|
| 2022 | 4.60 | 5.21 | 4.73 | 5.36 |
| 2025 | 6.13 | 7.44 | 6.43 | 7.80 |
| 2030 | 8.69 | 11.47 | 9.40 | 12.40 |
| 2035 | 11.00 | 15.42 | 12.19 | 17.08 |
| 2040 | 13.01 | 19.07 | 14.63 | 21.45 |
| 2045 | 14.79 | 22.46 | 16.78 | 25.48 |
| 2050 | 16.43 | 25.69 | 18.72 | 29.27 |

potential of critical metals from EVs. This paper uses the prediction data of the theoretical scrap quantity of electric passenger vehicles in previous research (Li et al., 2021), assuming the scrap electric passenger vehicles are fully recycled. The recycling potential of scrap electric passenger vehicles is shown in Table 7.

According to the current research, the potential recycling rate of Li, Co, Ni, Mn, and Cr is more than 90%, while the recycling rate of REE is low due to the large-scale mining and the need for mature technical support during recycling (Li X. Y. et al., 2019). The lowest recycling rate among REEs is for La, at 17%. Figure 7 shows the recycling quantity of each metal under the HR scenario from 2022 to 2030.

Under the HR scenario, the recycling potential of Li, Co, Mn, and Cr in 2030 is 48.03 thousand, 57.51 thousand, 34.45 thousand, and 35.59 thousand tons, respectively, and the recycling potential of Ni is the highest at 361.77 thousand tons. The overall recycling potential of REEs is not high, only 4.56 thousand tons. Looking at the nine REEs separately, Nd has the highest recycling potential, reaching 2,558.65 tons in 2030, while for GD it is only 0.07 tons.

The results of Section 3.2 show that under the scenario proposed in this study, the policy banning sales of FVs has a greater impact on the supply and demand of critical metals in the future than the ownership of passenger vehicles. In the future, EVs will become one of the largest consumers of critical metals, so they also represent the greatest potential for critical metal recycling in the future. According to the above description, this paper supposes that when an EV owner chooses not to replace the battery and directly scraps the vehicle after 8 years of use, the service life of the EV is consistent with that of the power battery; then the stock of critical metals of EVs in 2030 can be regarded as accumulated from 2022, and the scrap volume corresponds to 2022–2030.

Figure 8 shows the uses the sum of the theoretical amount of critical metals recycled from EOL EVs from 2022 to 2030 to compare with the critical metal stock of EVs in 2030.

It can be observed that under NBS, the recycling potential of Li, Co, Ni, Mn, and Cr in 2030 can cover 49.89, 49.37, 52.00, 49.89, and 47.27% of the stock, respectively. The recycling potential of most REE metals is low; the proportion of Dy covering its stock is the highest, at 41.24%. Gd and La can only cover 4.12 and 7.01% of their stock, respectively. Under the SBS scenario, the recycling potential of all critical metals decreases significantly, with Li, Co, Ni, Mn, and Cr decreasing to 26.38, 26.11, 27.49, 26.38, and 25.00%, respectively.

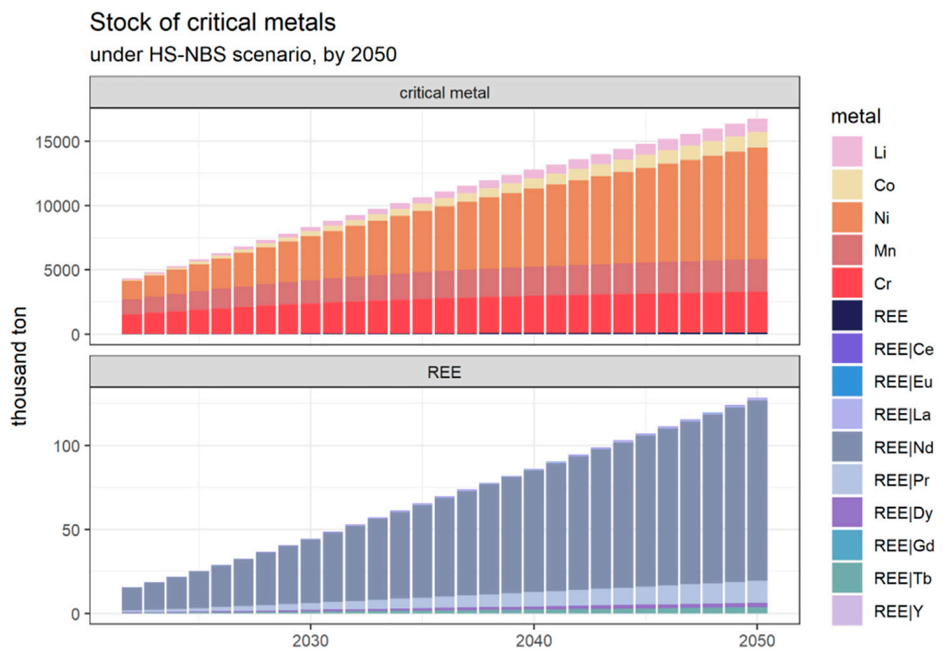


FIGURE 6
Stock of critical metals under HS-NBS scenario from 2022 to 2050 in China (thousand tons): total metal stock and the details in REE. Under the HS-NBS scenario, the stock of each critical metal continues to increase. Since the total REE stock is small, each REE metal details will be shown separately.

TABLE 7 Recycling potential of scrap electric passenger vehicles in China (million).

| Year | LR (minimum) | HR (maximum) |
|---|---|---|
| 2022 | 0.81 | 0.81 |
| 2023 | 1.05 | 1.06 |
| 2024 | 1.27 | 1.29 |
| 2025 | 1.48 | 1.57 |
| 2026 | 1.79 | 2.00 |
| 2027 | 2.22 | 2.67 |
| 2028 | 2.77 | 3.60 |
| 2029 | 3.46 | 4.86 |
| 2030 | 4.32 | 6.56 |

Source: This paper adopts the minimum and maximum data of theoretical scrap quantity of electric passenger vehicles of Li et al. (2021).

Next, we take CO, Ni, Li, and Mn as the object to analyze the recycling value of major critical metals, shown in Table 8.

For critical metals with high prices, the recovery rate has a great impact on the recycling income. For example, in 2030, under the HR scenario, the recycling income from the recycling of Li is 31.46 billion yuan, 10.73 billion yuan more than that of the LR scenario, showing a great economic value. Therefore, recycling critical metals with higher prices can relieve the economic pressure due to the resource imports.

To sum up, this study identifies the critical metals in the electrification transformation of the automobile industry, analyzes the stock changes of critical metals in the automobile industry from 2022 to 2050 under different passenger vehicle ownership saturation levels (LS and HS) and different energy-saving and emission reduction policies (NBS and SBS), and discusses the economic value and maximum recycling potential of critical metals in EV. The results of this study show that from 2022 to 2050, with the increase in income and population, China’s car ownership will increase rapidly, and the number of passenger vehicles in China will reach 547.50–623.77 million in 2050. According to China’s current energy conservation and emission reduction policies, China’s fuel vehicle (FV) ownership will reach a peak in 2042, with 488.17 million. If strict energy conservation and emission reduction policies are adopted, the ownership of FVs will be advanced to 2035, with the ownership of 402.65 million. Under any scenario, FV ownership will show a decreasing trend in the future. The policy banning FV sales will not only rapidly increase EV ownership but also accelerate the FV peaking. The rapid growth of EVs has accelerated the demand for critical metals. Therefore, long-term predictions of critical metals stock can effectively reveal the supply risk of critical metals. In this paper, we have

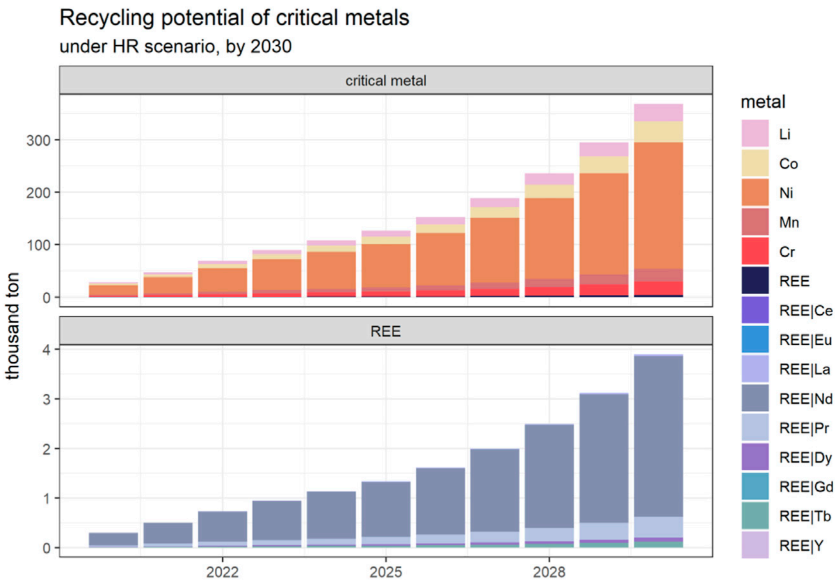


FIGURE 7
Recycling potential of critical metals under HR scenario from 2020 to 2030 in China (thousand tons): total metal recycling and the details in REE. The recycling potential of critical metals in EOL EVa is increasing year by year. HR scenario results based on Li et al. (2021).

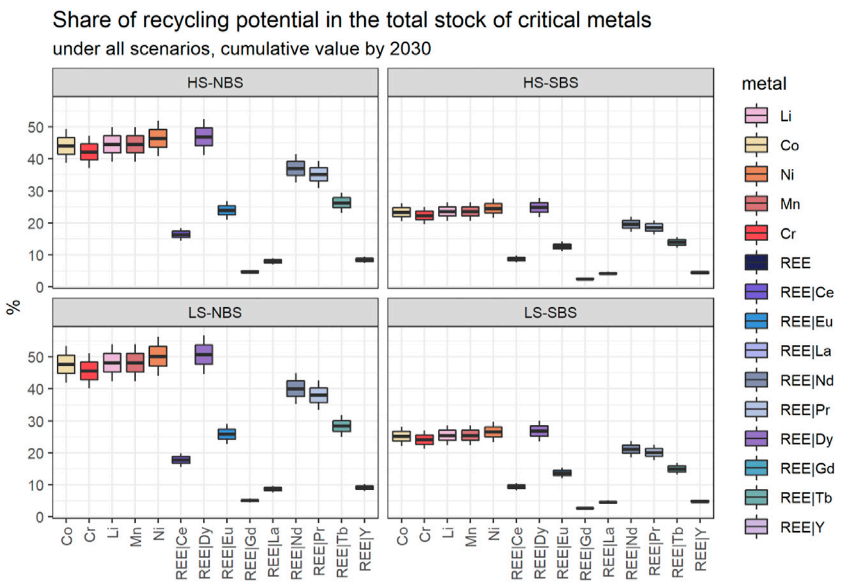


FIGURE 8
Share of recycling potential in the total stock of critical metals in China. Cumulative recycling of critical metals is the sum of theoretical recycling of critical metals of all EOL EVs from 2022 to 2030, and stock is critical metals of EVs in 2030.

identified 14 kinds of critical metals in the electrification transformation of China's automotive industry and estimated the stocks of critical metals under four scenarios from 2022 to 2050. The stock of all critical metals will increase rapidly in the future. Recycling can alleviate the pressure from meeting the supply and demand of critical metals. The stock of Ni will be the highest, which will be 9,685.26 thousand tons in 2050 under the HS-NBS scenario. Recycling can alleviate the

TABLE 8 The economic value of critical metals recycling in 2030 in China.

| Critical metal | Price (yuan/ton) | LR economic value (billion yuan) | HR economic value (billion yuan) |
|---|---|---|---|
| Co | 266,000 | 10.08 | 15.30 |
| Ni | 126,750 | 30.22 | 45.85 |
| Li | 655,000 | 20.73 | 31.46 |
| Mn | 12,750 | 0.29 | 0.44 |

Note: Price data from Li (2021).

pressure from meeting the demand of critical metals with the supply. We have discussed the recycling potential and economic value of critical metals in EVs. For critical metals with a high recycling rate, such as Li, Mn, and Ni, the resource reuse chain can be improved by establishing recycling channels and formulating relevant policies. For metals with a low recycling rate, such as REEs, the demand pressure can be relieved by developing alternative and recycling technologies. The results of this study show the policy banning sales of FVs will expand the gap between theoretical recycling and stock, thus increasing the pressure on the demand for critical metals. Therefore, considering the scarcity of some critical metals, it is necessary to implement a flexible policy for the process of automobile electrification. In order to alleviate the pressure of supply and demand of critical metals, countries have planned the layout in advance according to their own metal scarcity, developing alternative metals and improving recycling technology and recycling channels. The results of this study can provide data basis for material flow analysis in China's automotive industry. It can also be extended to the analysis of material stock and flow in different geographical regions and other industries. The estimation results based on this model can provide a scientific basis for promoting the recycling of material resources.

# 4 Discussion

## 4.1 The strategic risk assessment of critical metals

Global value chains are becoming more integrated and raising questions about trade, technological changes, economic growth, and environmental issues (Umer et al., 2022). The environmental sustainability contests facing the world's most pressing problems, including biodiversity loss, climate change, and increasing natural resources demand (Irfan et al., 2022a; Rehman et al., 2021). Natural resources play a critical part in animating economic expansion and maintaining technical standards (Tang et al., 2022; Irfan et al., 2022b; Islam et al., 2021). Countries with abundant natural resources also have higher wealth sources (Mingting et al., 2022), which will bring more economic advantages (Muhammad and Khan, 2021). Although the environmental impact of globalization is usually negative (Zhang et al., 2022), free markets can also expand access to new technology and increase feedstock supply (Irfan M. et al., 2022). Therefore, the strategic risk assessment of critical metals in the process of automobile electrification should be analyzed from two perspectives. First, from a global perspective, materials with a relatively low recovery rate and great difficulty in recovery for electrical transformation-oriented estimation of critical metals are more important because their recovery cannot alleviate the pressure of future demand. Therefore, material mining and storage should be strengthened. For materials with a high recovery rate and little recovery difficulty, effective recovery channels should be established to realize the multiplier effect of material reuse through resource recycling. In addition, the recovery potential can be improved as the recovery and alternative technologies mature. At present, pyrometallurgical/hydrometallurgical recovery technologies are relatively mature. In the future, high-efficiency composite technology could be used to improve the recovery rate and the efficiency of comprehensive resource utilization. Second, from the national perspective, due to differences in the geographical distribution of critical metals and the development levels of different countries, the strategic risks of critical metals are also different. For example, in 2020, China's Li resource reserves ranked fourth in the world. With the development of EVs, the consumption demand for Li resources is also growing rapidly. China has become the world's largest consumer of Li mineral resources. In 2020, the total consumption of metal Li is 52,000 t in China, accounting for 61.4% of the total global consumption. However, China's current technological constraints lead to the slow process of Li resource mining and industrialization, and 70% of Li resource still depends on imports (Qu et al., 2021). Import dependence is an important factor in assessing supply risk. It helps to assess areas where appropriate intervention is needed to avoid a shift to a predominantly import-dependent scenario.

## 4.2 Resource governance implication

The accelerated transformation of automobile electrification has led to a rapid increase in the demand for critical metals. Affected by multiple factors, such as industrial cycles, the coronavirus, and international tension, there are potential

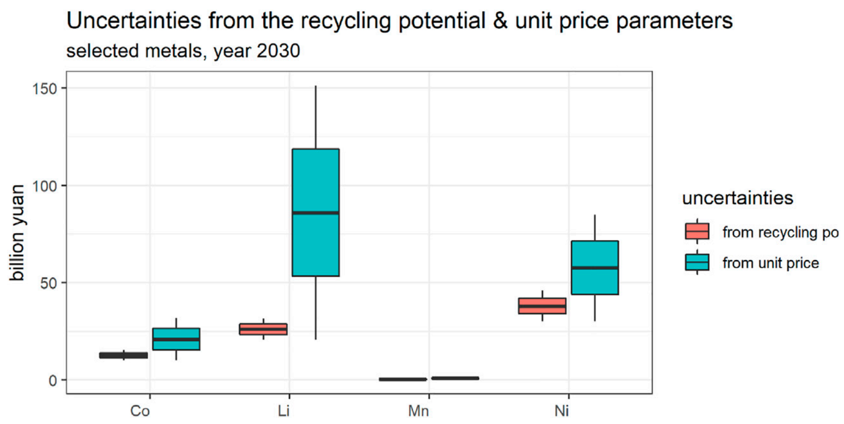


FIGURE 9
Uncertainties from the recycling potential parameters and from unit price parameters.

risks in the supply of critical metals. It is of great significance for the sustainable development of the automobile industry to accurately assess the changes in the stocks of critical metals in the medium and long term and to determine the risks in the supply-demand relationship of critical metals that may be caused by the development of EVs. Based on the importance of recycling to the supply of critical metals, a more perfect industry recycling chain needs to be established. For critical metals with low recycling potential, such as REEs, there is a large gap in cumulative recovery and stock. Although China is currently rich in REEs, very important metals in the electrification of the global automobile industry, it also needs to strengthen its metal reserves and layout in advance to alleviate the demand pressure by developing alternative metals and improving recycling technology. Therefore, different countries and regions should formulate more flexible energy conservation and emission reduction policies according to the scarcity of critical metals to effectively alleviate the pressure created by their supply. For critical metals with relatively high recycling potential, such as Li, Ni, and Co, more effective recycling channels should be established to improve the comprehensive utilization efficiency of renewable resources.

## 4.3 Uncertainties

The first type of uncertainty lies in the parameter recycling rate. The recycling rate in this paper refers to the potential recycling rate, which is the possible recycling degree in the future. Different recycling rate choices will affect the results. Taking the metal Dy as an example, with the development of technology, the potential recycling rate of Dy is high, which can reach 100% (Ciacci, et al., 2015; Zuo and Wang, 2020). However, according to the current recycling technology, the recycling rate of Dy is only 15% (Junne et al., 2020).

We compared the recycling of Dy with the mentioned two recycling rates under LR and HR recovery scenarios. Under the HR scenario, the recycling of 100% Dy will reach 122.83 tons in 2030, while the recycling of 15% Dy will only be 18.42 tons. From 2022 to 2030, the cumulative recycling of 100% Dy accounted for 56.81% of the Dy stock in 2030 under the LS-NBS scenario, while the cumulative recycling of 15% Dy accounted for only 8.52% of the stock. The uncertainty brought by the recycling rate of one specific metal might be huge, also indicating that Dy has great recycling potential with the improvement of recycling technology.

The unit prices of critical metals are also with large fluctuations, which brought uncertainties to our results. If focusing on the primary resource market, the unit prices of Li, Co and Ni are relatively high, especially Li, which reached 2.97 million yuan/ton in June 2022. Most uncertainties come from these four types of metals. Figure 9 shows the uncertainties from the recycling potential parameters and from unit price parameters.

Taking Li as an example, if we adopt the unit price of Li in 2021 as the unit price parameter, the total potential economic value of Li in 2030 may range from 29.78billion to 151.21billion yuan. If focusing on the secondary resource marking, still, taking the example of Li, based on the unit price of the recycled Ni in the 5 months from March 2022 to July 2022, the total potential economic value of Li in 2030 may range from 36.43 billion to 74.13 billion.

# 5 Conclusion

In this study, we set the saturation level of passenger vehicle ownership per thousand people (LS and HS, low and high saturation of passenger vehicles), forecasted passenger vehicle ownership in China from 2022 to 2050 under different saturation levels, and analyzed the impact of policies banning the sale of FVs (NBS and SBS, without and with the ban on the sales of FVs) on EV ownership in the future.

Under the two saturation scenarios, LS and HS, the number of passenger vehicles in China will reach 547.50 million and 623.77 million, respectively, in 2050. During the period from 2022 to 2050, FV ownership will reach a peak regardless of whether sales of FVs are banned or not, but the FV peak will occur significantly earlier under the SBS scenario. A strict energy conservation and emission reduction policy will advance the peak of FV ownership by 7 years, and EV ownership will also increase from 148.27 million to 293.90 million in 2050.

On this basis, the trend of the stock of critical metals from 2022 to 2050 under four scenarios was analyzed. Under the four scenarios, the stock of critical metals shows an upward trend year by year, among which that of HS-SBS is the largest. Under the HS-NBS scenario, the stock of critical metals such as Li, Co, and Ni will reach 1,145.20 thousand, 1,387.17 thousand, and 9,685.26 thousand tons, respectively, in 2050. The implementation of policies strictly banning the sale of FVs will lead to a rapid rise in the stock of critical metals. Under the HS-SBS scenario, the stock of critical metals such as Li, Co, and Ni will reach 2,267.18 thousand, 2,744.71 thousand, and 17,364.44 thousand tons, respectively. The results show that the massive popularization of EVs in the future will bring huge demand pressure on critical metals.

On the other hand, EVs, the largest consumers of critical metals, also represent the maximum potential for recycling critical metals in the future. This study thus further discusses the economic value of and maximum recovery potential for critical metal recycled from EOL EVs. It is found that recycling critical metals are an effective means to avoid the risk of a reduced critical metal supply. At the same time, the economic benefit brought by the metals with higher recycling prices would also be significant.

This paper can be further improved in the following two aspects. First, due to the availability of data, this study only analyzes the major critical metals with greater supply risk in the future automotive electrification transformation process. For example, as one of the critical materials, platinum group metals have not been included in the analysis object in this paper, as China's vigorous promotion of EVs will reduce the use of platinum group metals in the future. As the next step, we will investigate the supply risk and recovery potential of platinum group metals considering such adjustments in policies and regulations. Second, this study is based on the current material composition, which could be changed with the technical development. Traditional fuel vehicles will be gradually withdrawn from the market between 2030 and 2040 in many developed automobile industrial countries. The supply of critical metals will become a bottleneck problem restricting the electrification transformation of the global automobile industry in the future. We also consider expanding the research from China to more countries in the future, especially focusing on the advanced automotive technical standards and policies of developed countries, to verify the applicability of this study.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

LY and JY conceived of the study. LYh, LY, HS, and SL conducted the empirical analysis. LY and JY produced figures. LY, LYh, HS, SL, and JY wrote the manuscript, which is edited and approved by all the authors.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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# Reducing agricultural nitrogen use: A price endogenous partial equilibrium analysis in the Yangtze River Basin, China

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The overuse of nitrogen fertilizers in agricultural production in China, resulting in negative impacts on the environment, has become a serious issue. Thus, reducing agricultural nitrogen use has become one of the top priorities for achieving the sustainable development goals of the Chinese agricultural sector. Searching for effective approaches to reduce nitrogen use is essential to agricultural and environmental sustainability. In this study, we selected the Yangtze River Basin as the research area, owing to its critical role in Chinese agricultural production, and established a price endogenous partial equilibrium model to simulate the effect of nitrogen use reduction from nitrogen use optimization (NUO) and nitrogen use efficiency improvement (NUE+). Based on agricultural datasets in 2019, simulation results revealed that 1) NUO helped reduce nitrogen use and nitrogen loss by 6.99% and 7.50%, respectively; if changes in the acreage are considered, then the reduction effect will be less significant; 2) nitrogen use decreased continuously with NUE+, and the reduction rate was 7.85%, 15.38%, 22.65%, and 28.02% under the NUE+10%, NUE+20%, NUE+30%, and NUE+40% scenarios, respectively, and nitrogen loss was highly sensitive; and 3) the crop heterogeneity indicated that cereals are regarded as nitrogen-overuse crops and more sensitive to nitrogen use reduction under the NUE+ scenarios than oil crops. Accordingly, in this study, we suggested that practical NUO and NUE+ policies and incentives are necessary, and flexible adjustment strategies for crop-planting structures, such as enlarging the acreage for cereals, may be useful in reducing nitrogen use in the Yangtze River Basin.

KEYWORDS

**nitrogen use, nitrogen loss, the Yangtze River Basin, price endogenous partial equilibrium, crop heterogeneity**

# 1 Introduction

Nitrogen (N) is an essential nutrient for crops and one of the basic elements comprising living creatures (Houlton et al., 2019; Sun et al., 2020). As a major component of fertilizers, N has become the most important material input in global food production. Over the past decades, demand for N fertilizers increased rapidly, owing to the growing population (Liu et al., 2013; Ladha et al., 2016). However, agricultural N use has exceeded sustainable limits, causing massive environmental problems such as surface water eutrophication, groundwater nitrate enrichment, and greenhouse gas emissions (Wu and Chen, 2013; Keisman et al., 2018). As the most populous country in the world, China has exerted considerable effort to guarantee the supply of agricultural products since the early 1980s. During the last 40 years, China's total grain output increased by over 70%, whereas fertilizer use, especially N fertilizers, more than doubled. Currently, China consumes 27% of global N fertilizers and accounts for the highest quantity of N loss in the world. Therefore, N use reduction is one of China's priorities to achieve its sustainable development goals in agriculture (Jiao et al., 2018; Jin et al., 2021). According to the second national pollution census in 2020, 46.5% of the total N loss comes from agricultural sources, which rises to over 75% in the Yangtze River Basin (Wang et al., 2010; Liu et al., 2020).

Regarding the complexity of N absorption and utilization in agriculture, the optimization of management practices and increase in the nitrogen use efficiency (NUE) are regarded as the best solutions to global N challenges (Houlton et al., 2019). In agricultural production, only the N element absorbed by crops is believed to be effective, and the other elements are treated as emissions (Wei et al., 2011; Xie et al., 2018). From an economic perspective, the emitted N elements can be reduced without any yield loss; thus, efficiency terms may be evaluated by the ratio of output/input and divided by technical, allocative, and scale efficiencies (Jollands, 2006; Kros et al., 2013; Xiao et al., 2019). China's NUE was 21.6%–26.5% in the past decades, which is much lower than that of the EU and other developed countries, and N losses were estimated at 18.5%–24.7%, which is one-third higher than the global average (Zhang et al., 2015; Wang et al., 2020; Sun et al., 2020). To date, most existing studies focused on estimating NUE or identifying individual effects of specific management practices, such as the adoption of new cultivars or technologies (Zhang et al., 2015; Xiao et al., 2019; Liu et al., 2020), for instance, split N fertilization can significantly increase the N element absorption levels of crops from chemical fertilizers, thereby increasing NUE to 37.5% for 2-splits and 40% for 3-splits (Wang et al., 2010). Integrated soil–crop system management and slow-release fertilization would save around 20% of N fertilizer input and improve NUE by 5%–10%, in practice (Zhang et al., 2015). N nanofertilizers are also expected to improve NUE by increasing N delivery effectiveness in fields (Mejias et al., 2021). However, very few studies paid sufficient attention to reversed effects of NUE changes on N use and loss reduction, especially under a systematic framework of analysis covering multiple N management practices in agriculture. Additionally, empirical research in the context of the YRB, which contributes about 30% to China's total arable land and agricultural output each year, is lacking. Furthermore, the problem of agricultural N loss in China is far worse than the average situation.

Thus, we select the YRB as our study area. In addition, we consider seven main crops (i.e., rice, wheat, maize, soybean, peanut, rapeseed, and potato) that contribute more than 70% to Chinese agricultural production and are widely planted across the YRB and other regions in our analysis. Next, we employ a price endogenous partial equilibrium model (PEPEM) as a systematic framework to analyze the comprehensive effects on N use and N loss under different conditions. The overall objectives of our study are as follows: to assess the effects of N use reduction from nitrogen use optimization (NUO) and NUE improvement (NUE+), reveal the heterogeneity among the crops, and propose efficient policy recommendations for decision-makers for reducing N use and N loss in the YRB. Compared with previous studies, our study contributes to the literature in at least two ways. First, we evaluate reversed influences from NUE+ on N use rather than impacts of N use or other factors on NUE changes, which are widely discussed in the literature. Second, taking seven main crops for the analysis, we reveal crop heterogeneity in N use reduction.

The rest of this study is organized as follows: Section 2 introduces the study area; Section 3 details the model structure, data sources, and designed scenarios; Section 4 provides the simulation results under the designed scenarios and a discussion; Section 5 presents the conclusions and policy implications.

## 1.2 Study area

The Yangtze River, with a length of 6,300 km, is the third longest river in the world and the longest in China and Asia. The YRB is defined as the wide area where the trunk stream and tributaries of the Yangtze River run through (Figure 1). The trunk stream runs through 11 provinces, namely, Qinghai, Tibet, Sichuan, Yunnan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, and Shanghai, and the tributaries extend the basin to eight other provinces, namely, Guizhou, Gansu, Shaanxi, Henan, Zhejiang, Guangxi, Guangdong, and Fujian. The YRB is located at 24°30'~35°45′N, 90°33'~122°25′E, covering an area of 1.8 million $km^2$ and accounting for 18.8% of China's total land area.

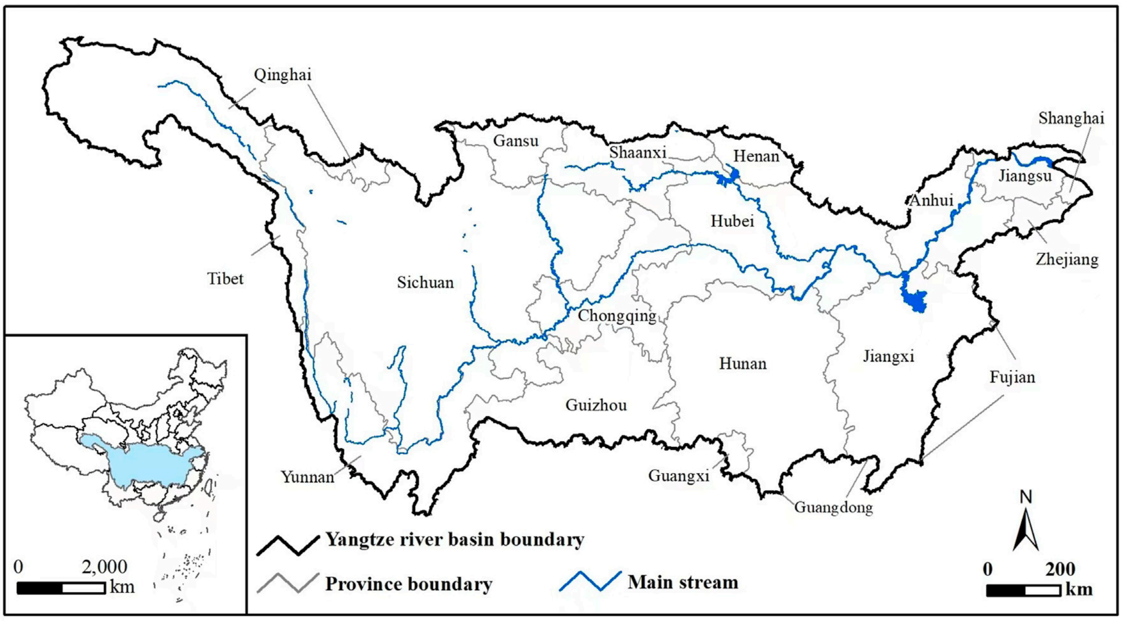


FIGURE 1
Location of the YRB.

TABLE 1 Overview of agricultural production in the YRB.

| | Acreage (million ha) | Output (million t) | Yield (t/ha) |
|---|---|---|---|
| Rice | 15.217 | 107.756 | 7.081 |
| | (50.40%) | (50.80%) | |
| Wheat | 5.647 | 27.475 | 4.865 |
| | (23.27%) | (20.90%) | |
| Maize | 6.189 | 32.914 | 5.318 |
| | (14.69%) | (12.80%) | |
| Soybean | 1.580 | 3.086 | 1.953 |
| | (18.78%) | (19.33%) | |
| Peanut | 1.191 | 3.935 | 3.304 |
| | (25.74%) | (22.70%) | |
| Rapeseed | 4.786 | 9.600 | 2.006 |
| | (73.08%) | (72.29%) | |
| Potato | 2.118 | 7.741 | 3.655 |
| | (42.86%) | (41.38%) | |
| Average | 36.728 | 192.508 | 5.241 |
| | (30.32%) | (28.90%) | |

[a]Notes: % in parentheses refers to the proportion in the overall quantity in China.
[b]Data are derived from the 2019 statistical yearbook.

With a humid subtropical climate, the YRB has extreme hydrothermal conditions for agriculture, contributing 30.32% and 28.9% to China's total arable land and agricultural output, respectively, in terms of the seven main crops of the country (Table 1). Specifically, the YRB contributes over half of the domestic rice supply and over 70% of rapeseed production in China.

# 2 Methodology

## 2.1 Model construction

To evaluate the impact of agricultural N use and loss reduction in the YRB from NUO and NUE+, we developed a multi-regional and multiproduct PEPEM. Based on the nonlinear mathematical programming approach, the PEPEM stands for the framework of partial equilibrium analysis to agriculture, which is widely used to reveal the impact of external policies on agricultural production and environmental performance (McCarl and Spreen, 1980; Beach and McCarl, 2010). Compared with general equilibrium models, the PEPEM endogenously determines market equilibrium prices and quantities by maximizing the surplus in the market, thereby demonstrating higher model structure flexibility and simulation accuracy (Yi et al., 2018; Ma et al., 2022).

In this study, we established the PEPEM to investigate the changes in agricultural N use under NUO scenarios and different NUE levels. We took seven main crops for the analysis and treated the 18 provinces in the YRB as the multiple regions in the model. Each region has different agricultural features, such as farming systems, arable acreages, labor forces, and other resource constraints. Meanwhile, the PEPEM has three basic assumptions: 1) the domestic agricultural market is integrated such that all products can be traded and transported freely across regions; 2) the domestic agricultural product supply is sufficient, and imports and exports remain stable; 3) agricultural producers are completely rational and, thus, can maximize social welfare by autonomously allocating production inputs. Based on the agricultural features of the regions and basic PEPEM assumptions, we constructed the research model as follows:

### 2.1.1 Objective function

$$Max\ WELF = \sum_{c} \int P_c^d\left(X_c^d,\ \omega_c\right) dX_c^d - \sum_{c,i} NC_{ci} - \sum_{c,i} EFC_{ci} - \sum_{c,i} WC_{ci} - \sum_{c,i} tc_{ci} * X_{ci}^s - \sum_{c} \times \int P_c^{im}\left(QA_c^{im}\right) dQA_c^{im} + \sum_{c} \int P_c^{ex} QA_c^{ex} dQA_c^{ex}, \tag{1}$$

where $WELF$ is the total social welfare of the agricultural sector in the YRB; $p_c^d\left(X_c^d,\ \omega_c\right)$ is the inverse demand function; c is the crop varieties; $X_c^d$ is the annual agricultural product demand for crop c; $NC_{ci}$ is the total cost of N fertilizers for crop c in region i; $EFC_{ci}$ denotes the total cost of all other fertilizers, except N fertilizers, for crop c in region i; $WC_{ci}$ is the total water cost of crop c in region i; $tc_{ci}$ is the production cost per unit output of crop c in region i, excluding the cost of nitrogen fertilizers and water; $X_{ci}^s$ is the annual supply of crop c in region i; $QA_c^{im}$ and $QA_c^{ex}$ are the annual import and export quantities of the agricultural products between the YRB and external market, respectively; $P_c^{im}$ and $P_c^{ex}$ are trading prices.

### 2.1.2 Constraints

a. Supply–demand balance

$$X_c^d + EX_C \le \sum_i X_{ci}^s + IM_C. \tag{2}$$

Eq. 2 expresses the market supply–demand balance of the crops, where $X_c^d$ refers to the demand for crop c within the YRB, $X_{ci}^s$ is the supply of crop c in region i, and $EX_C$ and $IM_C$ are the export and import quantities of crop c in the YRB, respectively. The total demand shall be no higher than the total supply.

$$\sum Y_{ci} * L_{ci} \ge X_{ci}^s. \tag{3}$$

Eq. 3 restricts the total production of crop c in the YRB to equal to or higher than the total supply, where $Y_{ci}$ is the yield of crop c per hectare, and $L_{ci}$ is the planting acreage of crop c in region i.b. Land use constraints

$$L_i = \sum \tau_i * h_{ci} + \sum \gamma_i * s_{ci}, \tag{4}$$

$$\sum \tau_i + \sum \gamma_i \le 1, \tag{5}$$

where $L_i$ is the planting acreage in region i, $h_{ci}$ is the historical planting acreage of crop c in region i, $s_{ci}$ is the maximum feasible planting area of crop c in region i, and $\tau$ and $\gamma$ are the weights of the planting acreage determined endogenously. The sum of the weights should not be higher than 1. Eqs. 4, 5 implicitly reflect the technological, management, and policy constraints of planting acreages by using the concave crop combination constraints within the limits of historical acreage observations (Chen and Onal, 2012).c. Irrigation constraints

$$\sum_c L_{ci} W_{cit} \le W_{it}, \tag{6}$$

where $W_{cit}$ is the amount of water used for the irrigation of crop c in region i for period t, and $W_{it}$ is the amount of water supply available for agricultural use in region i for period t. Eq. 6 indicates that the amount of water used for irrigation should not be more than the available water supply in the same period.d. Production function form

$$Y_{ci} = Y_{ci}\left(N_{ci}, W_{ci}; \theta_{ci}, \mu_{ci}\right), \tag{7}$$

where $Y_{ci}$ is the yield level of crop c in region i. Eq. 7 indicates that the crop yield is related to N use ($N_{ci}$) and the water supply ($W_{ci}$), where $\theta_{ci}$ and $\mu_{ci}$ are the prices of N fertilizers and irrigation water per hectare, respectively, for crop c in region i, corresponding to each fertilization scheme.

### 2.1.3 N loss estimation

Unabsorbed N elements will enter groundwater through surface runoffs and leaching, forming N loss and causing nonpoint agricultural and environmental pollution. Quantifying the N loss is important in analyzing the environmental influence of N use. In existing studies, N loss was estimated with the coefficient of N loss in farmlands. Following Ti et al. (2011) and Xia et al. (2018), we calculated the N loss estimation in this study as follows:

TABLE 2 Statistical and simulated values of the main crops in the YRB.

| | Acreage (million ha) | | Output (million t) | | Price (CNY/kg) | |
|---|---|---|---|---|---|---|
| | Statistical | Simulated | Statistical | Simulated | Statistical | Simulated |
| Rice | 15.217 | 15.363 (0.96%) | 107.757 | 109.367 (1.49%) | 2.59 | 2.64 (1.92%) |
| Wheat | 5.647 | 5.620 (−0.48%) | 27.474 | 27.474 (0.00%) | 2.22 | 2.22 (0.00%) |
| Maize | 6.189 | 6.189 (0.00%) | 32.914 | 32.914 (0.00%) | 1.75 | 1.75 (0.00%) |
| Soybean | 1.580 | 1.566 (−0.94%) | 3.086 | 3.087 (0.02%) | 3.84 | 3.84 (0.00%) |
| Peanut | 1.191 | 1.155 (−2.95%) | 3.936 | 4.067 (3.33%) | 5.70 | 5.84 (2.45%) |
| Rapeseed | 4.786 | 4.600 (−3.88%) | 9.601 | 9.601 (0.00%) | 5.23 | 5.23 (0.00%) |
| Potato | 2.118 | 2.057 (−2.90%) | 7.740 | 7.741 (0.01%) | 1.56 | 1.56 (0.00%) |
| Average | 36.728 | 36.550 (−0.48%) | 192.508 | 194.251 (0.91%) | – | – |

Notes: % in parentheses refers to the variations between the simulated and statistical values.

$$NL = \sum [(ro_{ci} + le_{ci})/ae_{ci}]*N_{ci}*L_{ci}, \quad (8)$$

where $NL$ refers to the N loss estimation, $ro_{ci}$ and $le_{ci}$ are the runoff- and leaching-induced N loss rates of crop c in region I, respectively, and $ae_{ci}$ is the NUE level hypothesized in advance.

## 2.2 Data

We divided the required data into three parts, namely, supply (production), demand (consumption), and related coefficients. We derived the crops' planting acreages and yields from the 2019 statistical yearbook of each province in the YRB. In addition, we collected the quantities and prices of agricultural inputs, such as the labor force, N fertilizers (including N fertilizers, non-N fertilizers, and compound fertilizers), pesticides, agricultural films, and irrigation water, from the Compilation of Cost and Benefit National Agricultural Products (2019). In this study, we defined N use as the sum of N fertilizers and compound fertilizers multiplied by their N weight. We estimated demand for the major agricultural products using the BRIC Agricultural Database from the perspective of feeding, industrial use, seeding, and wastage, according to the approaches proposed by Xue and Zhang (2019). Finally, we obtained the demand elasticities of the different crops fromWang et al. (2020)and N loss coefficients from Ti et al. (2011).

## 2.3 Model calibration

To verify the validity of the PEPEM, we first calibrated the data derived from the statistical materials, including acreages, outputs, and prices of the seven main crops in the YRB (Table 2). Based on the calibrations, we determined that the variations between the simulated and statistical values fell within 4%, indicating that the PEPEM can accurately simulate the production systems in the YRB. Hence, the model can be further used in the simulation analysis.

## 2.4 Scenario design

To compare the changes in N use and loss under different conditions, we designed the following scenarios:

### 2.4.1 Baseline (BL)

Based on the statistical data derived from the 2019 yearbook, we inserted calibrated values into the PEPEM simulation, which we used as the BL scenario in this study.

### 2.4.2 NUO

If technological conditions are given, the relationship between the crop yield and N use should fit the quadratic curve, that is, the yield will first increase if the N input is insufficient, whereas if N is overused, the yield curve will turn to decrease. Therefore, to achieve the maximum total social

TABLE 3 Agricultural production under the NUO scenarios and BL.

| | Acreage (million ha) | | Output (million t) | | Yield (t/ha) | |
|---|---|---|---|---|---|---|
| | BL | NUO | BL | NUO | BL | NUO |
| Rice | 15.363 | 14.681 (−4.44%) | 109.367 | 110.559 (1.09%) | 7.119 | 7.531 (5.79%) |
| Wheat | 5.620 | 5.358 (−4.66%) | 27.475 | 30.008 (9.22%) | 4.889 | 5.600 (5.79%) |
| Maize | 6.189 | 4.947 (−20.07%) | 32.914 | 32.914 (0.00%) | 5.319 | 6.653 (25.08%) |
| Soybean | 1.565 | 1.572 (0.45%) | 3.087 | 3.087 (0.00%) | 1.972 | 1.964 (−0.41%) |
| Peanut | 1.155 | 1.160 (0.43%) | 4.067 | 3.968 (−2.43%) | 3.519 | 3.422 (−2.76%) |
| Rapeseed | 4.600 | 4.311 (−6.28%) | 9.601 | 9.807 (2.15%) | 2.087 | 2.275 (9.01%) |
| Potato | 2.057 | 1.792 (−12.88%) | 7.741 | 7.741 (0.00%) | 3.764 | 4.321 (14.80%) |
| Average | 36.549 | 33.820 (−7.47%) | 194.251 | 198.084 (1.97%) | 5.315 | 5.857 (10.20%) |

Notes: % in parentheses refers to the variations between the NUO scenarios and BL.

welfare of the agricultural sector, we treated N use as an endogenous decision variable in the PEPEM. Meanwhile, we estimated the yield–N use relationship of the crops through the quadratic regression of the statistical data for the period of 2009–2018.

### 2.4.3 NUE+

NUE+, which is generally induced by agricultural technology advancement, will likely affect N use in agricultural production (Chen et al., 2014; Cui et al., 2018). In this regard, we designed four NUE+ scenarios, denoted as NUE+10%, NUE+20%, NUE+30%, and NUE+40%, to simulate N use and loss outcomes when NUE is increased by 10%–40%. In terms of the analysis of the integrated effects, the NUE + scenarios should simplify the comprehensive influences of different technologies or management applications.

## 3 Results and discussion

We performed the PEPEM simulations under different scenarios by GAMS 33.2.

### 3.1 NUO

The simulation results of agricultural production under NUO and BL are presented in Table 3.

According to the overall results, NUO increased the total agricultural output by 1.97% and simultaneously saved 7.47% of the arable land in the YRB, resulting in a 10.2% growth in the integrated yield level. The grain crops, including rice, wheat, maize, and potato, shared the same variation trend in the overall results of the BL and NUO scenarios. Specifically, the maize production considerably benefitted from NUO, which decreased the maize acreage by up to 20% and induced a 25% yield growth. By contrast, the variation trends in the production of soybean and peanut, which are the main oil crops in the YRB, are not consistent with the overall results, and the changes in the acreage and yield of the two oil crops were inconspicuous (less than 0.5% and 3%, respectively) compared with those of the rapeseed and grain crops.

Table 3 shows a rough comparison of the impact of NUO on the different crops, especially between the grain and oil crops. To further investigate the benefits of NUO, Table 4 presents the N use and N loss simulations at the total quantity and per unit levels. Apparently, NUO reduced N use and N loss in the YRB by 6.99% and 7.50%, respectively. Among the seven crops, rapeseed contributed the most to the N use (0.212 million t) and N loss (0.034 million t) reduction. If NUO is employed, we can see that nearly two-fifths of N use can be saved in the rapeseed production. With regard to the grain crops, over 5%, 9%, and 3% of N use and N loss were reduced under NUO in the rice, wheat, and maize production, respectively. However, it should be noted that N use and N loss increased in the soybean and peanut production. With an 18.92% and 14.52% growth in N use, the

TABLE 4 N use and N loss under the NUO scenarios and BL.

| | N use (million t) | | N loss (million t) | | N use (t/ha) | | N loss (t/ha) | |
|---|---|---|---|---|---|---|---|---|
| | BL | NUO | BL | NUO | BL | NUO | BL | NUO |
| Rice | 2.476 | 2.347 (−5.21%) | 0.208 | 0.197 (−5.29%) | 0.161 | 0.160 (−0.62%) | 0.0135 | 0.0134 (−0.81%) |
| Wheat | 0.999 | 0.907 (−9.21%) | 0.161 | 0.146 (−9.32%) | 0.178 | 0.169 (−5.06%) | 0.0286 | 0.0273 (−4.68%) |
| Maize | 1.154 | 1.118 (−3.12%) | 0.186 | 0.180 (−3.23%) | 0.186 | 0.226 (21.51%) | 0.0300 | 0.0364 (21.26%) |
| Soybean | 0.037 | 0.044 (18.92%) | 0.005 | 0.007 (16.67%) | 0.025 | 0.028 (12.00%) | 0.0038 | 0.0045 (16.67%) |
| Peanut | 0.124 | 0.142 (14.52%) | 0.020 | 0.023 (15.00%) | 0.107 | 0.122 (14.02%) | 0.0172 | 0.0197 (14.39%) |
| Rapeseed | 0.555 | 0.343 (−38.20%) | 0.089 | 0.055 (−38.20%) | 0.121 | 0.080 (−33.88%) | 0.0194 | 0.0128 (−34.09%) |
| Potato | 0.499 | 0.514 (3.01%) | 0.080 | 0.083 (3.75%) | 0.243 | 0.287 (18.11%) | 0.0391 | 0.0462 (18.25%) |
| Average | 5.822 | 5.415 (−6.99%) | 0.747 | 0.691 (−7.50%) | 0.159 | 0.160 (0.51%) | 0.0204 | 0.0204 (−0.05%) |

Notes: % in parentheses refers to the variations between the NUO scenarios and BL.

two oil crops led to a 16.67% and 15.00% N loss, respectively. Such numbers reached 3% in potato production. One possible explanation for these results is that N may be overused in the rapeseed and grain crop production in the YRB; thus, reducing N use will likely improve crop yields. By contrast, N use in the soybean and peanut production was insufficient, and inputting increased N fertilizers is beneficial to derive high output. Another explanation may be that soybean and peanut are leguminous crops, which require much more external N elements than cereals. In this regard, inputting increased N elements through fertilizer utilization may be an effective approach for meeting the N demand for crop growth and improving the yield level.

NUO can help reduce N use and N loss in the total quantity; however, if the changes in crop acreages are considered, then the reduction effect from NUO will seem to disappear at the per unit level. The changes in N use and N loss per hectare in the YRB were limited under the NUO scenarios and in BL, in which the variation rates were only 0.51% and 0.05%. Similarly, N use and N loss per hectare in rice production decreased by 0.62% and 0.81%, respectively, indicating that the reduction was mostly from the acreage changes. However, among the other crops, the variation rates remained significant. For instance, NUO reduced N use and N loss by 33.88% and 34.09% per hectare in rapeseed production, respectively, and by 5.06% and 4.68% in wheat production, respectively. Most of the changes in N use and N loss per hectare in the crops were moderately less than those in the total quantity, except for two crops, namely, maize and potato. Although they were reduced by around 3% in the total quantity, the simulated N use and N loss in maize production increased by over 25% per hectare. As for potato production, the increasing rates reached 18%, which is more than five times the total quantity. In this sense, we may reconsider whether N elements are overused in maize and potato production at present in the YRB and regard the two crops as N use insufficient crops similar to soybean and peanut.

## 3.2 NUE+

Based on the NUO simulations, we evaluated the influences of the different NUE levels. As the changes in agricultural production were less than 0.1%, we placed the simulation production results under the NUE + scenarios in Supplementary Table S1. The N use and N loss results of the main crops in the YRB under the four NUE+ scenarios, as well as the NUO results for comparison, are presented in Table 5.

Overall, N use and N loss in the YRB decreased continuously with NUE+, as expected. Compared with the NUO results, N use dropped from 5.415 million t to 3.898 million t (NUE+40%), and the reduction rates were 7.85%, 15.38%, 22.65%, and 28.02% under the four NUE + scenarios. N loss seemed to be highly sensitive to NUE+, decreasing from 0.691 million t to 0.356 million t, with reduction rates of 8.41%, 29.20%,

TABLE 5 N use and N loss under the NUE+ scenarios (million t).

| | NUO | | NUE+10% | | NUE+20% | | NUE+30% | | NUE+40% | |
|---|---|---|---|---|---|---|---|---|---|---|
| | use | loss | use | loss | use | loss | use | loss | use | loss |
| Rice | 2.347 | 0.197 | 2.135<br>(−9.03%) | 0.179<br>(−9.03%) | 1.958<br>(−16.56%) | 0.137<br>(−30.47%) | 1.808<br>(−22.95%) | 0.117<br>(−40.73%) | 1.680<br>(−28.42%) | 0.101<br>(−48.87%) |
| Wheat | 0.907 | 0.146 | 0.830<br>(−8.55%) | 0.134<br>(−8.56%) | 0.765<br>(−15.76%) | 0.103<br>(−29.80%) | 0.709<br>(−21.91%) | 0.088<br>(−39.93%) | 0.660<br>(−27.22%) | 0.076<br>(−48.02%) |
| Maize | 1.118 | 0.180 | 1.018<br>(−8.99%) | 0.164<br>(−8.94%) | 0.934<br>(−16.49%) | 0.125<br>(−30.41%) | 0.863<br>(−22.84%) | 0.107<br>(−40.65%) | 0.802<br>(−28.30%) | 0.092<br>(−48.79%) |
| Soybean | 0.044 | 0.007 | 0.040<br>(−8.98%) | 0.006<br>(−8.57%) | 0.037<br>(−16.49%) | 0.005<br>(−30.41%) | 0.034<br>(−22.85%) | 0.004<br>(−40.65%) | 0.032<br>(−28.30%) | 0.004<br>(−48.79%) |
| Peanut | 0.142 | 0.023 | 0.129<br>(−9.04%) | 0.021<br>(−9.17%) | 0.119<br>(−16.58%) | 0.016<br>(−30.49%) | 0.109<br>(−22.97%) | 0.014<br>(−40.75%) | 0.102<br>(−28.45%) | 0.012<br>(−48.89%) |
| Rapeseed | 0.343 | 0.055 | 0.330<br>(−3.74%) | 0.054<br>(−3.08%) | 0.300<br>(−12.37%) | 0.046<br>(−17.26%) | 0.267<br>(−22.05%) | 0.033<br>(−40.04%) | 0.249<br>(−27.39%) | 0.029<br>(−48.13%) |
| Potato | 0.514 | 0.083 | 0.469<br>(−8.82%) | 0.076<br>(−8.82%) | 0.431<br>(−16.21%) | 0.058<br>(−30.17%) | 0.398<br>(−22.49%) | 0.049<br>(−40.38%) | 0.374<br>(−27.28%) | 0.043<br>(−48.06%) |
| Average | 5.415 | 0.691 | 4.990<br>(−7.85%) | 0.633<br>(−8.41%) | 4.582<br>(−15.38%) | 0.489<br>(−29.20%) | 4.188<br>(−22.65%) | 0.412<br>(−40.44%) | 3.898<br>(−28.02%) | 0.356<br>(−48.52%) |

Notes: % in parentheses refers to the variations between the NUO and NUE+ scenarios.

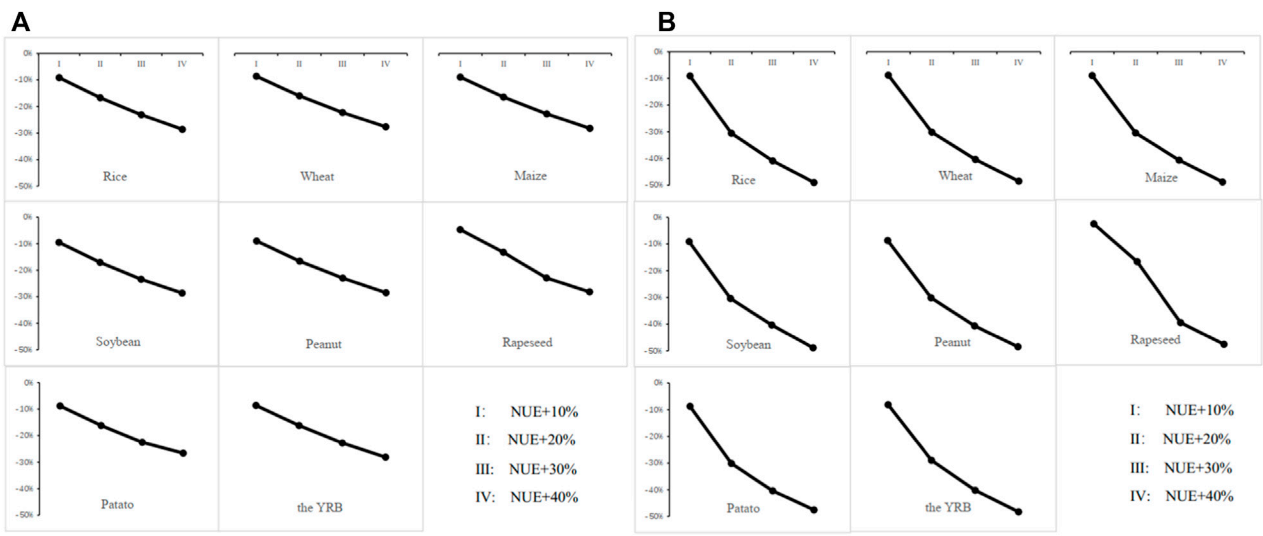


FIGURE 2
N use and N loss reduction rates (t/ha) in crops under the NUE + scenarios.

40.44%, and 48.52%. N use fell slightly with every 10% NUE+, whereas N loss dropped rapidly between NUE+10% and NUE+20%.

Most of the crops shared the same decreasing trend, that is, an N use (loss) reduction by around 9% (9%), 16% (30%), 22% (40%), and 28% (48%) under the four NUE + scenarios. Among the crops, rapeseed was the exception, whose reduction rate was 3.74% and 12.37% under the NUE+10% and NUE+20% scenarios, respectively, which are lower than the average rates. However, in the NUE+30% and NUE+40% scenarios, the N use and N loss reduction rates in rapeseed production returned to the average level and caught up with those of the other crops. Therefore, a larger jump existed in the N use (loss) in rapeseed between the interval of NUE+20% and NUE+30% than in the other crops. To clearly present the variation trends, the N use and N loss reduction rates of the seven main crops in the YRB under the four NUE + scenarios are illustrated in Figure 2A,B. The rates calculated in the figures considered the changes in the crop acreage. In this context, the curves in Figure 2 represent the N use and N loss trends at the per unit level.

According to Figure 2A, the N use (t/ha) of all the crops decreased gradually along with NUE+, except for rapeseed, whose reduction rates were smaller than those of the others under the NUE+10% and NUE+20% scenarios. N loss (t/ha) showed a slight difference, that is, its curves dropped quicker than those of N use, especially under the NUE+20% scenario. Similarly, rapeseed was the only exception, which demonstrated a quick drop under the NUE+30% scenario.

## 4 Discussion

In this study, we conducted a partial equilibrium analysis to evaluate the changes in N use and N loss instead of using econometric approaches. Unlike most studies, which used regression models to identify the influences of specific technologies and other driving forces (Zhao et al., 2012; Zhang et al., 2015; Liu et al., 2020), in our study, we used NUO scenarios to represent integrated effects. Additionally, we designed NUE+ scenarios. Previous studies estimated NUE with statistical data, site–year observations, and field plot surveys (Ma et al., 2014; Gu et al., 2017; Cui et al., 2018). In our study, we simplified this issue by hypothesizing a 10%–40% NUE growth to represent NUE+ or agricultural (technological) development instead of calculating time-serious NUEs. In addition, we constructed a reversed influence channel from NUE + to N use and N loss instead of examining the common impacts of N use or other forces on NUE changes, as in most existing studies.

We selected the YRB as the study area because of its critical role in China's agricultural sector, which contributes about 30% to the agricultural output and over half of the rice production in China. Moreover, we considered seven main crops, namely, rice, wheat, maize, soybean, peanut, rapeseed, and potato. Some studies focused on one crop, such as rice (Ma et al., 2014), wheat (Liu et al., 2020), or staple grains (Cui et al., 2018). Another stream of literature reports assessed integrated N use in agriculture (Gu et al., 2017; Wu et al., 2018; Sun et al., 2020). Contributing to the literature, our study compared the differences between the seven main crops and revealed the sufficiency of N use for each crop, as well as N use and N loss reduction rates under NUE + scenarios. In this study, we emphasized the heterogeneity among the crops and simulated N loss and revealed the sensitivity gap between the N use and N loss reduction effects.

Despite the highlights or contributions mentioned previously, our study has several limitations. First, the partial equilibrium model can be classified as a static simulation analysis method. Long-period information on crops' production is yet to be included, and prediction analysis is unavailable in the current framework. However, although the model covered multiple regions in the YRB, regional heterogeneity is yet to be investigated, owing to the data limitations for each region and data-induced simulation bias.

## 5 Conclusions

By employing the multi-region multiproduct price endogenous partial equilibrium analysis framework, in this study, we developed a PEPEM to analyze the impacts of NUO and NUE + on agricultural N use and N loss in the YRB. The simulation results indicated that 1) NUO increased the average yield level in the YRB by 10.2% and helped reduce N use and N loss in most of the crops, except for soybean and peanut; 2) N use in the YRB decreased continuously with NUE+, as expected, with the reduction rates of 7.85%, 15.38%, 22.65%, and 28.02% under the NUE+10%, NUE+20%, NUE+30%, and NUE+40% scenarios, respectively, and N loss was highly sensitive; 3) most of the crops shared the same decreasing trend, that is, N use (loss) was reduced by around 9% (9%), 16% (30%), 22% (40%), and 28% (48%) under the four NUE + scenarios, except rapeseed, whose reduction rates were around 4% and 12% under the first two scenarios; and 4) if the changes in the crop acreage are considered, then the reduction effects of NUO and NUE + will seem insignificant.

Overall, our study provides several insights into N use and N loss reduction in the YRB. First, NUO and NUE + are useful in agricultural N management. Specifically, a high level of NUE can increase N use and N loss reduction rates, thereby suggesting that NUO and NUE + policies and incentives are inevitable. In terms of heterogeneity among the different crops, another policy implication is related to the adjustment of the crops' planting structure in the YRB. Enlarging cultivated areas for cereals, rather than oil crops such as soybean, peanut, and rapeseed, may be effective in reducing N use and N loss if NUE increases continually. In future studies, the PEPEM, which is a static model, should be reconstructed into a dynamic model through mathematical recursive methods, which would enable the model to incorporate multiperiod datasets in simulations. However, in future studies, we will further evaluate the regional heterogeneity or crop heterogeneity in each region based on detailed datasets and a dynamic PEPEM.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

## Author contributions

SY: writing—reviewing and editing, formal analysis, and visualization; SF: writing the original draft, data collection, and software; CT: conceptualization and visualization; YM: conceptualization, writing—reviewing and editing, supervision, and funding acquisition.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.994023/full#supplementary-material

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# Study on spatial-temporal characteristics and influencing factors of urban environmental resource efficiency in the Yangtze River Basin of China

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There is a close relationship between environmental resource efficiency and the high-quality development of the river basin economy. Improving urban environmental resource efficiency is of great significance to the high-quality development of the river basin. Based on the environmental panel data of cities in the Yangtze River Basin from 2004 to 2020, this paper applies the DEA-Malmquist index model to explore the static characteristics and dynamic changes in the overall environmental resource efficiency of cities in the Yangtze River Basin. Then, the spatial and temporal aspects of the environment are discussed by combining the kernel density function method. The Tobit regression model is used to analyze the factors affecting the environmental resource efficiency of cities in the Yangtze River Basin and its importance. Finally, the grey prediction model is utilized to predict the undesirable output data of cities in the Yangtze River Basin from 2023 to 2025. The results show that the overall urban environmental resource efficiency level in the Yangtze River Basin is high. However, the number of cities that achieve DEA efficiency is less than that of non-DEA efficient cities. The Total Factor Productivity (TFP) of cities shows a "high-low-high" trend, and the technical efficiency change (Effch) and pure technical efficiency change (Pech) have an improvement trend. Industrial structure, regional factors, and openness are positively correlated with environmental resource efficiency, during the economic scale and environmental governance level negatively moderate environmental resource efficiency. The forecast results show that the undesired output of cities in the Yangtze River Basin has been somewhat controlled.

KEYWORDS
**Yangtze river basin, urban environmental resource efficiency, DEA Malmquist model, tobit regression model, Kernel density estimation method, grey prediction model**

## 1 Introduction

Environmental resource efficiency refers to the ratio of the consumption of resources and the environment in the process of economic production to the value of economic output. Calculating and analyzing environmental resource efficiency can make relevant departments take timely measures to effectively utilize resources to reduce consumption, improve productivity, and better satisfy the requirements of high-quality regional development. As an important indicator to evaluate whether a city meets the high-quality development standards, urban environmental resource efficiency has become the focus of urban research. The Yangtze River is the largest river in China. It originates from Tanggula Mountain and flows into the East China Sea. The mainstream of the Yangtze River has a total length of more than 6300 km and a water area of more than 1.8 million square kilometers, accounting for 18.8% of China's space, and flows through 11 provinces (autonomous regions and municipalities directly under the central government). It is an important region connecting east and west China, with solid ecological status, tremendous strength, and excellent development potential. Cities in the Yangtze River Basin were built and prospered by water. They are interdependent and interact with each other. The resident population accounts for about 32% of China's population, and the total economy covers 34% of the country. It is an essential guarantee for China's ecosystem. Based on ecological efficiency, the evaluation of urban environmental resource efficiency is to explore the loss of energy resources and the impact on the environment caused by the creation of specific production value in the city to measure the coordination level between urban economic development and the environment (Lin et al., 2021).

Up to now, scholars have proposed many research methods with theoretical and practical value in the evaluation of environmental efficiencies, such as the Laspeyres index decomposition method (Ebohon and Ikeme, 2006: Hu et al., 2016; Lu et al., 2015), TOPSIS model (Shih et al., 2007; Kaya and Kahraman, 2011; Jia et al., 2012), life cycle assessment method (Jolliet et al., 2003; Gulnur et al., 2016; Eichner and Elsharawy 2020), and ecological footprint method (Holden and Hoyer 2005; Venetoulis and Talberth, 2008; Lu et al., 2022). These evaluation methods evaluate the quality of the urban ecological environment based on the efficiency level of single or multiple environmental pressure indicators. Among them, the efficiency measurement based on a single environmental pressure indicator cannot reflect the comprehensiveness and complexity of the economic production process. Although the efficiency measurement based on multiple pressure indicators includes the various impacts of economic production on resources and the environment, it fails to consider the correlation and non-replication of different resources and environmental pressures in economic activities. Therefore, most studies constructed DEA with undesirable outputs and its modified model to evaluate the relative effectiveness of urban environmental resource efficiency. That is, the relative production efficiency of an inspected unit is measured in comparison with other units. (Gao and Wang, 2022). calculated and compared the environmental resource efficiency of 31 key provinces, districts, and cities in China based on the Four-stage DEA model and found that at least seven pilot provinces, districts, and cities did not meet the environmental resource efficiency standards. Yang (2019) used the Three-stage DEA-Malmquist model to analyze the important economic factors affecting the cities in Beijing-Tianjin-Hebei and the Yangtze River Delta regions. The results showed that economic openness was most conducive to improving urban economic efficiency. The "SBM-DEA" model constructed by (Tang and Wang, 2021) was used to study the environmental resource efficiency of 11 prefecture-level cities in Shanxi Province from 2014 to 2019. It was found that the ecological efficiency of Shanxi Province was increasing, but the overall efficiency was low. Zhou et al. (2021) applied the DEA model to evaluate China's regional energy investment and socio-economic and environmental performance index quantitatively. They concluded that there were significant differences in energy and environmental resource efficiency in different regions of China. Yang et al. (2015) calculated China's inter-provincial environmental resource efficiency from 2000 to 2010 through the DEA model. The results showed noticeable regional differences in environmental resource efficiency in China, and the environmental resource efficiency level of the eastern coastal provinces was better. (Carboni and Russu, 2017). used the DEA model to quantitatively analyze cities' economic growth rate and environmental development efficiency in 20 pilot regions of Italy from 2004 to 2011 and found significant differences between the northern and southern regions. Based on the Three-stage DEA model, Jing et al. (2020) analyzed the temporal and spatial characteristics of eco-environmental resource efficiency and the main factors affecting the regional environment in critical regions of China at this stage. It was found that the level of environmental resource efficiency in different regions of China was mainly affected by the difference between Pure Technical Efficiency (PTE) and Scale Efficiency (SE), and there were significant differences in the spatial distribution or regional level. (Tao and Li, 2017). Wielded the DEA model to calculate the environmental resource efficiency of 28 central inland provinces and cities in China in 2014 and further established and improved the analysis model of critical factors affecting the efficiency of regional environmental investment in China by the Grey Correlation Analysis method.

From the existing literature, the relevant research mainly analyzed urban environmental resource efficiency from qualitative and quantitative aspects. From the content point of view, the quantitative research on regional and national urban environmental performance is more detailed (Qin., 2019; Ding and Lin, 2021; Lin et al., 2022). Nevertheless, most of them take

China's provinces as the research objects (Wang and Zhu 2018; Peng and He 2020; Xu et al., 2021). And little attention has been paid to calculating environmental resource efficiency in the river basin. Even the research on the environmental resource efficiency of the whole Yangtze River basin is basically in the blank stage. From the perspective of the method, the DEA evaluation method is widely used by scholars. However, few works of literature use DEA-Malmquist, nuclear density model, Tobit model, and grey prediction model GM (1,1) to comprehensively study basin cities from static, dynamic, evolution process and characteristics, influencing factors, prediction, and other aspects. Based on this, the paper is committed to using appropriate methods to answer the following questions:

(Q1) How about the static and dynamic environmental resource efficiency of cities in the Yangtze River Basin?
(Q2) What are the overall evolution process and characteristics of urban environmental resource efficiency in the Yangtze River Basin?
(Q3) What are the restraining and driving factors of urban environmental resource efficiency in the Yangtze River Basin?
(Q4) What are the predicted results of industrial wastewater and industrial SO2 emissions of cities in the Yangtze River Basin in the next 3 years?

This paper selects the panel data of 38 prefecture-level cities in the Yangtze River Basin from 2004 to 2020. For (Q1), the paper makes static and dynamic analyses of the environmental efficiency of each prefecture-level city in the Yangtze River Basin using the DEA Malmquist model. For (Q2), the kernel density function is used to analyze the overall evolution characteristics of the basin's urban resource and environmental efficiency. For (Q3), the tobit regression analysis method is used to establish the corresponding ecological effect factors and analyze the influencing factors and direction of urban environmental resources in the Yangtze River Basin. For (Q4), the grey prediction model predicts the unexpected output results of the basin cities in the next 3 years.

The contributions of this study to the existing literature include: (1) Since the Yangtze River has a wide range of basins, and specific geographical and environmental characteristics, taking the cities in the Yangtze River Basin as the research object is better than the regional research of administrative division. (2) This paper takes 38 node cities in the Yangtze River Basin as the research object. Compared with the study of provinces in the basin, the study of spatial resource differences between cities can better reflect the spatial pattern of resource and environmental efficiency in the Yangtze River Basin. (3) The paper's research period is extended, making the research conclusions and suggestions more accurate and persuasive. (4) Relevant research is often carried out only on efficiency and influencing factors. This paper analyzes the static efficiency, dynamic efficiency, space-time evolution process and characteristics, influencing factors, and prediction. The research content is more extensive, concluding more targeted.

# 2 Method and data

## 2.1 Overview of the study area

In 2016, the Chinese government issued the "Outline of the Yangtze River Economic Belt Development Plan," which established a new development pattern for the Yangtze River economic belt. In the outline, there are 108 crucial prefecture-level cities in China's Yangtze River Basin Economic Belt (Lei et al., 2022; Shi and Bai 2022), including 39 core node cities in the basin (Wu, 2014; Zhao et al., 2022.). These cities have highlighted the agglomeration of regional economic resource elements and the characteristics of radiation and drive. Therefore, this paper selects 38 node cities in the Yangtze River Basin Economic Belt except Enshi City as the research object (the lack of data caused by the administrative division of Enshi City is excluded from the study), The specific cities and their provinces are shown in Table 1.

## 2.2 Methods

### 2.2.1 DEA model

This paper mainly studies the efficiency of the urban environment. DEA is an effective method in the study of efficiency. It is a planning model to evaluate the efficiency of evaluation objects. It is used to evaluate the non-parametric method with the same type of multi-input and multi-output decision unit (DMU). Since Charnes et al. (1979) proposed the DEA method in 1979, it has been widely used and developed rapidly. DEA model includes radial model and non-radial model. The BCC (variable returns to scale) model is a radial model as follows:

$$\begin{aligned}&\min \epsilon\\&s.t.\sum_{i=1}^{n}\lambda_i x_i + s^- = \epsilon X_i\\&\sum_{i=1}^{n}\lambda_i Y_i - S^+ = Y_i\\&\lambda_i \geq 0, s^- \geq 0, s^+ \geq 0\\&\sum_{i=1}^{n}\lambda_i = 1\end{aligned} \tag{1}$$

In the formula: $X$, $Y$, and $n$ represent input, output, and the number of decision units, respectively. $\varepsilon$, $\lambda$ express the efficiency and index combination coefficient of DMU. Slack variable $s^-$ and residual variable $s^+$ reflect low output and redundant input. When $\varepsilon = 1$ indicates DEA efficiency, otherwise DEA is invalid. According to the Total Efficiency (TE) and pure technical efficiency (PTE), the scale efficiency (SE) can be obtained, and the relationship between the three is SE = TE/PTE.

TABLE 1 Urban distribution in the Yangtze River Basin.

| — | |
|---|---|
| Municipality | Shanghai, Chongqing |
| Jiangsu | Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, Taizhou |
| Zhejiang | Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing, Zhoushan |
| Anhui | Hefei, Wuhu, Maanshan, Tongling, Anqing, Huangshan, Chizhou |
| Jiangxi | Nanchang, Jiujiang |
| Hubei | Wuhan, Huangshi, Yichang, Xiangyang, Ezhou, Jingzhou, Huanggang, Xianning |
| Hunan | Yueyang |
| Sichuan | Chengdu, Panzhihua, Luzhou, Yibin |

In the evaluation process of urban environmental resource efficiency, TE reflects whether the maximum output of environmental governance effect can be achieved under the given input conditions of environmental factors or the minimum input of environmental factors under the given output level. It is a comprehensive evaluation of capital, technology, and human resources. PTE represents the impact of scientific management decision-making methods on environmental resource efficiency. SE embodies whether cities' input in environmental management is redundant or insufficient, which is the gap between the actual and optimal scales (Li and Jing, 2021).

### 2.2.2 Malmquist index

The DEA model can only reflect the static efficiency of urban environmental management, and the Malmquist index can well reflect the dynamic change of efficiency, so an efficiency evaluation and analysis method based on the combination of static and dynamic DEA-Malmquist is formed.

The Malmquist index is used to measure the productivity changes in the two periods before and after the calculation. The results are expressed as Total Factor Productivity (TFP). This value shows that the total productivity of each factor in the production system can be decomposed into two parts: Technical Progress Efficiency (Techch) and Technical Efficiency (Effch). Technical Efficiency (Effch) can be further decomposed into Pure Technical Efficiency (Pech) and Scale efficiency (Sech), as shown in Eq. 2:

$$TFP = Techch \times Effch = Techch \times Pech \times Sech \tag{2}$$

$TFP > 1$ indicates that TFP has improved; TFP deteriorates when $TFP < 1$.

### 2.2.3 Kernel density estimation method

The kernel density curve can be obtained using the kernel density estimation method to estimate the environmental resource efficiency. By analyzing the changes in the distribution pattern, kurtosis, and location of the curve, we can see the historical dynamic evolution characteristics of the urban environmental resource efficiency index in the Yangtze River Basin. The kernel density function is as follows (Tong et al., 2018; Wang et al., 2019; Yang and Deng, 2019):

$$\widehat{f}_h(x) = \frac{1}{n}\sum_{i=1}^{n} K_h(x - x_i) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \tag{3}$$

In the formula: $x_1, x_2 \cdots, x_i$ are an independent distribution of $n$ sample points; $K(x)$ is a kernel function; the value of bandwidth $h$ has a direct impact on the smoothing degree of the kernel density curve.

### 2.2.4 Tobit regression model

The Tobit model, also known as the sample selection model, is a model whose dependent variable satisfies certain constraints. Based on this model, the influencing factors model of urban resource and environmental resource efficiency in the Yangtze River Basin is constructed, which can quantitatively analyze the influence of various factors on urban resource and environmental resource efficiency. Its basic form is as follows (Wang and Liu, 2019):

$$\begin{aligned} y_i^* &= x_i\beta + \mu \\ y_i &= \begin{cases} 0 & if \quad y_i^* < 0 \\ y_i^* & if \quad y_i^* > 0 \end{cases} \end{aligned} \tag{4}$$

In the formula: $x_i$ is the explanatory variable, $y_i$ is the explained variable, $\beta$ is the regression coefficient, and $\mu$ is a perturbation.

### 2.2.5 Grey prediction model

GM (1,1) grey prediction is a short-term prediction method based on a small amount of data. The modeling process is as follows:

1) The sequence $x^1 = \{x_1^1, x_2^1, \ldots, x_N^1\}$ can be obtained by accumulating the original data column $x^0 = \{x_1^0, x_2^0, \ldots, x_N^0\}$.
2) The difference equation model $\frac{dx^1}{dt} + ax^1 = u$ is established for $x^1$, and the following expression can be obtained after solving:

$$x_{k+1}^1 = \left(x^1, -\frac{u}{a}\right)e^{-ak} + \frac{u}{a} \tag{5}$$

3) The following equations are constructed by using the existing samples, and the least square method is used to solve the parameters $a$, $u$ to be estimated to obtain $\hat{a}$, $\hat{u}$. Then, it is substituted back to Equation 5, and Equation 5 can be used for prediction (Xu and Li, 2020).

$$\begin{bmatrix} x_2^0 \\ x_3^0 \\ \cdots \\ x_N^0 \end{bmatrix} = \begin{bmatrix} -0.5(x_1^1 + x_2^1) & 1 \\ -0.5(x_2^1 + x_3^1) & 1 \\ \cdots\cdots & \\ -0.5(x_{N-1}^1 + x_N^1) & 1 \end{bmatrix} \begin{bmatrix} a \\ u \end{bmatrix} \tag{6}$$

## 2.3 Index system construction

Since urban environmental resource efficiency emphasizes the unity of economic value and environmental benefits, the minimum input resource consumption produces the maximum economic benefits. Therefore, constructing the evaluation index system of urban resource and environmental efficiency in the Yangtze River basin covers three aspects: resources, environment, and economy.

Output factors are divided into two categories, expected output and unexpected output. In terms of expected output, referring to existing studies (Gai et al., 2014; Chen et al., 2015; Zhou et al., 2019; Huang et al., 2020), the urban GDP that can best reflect the level of urban economic output is selected as the expected output index to measure the economic development expectations of local cities. In terms of unexpected output, there is great flexibility in selecting unexpected output indicators. Cheng and Li (2009) selected wastewater, waste gas, and solid waste as unexpected output, and Tu (2008) selected $SO_2$ as unexpected output Wang et al. (2010). $SO_2$ and COD are selected as unexpected outputs. Hu et al. (2008) selected five indicators as unexpected output: wastewater, total discharge of industrial solid waste, total discharge of COD, $SO_2$, and $SO_2$. Considering that industrial $SO_2$ and industrial wastewater are the primary pollutants, which are relatively representative, and each city's industrial $SO_2$ and wastewater discharge data are relatively complete, this paper selects the industrial $SO_2$ discharge and industrial wastewater discharge of each city as the unexpected output.

Regarding input factors, capital, energy, and labor are the main factors of urban resource and environment input. Referring to Zeng and Niu (2019), this paper uses Total investment in fixed assets, Number of end-of-period employees, and Total electricity consumption to represent the capital investment, labor investment, and energy investment among the input factors, respectively. In actual production, Total investment in fixed assets includes all kinds of urban investment, which can best reflect the urban capital investment as an input index. The Number of urban employees includes the number of people in all three industries, which is the most representative of urban labor input. This paper takes energy as the primary source of unexpected output into the input index. On the one hand, China's thermal power generation is still the main form of power generation. The $SO_2$ produced by burning fossil fuels in thermal power generation accounts for a large proportion of the country's total $SO_2$ emissions. On the other hand, electric energy is also the leading energy for industrial operation, so Total electricity consumption is the most closely related to unexpected output. The specific index system is shown in Table 2.

According to the index data, this paper calculates the total values of the above six indicators from 2004 to 2020. It draws a line chart to reflect the changes of each indicator over time, as shown in Figure 1.

According to Figure 1, in terms of investment, total investment in fixed assets, number of end-of-period employees, and total electricity consumption in 38 prefecture-level cities in the Yangtze River Basin. In the early stage, it was in a state of rapid growth. After 2017, the growth rate slowed, but it is still in the growth trend. In terms of output, with time, the regional GDP of 38 prefecture-level cities in the Yangtze River Basin has maintained a high-speed growth in the past 17 years, while industrial $SO_2$ emissions and industrial wastewater discharge have shown a downward trend. It indicates that the Yangtze River Basin has achieved rapid economic development and changed its ecological environment protection, realizing protection in growth and development in protection. This conclusion is consistent with the research conclusion of Zhou et al. (2021) on the changes in the ecological environment in the Yangtze River Economic Belt in the recent 20 years.

## 2.4 Source of data

In this paper, all the data come from the "China Urban Statistical Yearbook", "China Environmental Statistical Yearbook", and the official annual statistical bulletin issued by municipal statistical bureaus.

# 3 Empirical study

## 3.1 Environmental resource efficiency analysis

### 3.1.1 Static analysis

According to the BCC model with variable returns to scale in the DEA model, the spatial distribution of the average TE, PTE, and SE of cities in the Yangtze River Basin in 2004, 2008, 2012, 2017, and 2020 is visualized by ArcGIS10.8 software. (Figure 2).

In Figure 2A, the average TE over the 5 years of cities in the Yangtze River Basin is above 0.5. Except that the TE of Nanchang is between 0.5 and 0.6, the other cities are above 0.6. The TE values of Wuxi, Suzhou, and Yibin all reach the DEA effective state. This conclusion is consistent with Qu (2018) and Hua et al. (2018). It can be seen that these cities have relatively perfect measures in environmental governance, which is in line with the coordinated development of the city's economy and environmental protection and is worthy of reference by other cities. From a regional perspective, many cities have high TE in the lower reaches of the Yangtze River, which is consistent with the research conclusion of Wang and Zhu (2022). The upper and middle reaches of the Yangtze River, Chongqing and Wuhan with high levels of urban economic development have not reached optimal efficiency. In contrast, Yibin and Yueyang have high efficiency, indicating no definite linear relationship

TABLE 2 Urban environmental resource efficiency evaluation index system.

| Index | Category | Metric name | Unit |
|---|---|---|---|
| Input | Capital input | Total investment in fixed assets | Ten Thousand Yuan |
| | Workforce | Number of end-of-period employees | Ten Thousand Person |
| | Energy elements | Total electricity consumption | kwh |
| Output | Expect output | Regional GDP | Ten Thousand Yuan |
| | Unexpected output | Industrial $SO_2$ emissions | Ton |
| | | Industrial wastewater discharge | Ten kilo-ton |

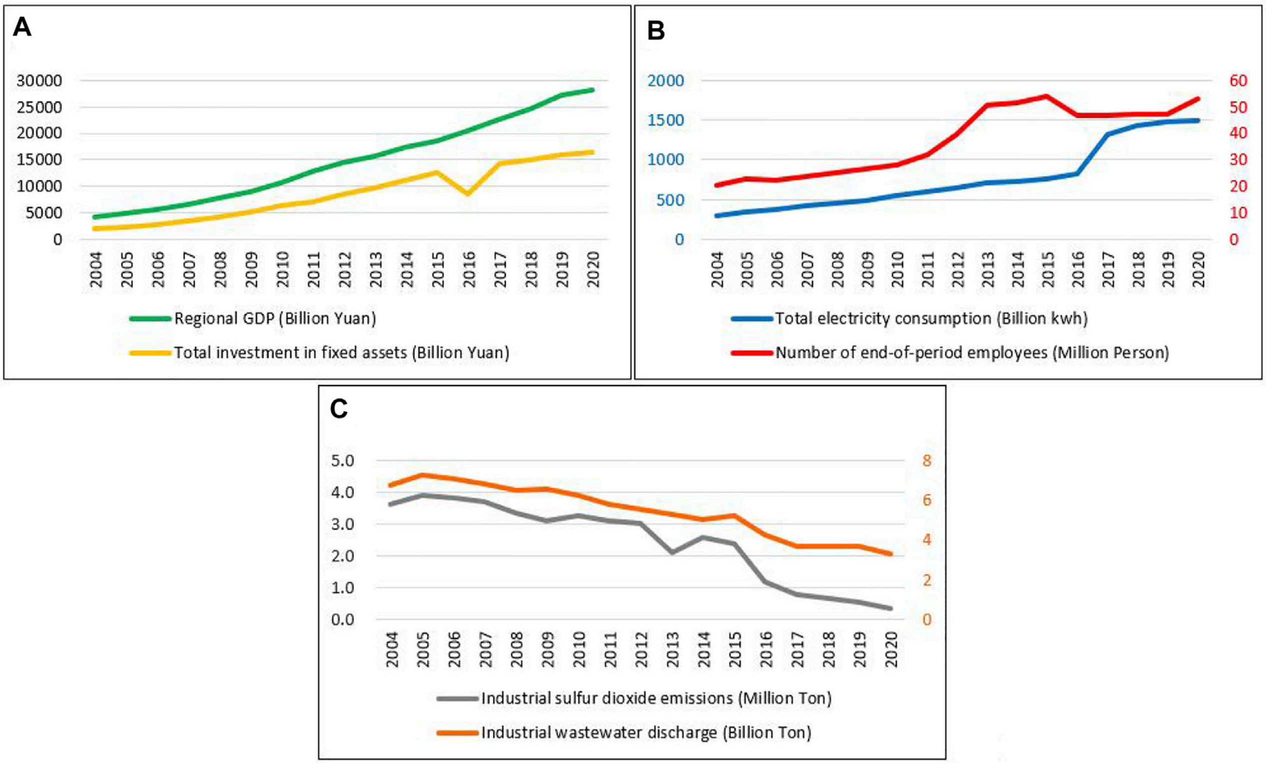


FIGURE 1
Descriptive statistics of each indicator. **(A)** Regional GDP and Total investment in fixed assets; **(B)** Total electricity consumption and Number of employees; **(C)** Industrial wastewater discharge and Industrial $SO_2$ emissions.

between the level of urban economic development and urban environmental efficiency.

As shown in Figure 2B, the number of cities with the best PTE exceeds that of cities with generally low production and scale efficiency, indicating that most cities in the Yangtze River Basin have high technical levels, strong management ability, and reasonable management methods. The number of prefecture-level cities whose PTE reaches DEA efficiency is 20, 23, 20, 18 and 20 respectively, accounting for 52.63%, 60.53%, 52.63%, 47.37 % and 52.63%. Overall, the average PTE is above 0.6, showing that the utilization rate of technical factors in prefecture-level cities is high. The 5-year PTE values of Shanghai, Wuxi, Suzhou, Maanshan, Huangshan, Chizhou, Chongqing, Panzhihua, and Yibin have reached an effective state. The average PTE in the upper reaches of the Yangtze River is generally higher than 0.9, while most cities in the middle reaches of the Yangtze River are between 0.8 and 0.9. For example, Nanchang, Yichang, Hefei, Jiujiang, Anqing, and Ezhou, Huangshi, which are relatively dependent on resources and energy as the leading industries, use the extended development model to support rapid economic growth. Still, the level of urban resource utilization and environmental governance technology needs to be improved.

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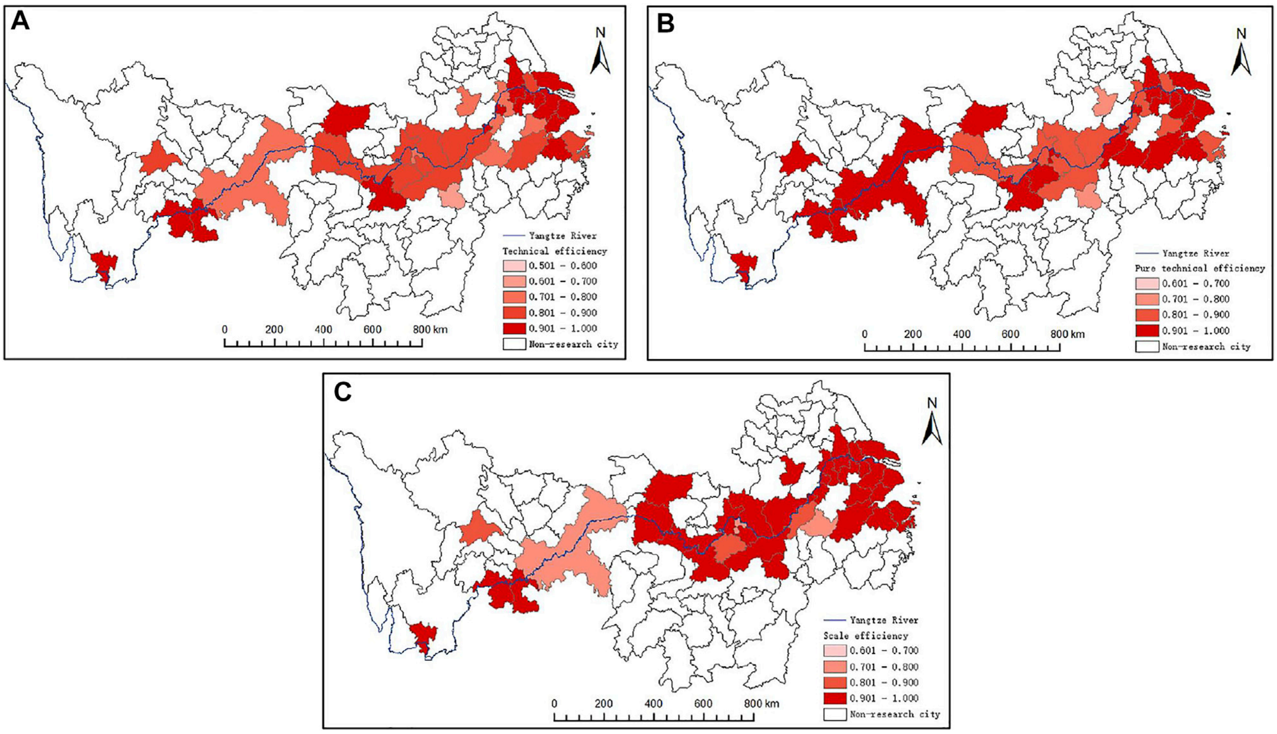


FIGURE 2
Five-year average TE, PTE, and SE. **(A)** TE; **(B)** PTE; **(C)** SE.

As shown in Figure 2C, the average SE of the whole Yangtze River Basin is high. Only some cities' average SE is between 0.6 and 0.7, indicating that the input and output ratio of cities in the region is reasonable and can make full use of existing resources. During the 5 years, the SE of 10, 14, 13, 14, and 16 cities reached the DEA effective state, accounting for 26.32%, 36.84%, 34.21%, 36.84%, and 42.11%, respectively. The average SE in the lower reaches of the Yangtze River is generally high, indicating that the input and output allocation of cities in this region to scale is reasonable. It can make full use of existing resources, which is consistent with the research conclusion of Wang and Zhu (2022). The SE of Nanchang, Yichang, Hefei, Jiujiang, Anqing, Ezhou, and Huangshi mentioned above is relatively high, consistent with their outward development model. On the whole, through continuous adjustment, the SE of cities in the Yangtze River Basin gradually tends to be reasonable.

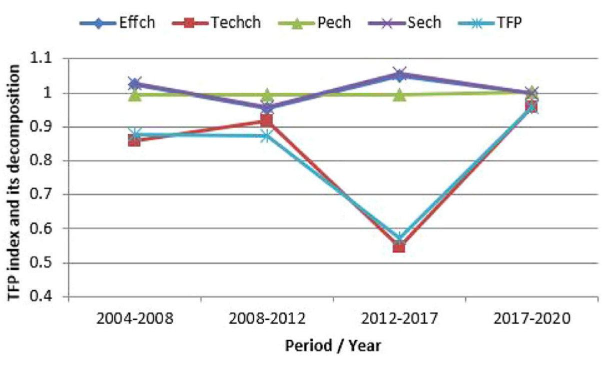


FIGURE 3
Change trends of Effch, Techch, Pech, Sech and TFP.

### 3.1.2 Dynamic evaluation

The BCC model in DEA can only reflect the static efficiency of the urban environment and management facilities. In order to understand the dynamic changes in environmental resource efficiency in each stage of the Yangtze River Basin in the future, based on the Malmquist index model, this paper analyzes the total factor productivity and other related indicators of environmental resource efficiency of 38 cities in the Yangtze River Basin from 2004 to 2020 through DEAP2.1 software.

Figure 3 shows the study period's changes in the Yangtze River Basin's Effch, Techch, Pech, Sech, and TFP. From the overall analysis, the average TFP of prefecture-level cities in the Yangtze River Basin from 2004 to 2020 is less than 1. The average TFP of cities in the Yangtze River Basin from 2004 to 2020 was

0.806. The overall environmental resource efficiency changes show a state of decline first and then increase, which is consistent with the research conclusion of Yu et al. (2021)'s "high-low-high." The reason is that in the early stage of the study, due to the gradual reversal of the urban extensive economic model and the gradual strengthening of the innovation leading trend, the urban environmental development achieved high efficiency with the attitude of "low input and high output." The urban ecological input in the Yangtze River basin gradually increases. Still, the output index enters the state of diminishing marginal utility, and the efficiency decreases accordingly. In October 2015, China's government put forward five development concepts focusing on green, marking that urban environmental resources governance has officially entered the core position of the overall national development. After that, with the optimization of the urban resource and environment investment system, the change rate of TFP in the Yangtze River Basin rebounded.

Effch fluctuates around "1" and fluctuates less. The average Effch is 1.006, with a slight increase, indicating that prefecture-level cities have a high level in using technical factors. Effch has played a catalytic role in improving environmental resource efficiency, but the effect is not apparent. As time goes on, although Pech does not reach the value of 1, it shows a steady growth trend. Up to now, the average Pech is still smaller than 1, showing that the change of Pech does not improve the TFP but inhibits its development trend. The average value of Sech is slightly larger than 1, and it can be seen that Sech plays a role in improving TFP.

According to the results of Techch, it changes during the study period has not reached 1, and the average technological progress efficiency is 0.801, indicating that the cities in the Yangtze River Basin need to be strengthened in the development and implementation of new technologies. In addition, it can be seen from Figure 3 that the changing trend of Techch indicators and TFP is generally consistent, indicating that the change in technological progress has a more significant impact on urban environmental resource efficiency. At this stage, the change of Techch has a particular impediment to the improvement of environmental resource efficiency, showing that urban economic input and output mode cannot adapt to the change of Techch. Therefore, cities in the Yangtze River Basin should pay more attention to the development of Techch, actively acquire and introduce new technologies, continuously improve their innovation ability, and promote the coordinated development of production input and output.

TABLE 3 TFP index and its decomposition.

| City | Effch | Techch | Pech | Sech | TFP |
|---|---|---|---|---|---|
| Shanghai | 1.033 | 1.079 | 1.000 | 1.033 | 1.115 |
| Nanjing | 1.054 | 0.874 | 1.040 | 1.013 | 0.921 |
| Wuxi | 1.000 | 0.924 | 1.000 | 1.000 | 0.924 |
| Changzhou | 1.042 | 0.938 | 1.037 | 1.004 | 0.977 |
| Suzhou | 1.000 | 0.866 | 1.000 | 1.000 | 0.866 |
| Nantong | 1.042 | 0.927 | 1.040 | 1.002 | 0.966 |
| Yangzhou | 0.961 | 0.994 | 0.962 | 0.999 | 0.955 |
| Zhenjiang | 1.005 | 0.975 | 1.001 | 1.004 | 0.979 |
| Taizhou | 0.917 | 0.835 | 0.924 | 0.993 | 0.766 |
| Hangzhou | 0.947 | 0.779 | 0.941 | 1.006 | 0.738 |
| Ningbo | 0.973 | 0.960 | 0.965 | 1.008 | 0.934 |
| Jiaxing | 1.028 | 0.733 | 1.039 | 0.989 | 0.753 |
| Huzhou | 0.922 | 0.727 | 0.930 | 0.992 | 0.671 |
| Shaoxing | 1.000 | 0.677 | 1.000 | 1.000 | 0.677 |
| Zhoushan | 1.027 | 0.998 | 0.969 | 1.060 | 1.025 |
| Hefei | 1.092 | 0.995 | 1.100 | 0.993 | 1.087 |
| Wuhu | 1.020 | 0.943 | 0.996 | 1.025 | 0.962 |
| Maanshan | 1.000 | 0.738 | 1.000 | 1.000 | 0.738 |
| Tongling | 0.970 | 0.697 | 1.000 | 0.970 | 0.676 |
| Anqing | 1.033 | 0.931 | 1.018 | 1.014 | 0.961 |
| Huangshan | 1.016 | 0.962 | 1.000 | 1.016 | 0.978 |
| Chizhou | 1.131 | 0.893 | 1.000 | 1.131 | 1.010 |
| Nanchang | 0.988 | 0.907 | 1.016 | 0.972 | 0.897 |
| Jiujiang | 1.032 | 0.608 | 1.026 | 1.006 | 0.627 |
| Wuhan | 1.097 | 0.911 | 1.004 | 1.092 | 0.999 |
| Huangshi | 0.956 | 0.594 | 0.955 | 1.001 | 0.568 |
| Yichang | 1.058 | 0.763 | 1.052 | 1.006 | 0.808 |
| Xiangyang | 1.000 | 0.718 | 1.000 | 1.000 | 0.718 |
| Ezhou | 1.074 | 0.708 | 1.000 | 1.074 | 0.761 |
| Jingzhou | 0.929 | 0.713 | 0.941 | 0.988 | 0.662 |
| Huanggang | 0.879 | 0.732 | 0.909 | 0.967 | 0.643 |
| Xianning | 1.038 | 0.813 | 1.000 | 1.038 | 0.844 |
| Yueyang | 1.000 | 0.738 | 1.000 | 1.000 | 0.738 |
| Chongqing | 0.988 | 0.681 | 1.000 | 0.988 | 0.673 |
| Chengdu | 1.031 | 0.965 | 1.009 | 1.021 | 0.994 |
| Panzhihua | 1.005 | 0.562 | 1.000 | 1.005 | 0.565 |
| Luzhou | 1.000 | 0.574 | 1.000 | 1.000 | 0.574 |
| Yibin | 1.000 | 0.517 | 1.000 | 1.000 | 0.517 |
| Average value | 1.006 | 0.801 | 0.996 | 1.010 | 0.806 |

Table 3 shows the TFP and its decomposition of urban environmental resource efficiency in the Yangtze River Basin from 2004 to 2020. From the efficiency indicators, the TFP and Effch of Shanghai, Zhoushan, Hefei, and Chizhou show an increasing trend, and the trend is consistent, indicating that the efficiency of the management level promotes the improvement of environmental resource efficiency. In the city of Yangzhou, Ningbo, Nanchang, Taizhou, Hangzhou, Tongling, Chongqing, Huzhou, Jingzhou, and Huanggang, Effch changes, Pech changes, and TFP all show a declining state. It shows that the decline of its environmental resource efficiency is closely related to the use of technological elements and the degree of technological innovation. The development and application of new technologies are conducive to improving environmental resource efficiency. Although the changes of Effch in Jiujiang, Luzhou, Panzhihua, Yibin, and other cities show an

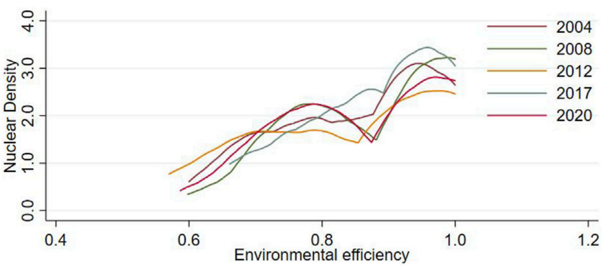


FIGURE 4
Kernel density curve.

improvement trend, the changes of Pech show a significant decline, among which Panzhihua and Yibin are at the end of all the research cities. In Huangshi City, except for the improvement of Sech, all indicators are in a downward trend, especially the Techch index is only 0.594, with an apparent downward trend. Therefore, slow technological development is the main reason for the decline of overall productivity factors, and the increase of Effch changes helps to improve the TFP.

## 3.2 Nuclear density analysis

In order to more intuitively reflect the overall evolution process and characteristics of urban environmental resource efficiency in the Yangtze River Basin, the kernel density function is used to estimate the urban environmental resource efficiency in the Yangtze River Basin in 2004, 2008, 2012, 2017, and 2020 through stata15.1 software. The kernel density function is further generated, as shown in Figure 4.

On the whole, in 2004, 2008, 2012, 2017, and 2020, the environmental resource efficiency of cities in the Yangtze River Basin is rough 'M' bimodal distribution, there is no strict unimodal form, showing a state of polarization, and the environmental resource efficiency of cities has regional differences. According to the analysis of the location of the peaks each year, the location of the peaks each year is roughly around 0.8, indicating that most cities in the Yangtze River Basin have high environmental resource efficiency, but there is still room for improvement. From the kurtosis analysis, the nuclear density curve of each year shows a trend of development from a broad peak to a sharp peak, showing that the changing trend of environmental resource efficiency of cities in the Yangtze River Basin is similar. From the perspective of location, the nuclear density curve in 2008–2012 shifted slightly to the left, and the nuclear density curve in 2004–2008 and 2012–2020 shifted to the right. It shows that during the study period, the urban environmental resource efficiency in the Yangtze River Basin shows a trend of first increasing, then slightly decreasing, and then gradually increasing. The overall fluctuation range of environmental resource efficiency is small, and the environmental resource efficiency fluctuates wildly around the value of 0.9.

## 3.3 Analysis of influencing factors

### 3.3.1 Variable selection and model setting

There are temporal and spatial differences in the environmental resource efficiency of cities in the Yangtze River Basin, and there are regional differences and spatial correlations in environmental levels of different regions and cities. Many factors cause spatial and temporal differences in environmental resource efficiency in the Yangtze River Basin. By referring to relevant literature, the preliminary analysis shows that the level of regional economic development, the deepening degree of regional opening up, and the ability of environmental governance are the critical factors that lay the differences and complexity of urban environmental resource efficiency in the Yangtze River Basin.

To comprehensively understand the influencing factors and degree of environmental resource efficiency of prefecture-level cities, according to the current research results (Gai et al., 2014; Chen et al., 2015; Zhang et al., 2015; Zhou et al., 2019; Zou et al., 2019; Huang et al., 2020), five factors affecting environmental resource efficiency are selected in this paper. Based on the openness and desirability of data, the explanatory variables are finally determined as follows: (1) Economic scale: Since the reform and opening up, the extensive economic growth mode has led to the deterioration of the ecological environment, and economic development has become an essential factor affecting the environmental quality. Urban construction in the Yangtze River Basin has become a national development strategy. Seeking a coordinated development path between economic structures and the Ecological environment has become an urgent problem to be solved. Therefore, Per capita gross regional product index is used to characterize the level of urban economic development. (2) Industrial structure: Different proportions of industries will have apparent differences in the efficiency of the ecological environment. The ratio of the output value of the tertiary sector in GDP reflects the degree of urban development. Therefore, the proportion of tertiary industry to GDP is selected to represent the level of industrial structure. (3) Regional factors: The Yangtze River basin covers many cities, and the regional population will affect the efficiency of urban resources and the environment. Simply taking population size as an influencing factor of ecological efficiency will ignore the impact of population spatial distribution characteristics. The urban Population density index describes the effects of population factors on urban environmental resource efficiency. (4) Environmental governance: Urban environmental governance will affect the efficiency of resources and the environment. Industries with capital and energy intensive

TABLE 4 Definition of environmental resource efficiency and Influencing Factors.

| Statistic variate | Variable name | Variable symbol | Variable definition |
|---|---|---|---|
| Interpreted variables | Environmental resource efficiency | EE | Dynamic environment resource efficiency values |
| Explanatory variables | Economy size | GDP | Per capita gross regional product |
| | Industrial structure | IDL | The proportion of tertiary industry to GDP |
| | Regional factors | PD | Population density |
| | The environmental governance utilization level | RRL | The comprehensive utilization rate of general industrial solid waste |
| | Degree of opening to the outside world | FDI | The foreign capital utilization level |

TABLE 5 Tobit regression results.

| Influencing factor | Correlation coefficient | Standard deviation | Z statistic | $p>\|z\|$ |
|---|---|---|---|---|
| GDP | −0.095 | 0.029 | −2.370 | 0.001** |
| IDL | 0.087 | 0.002 | −2.930 | 0.004*** |
| PD | 0.001 | 0.002 | 2.910 | 0.004 |
| RRL | −0.001 | 0.001 | −1.270 | 0.205*** |
| FDI | 0.023 | 0.015 | 0.426 | 0.543 |
| C | 1.143 | 0.103 | 4.100 | 0 |

Note The upper corner marks *** and ** indicate that they are significant at the 1% and 5% levels, respectively.

characteristics are the primary energy consumption and emissions, so the comprehensive utilization rate of general industrial solid waste is selected to express the environmental governance capacity of each region. (5) Opening to the outside world: Whether from the perspective of capital injection or talent accumulation, the degree of opening-up may affect the efficiency of urban resources and the environment, and the foreign capital utilization level can indicate the city's opening-up degree, so this index is selected as the influencing factor. The explained variable is the dynamic environmental resource efficiency of 38 cities in the Yangtze River Basin. On this basis, an analysis model of the influencing factors of environmental resource efficiency of prefecture-level cities in the Yangtze River Basin is constructed to quantitatively study the impact of different influencing factors on urban environmental resource efficiency. The explanation and description of the data are shown in Table 4.

### 3.3.2 Results and analysis

The Tobit model is established by Stata15.1 software for regression analysis. The results show that the effects of different independent variables on urban environmental resource efficiency are significantly different, as shown in Table 5.

It can be seen from Table 5 that the level GDP is significantly negatively correlated with EE at the 5% significant level, and its influence coefficient is -0.095. It shows that with the continuous expansion of economic scale, the environment of cities in the Yangtze River Basin has deteriorated. This also warns people that while developing an economy, cities should also pay attention to environmental governance and how to realize the coordinated development of economic growth and the environment is the focus of attention.

From the perspective of industrial structure, the influence coefficient of IDL on EE is 0.087, and its influence is evident at 1%. It shows that the higher the proportion of tertiary industry output value in GDP, the greater the value of environmental resource efficiency. With the rapid development of the computer software industry and other high-tech industries, the proportion of China's tertiary industry is increasing. Under the advocacy of national policies, most enterprises pay more and more attention to protecting the environment. The more significant the proportion of the tertiary industry, the less pressure on environmental governance, and the more conducive to environmental governance improvement.

The influence coefficient of PD on EE is 0.001, indicating that it positively affects environmental improvement. The influence of regional factors and environmental resource efficiency has a two-way promoting effect. However, the urban environmental resource efficiency in the Yangtze River Basin is only improved to a small extent with the increase of population density, and it is not sure that the pure promoting effect of population factors and environmental resource efficiency.

The influence coefficient of RRL is −0.001. This indicates that the reuse of industrial waste in cities around the Yangtze River

TABLE 6 Prediction results.

| year | 2023 | 2024 | 2025 | 2023 | 2024 | 2025 |
|---|---|---|---|---|---|---|
| City | Industrial wastewater | Industrial wastewater | Industrial wastewater | Industrial $SO_2$ | Industrial $SO_2$ | Industrial $SO_2$ |
| Shanghai | 33281.68 | 33687.84 | 34098.95 | 2345.10 | 1774.84 | 1343.25 |
| Nanjing | 9972.66 | 9218.67 | 8521.68 | 5372.40 | 4525.89 | 3812.75 |
| Wuxi | 15824.77 | 15069.65 | 14350.55 | 6298.08 | 4431.67 | 3118.36 |
| Changzhou | 10190.22 | 9769.67 | 9366.47 | 5216.08 | 3916.35 | 2940.48 |
| Suzhou | 21135.22 | 18733.90 | 16605.41 | 11943.57 | 8612.46 | 6210.41 |
| Nantong | 11597.26 | 11287.08 | 10985.19 | 1263.55 | 847.72 | 568.74 |
| Yangzhou | 3870.60 | 3469.34 | 3109.67 | 3692.06 | 2965.03 | 2381.17 |
| Zhenjiang | 3534.65 | 3256.88 | 3000.94 | 3278.30 | 2784.84 | 2365.66 |
| Taizhou | 4756.33 | 4804.46 | 4853.07 | 4226.87 | 3559.13 | 2996.87 |
| Hangzhou | 10054.09 | 8594.16 | 7346.21 | 964.19 | 554.54 | 318.94 |
| Ningbo | 13644.18 | 13431.47 | 13222.08 | 2959.62 | 2076.17 | 1456.43 |
| Jiaxing | 15003.31 | 14306.70 | 13642.42 | 2497.07 | 1718.20 | 1182.26 |
| Huzhou | 4927.84 | 4474.76 | 4063.34 | 3603.16 | 2639.92 | 1934.18 |
| Shaoxing | 24084.30 | 23871.54 | 23660.66 | 1450.33 | 971.56 | 650.83 |
| Zhoushan | 2728.51 | 3171.92 | 3687.39 | 1640.43 | 1662.71 | 1685.30 |
| Hefei | 7494.40 | 8096.82 | 8747.65 | 3544.70 | 2987.55 | 2517.97 |
| Wuhu | 2895.15 | 2774.00 | 2657.91 | 3231.42 | 2378.70 | 1751.00 |
| Maanshan | 8527.02 | 8469.20 | 8411.77 | 9562.55 | 8660.47 | 7843.50 |
| Tongling | 4685.36 | 5019.39 | 5377.24 | 1463.84 | 1036.76 | 734.29 |
| Anqing | 1563.84 | 1415.82 | 1281.82 | 1378.88 | 1058.61 | 812.72 |
| Huangshan | 765.49 | 775.17 | 784.97 | 593.45 | 448.37 | 338.75 |
| Chizhou | 695.91 | 738.17 | 783.00 | 12084.27 | 13088.17 | 14175.47 |
| Nanchang | 3744.99 | 3727.07 | 3709.24 | 1528.72 | 1092.79 | 781.17 |
| Jiujiang | 11383.23 | 12042.85 | 12740.70 | 4292.81 | 3405.87 | 2702.17 |
| Wuhan | 12682.59 | 12701.55 | 12720.54 | 7580.15 | 6821.71 | 6139.16 |
| Huangshi | 2448.85 | 2265.72 | 2096.29 | 5835.04 | 4912.34 | 4135.55 |
| Yichang | 24680.34 | 31775.68 | 40910.85 | 4024.17 | 3040.27 | 2296.93 |
| Xiangyang | 2223.31 | 1978.62 | 1760.87 | 2020.54 | 1609.22 | 1281.63 |
| Ezhou | 918.76 | 813.96 | 721.11 | 4617.26 | 4477.61 | 4342.18 |
| Jingzhou | 3786.93 | 3696.02 | 3607.29 | 4094.79 | 3533.81 | 3049.68 |
| Huanggang | 1990.58 | 2009.26 | 2028.11 | 1903.89 | 1613.45 | 1367.32 |
| Xianning | 1370.61 | 1340.95 | 1311.94 | 1717.67 | 1463.90 | 1247.62 |
| Yueyang | 6483.65 | 6468.68 | 6453.74 | 10072.19 | 9823.63 | 9581.21 |
| Chongqing | 24984.42 | 25966.75 | 26987.71 | 35411.23 | 27811.52 | 21842.80 |
| Chengdu | 10865.96 | 11420.09 | 12002.47 | 3164.47 | 2628.78 | 2183.77 |
| Panzhihua | 5510.03 | 5722.27 | 5942.68 | 14106.71 | 11273.79 | 9009.78 |
| Luzhou | 5223.37 | 5562.70 | 5924.08 | 7979.90 | 7418.55 | 6896.68 |
| Yibin | 4963.58 | 4774.43 | 4592.49 | 3574.86 | 2541.91 | 1807.44 |

Basin is still in a relatively rough development stage. The factory focuses on the quantity of recycling without paying attention to quality, resulting in the low quality of reused industrial raw materials and the destruction of environmental resources in the reproduction process. Government departments should pay attention to it.

FDI on EE is 0.023, showing a positive role. It shows that the introduction of foreign capital and new technologies are conducive to improving urban environmental governance in the Yangtze River Basin. However, the results are insignificant, indicating that the degree of opening to the outside world is not the main factor affecting environmental resource efficiency.

In summary, IDL, PD, and FDI positively correlate with EE in the Yangtze River Basin. The proportion of the tertiary industry is the most closely related to the development of environmental resource efficiency. The level of RRL harm EE, and the level of GDP has a more significant negative impact on EE.

## 3.4 Unexpected output projections

Based on the data on industrial wastewater and $SO_2$ emissions of 38 cities in the Yangtze River Basin from 2004 to 2020, this part uses the grey prediction model GM (1,1) to predict the industrial wastewater and sulfur dioxide emissions of cities in the Yangtze River Basin from 2023 to 2025, and analyzes their change trends. The results are shown in Table 6.

Table 6 shows the prediction results of industrial wastewater emissions of cities in the Yangtze River Basin from 2023 to 2025, the industrial wastewater emissions of 23 cities in the Yangtze River Basin from 2023 to 2025 will decrease year by year, accounting for 65.79%. However, 15 cities' industrial wastewater emissions show a slight upward trend. Industrial wastewater contains many toxic and harmful substances, which have caused great harm to the environment and the human body. Therefore, the treatment of industrial wastewater has become the focus of attention.

The preliminary prediction of $SO_2$ emissions in cities in the Yangtze River Basin shows that the industrial $SO_2$ emissions of 36 cities in the Yangtze River Basin will decrease year by year from 2023 to 2025, accounting for 94.74%. Only Zhoushan and Chizhou have a slight increase in industrial $SO_2$ emissions. The industrial $SO_2$ emissions of cities in the Yangtze River Basin have been effectively controlled.

# 4 Conclusions and policy implications

## 4.1 Conclusions

This paper uses the DEA-Malmquist-Tobit model to calculate the static and dynamic levels of environmental resource efficiency of 38 cities in the Yangtze River Basin from 2004 to 2020. The factors affecting the environmental resource efficiency of cities in the Yangtze River Basin and their relationship are analyzed. The grey prediction model GM (1,1) predicts the expected output emissions of industrial wastewater and $SO_2$. The following conclusions are drawn:

1) From the results of static analysis and evaluation of environmental resource efficiency, since 2004, the average value of urban environmental TE, PTE, and SE in the Yangtze River Basin has remained above 0.6. The number of non-DEA efficient cities in the analysis of urban environmental resource efficiency in the Yangtze River Basin is far more than that of DEA efficient cities. It shows that cities in the Yangtze River Basin still have room for environmental governance improvement. From the perspective of spatial distribution characteristics, cities in the Yangtze River Basin with DEA effective or ineffective environmental resource efficiency have no prominent geographical distribution characteristics.
2) The environmental resource efficiency dynamic analysis results show that the average TFP of cities in the Yangtze River Basin is less than 1, showing a downward trend. Among them, Effch continues to rise while Techch continues to decline, which is synchronized with the changing trend of TFP. From the perspective of composition, the Effch and Pech of most cities are more significant than 1, which is generally stable. During the evaluation periods of 2008–2012 and 2017–2020, the change of Sech showed a downward trend, and its annual growth rate was negative. In addition to Shanghai, the change of Effch in cities is less than 1, so improving the level of Techch plays a vital role in developing the urban environment in the Yangtze River Basin.
3) The results of the kernel density analysis show that the environmental resource efficiency of cities in the Yangtze River Basin presents a polarization state. However, the changing trend of environmental resource efficiency of each city is similar, mainly showing a trend of increasing first, then decreasing slightly, and then increasing gradually. Unexpected output prediction results showed that 65.79% of urban industrial wastewater emissions decreased yearly, and 94.74% of urban industrial sulfur dioxide emissions showed a downward trend year by year. Overall, industrial sulfur dioxide emissions have been effectively controlled. For the problematic situation of industrial wastewater emission reduction in some cities, the relevant urban governments should increase their control efforts and strengthen the emission reduction of industrial wastewater.
4) The analysis results of the environmental resource efficiency factors show that the factors negatively related to environmental resource efficiency include GDP and PPL in the Yangtze River Basin cities. IDL, PD, and FDI positively affect environmental resource efficiency. IDL has the most significant impact. Although PD and FDL have improved environmental resource efficiency, they have not passed the test of aboriginality and have little impact. Therefore, it is believed that by adhering to supply-side structural reform, optimizing the industrial structure, and increasing the proportion of the service industry in the national economy can improve environmental resource efficiency.

Although some achievements have been made, this study still has limitations. (1) This paper considers 38 node cities in the Yangtze River Basin as the research object and does not include all prefecture-level cities in the Yangtze River Basin. (2) This paper predicts the unexpected output from 2023 to 2025, and the prediction time series is relatively short. In future research, the authors will consider more comprehensive urban data. Extend the prediction time of unexpected output to improve the research's comprehensiveness and pertinence.

### 4.2 Policy implications

Urban environmental resource efficiency reflects the cost of resources and environment invested in creating a specific economic output in urban development. It can measure whether each city's economic development is friendly to the environment. It is an important indicator to examine whether the urban economy meets the high-quality development. The higher the efficiency of urban resources and environment, the more coordinated the urban economic development and environment, and the higher the level of resource utilization. By studying urban environmental resource efficiency and its influencing factors in the Yangtze River Basin, we can objectively evaluate the efficiency differences and changes in major cities in the Yangtze River Basin. It is of great practical significance to promote the high-quality development of cities in the Yangtze River Basin. Based on the analysis of this paper, the following suggestions are put forward for the problems of urban resources and environmental resource efficiency in the Yangtze River Basin:

1) Although the overall trend of urban economic development in the Yangtze River Basin is positive, there is a problem of low efficiency. Adhering to the resource-saving and environment-friendly development strategy will be the only way to improve the environmental resource efficiency of cities in the Yangtze River Basin.
2) There are many cities along the Yangtze River Basin, the geographical location runs through the eastern and western regions of China, and the economic development is uneven. Realizing the coordinated development of the upstream and downstream of the basin will essentially solve the widening trend of the economic development gap between the East and the West. All cities must work together to promote ecological protection and high-quality development in the Yangtze River Basin. Improve production technology through differentiation, reduce invalid input and output, and build the Yangtze River basin into an important leading green and coordinated development area.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

All authors contributed to the study conception and design. Conceptualization, JL and YZ; methodology, JL and YZ; software, JD and SL; validation, JL and JD; formal analysis, YZ and SL; investigation, JD and SL; resources, YZ; data curation, JD; writing—original draft preparation, JL; writing—review and editing, JD and YZ; supervision, SL; project administration, JL, YZ. All authors read and approved the final manuscript.


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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Environmental dilemma and sustainable development of resource-based cities: A case study from northeast china

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With ambitious carbon peak and carbon neutral targets, China has to realize it relies heavily on significant reductions in energy-related carbon emissions. Therefore, as the largest contributing region, resource-based cities (RBCs) must achieve an energy transition. Unfortunately, these cities are facing serious environmental problems. The aim of this study is to analyze the development history and problems of RBCs by using the example of the Northeast region. The results show the reasons blocking the green development of these cities include management policies and life cycles. This implies the management of RBCs needs to develop toward a win-win situation of industrial transformation and ecological protection. Finally, some policy recommendations are proposed to achieve emission reduction and sustainable development.

KEYWORDS

**resource-based cities, sustainable development, northeast China, environmental dilemmas, green transformation**

## Introduction

RBCs were once regarded as cities with a single extractive industry as the pillar industry and dominated by one industrial company. Moreover, they have been essential for industrialization and urbanization in China. Generally, they are also called mining towns or RBCs (Yan et al., 2019). In recent years, due to the decrease in recoverable resources, it has been more and more difficult to exploit the resources. With the pressure of survival and development, the exploitation intensity of natural resources has increased, and thus resource exploitation has transferred from developed countries to many developing ones (He et al., 2017; Wang Y. et al., 2020). However, due to the fragile economic foundation of these developing countries, resource development causes many economic problems, such as low per capita GDP, unbalanced economic and industrial structure, heavy labor pressure, and reduced tax revenue, hurting the long-term sustainability of the cities. (Li et al., 2013; Li et al., 2015; He et al., 2017; Li and Dewan, 2017; Ruan et al., 2020). Besides, large-scale resource extraction can also bring serious environmental problems to RBCs, including accelerated resource extraction and depletion, and increased pollution levels in the existing environment (Krueger and Grossman, 1991). Fossil energy extraction, for example, on the one hand, creates a large amount of solid waste, leading to surface and groundwater pollution and air pollution if not properly treated (Wiedensohler et al., 2009). On the other hand, it will cause ground collapse, ground fractures, and other geoenvironmental high-risk areas to expand (Tan J. et al., 2017), causing waste of land resources and further increasing environmental pressure (Zoundi, 2017). These crises threaten the development of RBCs in many developing countries. Some scholars (Xia et al., 2021) mentioned that the sustainable development of RBCs needs to be realized through a transformation because the resources are non-renewable. Naturally, how to solve the current problems of RBCs and finally realize the transformation of RBCs has become a hot issue.

In the context of carbon peak and carbon neutrality targets, the relationship between RBCs and carbon emissions has received much academic attention. However, the impact of RBCs development on carbon emissions is uncertain. On the one hand, Hou et al. (2018) argued that the development of RBCs was accompanied by a heavy reliance on fossil energy and an irrational industrial structure, i.e., the "lock-in effect". This implies the sloppy development pattern caused by this effect will further promote carbon emissions (Sun Q. et al., 2021). On the other hand, Zhou et al. (2022) suggested that RBCs with low carbon as the goal can enhance carbon emission efficiency, which will help to promote carbon emission reduction and achieve carbon peak and carbon neutrality in advance. Similar findings can be found in Zhang M. et al (2022), and Zheng and Ge (2022). Many scholars support this view and argue that China's achievement of carbon peak and carbon neutrality depends on RBC's low-carbon development (Ma et al., 2021; Guo, 2021; Liao et al., 2022). According to statistics, RBCs consume 60% of national energy (Fong et al., 2008; Zhang H. et al., 2022). The per capita carbon emission of RBCs is twice the national average. Besides, the carbon emission intensity of RBCs is 1.5 times the national average (Sun X. et al., 2021). Therefore, it is significant to achieve sustainable development through improving energy resilience among RBCs (Tan P. et al., 2017, 2020) under the carbon peak and carbon neutrality targets.

This study chooses Northeast China as a typical case to study China's RBCs. First and foremost, Northeast China not only includes many representative RBCs (Wang Y. et al., 2020) but also has to bear relatively high pressure on environmental governance, similar to other RBCs. Up to now, there are

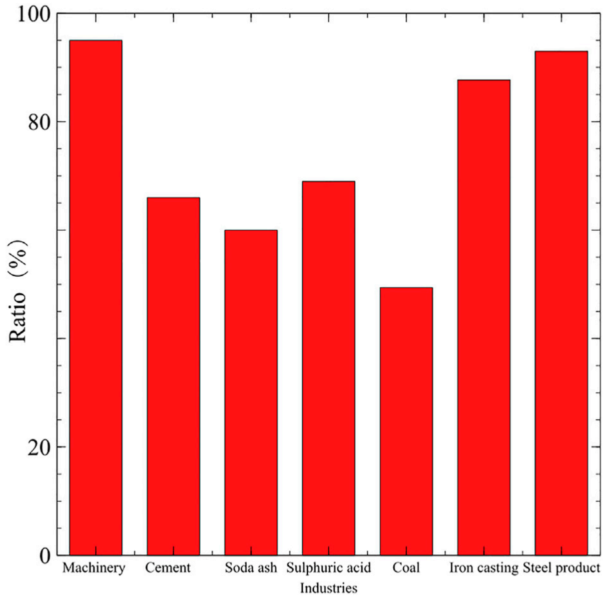


**FIGURE 1**
Ratio of resources in Northeast China to national output in 1940s.

39 RBCs in the urban agglomeration of Northeast China, with a single economic structure, dual management system, and differentiated urban functions (Tan J. et al., 2017). At the same time, according to the list of difficulties in transforming RBCs published by Peking University in 2017, the top four cities are located in Northeast China. To some extent, it reflects that the RBCs in Northeast China face relatively high transformation pressure. There are still some undiscovered and unsolved deep-seated contradictions to be solved. Hence, the ecological transformation of RBCs in Northeast China is imminent (Wang et al., 2020a, b). Secondly, the Chinese government has constantly been attaching great importance to urban construction in Northeast China, making the case particular. The Chinese government has promulgated a series of policies targeting the development of this area. However, as in many other countries rich in natural resources, the resources of these cities have not been the motivation for their development, but have left them far behind other cities, thus seriously hindering the overall progress of the country (Sachs and Warner, 2001; Chen et al., 2018; Ruan et al., 2020).

Therefore, this paper also used case studies (Omolade et al., 2019; John and Tasciotti, 2020; Nel and Connelly, 2020) to expound on the typical RBCs and analyze their dilemma and solutions for reference, with the following two contribution. First, compared to Reid and Gartell. (2013) and Mitchell and O'Neill. (2016), this paper can provide a more comprehensive overview of the development history of the Northeast region. Second, although the quantitative research methods used in

TABLE 1 List of RBCs in northeast China.

| Prov-ince | Prefecture level division | County-level city | Counties (autonomous regions and forest areas) | Municipal district |
|---|---|---|---|---|
| Liaoning (15) | Fuxin, Fushun, Benxi, Anshan, Panjin and Huludao | Beipiao city, Diaobingshan, Fengcheng, dashiqiao city | Kuandian Manchu Autonomous County, Yixian County | Changling District, Nanpiao District, Yangjiazhangzi Development Zone |
| Jilin (11) | Songyuan, Jilin *, Liaoyuan, Tonghua, baishan city *, Yanbian Korean Autonomous Prefecture | Kyushu, shulan city and Dunhua * | Wangqing county * | Erdaojiang district |
| Heilongjiang (11) | Heihe *, Daqing, Yichun *, hegang, Shuangyashan, qitaihe city, Jixi, Mudanjiang * and Daxinganling * | Shangzhi city *, wudalianchi city * | | |
| Eastern Inner Mongolia (2) | Chifeng and Hulunbeier | | | |

The cities marked with * are forest industry cities.

Zhang M. et al. (2022) (Zhang H. et al., 2022) and Zheng and Ge. (2022) did not be used, this paper, similar to Sunikka (2006) and Liu and Gallagher (2010), is an exploratory approach to considering what policies governments in developing countries can adopt to guide the development of RBCs in the context of the "paradox" of economic transformation and environmental protection.

The rest of this paper is structured as follows. The second part is a case study including the basic situation, the dilemma, and underlying causes in Northeast China. The third part is policy recommendations. The Final is the conclusion.

# Case study

## Basic situation of northeast china

Northeast China consists of three provinces and part of an autonomous region: Liaoning, Jilin, Heilongjiang, and eastern Inner Mongolia. The land area is 1.45 million square kilometers, and the total population is up to 120 million in this region (China Bureau of Statistics, 2019). As shown in Figure 1, resources in Northeast China accounted for a high proportion of national output in the 1940s. For this reason, Northeast China is known as China's old heavy industry base.

According to the ***National sustainable development plan for resource-based cities*** (***2013–2020***) (State Council, 2013), there are 39 RBCs in Northeast China, and their distribution is shown in Table 1.

## The dilemma of transformation and development in northeast China

Reviewing the development process of RBCs in Northeast China, there are the following development problems.

1) Northeast China has a large number of RBCs with diverse types and different development stages. In terms of resource types, the RBCs in Northeast China can be divided into coal-based cities, including Fushun; oil-based cities, such as Daqing, Songyuan, and Panjin; cities dominated by iron and steel industry, including Fuxin; dominated by nonferrous metal mineral RBCs and nonmetal RBCs, including Huludao, and Tieli city; forestry industry cities, including Yichun and Heihe. At the same time, from the development status of these cities, according to the division of RBCs in the Plan, 39 RBCs in Northeast China include two growing resource cities, 13 mature resource cities, 19 declining resource cities, and five renewable resource cities, as shown in Table 2.
2) RBCs in Northeast China have economic problems such as a single industrial structure and slow regional economic growth. At first, relying on unique natural resources, Northeast China was devoted to developing many serious pollution industries, such as metallurgy, machinery, and building materials. At the same time, other industrial sectors were still unchanged. It results in a single industrial structure, as shown in Figure 2.

After more than half a hundred years of exploitation and excavation, many RBCs in Northeast China began to experience resource depletion, economic recession, and population loss (Yang et al., 2022), and the low learning and innovation capacity hindered the development of alternative industries (Yu and Cheng, 2016). These problems led to the bankruptcy and relocation of many industrial enterprises (Yang et al., 2022), causing sharp urban unemployment and continuous urban population loss (Yu and Cheng, 2016). Meanwhile, most cities in Northeast China do not have medium and long-term development plans and cannot implement new energy projects to improve energy efficiency due to policy conflicts (Yu and Cheng, 2016). In addition, the labor force shortage has emerged,

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TABLE 2 Classification of RBCs in northeast China.

| Prov-ince | Prefecture level division | County-level city | Counties (autonomous regions and forest areas) | Municipal district |
|---|---|---|---|---|
| Growth (2) | Songyuan City, Hulunbeier City | | | |
| Mature (13) | Benxi, Jilin, Yanbien Korean Autonomous Prefecture, Heihe, Daqing, Jixi, Mudanjiang and Chifeng | DiaoBingshan City, Fengcheng City, Shangzhi City | DiaoBingshan City, Fengcheng City, Shangzhi City | |
| Recess-ion (19) | Fuxin, Fushun, Liaoyuan, baishan city, Yichun, hegang, Shuangyashan, Qitaihe city and Daxinganling | Beipiao city, Jiutai, shulan city, Dunhua, Wudalianchi city | Wangqing county | Changling District, Nanpiao District, Yangjiazhangzi Development Zone, Erdaojiang District |
| Regene-ration (5) | .Anshan, Panjin, Tonghua and Huludao | Dashiqiao city | | |

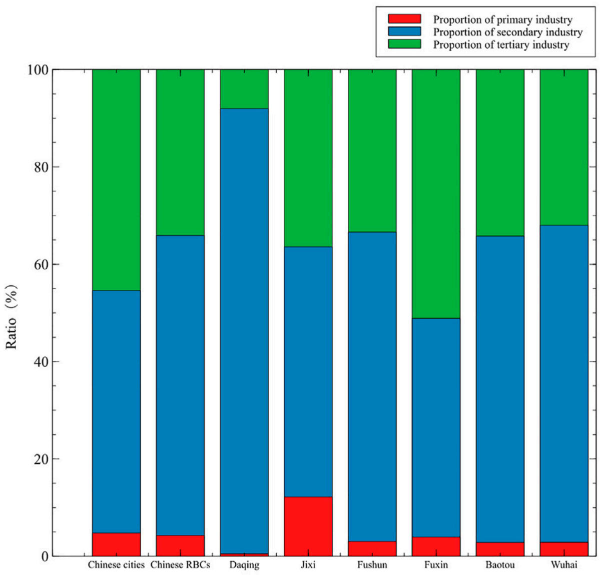


FIGURE 2
Industrial proportion of RBCs in northeast China in 2001.

and the alternative for high energy-consuming industries is still too immature to make up for economic losses, which comprehensively leads to the slow growth of the regional economy.

3) Environmental problems such as land collapse and soil erosion are common in RBCs in Northeast China. For coal mining, underground mining was carried out around mines in Northeast China, resulting in large-scale surface subsidence and destruction of various buildings, roads, bridges, and farmlands. According to the survey, at the end of 1995, the area of land collapsed by state-owned coal mines in China was about 350,000 ha. Taking Liaoyuan for instance, the subsidence area, mined-out area, and unstable subsidence area formed by history were 18.95, 14.58, and 15.66 square kilometers, respectively (Jilin Provincial government, 2016). Similarly, the coal mined-out area of Shuangyashan is 116.6 square kilometers, and the subsidence area was 62 square kilometers, involving 68,000 residents. Moreover, Datong produces two billion tons of coal annually and forms nearly 45,000 ha of mined-out areas. In addition, environmental problems such as industrial pollution, landslides, and soil erosion (Tan P. et al., 2017) in large areas of river basins are also severe. Taking Jilin Province as an example, the monitoring results show that the soil erosion area in 2019 was 41,800 square kilometers, accounting for 21.95% of the province's total land area (Jilin Provincial government, 2020).

## Dilemma causes

The dilemma faced by RBCs in Northeast China is caused by two factors. On the one hand, the plight of RBCs in Northeast China is closely related to management policies. As the first region in China to implement a planned economy, Northeast China, with its industrial base and a large number of natural resources, has undertaken most of the industrial production tasks of the new China since the 1950s (Li et al., 2013). Under the guidance of the planned economy, resource exploitation in the Northeast became more frequent in order to secure the needs of national economic development. Subsequently, reform and opening up emerged in China's southeast coastal regions. The Northeast failed to effectively attract foreign investment because of geographic constraints resulting in fewer new industrial layouts and a large population loss to the southeastern coastal regions (Yang et al., 2018). In the 1990s, China started a wave of state-owned enterprise reforms. This directly led to the layoff of eight million workers in Northeast China (accounting for nearly 30% of the country), making the development of this area increasingly difficult (Mak, 2008).

TABLE 3 Industrial characteristics and pillar industries of four types of RBCs.

| Type | Industrial structure characteristics | Transformation characteristics | | Key constraints | Examples | | |
|---|---|---|---|---|---|---|---|
| | | Before transformation | After transformation | | City | Before transformation | After transformation |
| Growth | With oil, natural gas and other advantageous resource industries as the pillar industries | Deepen the industrial chain around resource-based pillar industries and cultivate new industries in the primary and tertiary industries | Relying on abundant petrochemical and other advantageous resources | Resource efficiency and economic benefits | Songwon | Oil | Oil and gas extraction and chemical industry |
| Mature | Three pillar industries: petrochemical extraction, steel or mineral primary processing, and forest harvesting | Efficient use of advantageous resources, deep processing of resources, extension of industrial chain to new energy and new materialsetc. | Good economic base, combined with the development and application of high-tech technologies | Technology, talent, capital and innovative spirit | Yanbian Korean Autonomous Prefecture | Coal mining, forestry | Energy and hydropower, forest products processing, clothing and textiles and information electronics |
| Recession | Coal mining and forest harvesting as the mainstay of the industry | Equipment manufacturing and other industrial systems and green food and other industrial systems | Abandoning traditional industries is difficult and transformation development is slow | Suitable succession industries according to local conditions | Hegang | Coal Mining | Coal industry, graphite industry, green food processing industry, tourism |
| Regeneration | Traditional resource industries such as petrochemicals and iron and steel are dominant | Multi-industries such as resource deep processing, equipment manufacturing and new materials coexist | Breaking away from resource dependence by improving the level of industrial science and technology innovation | High-tech, science and technology innovation capabilities | Panjin | Petrochemical | Petrochemical and fine chemical industry, oil and gas equipment manufacturing, plastic new materials, marine engineering |

On the other hand, these difficulties are related to the characteristics of RBCs. According to the life cycle theory, RBCs have a four-stage development process (growth-maturity-recession, and regeneration). Similarly, RBCs in Northeast China first relied on natural resources such as coal and iron ore to form highly overwhelming energy-consuming industries to stimulate economic development during the formative years. Subsequently, the original pillar industries matured but were impacted by the emerging industries due to their low technology and slow development of successive replacement industries (Yu and Cheng, 2016). Then, during the recession phase, RBCs lose their original resource advantages due to the non-renewal of mineral resources, resulting in the frequent closure of industrial enterprises (Yang et al., 2022). Consequently, the labor force moved out due to fewer job opportunities. Finally, life cycle theory states RBCs in the regeneration stage can eliminate dependency on resources and achieve high-quality economic development and environmental protection benefits. However, for RBCs in Northeast China, most of them are in the maturity and decline stages, therefore, how to get rid of resource dependence and move to the regeneration stage are the main difficulties for RBCs in China at present.

## Policy implications

This paper shows the challenges faced by some RBCs in the development by taking Northeast China as an example. Overall, the case of Northeast China reveals the general characteristics of RBC. The leading solution to these problems is to develop replacement industries or improve the competitiveness of resource-based industries (Yu and Cheng, 2016) while building a green development mechanism of resource conservation, industrial optimization, environmental friendliness, and ecological harmony. Therefore, the policy recommendations are given as follows:

1) Promote industrial transformation. RBCs should exploit their comparative and late-mover advantages to cultivate leading industries (Zhang et al., 2021), especially high-tech equipment manufacturing and other new industries with

low environmental pressure and high added value. Table 3 compares the industrial development characteristics of the four types of RBCs and gives the suggested directions for the pillar industries after the transformation of the each type of city. More details are able to be found in the Supplementary Materials.

Subsequently, we propose development suggestions for each type of RBC. The transformation of pillar industries in growing resource cities has abundant resource advantages but is constrained by factors such as low resource utilization efficiency and economic efficiency. Take Songwon City as an example, its original pillar industries are petroleum, oil and gas extraction and chemical industry, respectively. Therefore, the city's transformed pillar industries should be related to petroleum resources, so that the added value of the pillar industries can be increased significantly and its sustainable development capacity can be enhanced.

Mature resource cities inherit a better economic foundation but are constrained by factors such as technology, talent, capital, and lack of innovation. We suggest that the transformed pillar industries should develop toward increasing the added value of resource industries or further expanding different types of industries. Taking Yanbian as an example, we suggest that the city should inherit the traditional advantageous industries such as coal mining and forestry while reforming towards energy and hydropower, forest products processing, garment and textile, and information and electronics industries.

Industrial transformation in recession resource cities is slow and difficult. Besides, it is difficult to find suitable successor industries. In Yichun, for example, we suggest that the city should develop in the direction of broadening the industrial chain based on the development of forestry, and further introduce the "1 + 1″ model to explore forestry-related fields, such as wood processing, forest food processing industry, forest ecotourism, etc.

Regenerative resource cities can gradually get rid of their dependence on resources by improving the level of industrial science and technology innovation, but they are often constrained by the low level of high technology and the general ability of science and technology innovation. Taking Panjin as an example, we suggest that the city, on the basis of inheriting the original petrochemical industry, further develop in the direction of material finishing and actively expand the petrochemical and fine chemical industry, oil and gas equipment manufacturing, plastic new materials, marine engineering, and other related industries. In order to achieve this, talent acquisition (Yu and Cheng, 2016; Yang et al., 2019) is a good way.

2) Consider environmental protection. Considering the severe pressure on ecological environment protection in Northeast China, we think the following three aspects are needed to integrate sustainable development into urban transformation.

The first is to strengthen ecological protection and restoration. For example, the ecological damage and environmental pollution caused by mining should be well evaluated according to the mine ecological planning before mining. The mining scheme should follow the principle of minimizing environmental costs. During the mining process, it is necessary to meet the requirements of the mine ecological environment evaluation index and minimize environmental loss when implementing green mining in the whole process. The mining scheme should always ensure that the reliable implementation of the mine fits ecological environment standards. The predicted loss should compare with the actual loss after mining. As for the ecological damage and the environmental pollution loss caused by mineral resources exploitation, the relevant stakeholders should be compensated following the green property rights system. Meanwhile, the ecological environment of mines should be repaired by their functions and structures to maintain the ecological structure, resistance, self-recovery, and sustainable development ability of the mining areas, and thus guarantee the quality of environmental restoration.

Secondly, strengthen innovations for green mining technology, mainly including water-preserved mining technology, ecological restoration technology of mining wasteland, building and land protection technology, and clean mining technology. Specifically, the government should take the lead in building a technological alliance, extensively appeal to experts and scholars to solve enterprises' problems in production, and improve the technical level with the goal of green and low carbon.

Thirdly, strengthening supervision can promote the intensive and comprehensive utilization of resources and develop a circular economy. Some valuable experiences of cases such as the Ruhr region in Germany can be referred to. Ruhr's government strictly implements environmental regulations on air quality management, pollution source control, and emission treatments. Emission control is realized through national environmental protection legislation, economic policy tools such as subsidies and taxes, and industrial structure adjustment (Hassink and Shin, 2005).

3) Optimize the guiding policies. First, for state-owned assets in the Northeast, there is an urgent need to establish a more optimal and equitable management system, optimize the separation of social and operational functions, and implement the main responsibility for safety management. In this process, using modern management theories, information technologies, and supervision measures can promote the proper operation of the economy of state-owned enterprises under the current laws and regulations. These measures can effectively avoid the loss of state-owned assets in economic transformation and strengthen

the public's awareness of supervision and willingness to participate, thus forming a good atmosphere for economic development.

Secondly, for environmental protection, governments at all levels should strictly implement laws and regulations on environmental protection and strengthen inspection measures while following the basic management principle of "whoever develops, whoever recovers". It is important to encourage private capital to participate in environmental protection, and ecological restoration according to local conditions. In addition, governments should constantly innovate new ecological restoration models and strictly implement environmental protection responsibility.

Thirdly, the governments should actively build a cooperation platform to deepen the exchange between Northeast China and other domestic and foreign regions. It should make full use of location superiority, implement the opening-up strategy, and establish a strategic partnership of sharing resources and achievements. Moreover, the governments should expand the industrial development space and deepen the integrated development of external resource elements and dominant industries.

Fourthly, the local governments should persist in adopting specific policies for each city, enterprise, and mineral to develop and utilize resources by considering the local conditions and thus enhance the resource support capacity. After introducing relevant policies, the government should introduce corresponding supporting measures to help loss-making enterprises out of their current predicament. For enterprises with overcapacity, it is necessary to reduce overproduction. The local government needs to take decisive measures to shut down the enterprises characterized by either inefficiency, high consumption, or low development. At the same time, more attention should be paid to properly handling the exit of zombie enterprises and arranging the transfer of a large number of surplus labor.

## Conclusion

This article mainly studies RBCs' problems and their development countermeasures.

1) RBCs in Northeast China have the standard features of global RBCs and the local particularities. More precisely, the common problems refer to economic-related problems, such as the single industrial structure and the low development of substitute industries (Yu and Cheng, 2016). Particularity refers to the environmental issues caused by exploiting natural resources in Northeast China, including industrial pollution, soil erosion (Tan J. et al., 2017), landslides, ground subsidence (Yu and Cheng, 2016).
2) The challenges faced by RBCs in Northeast China are closely related to their development realities and policy systems. Two of the reasons cannot be ignored. On the one hand, the management policies in the Northeast have brought these cities problems of population exodus, environmental damage, and slow economic growth. On the other hand, the characteristics of RBCs lead to a very difficult transformation of the predominantly mature and declining Northeast China.
3) Based on the plight of RBCs in Northeast China, this paper proposes practical policy recommendations from three perspectives: promoting industrial transformation, considering environmental protection and optimizing the guiding policies.

Compared to former studies, we followed the literature such by Heidenreich (2015), Jawadi and Fitti. (2019), Omolade et al. (2019), Nel and Connelly. (2020), John and Tasciotti. (2020), Ogbonna et al. (2020), and Zhang J. et al. (2022) by adopting the method of the case study. However, compared with previous studies, the contribution of this paper is to supplement the solution of how to solve the common and individual issues faced by RBCs. At the same time, compared with the studies of Reid and Gartrell. (2013), and Mitchell and O'Neill. (2016), our contribution derives from analyzing the possible impact of the severe environmental issues faced by RBCs on the follow-up policies and accordingly putting forward targeted measures to guide various RBCs in developing countries, to achieve sustainable development, just like Sunikka (2006), Liu and Gallagher (2010), Omer (2008) and OECD economic surveys European Union 2009, 2009.

Finally, this paper does not explain why both economic transformation and environmental protection in RBCs in China are still in the exploratory stage, but objectively discusses the current development dilemma of RBCs in Northeast China.

Therefore, in future research, it is necessary to discuss how to combine economic transformation and environmental protection (Yang et al., 2019; Zhang et al., 2021), to be able to predict the future trends of RBCs in China from multiple perspectives. In addition to this, we believe that similar to Wei et al. (2022), how to reasonably plan the future resource development of RBCs with an ambitious carbon neutrality target is also a worthy research direction for the future.

## Author contributions

YQ led the whole design of the manuscript. WG: editing. GC: Writing-Review. YQ wrote the initial drafts. XN and HW:

revision. All authors reviewed the manuscript and provided comments and feedback.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

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# Resource efficiency and environmental impact of juglone in *Pericarpium Juglandis*: A review

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Black walnut (*Juglans nigra*) is considered one of the most valuable plants, with a global production of 3.5 million tons of dried fruit yearly. Throughout the past two millennia, its allelopathic effects have been widely recognized. Black walnuts produce a natural naphthoquinone called juglone, which occurs naturally in all parts of the tree, particularly the green husk, and contributes significantly to the allelopathic effects of black walnut. Except for the fruit's edible nature, the walnut green husk (*Pericarpium Juglandis*) has been used for centuries to make wine, natural dyes, and traditional medicines to cure certain diseases. Within the extracts of walnut green husk, 1,4-naphthoquinones, gallic acid, caffeic acid, and quercitrin were separated and characterized. Among these compounds, the major active ingredient with a good application prospect is juglone, which has proven to be a natural chemical compound with anticancer, antitumor, antibacterial, and antiviral activities, especially the strong anticancer activity. Juglone is also an environmentally friendly biological pesticide and herbicide. Certainly, the environmental impact of juglone also needs to be considered. Significant quantities of walnut green husk are currently produced as a byproduct of walnut production; however, its value has not been fully utilized and explored, which raises environmental concerns. This review attempts to: 1) summarize the origin and historical use of walnut and walnut green husk; 2) introduce the structure, biosynthesis pathway, extraction method, biological activity, and potential applications of juglone, as well as its environmental impact assessment.

KEYWORDS

**Juglone, walnut green husk, anticancer, environmental impact assessment, natural product (NP)**

## 1 Introduction

Walnut is one of the most important dried fruits in the world, and it is from the Juglandaceae family, which is considered one of the oldest cultivated nut species worldwide in human history. The Juglandaceae family consists of two major clades, two tribes, two sub-tribes, seven genera, and about 60 deciduous and monoecious species

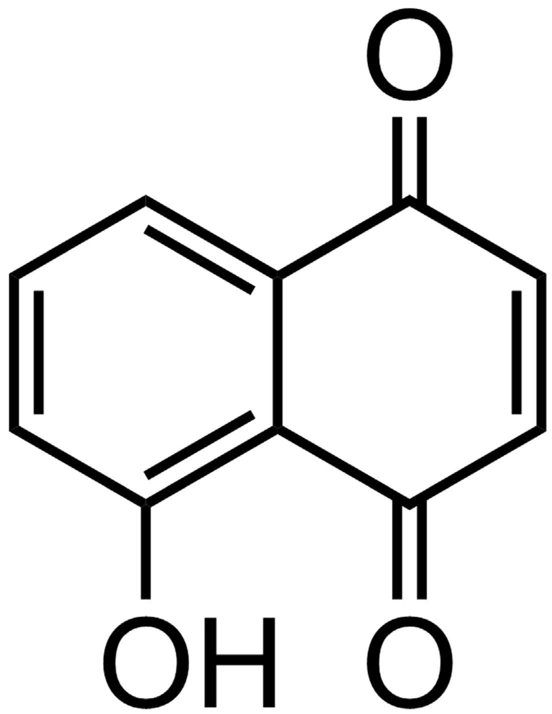


FIGURE 1
The chemical structure of juglone.

(Thakur 2011). Due to its high commercial values, the Juglandaceae family has been artificially cultivated in most temperate regions of the northern hemisphere, including central Asia, the Balkan regions of Europe, the Indian sub-continent, and those on the periphery (Polunin 1977; Manning 1978; Manos and Stone 2001).

Walnut has high nutritional value and health care functions, and the walnut tree has been widely cultivated in more than 50 countries and regions all over the world. In recent years, with the improvement of living standards and enhancement of health awareness, the demand for walnut products is rapidly increasing. According to the data from United Nations Food and Agriculture Organization (FAO), the trading amount of walnuts has increased year by year, and China is one of the most important suppliers of walnuts all over the world. As a matter of fact, China's walnut industry chain has been fully improved from the planting, picking, primary processing and deep processing to a wide variety of walnut and walnut-related products. All of these observations indicate that walnuts manufacturing industry has become the pillar industry in specific regions of China (Liu et al., 2021).

Apart from being used as economic plants, the species in the Juglandaceae family have also been recognized as medicinal plants necessary to cure certain diseases and produce bioactive natural products. In traditional medicine, different parts of walnut trees almost had essential uses. For example, ethanol extracts of green husks (*Pericarpium Juglandis*) had an antihypertensive activity and could inhibit the effects of angiotensin-converting enzyme (ACE) by 40% (Ziai et al., 2006). Moreover, walnut roots were generally used to treat diabetes, its leaves have been used to treat rheumatic pains, fever, diabetes, and skin diseases, and its flowers to treat malaria and rheumatic pain (Mohammadi et al., 2011; Shah et al., 2013; Delaviz et al., 2017).

Juglone (Figure 1), derived from the word "Juglans" as a part of the scientific name for walnut trees, is a substantial natural product existing in *Juglans regia*, *Juglans nigra*, *Juglans cineraria,* and other species belonging to the family Juglandaceae, for example, *Carya olivivaeformis*, *Pterocarya caucarica,* and *Pterocarya stemoptera* (Thomson 1971).

Sina et al. established an RP-HPLC method to determine the juglone content in different species of *Juglans regia* and in different parts of the plant. According to the findings, juglone was found primarily in the green husk (average value of cultivars is about 31.308 mg/100 g, ranging from 20.56 to 42.78 mg/100 g) and leaves (average value of cultivars is about 12.289 mg/100 g, ranging from 5.42 to 22.82 mg/100 g), implying that walnut green husk and leaves are the most important sources of juglone and related walnut phenolics. In addition, the juglone content in green husks is significantly higher than that in the leaves of all cultivars (Cosmulescu et al., 2011).

Furthermore, the allelopathic effects of several species in the Juglandaceae family have been recorded for at least 2000 years. The allelopathic properties, also called "walnut blight," were known to kill or destroy nearby plants (Willis 1985; Jose 2002). However, the cause of walnut blight was almost unknown for centuries until the isolation of walnut lignin from walnut trees for the first time in the 1850's (Vogel and Reinschauer 1856). In 1881, the first scientific paper explaining walnut allelopathy was published (Stickney and Hoy 1881), and in 1887, this "walnut lignin," also called juglone, was first synthesized and characterized (Bernthsen and Semper 1887; Maryon; Strugstad and Despotovski, 2012). Since juglone and related naphthoquinones were rich in walnut green husks, which had allelopathic effects and medical properties, this review first provides a brief overview of the historical uses of walnut green husk and its environmental impact, and then concentrates on the biosynthesis, extraction, properties, and potential uses of juglone as the most important phenolic lignin in the green husk.

## 1.1 Historical uses of walnut green husk

Wine-making is one of the most prestigiously historical uses of walnut green husk; other applications include dyeing and traditional medical use. The Italian nocino (Culpeper 1826) and traditional walnut liqueur (Stampar et al., 2006) were made of black walnut husks. Nocino, a dark-brown liqueur, was made from unripe green walnuts. According to a sixteenth-century publication by Conrad Gessner, nocino was used to relieve pain from wounds and deadly anthrax. Drinking nocino could also make people immune to pestilence and certain diseases (Culpeper 1826). Also, walnut liqueur, rich in phenolic compounds and vitamins, is a truly popular wine in Slovenia. It is reported that the young green walnuts are much appreciated in traditional folk medicine for making an alcoholic wholesome drink–walnut liqueur. This liqueur takes the walnut green husk just before the hardening of the endocarp (Stampar et al., 2006).

Textile and clothing serving as an essential part of human beings' everyday life is one of the most important global industries in the world, which created a value of 3 trillion USD each year, contributes 2% of the entire global gross domestic product (GDP) and employs over 300 million people worldwide (Desore and Narula 2018; Gbolarumi et al., 2021). Natural dyes were used for coloration of various textile industry, as well as cosmetic industry, pharmaceutical industry, food industry, etc. (Yusuf et al., 2017). The green husk, containing valuable phenolics (natural colorants) and quinonoids which are widely dis-tributed and occurs in large numbers in nature ranging from yellow to red, was used as a natural source of dye of long standing (Beiki et al., 2018). Further, several studies indicated that all parts of walnuts could also be used as a dye. For instance, the Romans used the walnut tree for dyeing black fabric. Evidence of dyeing with the walnut tree was also found at Pompeii. Walnut shells from the *Juglans regia* species were found in Viking settlements (Hedeby) and on burial sites (Oseberg), and Vikings used the walnut tree as a dyeing source. In the Middle Ages, the guilds in European countries structured the different steps in the dyeing process and even had a group dedicated to black dye in Germany. With research and studies, books about dyeing were already published in the mid-sixteenth century. Moreover, in India, it can be traced back to the Bhotiya community in Kumaon, where walnut trees were grown extensively throughout Himalayan Uttarakhand. Native Americans also used the Juglans nigra species, the black walnut, which led to the Meskwaki tribe of the Great Lakes being known for producing black dye from the bark (Bose and Nag 2012). This natural dyes are currently classifyied as disperse dyes that are water insoluble dyes and dye polyester and acetate fibres and possess remarkable antimicrobial activity. Sadeghi-Kiakhani et al. (2019) used two natural dyes extracted from Pomegranate peels and Walnut Green husks to dye for wool fibers and achieved antimicrobial finishing of wool fibers. Moreover, it can be used for antimoth finishing and show an quite effective activity in protecting wool fabric against black carpet beetles (Park et al., 2005).

Walnut green husk is a great source of traditional Chinese medicine, with high medicinal value and broad developmental prospects. For over a thousand years, the green husk and its stem bark have been used as a clinical application in traditional Chinese medicine. The medical use of green husk was originally published in *Kaibao Bencao* (the Song Dynasty), which described its effects in tonifying and repairing the essence of the kidney, astringing the lung and reducing the effects of asthma, inhibiting bacteria, suppressing cough, and acting against cancer. These effects have also been documented in *Chinese Materia Medica*. In addition, medicinal applications of husk include fever relief, liver function improvement, and the treatment of eye infections (Li et al., 2022).

Furthermore, allelopathy is an important mechanism for mediating plant interference by introducing secondary products produced by plants into the soil rhizosphere (Weston and Duke 2003). Allelochemicals can be found in all types of plants and tissues and are released into the soil rhizosphere to make sense. Juglone is the most common plant-produced secondary product and allelochemical in walnut. With the exception of juglone, many substances exist in the inner and outer husk, buds, and bark of walnut, including quinones and their derivatives, flavonoids, tannins, diarylheptanoids, triterpenoids, coumarins, phenylpropanoids, and volatile oils. Previous studies identified a total of 83 compounds in the cultivar Persian walnut (Medic et al., 2021a). It was also noted that juglone was not the only allelochemical representation in the extraction from Juglans regia (Medic et al., 2021b). Cui et al. (2012) have investigated the mechanism, and with different polarity solvents, the extraction from the rhizosphere soil, the rhizosphere, and adjacent soil beneath walnut trees, inhibited seed germination and the length of cabbage seedlings than control, indicating the presence of compounds in the rhizosphere soil of walnut trees with allelopathic effects on cabbage. The extractions from different parts of walnut trees have been reported to inhibit rooting of Tomato (Bamel and Gupta 2022) and exhibited strong inhibition against the seed germination and seedling growth of plants, including Wheat, Cabbage, Mung bean (Yan et al., 2012), Ryegrass, Cole, Radish, Shamrock, Cucumber (Zhao et al., 2005), Ballonflower (Xiaobang et al., 2011a), Salvia miltiorrhiza Bunge (Xiaobang 2011) and Scutellaria (Xiaobang et al., 2011b). Sun et al. researched the interaction between juglone and soil microorganisms and proved that juglone inhibited the growth of soil microorganisms, including Gram-positive bacteria, Gram-negative bacteria, fungi, and actinomycetes. Meanwhile, soil microorganisms could promote the decomposition of juglone (Sun et al., 2013).

In addition to allelopathy, which has been observed for at least two millennia, because of its antibacterial (Fernández-Agulló et al., 2013; Han et al., 2021a), antiprotozoal activities have been reported (Jha et al., 2015; Jahanban-Esfahlan et al., 2019) as well as the toxicity and cytotoxicity of quinones (Arasoglu et al., 2017). More and more studies are focusing on using walnut green husk as a natural pesticide, such as bioherbicidal (Soto-Maldonado et al., 2022) and nematicides (Maleita et al., 2022). Moreover, as the dyed hair exhibited appropriate color strength and had excellent morphology, walnut green husk could be used in practice as a natural hair dyeing agent that demonstrated maximum antimicrobial activity compared with semi-synthetic and commercial hair dyes (Beiki et al., 2018). It has also been reported that it is used as a natural dye, and researchers always extract the juglone from walnut green husk using ultrasonic radiation (Han et al., 2018). Thus, this eco-friendly and green tool possesses not only good dyeing properties but also strong antifungal and solar ultraviolet ray protection properties (Ebrahimi and Gashti 2015).

Furthermore, the extraction of the green husk has a long history of use in traditional medicine and has been widely reported to have antitumor properties. As a result, juglone and its derivatives are used to prepare chemotherapeutic agents against malignant brain tumors (Hua and Mao, 2021). It also has anticancer properties, showing proliferation inhibition and apoptosis induction of colon cancer cell lines cultured *in vitro* and the inhibition of gastric cancer cells that grow both *in vivo* and *in vitro* (Bayram et al., 2019; Zhang et al., 2022). In addition, recent studies indicate that juglone has inhibitory efficacy against the main protease of SARS-CoV-2, which has significantly impacted world politics, the economy, human life, and health since 2020 (Cui and Jia 2021).

## 1.2 The environmental impact of walnut

As the most common dried fruit in the world, more than 3.5 million tons of walnuts are produced and commercialized annually. China, the United States, and Chile are the world's largest exporters of walnuts. There are a number of planting areas for walnut in the world, and the global walnut resources are vibrant (Yanyshyn et al., 2020). In the process of walnut production for edible products, there are usually three categories of waste: green husks, walnut shells, and walnut cleaning industrial wastewater. Among the three kinds of waste, green husk and walnut shells, as agricultural solid waste, are the most difficult to treat (Huang et al., 2021; Liu et al., 2021). For the treatment of solid wastes, incineration and landfill are usually adopted. However, they may result in hazards such as fire and explosions, vegetation destruction, unpleasant smell, landfill settlement, groundwater pollution, etc. (ElFadel et al., 1997). Due to their adaptation to the Italian climate and soil, walnut trees are reported to cover more than 6,500 ha in Italy alone. They are used mainly for furniture production, generating a large amount of walnut waste (Cambria and Pierangeli 2012; Doty et al., 2016). In addition, industrial wastewater from walnut husk washing was implied to have damage and inhibition on lettuce (cv) and spinach (radicle) (Ciniglia et al., 2012). Consequently, the peel derelict of hazardous substances from walnut fruit picking and processing has given rise to concerns worldwide (Yang et al., 2014). Currently, there are fewer methods for treating walnut waste, mainly through recycling. Due to the physical characteristics of walnut shell (density, compressive strength, inelasticity, etc.), it is ground and broken to make building materials by filling and mixing, as well as filler to produce modified composite materials (Salasinska et al., 2018; Jannat et al., 2021). Additionally, due to the porosity of walnut shell, it is used as a biological adsorption material and its properties were tested, demonstrating that industrial wastewater can be treated, recycled, and utilized through water treatment methods (Kerrou et al., 2021). However, recycling green husk has become a significant challenge in waste disposal. Since 2010, China has successively issued official documents including "Technical Guidelines for Agricultural Solid Waste Pollution Control," "Guiding Opinions on Accelerating the Development of Agricultural Productive Service Industry," and "Opinions on Comprehensively Strengthening Ecological Environmental Protection and Resolutely, Fighting the Tough Battle of Pollution Prevention and Control." In these issued documents, financial funds were authorized to support the resource utilization of agricultural waste, to carry out green planting and breeding circular agriculture, and to increase forest and grassland ecological protection subsidies, etc. Chinese government has also strived to realize the recycling, reduction and harmlessness of agricultural solid waste. As mentioned earlier, the walnut green husk contains juglone (average value of cultivars is about 31.308 mg/100 g) and other phenolic or quinonoid compounds, which have positive utilization prospects and deserve to be utilized effectively. According to government information, a project in Baoji, Shaanxi Province (located in the southwest of the province), is planned to produce 5 tons of walnut green husk extraction (juglone) per year. The annual revenue of this project is expected to reach 86 million yuan and an annual profit of 13.5 million yuan. Such projects can solve not only solid waste pollution but also generate thriving economic benefits. Thus, it is believed that it will be promoted and applied on a larger scale in the future.

# 2 Biosynthesis, extraction, properties, and potential uses of juglone

## 2.1 The structure and chemical of juglone

Juglone ($C_{10}H_6O_3$) has a scientific name, 5-hydroxy-1,4 naphthoquinone. It is also called regianin as a synonym and a trade name. As shown in Figure 1, the structure of juglone has a bicyclic skeleton with a naphthoquinone functional group. It is made of yellow needles from benzene plus petroleum ether and gives a purplish-red solution in aqueous solutions of alkalis. It has a melting point of 155°C and a solubility that is slightly soluble in hot water, as well as soluble in alcohol, acetone, chloroform, benzene, and acetic acid. As a natural naphthoquinone pigment, juglone exists in the green husks, roots, leaves, bark, and wood of walnuts. Many plants,

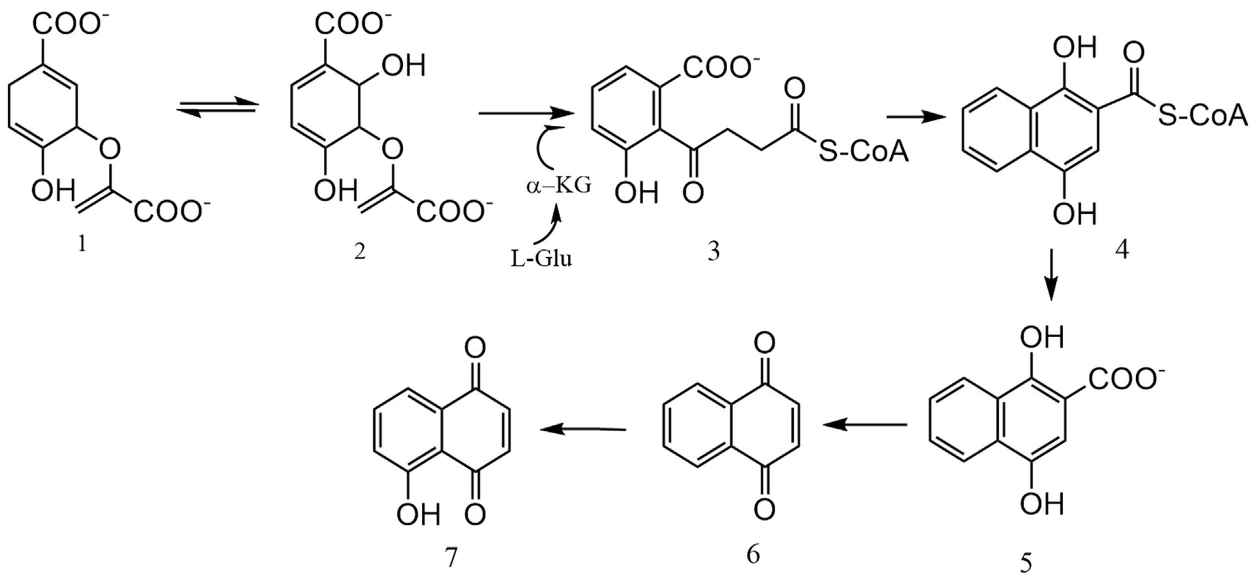


FIGURE 2
Biosynthetic pathway of juglone in walnut (McCoy et al., 2018).

including tomatoes, potatoes, cucumbers, etc., may be damaged or killed when placed within the root zone of juglone-releasing trees due to their chemical properties with allelopathy (Program U. S., 1999).

## 2.2 Biosynthesis of juglone in walnut

The biosynthetic pathway of juglone is shown in Figure 2. All plants synthesize phylloquinone (Vitamin K1), which is required for blood coagulation and bone and vascular metabolism in humans and other vertebrates. In addition, phylloquinone from green leafy vegetables and vegetable oil represents the primary dietary source of vitamin K for humans (Basset et al., 2017). The classical labeling experiments using English walnut leaves for radiotracer studies revealed that the benzene ring of juglone derives from shikimate (Leistner and Zenk 1968). Later labeling experiments revealed that o-succinylbenzoic acid (OSB) and 1,4-dihydroxynaphthoic acid (DHNA) could be incorporated into juglone, which suggests that juglone's quinone ring originates from L-glutamate via α-ketoglutarate pathway (Müller and Leistner 1976). McCoy et al. hypothesized that biosynthesis of juglone's naphthalenoid moiety is shared with biochemical steps of the phylloquinone pathway. They began by using targeted metabolic profiling and comparative RNA sequencing (RNA-seq) to inspect the co-occurrence between 1,4-naphthoquinones (1,4-NQs) natural product pools and the expression of phylloquinone pathway genes in organs of black walnut, the species with the highest content of juglone. Second, they investigated whether stable isotopically labeled glutamate fed to axenic black walnut root cultures is incorporated into juglone with the same mass shift as expected. If so, juglone is derived from an intermediate of the phylloquinone pathway. However, the results fit the previous hypothesis. Using comparative transcriptomics and metabolic profiling, it was observed that phylloquinone pathway genes encoding enzymes involved in DHNA formation are expressed in black walnut roots to support the production of a metabolite other than phylloquinone, demonstrating that labeling DHNA fed to English walnut leaves could be incorporated into juglone. Feeding stable isotopically labeled glutamate to axenic black walnut root cultures revealed that labeling glutamate incorporates juglone with the same mass shift as that expected for phylloquinone, which can reveal that juglone is *de novo* synthesized in black walnut roots from the DHNA derived via the phylloquinone pathway (McCoy et al., 2018).

## 2.3 The extraction and purification of juglone from nature origin.

Due to the limited concentration of juglone in walnut green husks (Han et al., 2018), which essentially affects its biological activity and use, it must be extracted and purified using specific methods. Common methods include vacuum distillation (Molong et al., 2007), supercritical carbon dioxide extraction (Ramezani et al., 2020; Romano et al., 2021), high-pressure solvent extraction (Seabra et al., 2019), microwave-assisted efficient extraction (Sharma et al., 2009; Xu et al., 2016), a combination of ultrasonic and microwave methods (Xu et al.,

TABLE 1 The conditions and effects of different extraction methods.

| Extraction methods | Conditions | Times | Extractive | Yield of juglone | Reference |
|---|---|---|---|---|---|
| Vacuum distillation | Ultrasonic power 300–500 W, temperature 30–50°C | Extraction time 10–30 min | 1,4-naphthaoquinone/ 5-hydroxy-1,4-naphthaoquinone/ 5-hydroxy-1,4-naphthaoquinone | 0.09% | Molong et al. (2007) |
| Supercritical carbon dioxide extraction | $p$ = 300 bar, T = 50°C, flow = 10 ml $min^{-1}$ | Extraction time 195 min | Juglone, Ferulic acid, Syringic acid, Hydroxybenzoic acid | 1192.04 ± 17.26 mg/100 g | Romano et al. (2021) |
| High-pressure solvent extraction | 45°C and 30 MPa (maximum juglone yield) | 1st step (8.7–17.6 min) 2nd step (21.5–126.6 min) | Juglone, 1,4-naphthoquinone, isosclerone, neophytadiene, etc. | 0.39–2.34 mg/g | Seabra et al. (2019) |
| Microwave-assisted efficient extraction | 150 W microwave power and 50°C temperature | Extraction time 20 min | Juglone, Gallic acid, Caffeic acid, Quercitrin, Myricetin, Quercetin | 0.0147% (ethyl acetate solvent)/ 0.0029% (methanol solvent) | Sharma et al. (2009) |
| Combination of ultrasonic and microwave methods | solvent to sample ratio 300:1 and ultrasonic power 600 W | Ultrasonic time 25 min, microwave time 90 s | Juglone | 624.2–840.9 μg/g | Xu et al. (2016b) |
| Using macroporous resin | Static adsorption (Sealed on a 175 r/min shaker at 25°C) | Adsorption for 12 h, desorption for 12 h | Juglone with high purity after separation by D101 macroporous resin | Maximum adsorption rate 81.85%, desorption rate 76.5% | Ma et al. (2016) |
| | Dynamic adsorption (different flow rate) | The flow rate was 1.0 ml/min; the elution rate was 0.33 ml/min | | | |

2016), and even using resin (macroporous resin) (Ma et al., 2016). The extraction effects of the above six methods are shown in Table 1. It can be observed that the different extraction methods and solvents have significant effects on phenolic components and the antioxidant capacity of walnut extract (Trandafir et al., 2017).

## 2.4 The biological activity and potential use of juglone.

As a natural product, juglone exhibited striking anticancer, antibacterial, and antiviral activities. In recent years, pesticides and herbicides containing juglone as the main ingredient have also been developed. Due to its antiplatelet aggregation properties, it has long been used for dyeing and as an effective medicine for treating high blood pressure.

### 2.4.1 Anticancer

Nowadays, a number of studies have been conducted to evaluate the anticancer activity of juglone. In addition, juglone derivatives were also designed, synthesized, and tested for anticancer activities. The anti-cancer mechanisms of juglone can be classified as inhibition of tumor cell proliferation, induction of autophagy, antiangiogenesis via inhibiting vascular endothelial growth, inhibition of tumor cell migration and invasion, and others including antiplatelet and inhibition of cellular transformation through PI3K (Phosphati-dylinositide 3-kinases) signaling, inhibition of protein SUMO1-sumoylation (Small ubiquitin-related modifier 1- sumoylation), promotion of DNA damage, inhibition of the growth of cancer stem cells (CSCs) and enhancement of immune function (Tang et al., 2022). For instance, juglone exhibited potent anticancer activity against human cervix cancer (Zhang et al., 2012), breast cancer (Ji et al., 2016), prostate cancer (Mahdavi et al., 2019), colon cancer (Seetha et al., 2020), gastric cancer (Zhang et al., 2022), pancreatic cancer (Narayanan et al., 2022), ovarian cancer (Fang et al., 2015), and several kinds of glioblastomas (like malignant gliomas). So far, twenty-seven naphthoquinones and derivatives have been extracted and identified from walnut green husks. The results from biological evaluation indicated that a few derivatives inhibited the growth of HepG-2 human cancer cells bearing a juglone skeleton (Figure 3), with the $IC_{50}$ values below 22.38 μM (Table 2). Other structurally different naphthoquinones possessed lower cytotoxic activities, with the $IC_{50}$ values far beyond 56.87 μM or without any cytotoxic activity (Zhou et al., 2015). Shi et al. investigated the anticancer activity of juglone against OVCAR-3 ovarian cancer cells, and the results demonstrated that juglone significantly inhibited the growth of OVCAR-3 with an $IC_{50}$ of 30 μM. Juglone displayed an $IC_{50}$ value of 100 μM against human normal SV40 ovarian cells. The results indicated that juglone was a somewhat selective anti-ovarian cancer drug candidate. In addition, the mechanistic investigations implied that juglone caused nuclear fragmentation of the OVCAR-3 cells, leading to the apoptosis of cancer cells. At 60 μM, the percentage of the apoptotic OVCAR-3 cells increased from 2.15% in control to 45.24%. Moreover, upon incubation, juglone caused an upsurge in the Reactive Oxygen Species (ROS) levels in OVCAR-3 cells. It suppressed the migration and invasion of the OVCAR-3 cell, demonstrating the benefit of juglone in ovarian cancer treatment (Shi et al., 2020). Bayram et al. investigated the antiproliferative

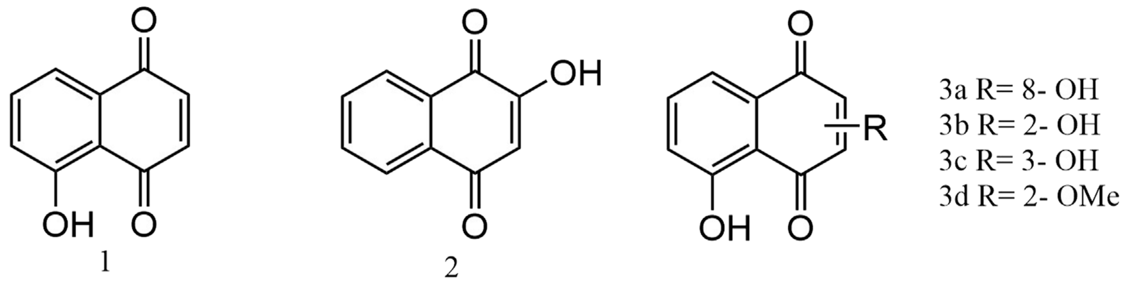


**FIGURE 3**
Chemical structures of anticancer compounds with juglone skeleton.

**TABLE 2** The $IC_{50}$ value of the compounds bearing juglone skeleton.

| Compound | $IC_{50}$ for HepG-2 (μM) | Standard deviation | Reference |
|---|---|---|---|
| 1 | 8.14 | 1.95 | Zhou et al. (2015) |
| 2 | 18.83 | 2.98 | |
| 3a | 15.37 | 1.63 | |
| 3b | 7.33 | 0.52 | |
| 3c | 22.38 | 0.66 | |
| 3d | 56.87 | 4.27 | |

activity of juglone against CCL-228-SW-480 colon carcinoma cells and found that the growth inhibition rate was higher in the CCL-228-SW-480 cells treated with juglone compared to control cells. The natural naphthoquinone significantly inhibited cellular proliferation and induced the apoptosis of CCL-228-SW-480 cells *in vitro* (Bayram et al., 2019). Furthermore, based on the chemical structure of juglone, several novel hybrids were synthesized by Mallavadhani et al. and were evaluated for their anticancer activities against seven human cancer cell lines, including the cervix (ME-180 and HeLa), breast (MCF-7, MDA-MB-453, and MDA-MB-231), prostate (PC-3), and colon (HT-29) cells *in vitro*. The results showed that most of the synthesized compounds exhibited strong anticancer activities. Two compounds, in particular, demonstrated more potent antiproliferative activities against prostate and breast cancer cells than etoposide as the positive control (Mallavadhani et al., 2014). In addition, juglone could potentiate the anticancer activity of certain compounds against the proliferation of cancer cells. Arikoglu et al. evaluated the synergistic effects of Juglone-Selenium combination on invasion and metastasis in PANC-1 and BxPC-3 pancreatic cancer cell lines and suggest that the combination has a cytotoxic and dose-dependent suppressive effect on invasion and metastasis of these two pancreatic cancer cells (Arikoglu et al., 2022). Nowadays, with the development of nanomaterials and nanoscience, juglone nanoparticles have been prepared to increase the anticancer activity of juglone. Zhao et al. created juglone-loaded metal-organic frameworks, JMIL101NPs, by encapsulating juglone into porous Fe-based MOFs and then coating them with a cell membrane for homologous tumor-targeting capability. The mechanism of this drug is that the pH-responsive NPs will degrade to selectively release anticancer juglone once they reach the intracellular environment. On the one hand, the released juglone can inhibit Pin1 activity, causing apoptosis. On the other hand, intracellular $H_2O_2$ levels will be elevated based on the juglone-mediated electron reduction cascade reaction spontaneously. The results showed that, both *in vitro* and *in vivo*, the usage of this nanoparticle with metal-organic frameworks could activate the cascade to provide sufficient $H_2O_2$ with outstanding antitumor efficacy (Zhao et al., 2022).

### 2.4.2 Antibacterial

Juglone demonstrated excellent antibacterial activities by inhibiting the formation of bacterial or fungal biofilms or by inducing abnormal oxidative stress and DNA insertion (Gumus et al., 2020). The function object includes *Escherichia col*i (Wang et al., 2016a), *Staphylococcus aureus* (Wang et al., 2016a), Oral Pathogens (Jeon et al., 2009) (including *Porphyromonas asaccharolytica*, *Porphyromonas gingivalis*, *Streptococcus mutans*, *Streptococcus sobrinus*, *Actinomyces viscosus*, *Streptococcus salivarius*, *Lactobacillus rhamnosus*) etc. And the

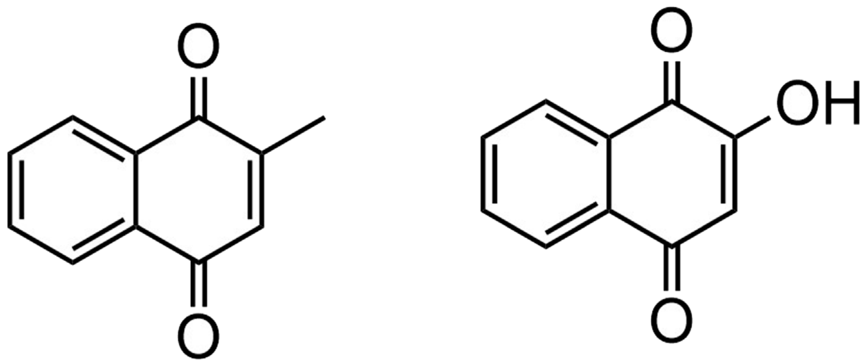
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FIGURE 4
Menadione (1) and 2-Hydroxy-1,4-naphthoquinone (2).

TABLE 3 The antibacterial activities of juglone.

| Bacterial species | Gram-negative/Gram-positive bacterium | Bacterial distribution | Activity of juglone | Reference |
|---|---|---|---|---|
| *Escherichia coli* | Gram-negative | Commonly found in the gut of warm-blooded organisms | MIC = 75 μg/ml | (Yuan 2009; Wang et al., 2016b) |
| *Staphylococcus aureus* | Gram-positive | Parasitic on human and animal skin, nasal cavity, throat, stomach, etc | MIC = 37.5 μg/ml | Yuan (2009) |
| *Porphyromonas asaccharolytica* | Gram-negative | | MIC = 0.25 mg/disc | |
| *Porphyromonas gingivalis* | Gram-negative | | MIC = 0.25 mg/disc | |
| *Streptococcus mutans* | Gram-positive | | MIC = 0.25 mg/disc | |
| *Streptococcus sobrinus* | | Human or animals oral Pathogens | MIC = 0.10 mg/disc | Jeon et al. (2009) |
| *Actinomyces viscosus* | | | MIC = 0.10 mg/disc | |
| *Streptococcus salivarius* | | | MIC = 0.10 mg/disc | |
| *Lactobacillus rhamnosus* | | | MIC = 0.5 mg/disc | |

activities are shown in table 3. In addition, Han et al. examined the inhibitory effects of juglone against *Pseudomonas syringaepv Actinidiae* (*P. syringae*) and found that juglone, at a concentration of 20 μg/ml, exhibited significant inhibition against *P. syringae* (107 CFU/ml). It was also found that upon the application of juglone, the permeability and integrity of the cell membrane of *P. syringae* were damaged. In addition, juglone not only caused abnormal intracellular oxidative stress but also became embedded in genomic DNA and affected the normal function of DNA in *P. syringae*. Moreover, the environmental scanning electron microscopy results indicated that juglone efficiently restricted extracellular production and prevented cell membrane formation (Han et al., 2021a). The authors also evaluated the activity of juglone against the drug-resistant *Pseudomonas aeruginosa* (*P. aeruginosa*). It was found that juglone destroyed the permeability and integrity, induced the abnormal accumulation of ROS in cells, and affected the formation of cell membranes. The RT-qPCR study showed that five virulence genes and two genes that participated in the production of extracellular polymers were blocked by juglone to decrease the toxicity and infection of *P. aeruginosa* and prevent the extracellular polymers. Additionally, the juglone nanoparticles have been used for antibacterial assays (Han et al., 2021b). Several experiments have demonstrated that the antibacterial activity of nanoparticles is superior to that of free juglone (Arasoglu et al., 2017). For example, Gumus et al. (2020) prepared juglone nanoparticles using a single emulsion solvent evaporation method and studied their effects against *Candida albicans* and biofilms, which were compared with free juglone and fluconazole. The result showed that the less active juglone nanoparticles could achieve a similar inhibition due to controlled release. For pre-established biofilms, juglone nanoparticles were shown to strongly inhibit it, which demonstrated that juglone encapsulated nanoparticles were much more effective.

### 2.4.3 Antiviral

Compared to anticancer and antibacterial activities, there are relatively fewer assays on the antiviral activity of juglone. Acquired immunodeficiency syndrome (AIDS) caused by the human immunodeficiency virus (HIV) is the most difficult to treat. During the life cycle of HIV, the reverse transcriptase (RT) enzyme is the most significant factor in viral replication. The enzyme mainly has the following activities: RNA-dependent DNA polymerase (RDDP) activities, DNA-dependent DNA polymerase (DDDP) activities, and ribonuclease H (RNase H) activity, respectively. Min et al. discovered a series of natural products capable of selectively inhibiting RNase H activities. These naturally occurring compounds include benzoquinones, naphthoquinones, anthraquinones, and diterpenoid quinones. In addition, the naphthoquinone juglone demonstrated potent inhibitory activity against RDDP. It also exhibited an $IC_{50}$ value of 5 μM against DDDP. The results indicated that juglone is a bi-target inhibitor against the replication of HIV. Conversely, its single hydroxylated derivative demonstrated much lower inhibitory potency against RNase H activities with an $IC_{50}$ value of only 95 μM (Min et al., 2002). Relevant studies have also been conducted employing computational molecular simulations to explore the antiviral activity of juglone (Vardhini 2014), and the molecular docking studies between juglone and surface glycoproteins of *Influenza viruses* were also investigated (Yang et al., 2013). Recent studies indicate that juglone has inhibitory activity against the main protease ($M^{pro}$) of SARS-CoV-2, contributing to the replication and transcription of SARS-CoV-2 in host cells. This study synthesized a series of 1,4-naphthoquinones with a juglone skeleton and evaluated their inhibitory efficacy against SARS-CoV-2 $M^{pro}$. The results showed that more than half of the tested naphthoquinones exhibited potent inhibition against the target enzyme, with an inhibition rate of more than 90% at a concentration of 10 μM. The results from *in vitro* antiviral activity evaluations showed that the most potent $M^{pro}$ inhibitor could significantly restrict the replication of SARS-CoV-2 in Vero E6 cells with an $EC_{50}$ value of about 4.55 μM; however, without any toxicity towards the host Vero E6 cells under tested concentrations (Cui and Jia 2021). The research results provided the rational basis for further research and development of new drug candidates for the SARS-CoV-2 epidemic.

### 2.4.4 Juglone as a natural pesticide

Researchers have been widely concerned about walnut blight (Meyer et al., 2021; Motmainna et al., 2021). However, with the extraction and isolation of different walnut parts, the allelopathic effects of juglone have been widely reported and gradually developed into green pesticides (Soderquist 1973; Rietveld 1983; Rietveld et al., 1983). It was reported that at high concentrations, juglone could be toxic to associated plants, which Macias thought was a natural alternative for weed control and was developed as a natural pesticide (Macias et al., 2007). Some naturally occurring and semi-synthetic naphthoquinones with naphthoquinone backbones were proposed for barnyard grass and perennial ryegrass allelopathy. And some of them showed strong inhibitory effects on root length, indicating their potential as models in the development of natural herbicides (Duran et al., 2019). In addition, the insecticidal effect of juglone, its disturbance in the metabolic profiles of *Aphis gossypii* (Lv et al., 2018), and the acaricidal and enzyme inhibitory activities of naphthoquinones and their analogs against *Psoroptes cuniculi* (Shang et al., 2018) have been reported, indicating that juglone can be used as a potential alternative bio-acaricide in agriculture.

### 2.4.5 Miscellaneous

In addition to the above-mentioned biological activities, many studies have reported its application in dyeing. Juglone is an environmentally friendly natural dye that imparts a natural red-brown color (Waseem ul et al., 2021) and has better dyeing performance with sodium sulfate as a mordant (Han et al., 2018). It exhibited antibacterial activity and also reduced UV absorption to achieve a protection effect (Ebrahimi and Gashti 2015). Based on the dyeing activity, juglone demonstrated the potential to be a natural colorant for biodegradable polymers (polylactide and polyhydroxybutyrate), with no change in the properties of the polymers, including mechanical properties and thermal stability (Latos et al., 2019). Moreover, it can be used as an antihypertensive agent that exerts its antihypertensive effect through vasorelaxation, which is mediated by nitric oxide, inhibition of intracellular calcium release, and opening of $K^+$-channels (Ahmad et al., 2020). Similarly, it can be used to design and develop collagen with juglone functionalized silver nanoparticles as a novel wound dressing material with the potential to be used in rapid wound closure (Natarajan and Kiran 2019). Trypanosomiasis (including American trypanosomiasis and African trypanosomiasis caused by *Trypanosoma cruzi* and *Trypanosoma brucei*) is a serious illness that is eventually fatal if not treated and has variable surface antigens which makes it non-availability of vaccines against trypanosomes. Rani et al. have researched the juglone and their derivatives as potential drug molecules against trypanosome parasites and enumerated the antitrypanosomal properties of more than 30 compounds which all showed excellent activities (Rani et al., 2022). Furthermore, more advanced research also involves electrochemistry, renewable-juglone-based high-performance sodium-ion batteries developed by a renewable-biomolecule-based electrode. Also, the hybridized electrodes can be fabricated with arbitrary size and shape and exhibit superior capacity and cycle performance, which is expected to find application in future energy-storage devices (Wang et al., 2015).

## 3 Environmental impact of juglone

Naphthoquinones, a group of highly reactive organic chemical species, are found in the environment as byproducts of fuel combustion, tobacco smoke, and plants. Juglone is the primary derivative of 1,4-naphthoquinones and 1,2- and 1,4-naphthoquinones, which are toxic metabolites of naphthalene, the major polynuclear aromatic hydrocarbon present in ambient air. When exposed to the environment, they interact with biological systems and induce toxicity (Kumagai et al., 2012). For example, relevant particles less than 2.5 μM in diameter activate the epidermal growth factor receptor (EGFR) system (Blanchet et al., 2004), causing structural damage to the bronchial epithelium and triggering asthma (Davies et al., 2003).

### 3.1 Effects of juglone on marine organisms

Juglone (5-hydroxy 1,4-naphthoquinone) and also its derivative plumbagin (5-hydroxy-2-methyl-1,4-naphthoquinone) were reported to have the most significant toxicity against most aquatic organisms (Wright et al., 2007a). Juglone was reported to be an apparent fish toxicant (Marking 1970), which demonstrated that at concentrations ranging from 27 to 88 ppb within a 96-h treatment period, juglone was highly toxic to nine species of fish, including rainbow trout (*Salmo gairdneri*), northern pike (*Esox lucius*), goldfish (*Carassius auratus*), carp (*Cyprinus carpio*), whitesucker (*Catostomus commersoni*), black bullhead (*Ictalurus melas*), channel catfish (*Ic-talurus punctatus*), green sunfish (*Lepomis cyanellus*), and bluegill (*Lepomismacrochirus*). Juglone has been shown to be toxic to *Tetrahymena pyriformis (T. pyriformis),* and it has almost the highest toxicity of the eight naphthoquinones. It was also concluded that the quinone toxicity was not related to hydrophobicity or the oxidative stress mechanism, with the initiation of cell damage rooted in the ability of the quinone to form free-radical metabolites such as semiquinones (Schultz and Bearden 1998). Juglone also exhibited toxicity toward other marine organisms such as *Glenodinium* (the chloroplast deterioration was apparent after 7 days of exposure), *phytoplankton* (juglone concentrations as low as 0.1 mg/L inhibited phytoplankton growth), and *Vibrio fischeri* (the toxicity could reach as low as 0.005 mg/L) (Wright et al., 2007b). In addition, the possible toxicity of *Daphnia magna (D. magna)*, a *planktonic crustacean*, plays a vital role in aquatic food webs. Though there is no direct experimental evidence, the derivative and isomeride of juglone, menadione, and 2-hydroxy-1,4-naphthoquinone (Figure 4) have been reported to be toxic to *D. magna*, with the 48 h $EC_{50}$ of 0.531 mg/L (very toxic) and 20.297 mg/L (harmful), respectively (Song et al., 2011). Moreover, these two compounds have also been reported to be toxic to zebrafish (*Danio rerio*), with a 96 h $LC_{50}$ of 0.178 mg/L (very toxic) and 25.752 mg/L (harmful), respectively (Song et al., 2010). Another study found that both compounds are toxic to *Chlorella pyrenoidosa,* with a 72 h $EC_{50}$ of 5.367 mg/L (toxic) and 18.485 mg/L (harmful) (Guo et al., 2010). The toxicity of chemicals for the above three assays was classified into three classes according to the guidelines of the European Chemicals Bureau (European, Commission and Fang 1996) and the Organization for Economic Co-operation and Development (OECD 2002). However, a study indicated that 1,4-Naphthoquinone derivatives showed no toxicity toward zebrafish embryos, indicating the need for further research (Janeczko et al., 2018).

### 3.2 Effects on animals

Researchers have suggested that juglone could completely inhibit the formation of rat aortic new vessels, reduce the number of endothelial cells, stimulate the existing blood vessels in the chorioallantoic membrane of chick chorioallantoic, and have vascular stimulation, hemolyzation, and agglutination in a dose-dependent manner, with the inhibition of angiogenesis at a concentration of 12.5 mumol/L, indicating that juglone can inhibit the formation of new vessels (Chen et al., 2010). According to previous studies, juglone can inhibit the development of bovine oocytes by directly inducing ROS accumulation, apoptosis, and mitochondrial dysfunction (Mesalam et al., 2021). The toxicity of juglone to isolated rat hepatocytes has been evaluated previously. Both 5-OH (5-OH-1,4-NQ the juglone) and 2-OH (2-OH-1,4-NQ the lawsone) -1,4-naphthoquinone induced concentration-dependent cytotoxicity to isolated rat hepatocytes accompanied by intracellular glutathione depletion. Furthermore, the mechanism of juglone toxicity involves the formation of its corresponding naphtho semiquinone, active oxygen species, and redox cycling, as it stimulates a disproportionate increase in both microsomal NADPH oxidation and oxygen consumption (d'Arcy Doherty et al., 1987). Another study also investigated the effect of hydroxy substitution on 1,4-naphthoquinone toxicity in cultured rat hepatocytes. The findings revealed that the toxicity of the quinones decreased from 5,8-dihydroxy-1,4-naphthoquinone > 5-hydroxy-1,4-naphthoquinone > 1,4-naphthoquinone > 2-hydroxy-1,4-naphthoquinone. Further tests showed that the toxicity of 1,4-naphthoquinone and 5-hydroxy-1,4-naphthoquinone has an electrophilic addition component, whereas the toxicity of 5,8-dihydroxy-1,4-naphthoquinone is due to free radical formation (Ollinger and Brunmark 1991). Furthermore, the complexes based on the juglone ($Fe_{(III)}$ and $Fe_{(II)}$) were toxic to isolated rat hepatocytes within the naphthoquinone series, with the order of toxicity being $Fe_{(II)}$ > parent naphthoquinone > $Fe_{(III)}$. The juglone complex had higher toxicity than the lawsone complex, and the juglone complex facilitates the formation of stable semiquinone species (Kumbhar et al., 1996). Additionally, it has been concluded that the isomeride 2-hydroxy-1,4-naphthoquinone has hemolytic activity and nephrotoxicity in rats (Munday et al., 1991). Beyond these, the derivatives of juglone, 2-hydroxy-3-alkyl-1,4-naphthoquinones (Munday et al., 1995a), 2,3-dialkyl-1,4-naphthoquinones (Munday et al., 1995b), etc., have also been reported to be toxic to animals, indicating that the biotoxicity of juglone and its derivatives should be given significant consideration.

## 4 Discussion

According to previous studies, more than 3.5 million tons of walnuts are produced worldwide annually. Consequently, walnut green husks, an abundant byproduct of dry fruit production, have not been fully explored and utilized, and their value has also not been fully recognized and developed.

This review describes in depth the historical application and environmental impact of walnuts (Juglans regia) and walnut green husks. The natural naphthoquinone juglone, produced in walnut green husks, contributed to the biological activity of the husk. Its structure, biosynthesis pathway, extraction method, biological activity, and potential application were also discussed, as well as its environmental impact assessment.

Juglone is natural product, which was isolated from the husks, leaves, roots of walnut trees and efficient synthetic methods of the natural naphthoquinone have also been developed in recent years (Shvydkiv et al., 2012; Pasha et al., 2022). Juglone exhibited potent anticancer, antibacterial, and antiviral activities as a natural naphthoquinone. With the development of nanotechnology that described above (Arasoglu et al., 2017; Natarajan and Kiran 2019; Sadeghi-Kiakhani et al., 2019; Gumus et al., 2020) and the gradual discovery of synergistic effects ((Arikoglu et al., 2022)), the biological activities of juglone have been greatly improved. However, due to the lack of clinical applications, clinical studies of juglone should be further explored (Tang et al., 2022). It is also an environmentally friendly biological pesticide and herbicide, which offers a new option for developing novel natural product-based effective pesticides and agrochemicals. This chemical is a major component of the yellow-orange pigment for dyeing. All of these properties suggest an excellent application prospect for this natural naphthoquinone. However, its impact on environmental ecosystems should be further investigated, especially for marines and animals, and the mechanisms therein should also be explored significantly.

Juglone occurs naturally in all parts of walnut trees, especially in the green husk, and the dry fruit industry generates vast quantities of green husks as a byproduct. Therefore, its potential use should be developed to avoid producing solid waste as well as reduce wastewater production. As an allelochemical product, juglone produced by walnut trees should also be investigated for its applications across various agricultural applications, as conventional synthetic pesticides and agrochemicals pose severe environmental threats to contemporary agriculture. Establishing an efficient extraction method for juglone from green husks and using this allelochemical as a green pesticide to meet consumer needs for greener and more sustainable agricultural solutions should be one of the resolutions to reduce the environmental impact of a huge amount of green husks. The most significant aspect is that this natural active ingredient can be used in many fields to maximize the use of natural resources and improve the efficiency and quality of resource utilization. Unquestionably, it is crucial that we pay more attention to this deep-seated utilization of natural resources.

## Author contributions

The conception and design of this review was primarily done by the first author and supervised by the two corresponding authors. The first and second authors collected literature and data together. The paper writing and the drawing of the pictures used in the paper are done by the first author and the second author. Corresponding author Pro. JC guided the two authors to complete the revision and improvement of the paper.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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# Paths to carbon neutrality in china's chemical industry

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Chemical industry is an important pillar industry of China's economy with high energy consumption and carbon emissions. In the context of "peaking carbon emissions and carbon neutrality" target in China, it is imperative for the chemical industry to reduce carbon emissions. Based on literature on carbon emission reduction path and the analysis of the development status of chemical industry, this paper identifies the opportunities and challenges of carbon emission reduction in the chemical industry and proposes several feasible paths for China's chemical industry to achieve carbon neutrality.

KEYWORDS

**chemical industry, carbon neutrality, carbon emission reduction path, CCUS, technology**

## 1 Introduction

The report Climate Change 2022: Impacts, Adaptation and Vulnerability released by the United Nations Intergovernmental Panel on Climate change (IPCC, 2022) in 2022 shows that climate change will have negative impacts on most species, and some of the ecological losses caused by climate change are irreversible or nearly irreversible (IPCC, 2022). As the social, economic and ecological environment problems caused by climate change have become more and more serious, the international community also pays more attention to carbon emission reduction. As a large developing country, China has also actively promoted carbon emission reduction and put forward the influential "peaking carbon emissions and carbon neutrality" target, that is, China will strive to reach the peak of carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. Since then, the Chinese government has issued a series of policy documents to guide and urge all production sectors to reduce carbon emissions. For example, the fourteenth Five-year plan for National Economic and Social Development of the People's Republic of China and the outline of long-term goals for 2035 propose that during the "fourteenth five-year plan" period, energy consumption and carbon dioxide emissions per unit of GDP should be reduced by 13.5% and 18% respectively; The Opinions on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job on carbon peak and carbon neutralization have systematically deployed the carbon peaking and carbon neutralization work (General Office of the Communist Party of China Central Committee, 2021); Action Plan for Carbon Dioxide Peaking Before 2030 clearly requires that the industrial structure and energy structure must be developed in a clean manner, and the energy utilization efficiency of key industries needs to be greatly improved (The State Council Of the People's Republic of China, 2021). China's deployment and planning of carbon emission reduction are gradually specific and in-depth.

As a pillar industry of economic development, the chemical industry is a typical industry with high energy consumption, high pollution, and high carbon emissions (Gu et al., 2013). Under the background of low-carbon economic development, the chemical industry is facing great pressure on carbon emission reduction, which also means that the chemical industry has rich potential in carbon emission reduction. The path of carbon emission reduction and achieving carbon neutrality in the chemical industry has become one of the research focuses internationally.

In this paper, Section 2 summarizes research on carbon dioxide emission reduction in chemical industry; Section 3 analyzes the current development status of chemical industry in China; Section 4 identifies major opportunities and challenges for chemical industry in China under the national carbon neutrality goal. Finally, Section 5 discusses paths and policy implications.

## 2 Manuscript formatting

### 2.1 Relevant research on carbon emission reduction paths in chemical industry

At present, many scholars have studied the carbon emission reduction measures in chemical industry. In the short term, the main measures to reduce carbon dioxide emissions from coal chemical industry are the application of advanced technology and the elimination of backward production capacity. The main measures to reduce carbon emissions in the medium and long term, however, are to promote the transformation of energy structure and to improve of energy efficiency (Huang et al., 2019). At the same time, improving the circularity of resources and promoting value chain collaboration can also reduce carbon emissions (ECF, 2014).

Some studies focus on the comparative analysis of the role of advanced technology on carbon emission reduction in chemical industry. For example, the mixed SD-LEAP model is used to compare the carbon dioxide emissions and emission reduction potential of the South Korea's oil refining industry under different technology scenarios (Park et al., 2010). Other studies use scenario analysis to examine the impacts of technological improvement on carbon dioxide emission reduction in China's chemical industry (Zhu et al., 2010). However, some studies have found that the reduction of carbon dioxide emissions brought by technological improvement cannot offset the increase of carbon dioxide caused by scale effect (Liang and Zhang, 2013), while optimizing the energy structure can promote carbon emission reduction (Fan et al., 2013). Carbon capture and utilization (CCU) also has the technical potential to achieve carbon neutrality in the chemical industry, but it will also lead to a massive increase of demand in greenhouse gas emits from low-carbon electricity (Kätelhön et al., 2019), and the technical cost of carbon capture and storage (CCS) is very expensive (The European Chemical Industry Council Cefic, 2013). Griffin et al. (2018) believes that promoting CCS, improving energy efficiency, the use of bioenergy and other key technologies are considered to be the keys to effectively reduce carbon emissions. Gabrielli et al. (2020) evaluated three technology paths (CCS path, CCU path and BIO path (Use of biomass for particular purposes in the production of chemicals)) which can achieve carbon neutrality in the chemical industry in a qualitative and quantitative way and analyzed the advantages and disadvantages of each technology path.

Other studies have discussed the possible ways of emission reduction in the chemical industry from a more comprehensive perspective of project technology management and information management, such as improving project standardization, strengthening the training of professional technicians, and establishing enterprise energy-saving information platform (Wang, 2008). In addition, based on the concept of circular economy, eco-industrial parks can also reduce the carbon emissions from chemical enterprises by realizing rational allocation and efficient utilization of resources (Gao et al., 2009).

### 2.2 Development status of chemical industry in china

China is one of the largest producers and consumers of chemical products in the world (Lin et al., 2012). Due to the large scale of the chemical industry and a wide range of products, different studies define the scope of the chemical industry differently. Referring to the method of Wei et al (2018), the statistical caliber of the chemical industry in this paper is chemical raw materials and chemical products manufacturing (except Figure 2). Although the number of enterprises in the chemical industry has remained generally stable since 2011, the assets of the chemical industry have shown an upward trend (Figure 1). By 2020, the number of chemical industry enterprises in China has reached 22,008, with total assets of 7,865.15 billion yuan. According to Figure 2, the growth rate of the added value of China's chemical industry has been in a downward trend since 2011, falling from 14.8% in 2011 to 3.4% in 2020. In 2021, the growth rate is estimated to be 7.4% (National Development and Reform Commission, 2021).

From the perspective of the product structure of the chemical industry, China has a high proportion of low value-added and rough-processed chemical products, showing the current product structure of low-end surplus and high-end shortage.

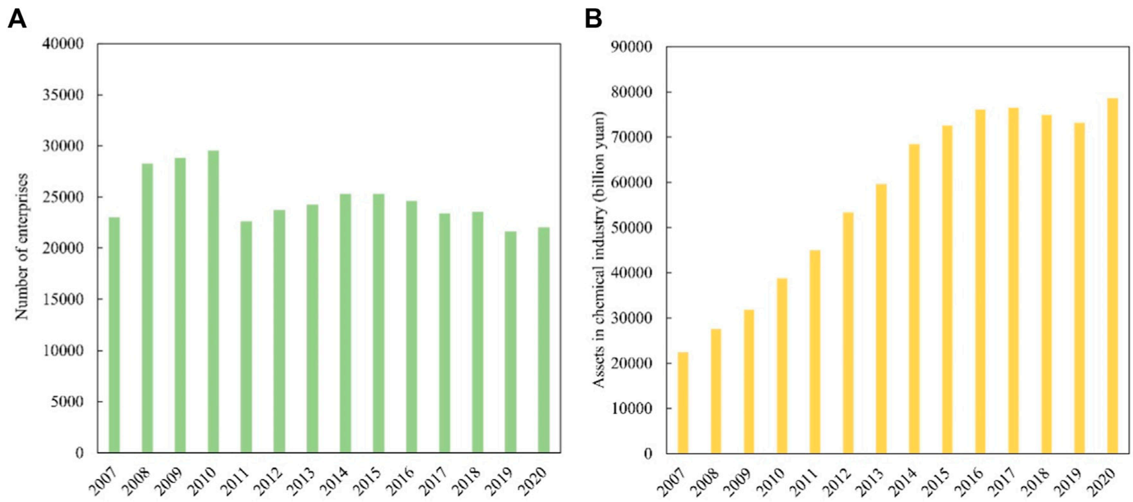


FIGURE 1
Number of enterprises **(A)** and total assets **(B)** in the chemical industry (Data source: China Statistical Yearbook).

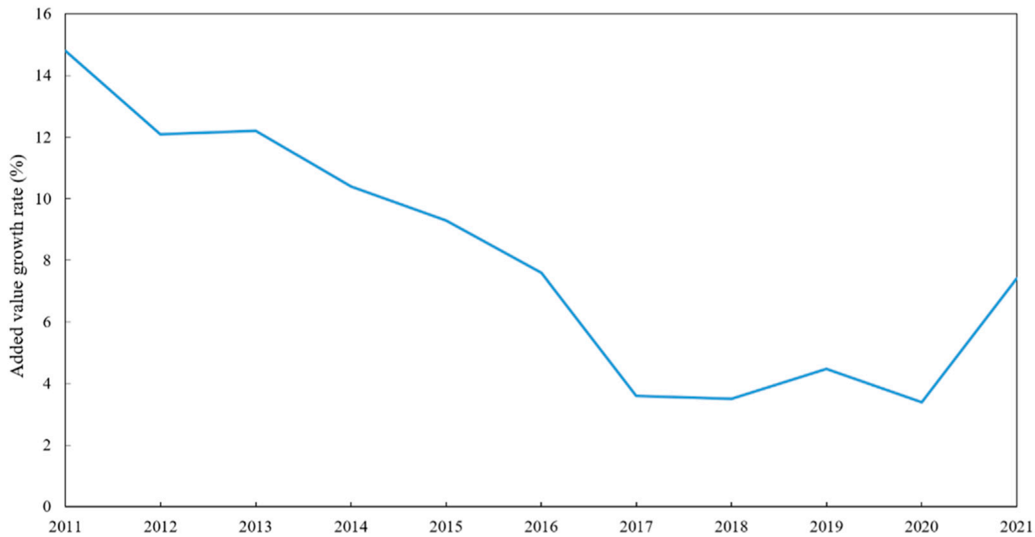


FIGURE 2
Growth rate of added value of chemical industry (Data source: https://www.ndrc.gov.cn/fggz/jjyxtj/hgjjyx/?code=&state=123)

On the whole, there is a gap between China and developed countries in terms of the diversity and quality of chemical products (Wang and Li, 2018). It can be found that the production process technology of China's chemical products is still relatively backward, and the negative impacts of chemical products on the environment is significant. Methanol, synthetic ammonia, oil refining, ethylene, and modern coal chemical industry are the top five key emission sub-industries of China's chemical industry (Wen et al., 2022). Generally speaking, since 2005, the carbon emissions of China's chemical industry have fluctuated and increased, reaching a peak of 593.89 million tons in 2015, accounting for 18.46% of the total industrial carbon emissions. After that, with the strengthening of China's response to global climate change, the carbon emissions of the chemical industry have steadily decreased. In 2020, the carbon emissions of the chemical industry were 486.33 million tons, a decrease of 18.11% compared with 2015, and the proportion of the chemical

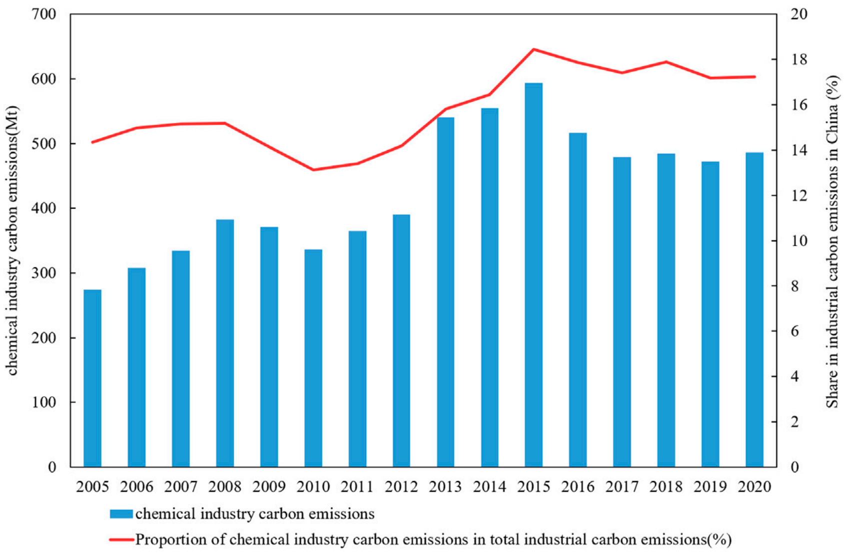


FIGURE 3
Carbon dioxide emissions of chemical industry and its proportion in total industrial carbon dioxide emissions (Data source: China Energy Statistics Yearbook, 2021).

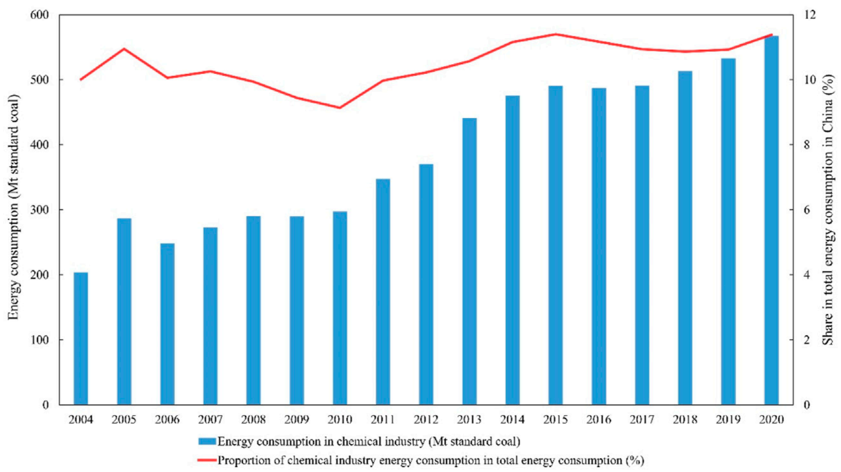


FIGURE 4
Energy consumption in the chemical industry and its proportion in total energy consumption in China (Data source: China Statistical Yearbook).

industry in the industrial carbon emissions decreased to 17.24% (Figure 3).

In general, the energy consumption of the chemical industry shows an upward trend (Figure 4). In 2020, China's total energy consumption was 4,983.14 million tons of standard coal, and the chemical industry consumed 567.23 million tons of standard coal, accounting for 11.38% (China Statistical Yearbook, 2021). China is rich in coal but has oil and gas shortages; therefore, coal contributes the most to the energy consumption in the chemical industry (Lin and long, 2016). According to Figure 5, the proportion of raw coal consumption has shown a downward trend since 2015, but it is still the most important energy source, contributing to 55.92% of total energy consumption in chemical industry in 2020; The proportion of coke consumption has continued to rise since it surpassed natural gas in 2014, ranking second steadily; Natural gas consumption occupies

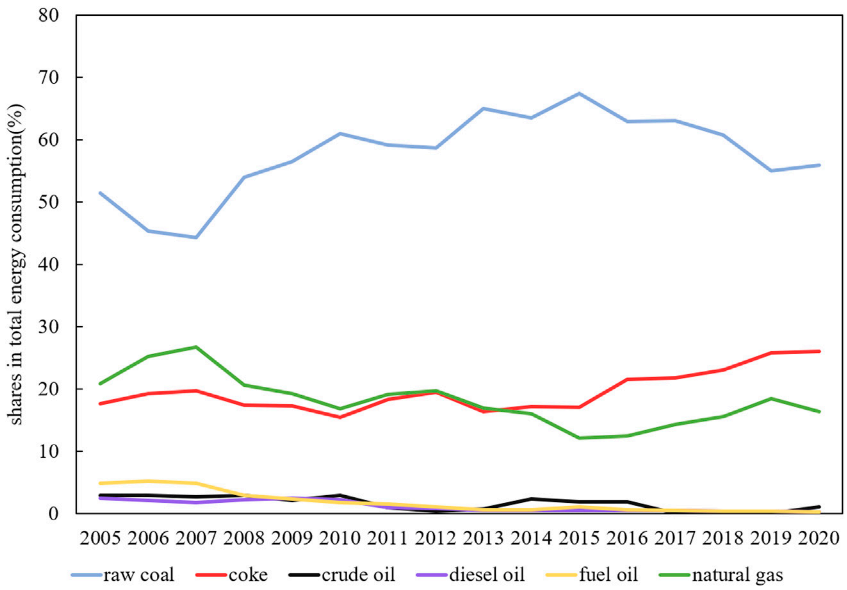


FIGURE 5
Energy consumption structure of chemical industry (Data source: China Energy Statistics Yearbook).

the third place. Among the numerous chemicals in the chemical industry, the largest energy consumption is coal-based ammonia, calcium carbide, caustic soda, coal-based methanol, sodium carbonate and yellow phosphorus (Zhu et al., 2010).

## 2.3 Opportunities and challenges

### 2.3.1 Opportunities for chemical industry under carbon neutrality target

In long run, low-carbon development in the chemical industry is an inevitable trend. In the context of high-quality economic development, various national departments have issued a series of policies and measures to promote the high-quality development of the chemical industry. For example, The Guiding Opinions on Promoting the High-quality Development of the Petrochemical and Chemical Industry During the 14th Five-year Plan (The Central People's Government of the People's Republic of China, 2022) clearly proposed to speed up the transformation and upgrading of traditional industries and to improve the level of cleaner production in the chemical industry. This means that the approval of projects with high energy consumption and high emissions will be stricter, and the future development space of enterprises with poor carbon emission control ability will be compressed. In the same time, the development advantages of clean production enterprises will gradually become prominent, and the market influence of chemical enterprises with "green advantages" will increase. Furthermore, these policies and measures will improve consumers' consumption preference and stimulate the demand for green products, thus encouraging enterprises to put more effort on research, development and demonstration (RD&D) and large-scale practice of low-carbon technologies. The two-way interaction between consumers and chemical enterprises will accelerate the diversification and low-carbon development of chemical products.

### 2.3.2 Challenges for chemical industries to reduce carbon emissions

On the one hand, in the terminal primary energy consumption structure of the chemical industry, coal consumption accounts for the highest proportion (Figure 5). The energy structure needs to be changed to cleaner. However, there are still some obstacles to the universal, efficient and stable application of clean energy (such as wind energy and solar energy), and it takes time for people to change their cognitive level and habits on energy consumption. Therefore, it is difficult to change the energy structure in a short time.

On the other hand, As China's carbon emission reduction efforts continue to increase, the chemical industry and its related upstream and downstream industries are facing the demand of carbon reduction. However, at present, China's chemical product structure shows a pattern of "low-end surplus and high-end shortage" (Ministry of industry and information technology, 2016; Wang and Li, 2018), and backward production capacity still needs to be digested and eliminated. However, many enterprises are used to the extensive development mode of emphasizing quantity over quality and have not formed sufficient attention on emission reduction. In addition, the RD&D of advanced green technologies and equipment need significant capital investments, high-end talents and other supportive conditions, which will also bring more difficulties to put advanced technologies into practice.

## 2.4 Feasible paths for china's chemical industry to achieve carbon neutrality

Firstly, China needs to develop high-end and green chemical products. Outdated production capacity should be eliminated in a timely manner and replaced, transformed and upgraded. With the development of national economy and improvement in living standard, people also have a more qualitative and diversified demands for chemical products. High-end and diverse production has gradually become the new trend for the development of the chemical industry. This requires relevant enterprises to increasingly support RD&D and professional technicians, to break through the bottleneck of key technology research, and to promote the transformation of products from low value-added and extensive development mode to specialized and intensive development mode.

Secondly, promote green technology support and application in chemical industry. On the one hand, the breakthrough of renewable energy exploitation and application technology will promote the transformation of energy consumption structure in the chemical industry; On the other hand, the combination of the renewable energy sector and the chemical industry sector may be an important way to reduce carbon emissions. For example, using green hydrogen (converting renewable energy into hydrogen) instead of traditional gray hydrogen (using traditional fossil fuels to produce hydrogen) has great potential to reduce carbon emissions. Therefore, the government should focus on promoting industry-university-research cooperation, actively provide policy and funding support for green chemical enterprises at the start-up stage, and shorten the cycle of green technology from RD&D to landing and then to large-scale application.

Thirdly, large-scale green integrated chemical industrial parks should be built to save resource and costs and to reduce carbon emissions. In the process of planning and construction, industrial park needs to consider the supply of energy and materials, the layout of upstream and downstream industries, and the construction of public infrastructure, so that chemical companies can share public resources and improve the efficiency of resource and logistics utilization. In terms of operation management, it is necessary to implement unified and standardized management of project access and production process technology to control the quality of the entire life cycle of products, as well as to improve the quality of chemical products. Since the product quality of many small and medium-sized chemical enterprises varies, after these companies enter the park, the quality of their products will be improved accordingly under the unified management of the park. In addition, by building a smart production management platform, a refined management of carbon emissions in the parks can be achieved through real-time monitoring of the production carbon emissions; this can also improve the green competitiveness of the chemical products.

Fourth, the government should collaborate with industries to promote the development of CCUS. CCUS is an important technology to realize carbon neutrality, and the development of CCUS technology is increasingly valuable internationally. Currently, remarkable technical progress has been made in various steps along the production chain of CCUS in China (Cai et al., 2021). The captured high concentration carbon dioxide can be used as basic raw materials for food processing, chemical manufacturing and other industries (Gan et al., 2022). The production process of petrochemical industry will produce high concentration of carbon dioxide, and the application cost of CCUS technology is lower than that of low concentration carbon emission sources (Cai et al., 2021). Therefore, the petrochemical industry has significant advantages in reducing carbon emissions and achieving carbon neutrality by applying CCUS. In order to achieve the goal of carbon neutrality in China's chemical industry, China still needs to speed up the research of CCUS technology, establishing an integrated cooperation framework between industry, university and research institutes to actively explore the practical path of carbon dioxide resource utilization and promote the recycling of resources.

Last but not the least, carbon dioxide emission reduction in chemical industry is an opportunity to promote cross-regional cooperation between energy supply regions and demand regions in China. Western China is rich in renewable energy, but the level of local economic development limits its capacity to consume renewable energy. The proposed "West-East Gas Transmission" project and the "West-East Power Transmission" project are of great significance to alleviate the spatial imbalance of resources, promote the transformation of energy structure, improve the quality of ecological environment, and accelerate the economic development of the Western China. For example, Xinjiang has great potential to develop wind and solar energy, while the level of economic development is relatively backward; yet Shanghai has a high level of economic development and high efficiency of resource utilization, but the local resource endowment is limited. Through the cross-regional transmission of clean energy, the exchange of advantageous resources between two regions is realized, which is conducive to clean energy transformation in Shanghai's chemical industry, and Xinjiang's economic development can also benefit from it. Therefore, it is necessary to further improve the inter-provincial and cross-regional transmission channels by implementing relevant policies and establishing collaboration networks among energy supply regions and demand regions.[1]

1 https://data.cnki.net/Yearbook/Navi?type = typeandcode = A

## Author contributions

YL: Formal analysis, Writing—review and editing, Data curation, Writing—original draft. YM: Formal analysis, Writing—review and editing, Visualization. TZ: Writing—review and editing. YX: review.

## Conflict of interest

TZ was employed by Xinjiang Zhongtai Innovation and Technology Institute Co., Ltd. YX was employed by China International Engineering Consulting Corporation.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# The current state and prospects of China's environmental, social, and governance policies

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In recent years, climate change is getting more and more attention all around the world. China is a major participant in global climate governance. Enterprises play an important role in climate change governance, and the development of ESG concept is highly unified with the realization of global climate change governance and the "peaking carbon emission and carbon neutrality" goal in China. However, the development of ESG in China still faces many challenges. Based on the existing literature, data and policy documents, we analyze the current situation and existing problems of ESG development in China. Moreover, we propose ESG development policy recommendations that are suitable for China's national conditions. Finally, in the context of environmental protection and resource conservation, our study will help enterprises achieve sustainable development.

KEYWORDS

**environmental, social and corporate governance, carbon neutrality, peak carbon emission, climate change, enterprise**

## 1 Introduction

In recent years, global climate change issue has become increasingly serious. The occurrence of climate change-related phenomena such as extreme weather, ice-sheet melting and sea-level rise have caused huge damage to the ecological environment and brought severe challenges to human society. Countries around the world have attached greater importance to climate change issues and global climate governance has attracted more and more attention. China is an important participant, contributor, and leader in global climate governance. Meanwhile, China was also one of the first signatories of the United Nations Framework Convention on Climate Change, making significant contributions to the Kyoto Protocol and the Paris Agreement and their implementation rules (Hu, 2021).

In the context of global climate change, facing the increasingly severe environmental problems and scarcity of resources, China has pledged to peak carbon emission by 2030 and achieve carbon neutrality by 2060 (The Central People's Government of the People's Republic of China, 2020a). In order to achieve this target, Chinese government has proposed a "1 + N" policy framework, including implementation plans and supporting measures for key areas and sectors to reduce their carbon emissions (The Central People's Government of the People's Republic of China, 2020b). Furthermore, the Ministry of Ecology and Environment issued the Administrative Measures for Legal Disclosure of Enterprise Environmental Information, which included carbon dioxide emissions in the scope of information disclosure for the first time (The Ministry of Ecology and Environment of the People's Republic of China, 2021). Environmental, social and corporate governance (ESG) is a necessary way for companies to contribute to the national "peaking carbon emissions and carbon neutrality" target. To build a well-developed ESG policy system and to make ESG become the main standard for investments and productions will also contribute to the improvement of corporate value.

The ESG concept originated in the 1970s (Moskowitz, 1972). And the term ESG was first widely used in 2004 in the "Who Cares Wins" report, which was a joint initiative of financial institutions invited by the United Nations (UN Environment Programme-Finance Initiative, 2004). ESG is the abbreviation of environmental, social and governance. "E" in ESG represents the environmental and resource impacts of corporate activities, including carbon emissions, pollution emissions, and the use of natural resources such as energy and water. "S" focuses on corporate social responsibility (CSR), mainly including employee welfare, supply chain management, product responsibility, and social welfare. "G" means corporate governance, including the composition and power norms of the senior executives, risk management and internal control, investor relations, executive compensation, corruption, and others (Qiu and Yin, 2019). ESG concept is consistent with the United Nations Sustainable Development Goals (SDG). It is an important basis for socially responsible investment, and a wide-accepted criterion for international community to evaluate whether companies are in line with the level of green and sustainable development (China Banking and Insurance News, 2022). ESG directly reflects the modernization of national governance system and governance capacity at the micro and medium level enterprises. And it encourages enterprises and industries to build more scientific and comprehensive development modes.

The development of ESG has been relatively mature in many western countries; but in China, it is still at the beginning stage. Under the background of realizing the ambitious carbon neutrality target, China has a broad development space to establish the ESG concept with Chinese characteristics, but there are also many problems and challenges. Promoting the concept of ESG in China will not only help control the greenhouse gas emissions in different sectors, especially the high-emission sectors, but also effectively enhance the development of carbon market. Furthermore, inclusion of ESG concepts in the financial system and company development strategies will help accelerate the green and low-carbon transformation of industries. Ultimately, efforts from Chinese companies on green and sustainable businesses can contribute to global climate change mitigation.

ESG takes the holistic view that sustainability extends beyond just environmental issues. It is best characterized as a framework that helps stakeholders understand how an organization is managing risks and opportunities related to environmental, social, and governance criteria (Kyle, 2022). The concept of environmental in ESG is very consistent with the concept of environmental protection and resource conservation and the "peaking carbon emission and carbon neutrality" goal in China. Meanwhile, enterprises are not only an important guarantee for China's economic development, but also environmental pollution and resource consumption. At this stage, China actively promotes enterprises to publish ESG development reports, which helps ensure that the State formulates more precise emission reduction policies according to different industries and regions, and better realizes the sustainable development of Chinese enterprises.

This paper summarizes existing literature, data reports and policy documents related to ESG, and analyze the current situation and problems of ESG development in China. It helps us to grasp the specific situation of China's ESG practice development comprehensively and accurately. The remainder of this paper is organized as below. Section 2 reviews relative research on ESG. And we analyze the current situation and problems of ESG development in China. Section 3 proposes some policy recommendations on how to promote the development of ESG in China and draws the research conclusions.

## 2 Manuscript formatting

### 2.1 Literature review of ESG

Research on ESG started in and is mainly about western countries, while in China such research is limited. Previous research mainly focuses on the impact of ESG on enterprise performance and investment efficiency.

#### 2.1.1 The effect of ESG on enterprise performance

Researchers have not reached a unified conclusion on the relationship between ESG and enterprise performance. On the one hand, many researchers believe that there is a positive correlation between them. Friede et al. (2015) used microdata from 2,200 academics and investors to analyze the relationship between ESG and financial performance. They found that it was a significant positive relationship between ESG and financial performance. Ghoul et al. (2017) studied countries with different development levels of market economy system; they found that there was a significant positive correlation between ESG and enterprises in countries with the imperfect market economy system. For the environment aspect of ESG, Yang and Zhou (2004) found that the environmental performance of enterprises can promote the formulation of effective environmental management plans to control pollution prevention and control and resource use, increase the efficiency of resource use and improve the environmental protection effect. This can improve the competitive advantage of enterprises to a certain extent. For the social aspect of ESG, Li and Xiao (2009) found that enterprises with good social performance can create greater profits to a certain extent. From the corporate governance aspect of ESG, Li et al. (2019) found that companies with good governance have better performance.

On the other hand, some researchers hold the opposite view. Brammer and Pavelin (2006) found a negative relationship between ESG and enterprise performance, which means the higher the enterprise ESG score is, the worse the enterprise performance is. Sassen et al. (2016) use European companies as a case study. They found the improvement of ESG level has a negative impact on enterprise performance.

#### 2.1.2 The effect of ESG on investment efficiency

Researchers also have different views on the relationship between ESG and investment efficiency. Bhandari and Javakhadze (2017) used the ESG score of 15,670 samples in KLD database. They found that there is a positive relationship between ESG performance and investment efficiency from 1992 to 2014. On the contrary, Muslu et al. (2015) believe that the voluntary disclosure of non-financial information of from listed companies can help reduce the risk of bias investors. Healy and Palepu (2001) argued that managers will use disinformation disclosure to get more investment to boost earnings. Shen et al. (2010) found that the more information about environmental indicators disclosure of high polluting listed enterprises, the lower their financing costs to a certain extent.

The research on ESG in China is still in the stage of theoretical accumulation due to the limitation of ESG practices and data availability. It is very important to further promote ESG research and analysis, in order to provide valuable supports for decision making and enterprise strategic planning from a scientific point of view.

### 2.2 Current state of ESG development in China

#### 2.2.1 ESG policymaking in the context of environmental protection and resource conservation

The Chinese government attaches great importance to the development of ESG in recent years. Since 2017, the Chinese government has issued a series of policy documents, ranging from voluntary disclosure to mandatory restrictions on disclosure of environmental information. A list of formal policy documents related to ESG in China is included in Supplementary Table S1. In general, Chinese government has proposed increasingly strict regulations on companies' ESG disclosure in the past 5 years. Policy documents before 2020 all came from the securities regulatory authorities. Since 2020, the Ministry of Ecology and Environment has begun to make substantive requirements for environmental information disclosure of enterprises. This means that the relationship between environmental and natural resource management issues and enterprise production is gradually reflected in government planning. However, China still lacks a complete ESG policy system, and the existing ESG evaluation has not received widespread social attention.

#### 2.2.2 The ESG information disclosure in China

##### 2.2.2.1 The quantity of ESG information disclosure in China

At present, China's ESG disclosure mainly comes from A-share listed companies, followed by large enterprises, while the number of small and medium-sized companies is very limited. According to the newly published "China ESG Development Report 2021", the amount of information disclosure varies with the nature of enterprises (Wang, 2022). As shown in Figure 1, the number of A-share listings has grown from 946 in 2019 to 1,130 in 2021. The overall disclosure rate of listed companies slightly increased from 26.22% to 26.92%, respectively. Among the 300 listed companies in CSI 300 Index, in which only large corporates were included, 266 issued CSR reports, accounting for 88.67%, which was much higher than the disclosure rate of small and medium-sized enterprises. However, only 66 Chinese companies provided comprehensive ESG report in 2021, only 1.5% of the total (Breuer et al., 2022; Kays, 2022).

The equity nature of companies also plays a role in their ESG disclosure. As shown in Figure 2; Table 1, the number of ESG-related reports issued by state-owned companies was much higher than that of other types of companies, and the number of ESG-related reports increased year by year, with a disclosure rate of 48.67% in 2021. Which means nearly half of the state-owned companies have published ESG-related reports. Unlike state-owned companies, only 18.07% of the private companies provided ESG-related reports in 2021. Fortunately, the number of companies disclosing ESG information has grown rapidly by 33.25% from 2019 to 2021, compared to 9.23% and 21.27% for state-owned enterprises and other types of enterprises, respectively.

##### 2.2.2.2 The content of ESG information disclosure in China

In China, among the three dimensions of ESG, corporate governance dimension is the most frequently disclosed content, and the environmental dimension is reported by fewest companies. As shown in Figure 3, in terms of

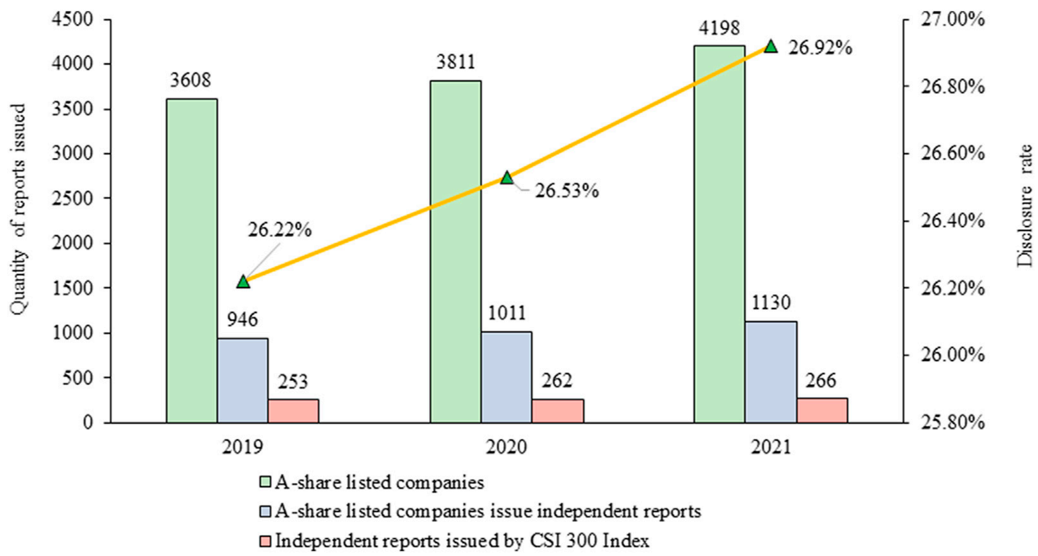


FIGURE 1
The ESG-related reports for 2021 listed companies in 2019–2021 (Wang, 2022).

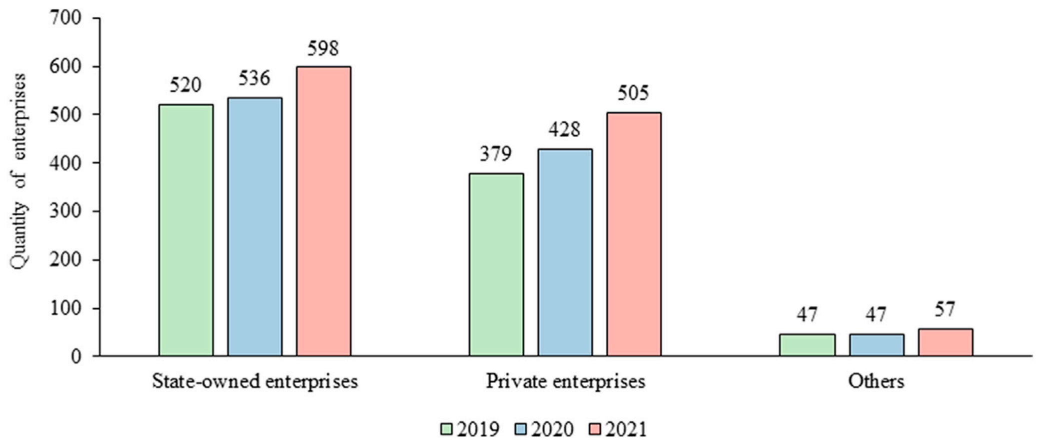


FIGURE 2
The release of ESG-related reports of A-share listed companies with different equity types in China in 2019–2021 (Wang, 2022).

**TABLE 1 The proportion of ESG reports issued by 2021 companies in 2019–2021 (Adopted from Wang, 2022).**

| | 2019 (%) | 2020 (%) | 2021 (%) |
|---|---|---|---|
| State-owned enterprises | 46.68 | 47.18 | 48.67 |
| Private enterprises | 16.39 | 17.31 | 18.07 |
| Others[1] | 36.93 | 35.51 | 33.26 |

Includes Hong Kong, Macao, Taiwan-invested enterprises, sino-foreign joint ventures, foreign-funded enterprises and other enterprises with different types of equity nature.

different corporate disclosures, among the 300 listed large corporates in CSI 300 Index, the disclosure rate for "Director remuneration" is 92%, while the rate for "Anticompetitive conduct" is only 4%.

On average, the disclosure rate of environmental indicators was the lowest (36.33%); the disclosure rate of social indicators was 38.67%, and the disclosure of corporate governance was the highest (47.02%).

Enterprises actively disclose environmental information according to law, which can effectively enhance long-term

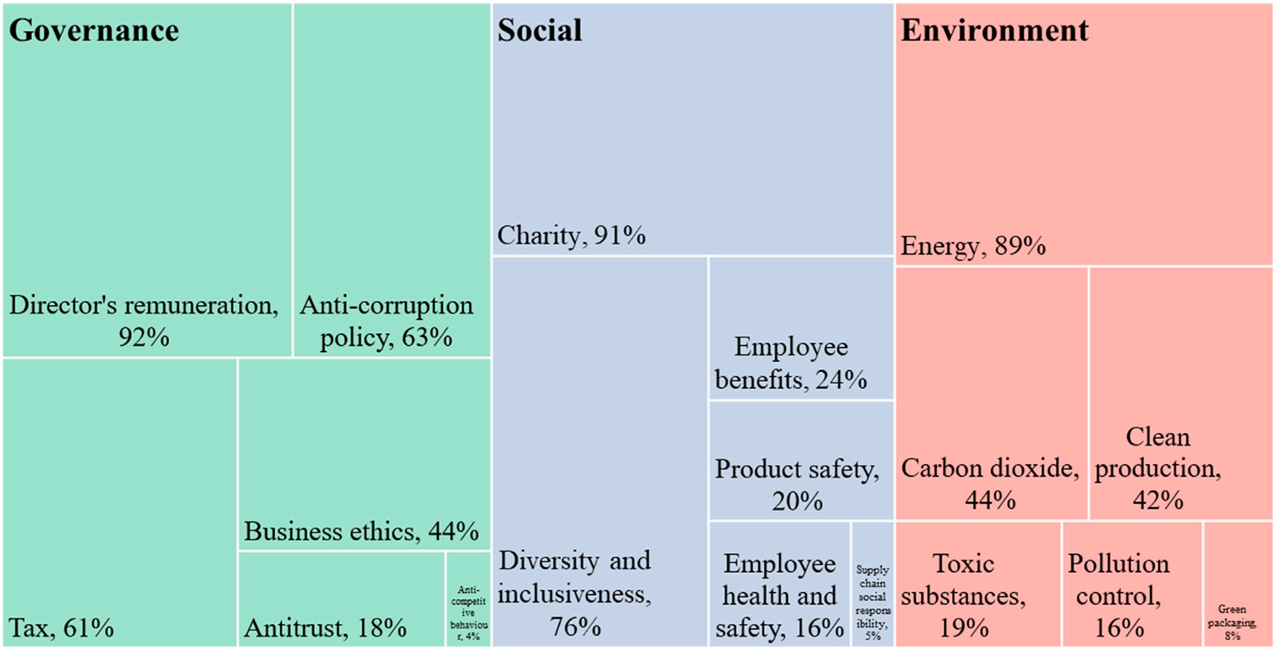


FIGURE 3
Chinese CSI 300 Index companies ESG-related report common indicators of disclosure rate in 2021 (Wang, 2022).

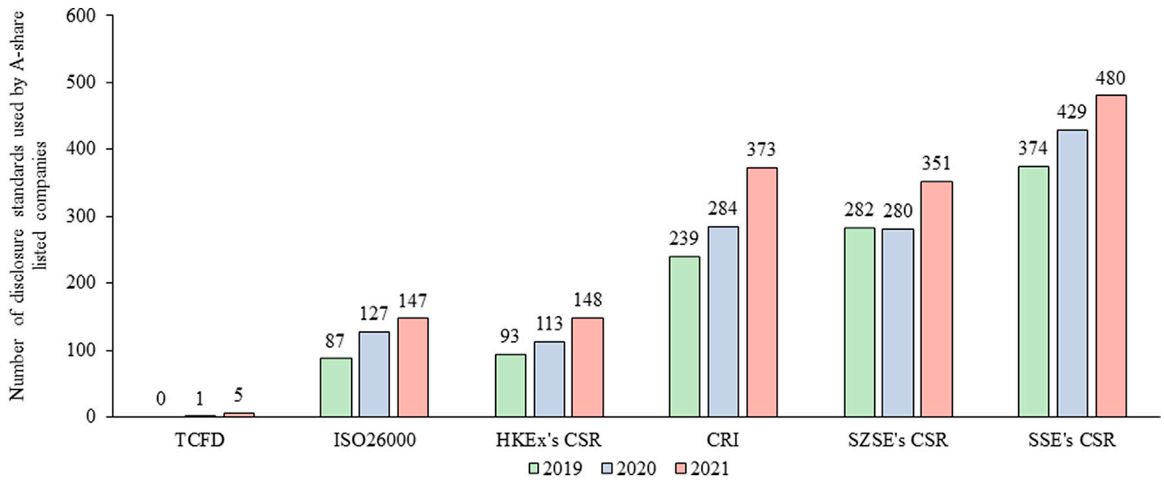


FIGURE 4
The disclosure standards used for reference by 2021 listed companies in 2019–2021 (Wang, 2022).

competitiveness. Fortunately, both the Chinese government and enterprises attach great importance to the disclosure of enterprise environmental information. The level of enterprise environmental information disclosure is rising year by year. Typically, under the constraint of resources and environment, the environmental information disclosure level of the heavy pollution industry increased from 34 points in 2015 to 50 points in 2020 (Li, 2022).

#### 2.2.2.3 The standards of China's ESG information disclosure

In recent years, China's ESG disclosure standards are based on the Shanghai and Shenzhen stock exchanges CSR, while the TCFD standard, a measure of climate change, is seldom used. Figure 4 shows the disclosure standards used by listed companies in 2019–2021. These companies used 10 different standards.

Especially, TF securities in China specially disclosed the environmental information disclosure report. Its behavior lays a good foundation for enterprises to achieve sustainable development. The most adopted CSR guidelines are issued by the Shanghai Stock Exchange and the Shenzhen Stock Exchange. Several international standards were also used by many companies, such as the GRI standard which ranked third. GRI standard is relatively loose, giving enterprises a greater degree of freedom to disclose.

#### 2.2.2.4 The problem of ESG information disclosure in China

Based on the analysis of the quantity, content, and standard of ESG disclosure in China, the following problems are noted. First, ESG disclosure in China is dominated by listed companies and other large enterprises, while small and medium companies' participation is lacking. Second, China does not have mandatory requirements on the content of ESG disclosure. Many companies will not voluntarily disclose ESG-related information, which creates data availability problem and hinders companies' ESG performance tracking. Although some enterprises have taken the initiative to disclose ESG reports, most of the reports are mainly descriptive and the quality of ESG reports varies (Wang and Zhang, 2022). Moreover, some indicators measuring corporate sustainability are rarely involved. Last but not the least, China currently lacks nationally agreed ESG disclosure standards. Most of the standards adopted by enterprises are CSR guidelines that emphasize social responsibility. Standards that cover comprehensive ESG topics are not dominantly used, and current standards do not incorporate China's peak carbon emissions and carbon neutrality goals.

### 2.2.3 The ESG rating in China

#### 2.2.3.1 Current status of ESG rating in China

ESG rating has become the mainstream trend of international market development. At present, the most authoritative rating agencies in China are Syo Tao Green Finance, China Alliance of Social Value Investment, Harvest Fund, International Institute for Green Finance, Central University of Finance and Economics, Sino-Securities Index Information Service (Shanghai) Co. Ltd., Rankins CSR Ratings and Asset Management Association of China. The main functions of these rating agencies include standard-setting, disclosure requirements, data collection and rating. The evaluation system of these rating agencies mainly formulated with reference to the standards published by international organizations or stock exchanges. Industry information and data are derived from questionnaires sent to enterprises. Supplementary Table S2 included the introduction and official websites of main ESG ranking agencies in China.

#### 2.2.3.2 The problems with ESG rating in China

First, the development of ESG rating agencies in China is still in the beginning stage. The social and market acceptance of many rating agencies and their reports is relatively low (Wang and Zhang, 2022). Second, the evaluation process of different rating agencies is not transparent, the indicator setting, and the evaluation method are subjective. Therefore, the evaluation of enterprise ESG level may be biased. Sometimes, different rating agencies give diametrically opposite evaluations to the same company Third, current ESG evaluation system in China is adopted from developed countries, with little consideration of China's environmental, social and economic characteristics. These problems are caused by multiple reasons. For example, unlike the traditional financial data, ESG data does not have neutrality; the rating subjects and topic coverage vary among different ESG rating methods; the various levels and weight of indicators are subjective. Furthermore, the lack of real-time monitoring, information asymmetry and other external factors also hinder the development of ESG rating in China.

### 2.2.4 The ESG investment in China

#### 2.2.4.1 The current situation of ESG investment in China

The application of ESG investment strategy in China's capital market has just started. Many investment institutions are in the theoretic development stage of ESG strategy. In terms of investment willingness, by the end of 2018, a total of 18 institutions in China had joined the United Nations Principle of Responsible Investment (UNPRI), including 13 investment managers and five other institutions. Compared with the United States (414), the United Kingdom (339), and other countries with better financial market system, there are still some gaps. In terms of investment practice, there are only a few of ESG-related funds and other asset management products in China. By the end of 2018, of the total 7,851 public funds, only one fund explicitly invested in ESG stocks, and the net assets of the fund was only 845.8 million yuan. If a broad scope of ESG, including topics such as "sustainable development" and "green", is considered, the number of related funds is only 10, with the net assets of only 8.359 billion yuan (Ma, 2019). The situation of ESG investment became better after 2018. According to incomplete statistics by the China Finance and Green Gold Institute, by September 2020, there were 114 ESG-related public offering fund products in China's fund market, and the total assets reached 114.4 billion yuan (Asset Management Association of China, 2020). However, compared to Europe and the United States, China still need more efforts to create better environment for the development of ESG investment.

#### 2.2.4.2 The problem of ESG investment in China

The main factor restricting ESG is that companies have less ESG information disclosure, and it is difficult to obtain company ESG performance information. Specifically, at this stage, few listed companies in China actively disclose ESG reports, and investors are difficult to obtain sufficient information and data to make a relatively comprehensive ESG assessment of listed companies. Moreover, the ESG evaluation system used in China mainly refers to the mature ESG evaluation system in European and American markets, which usually do not consider China's characteristics, and the ESG evaluation system in China has not been unified and widely accepted. In this case, different investors often have different opinions on ESG of listed companies, resulting in many contradictions, which is not conducive to the long-term development of ESG in China.

### 2.3 Policy recommendations

Based on the analysis above, the quality of ESG information disclosure in China at this stage is uneven, and enterprises' disclosure in the environmental (E) dimension is very few. At present, China lacks an influential evaluation system that conforms to China's situation and widely accepted by enterprises. ESG-related financial products are limited in number and small in investment scale. Therefore, the following policy recommendations are proposed.

Firstly, the Chinese government should create an environment that is more conducive to the development of ESG. To ensure that companies develop on the direction of the ESG concept, Chinese government should propose more policies and regulations related to the ESG development concept and provide subsidies, tax cuts and other favorable policies for companies with good ESG performance. Furthermore, the government can integrate government agencies with different functions and strengthen organizational cooperation among agencies and institutes to accelerate the development of ESG in China. In addition, the government needs to carry out more publicity, so that companies and investors have a deeper understanding of the concept and the importance of ESG.

Secondly, it is crucial to establish a comprehensive ESG information disclosure system. ESG information disclosure is the basis of ESG rating. The Chinese government should speed up the formulation of unified ESG information disclosure standards. Also, it is necessary to make reasonable use of the compulsory function of government in China to encourage companies to formulate development plans that consist with the ESG concept and strictly supervise the effective and truthful disclosure of company ESG information. Moreover, the government can also enhance the development of third-party ESG organizations, which provides professional supportive service to companies to help them improve ESG governance system and information disclosure quality.

Finally, an ESG evaluation system based on China's reality should be built. On the basis of fully considering the actual situations of China, relevant government agencies should cooperate with private institutions to build a comprehensive government-enterprise ESG evaluation and management framework with unified ESG evaluation criteria. The government should encourage the development of domestic ESG rating agencies and carry out ESG pilot projects in high carbon emission industries (China Securities Journal, 2022). Furthermore, it is necessary to construct China's ESG rating database. To improve the ESG rating accuracy, the database should also include in-time updates and adjustments according to policy changes.

In summary, the relationship between international and domestic ESG evaluation standards is accurately mastered. On the one hand, the definition of the most advanced ESG evaluation standards in the world has been profoundly clarified. On the other hand, in the context of China's national conditions, an ESG evaluation system that is suitable for China's development should be constructed. Meanwhile, enterprises, as participants in achieving the "peaking carbon emission and carbon neutrality" goal, have fully played their important role.

## 3 Conclusion

The study has certain theoretical and practical significance for the development of ESG in China. Theoretically, the study comprehensively analyzes the current situation and existing problems of China's ESG disclosure, rating and investments. It can enrich the relevant research scope of ESG to a certain extent. In practice, for enterprises, it helps them pay more attention to the latest ESG related information and adjust the development direction of enterprises in time. Therefore, it can help improve the value and competitiveness of enterprises. By analyzing the current situation and existing problems of China's ESG, we are able to provide the Chinese government with a favorable guarantee that ESG will be optimized and improved. This will lay a good foundation for constructing the system framework of an ESG with Chinese characteristics.

Under the background of environmental protection and resource conservation, ESG is the direction of improving the quality and efficiency of corporate activities based on their core competitiveness. It can also lead companies to become important contributors to China's "peaking carbon emissions and carbon neutrality" target. The Chinese government should create an environment that is friendly to ESG development, establish a comprehensive ESG information disclosure system, and build a government-enterprise ESG management framework which is suitable for China's specific situations. These actions can promote the development of ESG for Chinese companies, help China to form a friendly pattern of resource conservation and environmental protection, and contribute to the global green, low-carbon and sustainable development.

## Author contributions

BJ: Formal analysis, Writing—review and editing, Data curation, Writing—original draft. XS: Formal analysis, Writing—review and editing, Data curation, Writing—original draft, Visualization. YM: Formal analysis, Writing—review and editing, Visualization.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

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# Assessing the effectiveness of innovative city pilots in improving urban carbon emission performance: A spatial difference-in-difference approach

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Existing studies have focused on the impact of innovation on carbon emission performance but ignore the importance of government support for innovation. To overcome this challenge, this paper adopts a spatial difference-in-difference (DID) model to assess the impact of government support for innovation on urban carbon emission performance based on a quasi-natural experiment of innovative city pilots (ICP) in China. Using the high-resolution carbon emission data of 1 km × 1 km for 238 cities from 2008 to 2019 in China, this paper employees an extended stochastic frontier analysis (SFA) model to measure urban carbon emission performance. Our findings indicate that ICP implementation leads to a 1.3% improvement in local carbon emission performance. Meanwhile, there is a significant spatial spillover effect of ICP implementation, with a 3.3% improvement in the carbon performance of the surrounding areas. The results of the mechanism analysis suggest that government innovation support affects carbon emission performance by promoting total factor productivity improvement, green innovation, and industrial upgrading. Further analysis shows that ICP has the strongest impact on carbon performance in the eastern region, and the impact is stronger for large cities and resource-dependent cities. Finally, the paper carries out a series of robustness tests to ensure the reliability of the analytical results, including parallel trend tests, placebo tests and re-estimation of different methods. Based on the findings, this paper proposes feasible policy recommendations in terms of continuous promotion of government innovation support, regional cooperation and differentiated innovation support formulation.

KEYWORDS

**carbon emission performance, innovative city pilots, spital difference-in-difference model, stochastic frontier analysis, spatial spillover effect**

# 1 Introduction

In recent years, the rapid increase in greenhouse gas emissions has exacerbated global warming and extreme climate phenomena, which have seriously threatened the sustainable development of human society (Magazzino, 2017a; Bai et al., 2019; Du and Li, 2019; Chen and Lin, 2020; Statistical Review of World Energy, 2021; He et al., 2021; Li Y et al., 2022, Li Z et al., 2022; Wang K-L et al., 2022; Wu C et al., 2022). As the country with the highest carbon emission in the world, China's total carbon emission has increased from 1.419 billion tons in 1978 to 9.899 billion tons in 2020, an increase of 6.98 times (BP, 2021). This means that China faces enormous pressure to reduce emissions. In 2020, the Chinese government also proposed the dual carbon goals of "2030 carbon peak" and "2060 carbon neutrality", aiming to alleviate the climate problems caused by greenhouse gas emissions. Improving carbon emission performance, i.e., the output per unit of carbon emission, is regarded as the most powerful policy instrument to achieve the dual carbon goals. How to improve carbon emission performance has attracted a large number of scholars to study and discuss.

However, the existing literature has not reached a consistent conclusion on the impact of government support for innovation on carbon emission performance. One view is that government support for innovation can effectively improve carbon emission performance. Pan A et al. (2022) selected enterprise-level panel data from 2010 to 2018 to investigate the effect of the pilot carbon emission trading scheme (CETS). He found a significant positive effect of government support on carbon emission performance and total factor productivity based on the PSM-DID model. Doğan et al. (2022) used data from the G7 countries from 1994 to 2004 to study the effects of environmental taxes on carbon emissions, natural resource rents, and renewable and non-renewable resources. He found environmental tax policies can significantly reduce carbon emissions and improve carbon emission performance in these countries. The opposite view is that government support for innovation has a very limited effect on improving carbon emission performance. Fu et al. (2022) adopted a game-theoretical framework to examine firms' operational strategies under a carbon tax policy. They concluded that carbon taxes do not necessarily lead to the adoption of green technologies and the improvement of carbon emission performance. Yıldırım et al. (2022) empirically investigated the impact of environmental innovation on $CO_2$ emissions in the energy sector based on a large dataset of 32 OECD countries from 1997 to 2018. Using a panel smooth transition regression (PSTR) model, they found that the impact of government innovation on carbon emission performance is unstable at different stages due to rebound effects.

Improving carbon emission performance through technological innovation is an important measure for countries to mitigate climate problems in the future (Adedoyin et al., 2022; Pan X et al., 2022). The motivation of this paper is to comprehensively assess the impact of government innovation support on carbon emission performance. This paper argues that existing research faces three challenges, ignoring these challenges may lead to conflicting views. The first challenge is to select a more effective model to assess carbon emission performance. The most widely used methods are data envelopment analysis (DEA) and stochastic frontier analysis (SFA) (Kumbhakar et al., 2014; Filippini and Hunt, 2015; Kang et al., 2022). DEA based on linear programming ignores unobserved city heterogeneity in carbon emission performance (Filippini and Hunt, 2015). Meanwhile, the traditional SFA method cannot remove individual effects, time effects and unobserved heterogeneity at the same time (Kumbhakar et al., 2014). This can lead to over- or underestimation of city carbon emission performance and interfere with the impact of government support for innovation. The second challenge is to circumvent the endogenous interference of government innovation support. Existing literature generally uses indicators such as government subsidies and tax incentives to measure the government's support for innovative behavior, but such indicators have a strong correlation with urban economic development (Rawte, 2017; Fu et al., 2022; Tang C et al., 2022). Carbon emission performance is also strongly related to economic development, and the resulting endogenous interference will reduce the reliability of the estimated results. The third challenge is to overcome the effect of spatial factors on the results. There are many industrial clusters in China, which makes the economic development of neighboring cities and carbon emissions have obvious spatial correlation (Liu et al., 2022; Zhang Y et al., 2022). In addition, the talents and technologies attracted by the local government through innovation support also accumulate innovation elements for the surrounding areas, thereby affecting the carbon emission performance of the surrounding areas (Peng H et al., 2021; Gao and Yuan, 2022; Zhao and Sun, 2022). Ignoring the potential impact of spatial factors on carbon emission performance in the evaluation model reduces the reliability of the results. To overcome the above challenges, this paper adopts a spatial difference-in-difference (DID) model and uses a quasi-natural experiment in China to assess the impact of government innovation support on urban carbon emission performance.

The contribution of this paper is mainly in the following three points. First, based on the prefecture-level panel data from 2008 to 2019, this paper adopts the extended SFA model proposed by Kumbhakar et al. (2014) to evaluate carbon emission performance. This approach considers all the time-varying, time-invariant, and city characteristics, which help obtain more reliable calculation of carbon emission performance. Second, this paper assesses the impact of government innovation support on carbon emission performance through a quasi-natural experiment. To explore the role of the government in urban innovation, China has implemented the policy of innovative city pilots (ICP), which is committed to improving the agglomeration of urban innovation elements through government participation. ICP identified Shenzhen as the first pilot city for innovation, and in 2009, 14 cities including Dalian and Qingdao were identified as pilot cities for innovation. From 2010 to 2013, more than 40 innovative city pilots were successively approved. In April 2018, another 17 cities were approved to build national innovative cities, and the number of innovative city pilots increased to 78. This policy has strong exogenous nature and can avoid the interference of endogeneity on the evaluation results to a certain extent. The ICP from China is an incremental reform that provides important lessons for other countries and regions committed to improving carbon emission performance through government innovation support policies. Finally, this paper incorporates spatial factors in the traditional DID model. The results estimated through spatial DID model reduce the interference of spatial factors, which can more reliably assess the impact of government innovation support on carbon emission performance.

The reminder of this study is organized as follows: Section 2 provides the literature review. Section 3 provides the policy background and research hypothesis, Section 4 provides the methods and data, Section 5 provides the results, and Section 6 provides the conclusions, recommendations, and limitations.

## 2 Literature review

The existing literature focuses on two aspects of carbon emission performance, including the measurement of carbon emission performance and the impact of technological innovation on carbon emission performance. First, in the measurement of carbon emission performance, the previous studies used the indicator of economic output per unit of carbon emissions (Lee et al., 2002; Filippini and Hunt, 2015; Chen et al., 2022; Kang et al., 2022). The higher the value of this indicator, the higher the level of carbon emission performance. However, this indicator is limited in that it ignores the potential influence of other factors on carbon emission performance, such as population and industry level (Kang et al., 2022). To overcome this limitation, recent studies widely use DEA and SFA to measure carbon emission performance (Hua et al., 2007; Filippini and Hunt, 2015; Cao and Wu, 2022; Kang et al., 2022). It solves for the optimal combination of input and output factors, and measures carbon emission performance through the gap between actual carbon emissions and expected carbon emissions of optimal combination (Hua et al., 2007; Choi et al., 2012; Molinos-Senante et al., 2014; Liu et al., 2021; Zhang et al., 2021). However, this approach does not consider the unobserved heterogeneity among cities. The bias is acceptable in small samples. However, for large samples, the overestimation or underestimation due to unobserved heterogeneity must be considered (Filippini and Hunt, 2015; Kang et al., 2022). SFA measures carbon emission performance through extracting the residuals from the stochastic frontier function estimates (Aigner et al., 1977). The closer the regression residuals are to zero, the higher the carbon emission performance. However, the traditional SFA model still cannot separate the unobserved heterogeneity in the residuals. Kumbhakar et al. (2014) proposed an extended SFA model that can separate the time-varying characteristics, time-invariant characteristics, and urban heterogeneity in the residuals simultaneously. Therefore, this extended SFA model will be applied in this paper to evaluate urban carbon emission performance more reliably. As an important tool for climate mitigation, how to improve carbon emission performance is a key academic concern. According to previous studies, economic development, industrial structure, government intervention, the level of financial development and the level of foreign investment are the key factors influencing carbon emission performance (Magazzino, 2016; Ashraf et al., 2020; Song et al., 2021; Li L et al., 2022; Pan A et al., 2022; Wang L et al., 2022).

Second, with the rise of emerging technologies such as industrial robots, big data, cloud computing and artificial intelligence, whether technological innovation can provide new impetus for energy conservation and emission reduction has become a hot research topic (Su et al., 2020; Prasath Kumar et al., 2021; Wang K-L et al., 2021; Li N et al., 2022; Saheb et al., 2022). The improvement of cleaner production technology can reduce carbon emissions in the process of production of enterprises and reduce carbon emissions per unit of output (Zhou and Zhao, 2016; Zhou et al., 2021). Zhang and Liu (2022) and studied the impact of digital finance and green technology innovation on carbon emissions in China and found that technology innovation enhances carbon emission performance. Also, Kuang et al. (2022) explored the impact of green technology innovation and renewable energy investments on reducing carbon emissions and found that in the long-term technology innovation can enhance carbon performance. However, studies have also shown that technology innovations increase the risk of enterprises, and the returns to enterprises are particularly limited (Li W et al., 2022; Su and Fan, 2022). Shaikh and Randhawa (2022) found that open technological innovation can also create risks within the organization that can jeopardize the company's operations. Wang S et al. (2022) conducted an in-depth study on the behavioral decisions of executive teams and corporate green technology innovation. He suggested that technological innovation is characterized by long cycles, high investments and high risks for companies.

Previous studies show that energy saving, and emission reduction cannot be achieved solely by enterprises themselves through technological innovation (Qiu, 2022; Zhang R et al., 2022). One important reason is that technological innovations that focus on energy efficiency and emission reduction do not bring higher excess returns to companies (Li W et al., 2021). Companies will devote limited resources to more profitable projects (Salmani and Partovi, 2021; Gabdullina et al., 2022). At this point, the government must subsidize and support the innovative behavior of enterprises to reduce the R&D risks of enterprises (Ma and Li, 2021; Fan et al., 2022). Especially for green production technology, government incentives can stimulate the innovation of enterprises to a certain extent. Therefore, it is necessary to pay attention to the role of government innovation support in the improvement of urban carbon emission performance.

## 3 Policy background and research hypothesis

### 3.1 Policy background of innovative city pilots

ICP is an important policy proposed by China based on the increasingly competitive international situation (Yang J et al., 2022). This is to enhance the innovation capacity and realize the national development plan. In the future, China hopes to use independent innovation as a driving force to promote the restructuring of the industrial economy and the construction of a sustainable society. In 2008, Shenzhen became the first innovative pilot city. The country leverages Shenzhen's good innovation capability base to radiate neighboring cities. It is hoped that the leading role of science and technology will be brought into play to achieve an overall improvement in the level of innovation in the region. At the beginning of 2010, 14 more cities, including Dalian and Qingdao, joined the list of pilot innovative cities. With the accelerated expansion of the pilot scale of innovative cities, the number of innovative cities nationwide has reached 78 as of 2018 (see Figure 1). From the lo-cation of the pilot innovative cities, there are a certain number of pilots distributed in the east, middle and west of the country. The relatively economically developed coastal provinces in the east have more pilot innovative cities (Yang Z et al., 2022). In terms of the development of innovative cities, the goal of building innovative cities is gradually evolving from enhancing innovation to restructuring urban industries and building sustainable societies. The country is leveraging the policy advantages of these innovative cities and promoting the synergistic development of innovation levels in the surrounding areas (Gao and Yuan, 2022). Such a trend is important to China's early entry into the forefront of innovative countries.

### 3.2 Research hypothesis

In this study, we suppose that government innovation support will enhance local carbon emission performance through three main channels. First, government innovation support will improve local carbon performance by enhancing total factor productivity. It has been documented that government innovation support significantly increases total factor productivity (Pan A et al., 2022). This implies that the output from the given total carbon emissions also increases significantly, leading to an increase in carbon emission performance. Second, government innovation support drives the level of local green innovation and thus enhances carbon performance. Government innovation support can effectively reduce the risk of enterprise innovation and greatly stimulate enterprises' innovation behavior in energy saving and emission reduction and other green technologies (Lin and Ma, 2022). Thus, green innovation can significantly reduce carbon emissions per unit of output, i.e., lead to the improvement of carbon emission performance. Finally, government innovation support will also promote industrial upgrading, thus improving the urban carbon emission performance. Government innovation support can accelerate the transformation of local enterprises from production and processing to R&D, i.e., industrial upgrading (Su and Fan, 2022). Industrial upgrading leads to a decrease in the share of energy inputs in enterprise production and an increase in the value added of products (You and Zhang, 2022). Therefore, enterprises can achieve higher output with lower resource inputs, which leads to the improvement of urban carbon emission performance. Based on the above analysis, this paper proposes the first research hypothesis.

H1: Government innovation support can improve local carbon emission performance through promoting total factor productivity, green innovation and industrial upgrading.

In addition to influencing local carbon performance, local government innovation support may also affect the carbon emission performance of neighboring regions through spillover effects. Government innovation can effectively attract various innovation factors to cluster locally, such as R&D personnel and R&D funds (Li X et al., 2021). Has mentioned in his study that government environmental support has a significant innovation agglomeration effect. Similarly, this idea was also supported by the study of (Peng W et al., 2021). Neighboring regions can then share the benefits of local innovation agglomeration through technological cooperation. Thus, they can improve their own carbon emission performance. In addition, neighboring regions can provide a broad market for the output of local innovation factors and match technical talents. The resulting industrial upgrading will improve the overall carbon emission performance of the region (Yang and Liu, 2020; Kuang et al., 2022; Yang Z et al., 2022). Therefore, the second hypothesis is proposed in this paper.

H2: There is a significant positive spillover effect of government innovation on the carbon emission performance of neighboring regions.

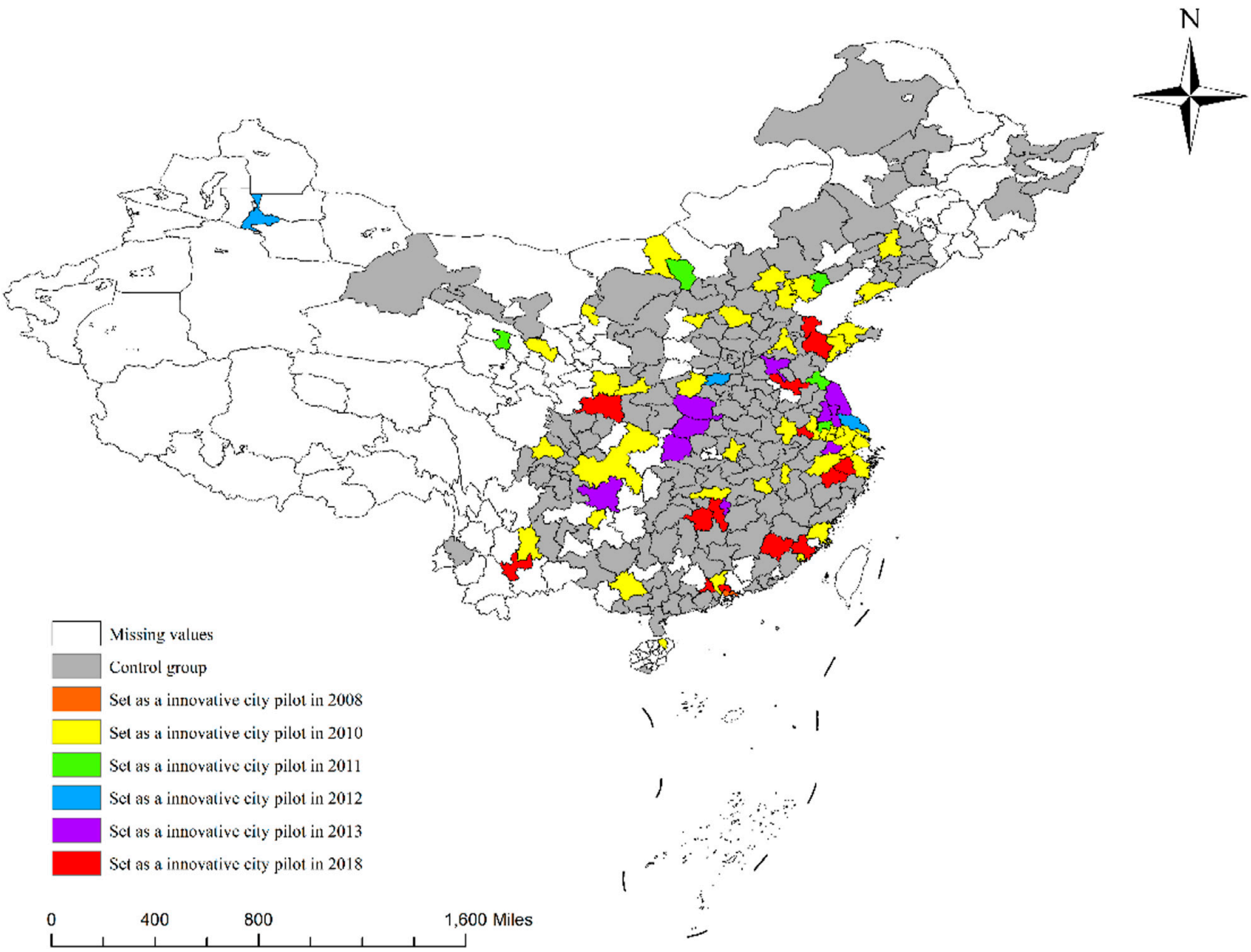


FIGURE 1
Distribution of innovative city pilots in China.

# 4 Methods and data

## 4.1 Spatial difference-in-difference model

This paper employees the ICP as a quasi-natural experiment and adopts the DID model to assess the impact of government support for innovation on urban natural carbon emissions. Selecting the implementation of ICP as dependent variables can reduce the potential interference caused by endogenous problems to a certain extent. In addition, considering the spatial spillover effect of urban carbon emissions (Gao and Yuan, 2022; Zhao and Sun, 2022), this paper further incorporates spatial factors into the traditional DID model, and uses the spatial DID to evaluate the impact of the implementation of ICP on urban carbon emission performance.

In the inclusion of spatial factors, the most widely used methods are Spatial Lag Model (SLM), Spatial Error Model (SEM) and spatial Durbin Model (SDM) (Zhao and Sun, 2022). SLM includes the spatial lag term of the dependent variable in the model. SEM incorporates the spatial lag term of the error term into the model. SDM incorporates both the spatial lag terms of the independent variable and the dependent variable into the model. Considering the robustness, this paper will report the estimated results of these three models in the benchmark analysis. First, the spatial DID model based on SLM is constructed as follows:

$$Y_{it} = \alpha + \delta \sum_{j=1}^{n} W_{ij} Y_{it} + \beta ICP_{it} + \varepsilon_{it}, \quad \varepsilon_{it} \sim N\left(0, \sigma^2 I\right) \tag{1}$$

where $Y_{it}$ denotes the urban carbon emission performance of city $i$ in year $t$, $ICP_{it}$ denotes implementation of the innovative city pilots, $\delta \sum_{j=1}^{n} W_{ij} Y_{it}$ denotes the spatial lag of carbon emission performance. Then, the spatial DID model based on SEM is specified:

$$Y_{it} = \alpha + \beta ICP_{it} + \varepsilon_{it} \tag{2}$$

TABLE 1 Variable definition.

| Classification | Symbol | Definition | Measurement |
|---|---|---|---|
| Dependent variable | cep | Carbon emission performance | Calculation based on expanded SFA model |
| Independent variables | ICP | innovative city pilots | Takes the value of 1 if ICP is implemented, 0 otherwise |
| Control variables | lnrgdp | Economic development | Logarithm of GDP per capita |
| | is | Industry structure | Value added of tertiary industry/value added of secondary industry |
| | gov | Government intervention | Government expenditure/GDP |
| | fin | Financial development | Deposit and loan balance of financial institutions/GDP |
| | fdi | Level of foreign investment | Actual amount of foreign capital utilized/GDP |
| Variables in KLH-SFA | ∅lngdp | Economic aggregate | Logarithm of GDP |
| | ∅lnpop | Total population | Logarithm of population |
| | ∅lngov | Government expenditure | Logarithm of government expenditure |
| | ∅lnind | Total industrial output | Logarithm of total industrial output |

TABLE 2 Descriptive statistics.

| Variable | Obs | Mean | Std | Min | Median | Max | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|
| cep | 2,856 | 0.497 | 0.169 | 0.071 | 0.505 | 0.818 | −0.355 | 2.232 |
| ICP | 2,856 | 0.171 | 0.377 | 0.000 | 0.000 | 1.000 | 1.746 | 4.047 |
| lnrgdp | 2,856 | 0.481 | 0.099 | 0.117 | 0.482 | 0.851 | −0.258 | 5.283 |
| is | 2,856 | 0.174 | 0.079 | 0.044 | 0.158 | 1.485 | −0.209 | 3.615 |
| gov | 2,856 | 0.934 | 0.579 | 0.112 | 0.752 | 6.071 | 2.979 | 33.115 |
| fin | 2,856 | 0.003 | 0.003 | 0.000 | 0.002 | 0.030 | 2.216 | 10.399 |
| fdi | 2,856 | 0.481 | 0.099 | 0.117 | 0.482 | 0.851 | 2.032 | 11.309 |
| ∅lnco2 | 2,856 | 16.887 | 0.920 | 13.795 | 16.860 | 19.452 | −0.153 | 3.035 |
| ∅lngdp | 2,856 | 16.552 | 0.918 | 14.067 | 16.452 | 19.760 | 0.464 | 3.238 |
| ∅lnpop | 2,856 | 14.723 | 0.831 | 12.387 | 14.694 | 18.241 | 0.579 | 4.307 |
| ∅lngov | 2,856 | 5.965 | 0.641 | 3.833 | 5.986 | 8.134 | −0.358 | 3.392 |
| ∅lnind | 2,856 | 15.796 | 0.946 | 12.863 | 15.754 | 18.469 | 0.120 | 3.008 |

$$\varepsilon_{it} = \lambda W_{it}\varepsilon + \mu, \quad \mu \sim N\left(0, \sigma^2 I\right) \tag{3}$$

where $Y_{it}$ denotes the carbon emission performance, $ICP_{it}$ denotes implementation of the innovative city pilots, $\lambda$ denotes the estimated coefficient of the spatial auto-correlation error term; $\mu$ denotes the error term. Finally, the spatial DID model based on SDM is specified:

$$\begin{aligned} Y_{it} &= \alpha + \delta\sum\nolimits_{j=1}^{n} W_{ij}Y_{it} + \beta ICP_{it} + +\xi\sum\nolimits_{j=1}^{n} W_{ij}ICP_{it} + \lambda Con_{it} \\ &\quad + \tau\sum\nolimits_{j=1}^{n} W_{ij}Con_{it} + \varepsilon_{it}, \\ \varepsilon_{it} &\sim N\left(0, \sigma^2 I\right) \end{aligned} \tag{4}$$

where $Y_{it}$ denotes the carbon emission performance, $ICP_{it}$ denotes implementation of the innovative city pilots, $Con_{it}$ is the control variables; $\sum_{j=1}^{n} W_{ij}Y_{it}$ denotes the spatial lag term of carbon emission performance, $\sum_{j=1}^{n} W_{ij}Con_{it}$ is the spatial lag term of control variables; $\sum_{j=1}^{n} W_{ij}ICP_{it}$ is the spatial lag term of implementation of the ICP. According to the study of LeSage and Pace (2009), if the spatial panel model has spatial hysteresis, the use of point estimation method to test the spatial spillover effect may lead to bias. Therefore, the total effect can be divided into direct effect and indirect effect by calculus method. The original SDM model can be rewritten into the following form:

$$Y_t = (1 - \delta W)^{-1}(\beta ICP_t + \gamma WICP_t) + (1 - \delta W)^{-1}\varepsilon_t \tag{5}$$

Taking the $k$-th independent variable as the example, the result can be expressed as a partial differential matrix according to the above formula:

$$\left[\frac{\partial Y}{\partial X_{1k}} \cdots \frac{\partial Y}{\partial X_{NK}}\right]_t = (1 - \delta W)^{-1}\begin{bmatrix} \beta_k & W_{12}\lambda_k & \dots & W_{1N}\lambda_k \\ W_{21}\lambda_k & \beta_k & \dots & W_{2N}\lambda_k \\ \vdots & \vdots & \ddots & \vdots \\ W_{N1}\lambda_k & W_{N2}\lambda_k & \cdots & \beta_k \end{bmatrix} \tag{6}$$

The above matrix reflects that the average values of diagonal elements and off-diagonal elements are respectively displayed in the partial differential matrix, and the changes of the independent variables in this region and other regions denote the direct and indirect effects.

## 4.2 Variable

### 4.2.1 Dependent variable

Based on the review of existing carbon emission performance assessment approaches, the extended SFA model proposed by Kumbhakar et al. (2014) is adopted in this paper. This model can separate the time-varying inefficiency, time-invariant inefficiency, and urban heterogeneity in the residuals at the same time. The model is specified as follows:

$$CE_{i,t} = \beta_0 + f(X_{i,t};\beta) + \mu_{it} + \lambda_i - \tau_{it} - \gamma_i \tag{7}$$

$$PCEP_i = exp(-\hat{\gamma}_i) \tag{8}$$

$$RCEP_{i,t} = exp(-\hat{\tau}_{it}) \tag{9}$$

$$CEP_{i,t} = PCEP_i \times RCEP_{i,t} \tag{10}$$

where $CE_{i,t}$ denotes the carbon emission of city $i$ in year $t$; $f(X_{i,t};\beta)$ is the random frontier function of the carbon emission. $X_{i,t}$ denotes the output factor related to carbon emissions (Filippini and Hunt, 2015; Mele and Magazzino, 2020); $\beta$ is the regression coefficient; $\mu_{it}$ is the regression error term; $\lambda_i$ is the urban effect; $\tau_{it} \geq 0$ and $\gamma_i \geq 0$ are the inefficiency of continuous carbon emission and residual carbon emission respectively. Meanwhile, they meet the following mathematical distribution requirements: $\mu_{it} \sim N(0, \sigma_u^2)$, $\lambda_i \sim N(0, \sigma_\lambda^2)$, $\tau_{it} \sim N^+(0, \sigma_\tau^2)$, $\gamma_i \sim N^+(0, \sigma_\gamma^2)$. Furthermore, the total carbon emission performance (CEP) is calculated by multiplying the persistent carbon emission performance (PCEP) and the residual carbon emission performance (RCEP).

### 4.2.2 Independent variable

ICP is an incremental reform, with six batches of cities implementing ICP. Specifically, 77% of the pilot cities establishment concentrated between 2010 and 2013, including 41, 6, 3 and 10 cities in 2010, 2011, 2012 and 2013, respectively. Only Shenzhen was established in 2008, and the remaining 17 pilot cities were established in 2018. This study adopts the implementation of ICP as the independent variable to assess the effect of government support for innovation on the improvement of urban carbon emission performance. The value is 1 if city $i$ has implemented ICP in year $t$ and 0 if it has not implemented ICP.

### 4.2.3 Control variable

To assess the impact of ICP on urban carbon emission performance more reliably, this paper incorporates a series of control variables in the model, including the level of economic development (lnrgdp), industrial structure (is), government intervention (gov), the level of financial development (fin) and the level of foreign investment (fdi) (Magazzino, 2017b; Ashraf et al., 2020; Song et al., 2021; Wang B et al., 2021; Pan X et al., 2022; Wang and Huang, 2022; Wang S et al., 2022; Wang W et al., 2022; Wu D et al., 2022). The specific measures of each variable are shown in Table 1. Table 2 further reports the descriptive statistics for each variable.

## 4.3 Data

This paper is based on the open-source spatial grid monthly dataset of anthropogenic carbon emissions (ODIAC) deduced by the team of Oda et al. (2018). This dataset reports high-resolution carbon emission data of 1 km × 1 km, which is aggregated to form a prefecture-level city panel carbon emission dataset. The period of the sample is from 2008 to 2019. The control variables selected in this paper come from the Chinese City Statistics Database (CCSD) in Chinese Research Data Services (CNRDS) Platform (https://www.cnrds.com/Home/Index#/FinanceDatabase/DB/CCSD) and the China Urban Statistical Yearbook. Since the spatial DID model requires the data structure to be a balanced panel, this paper excludes city samples with missing values in any year. The balanced panel dataset contains 238 cities per year with a total of 2856 samples.

# 5 Results

## 5.1 Measurement of carbon emission performance

Figure 2 shows the carbon emission performance maps of cities based on SFA model in 2010, 2015 and 2019. In the same year, the darker color denotes the higher carbon emission performance. In terms of the national carbon emission performance distribution, the average carbon emission performance of northern cities is relatively high in these 3 years. While the carbon emission performance of southern cities is relatively low on average. Meanwhile, the carbon emission performance of coastal cities is on average higher than that of inland cities at similar latitudes. We also found that the pattern of carbon emission performance in China remains roughly the same from 2010 to 2019, but there is an overall increase in carbon emission performance.

## 5.2 Spatial autocorrelation test

This paper tested the spatial correlation of carbon emission performance of cities. Scatter plots of Moran index can reflect the spatial correlation of carbon emission performance more visually. Figure 3 shows the scatter plots of carbon emission

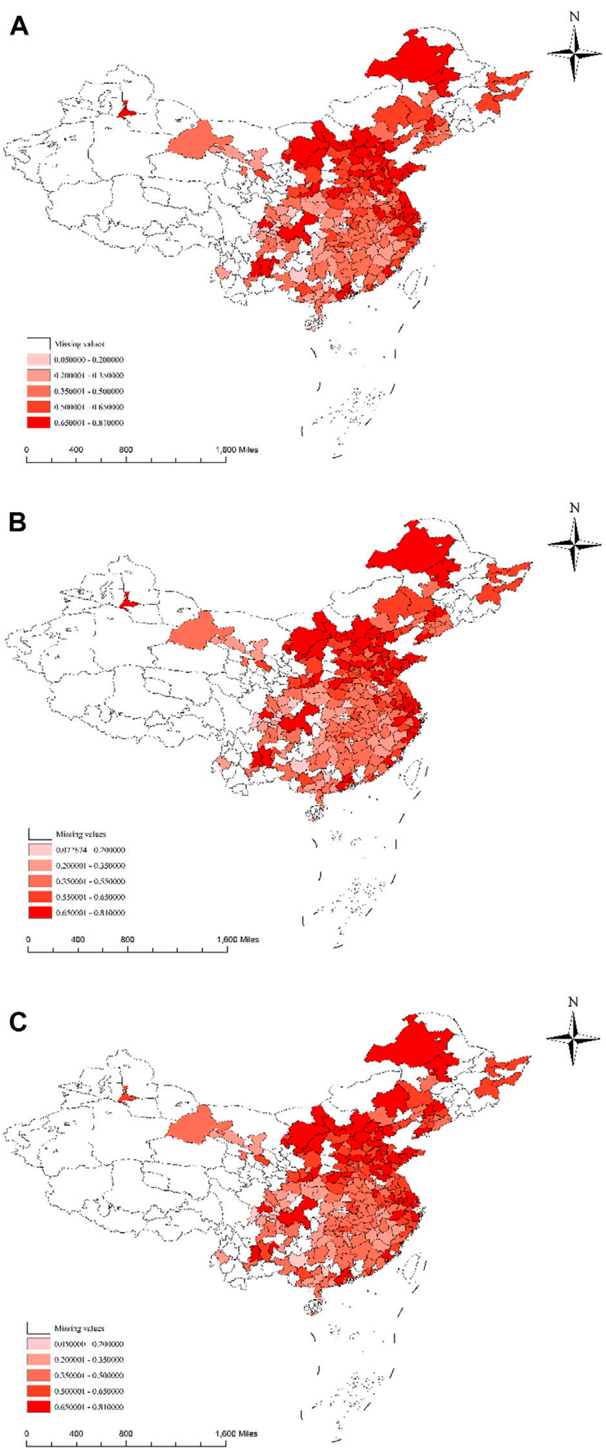


FIGURE 2
Carbon emission performance maps of cities. **(A)** denotes the maps in 2010, **(B)** denotes the maps in 2015, and **(C)** denotes the maps in 2019.

performance of cities in 2010, 2015 and 2019. In these three plots, the horizontal axis represents the standardized carbon emission performance, and the vertical axis represents the spatial lagged values. The coefficients of the primary fit line according to the scatterplot are significantly smaller than zero, which indicates that there is a spatial negative correlation between the urban carbon emission performance. Table 3 shows the specific results of Moran index of carbon emission performance. The Moran index is significantly negative at the 1% level for the period 2008 to 2019. The values of the indexes are between -1 and 0. This shows that the carbon emission performance of cities in China has a strong spatial correlation. Therefore, spatial factors should be considered in the estimation model.

## 5.3 Impact of innovative city pilots on carbon emission performance

Table 3 reports the baseline regression results. For comparison and to ensure the robustness of the results, here we report the regression results including the fixed effects model, the SLM model, the SEM model, and the SDM model. According to the results, there is a significant positive contribution of ICP policy on carbon emission performance. The coefficients of ICP on carbon emission performance calculated by the four models are 0.9% ($p < 0.01$), 1.7% ($p < 0.01$), 1.2% ($p < 0.01$) and 1.3% ($p < 0.01$), respectively. Since SDM considers both spatial lag effects and spatial error effects, its assessment of ICP effects is more reliable. Thus, the implementation of ICP leads to a final improvement of urban carbon emission performance by 1.3% after excluding the spatial factor interference.

The results indicates that ICP policy can improve carbon emission performance. Meanwhile, the pilot of innovative cities helps to respond to cities for green development and economic improvement. In terms of other control variables, the effect of GDP per capita on carbon emission performance is significantly negative at the 1% level in all four models. The effect of industrial structure on carbon emission performance is also negative at the 1% level. The effect of government expenditure on carbon emission performance is still significantly negative at the 1% level in all four models. On the contrary, the effect of deposit and loan balances of financial institutions on carbon emission performance is significantly positive at the 1% level in all four models. The effect of actual utilization of foreign finance on carbon emission performance is insignificant.

The estimation results of SDM model show that ICP policy has an important enhancement effect on carbon emission performance. Since ICP pilot cities are distributed across the country and carbon emission performance is also spatially correlated, it is necessary to discuss the spatial spillover effects. Table 5 further reports the spatial spillover effects of ICP policies on carbon emission performance. Specifically, the direct, indirect, and total effects of ICP policy on carbon emission performance improvement are significantly positive at the 1% level. This indicates that ICP policies in the region can significantly contribute to the carbon emission performance of

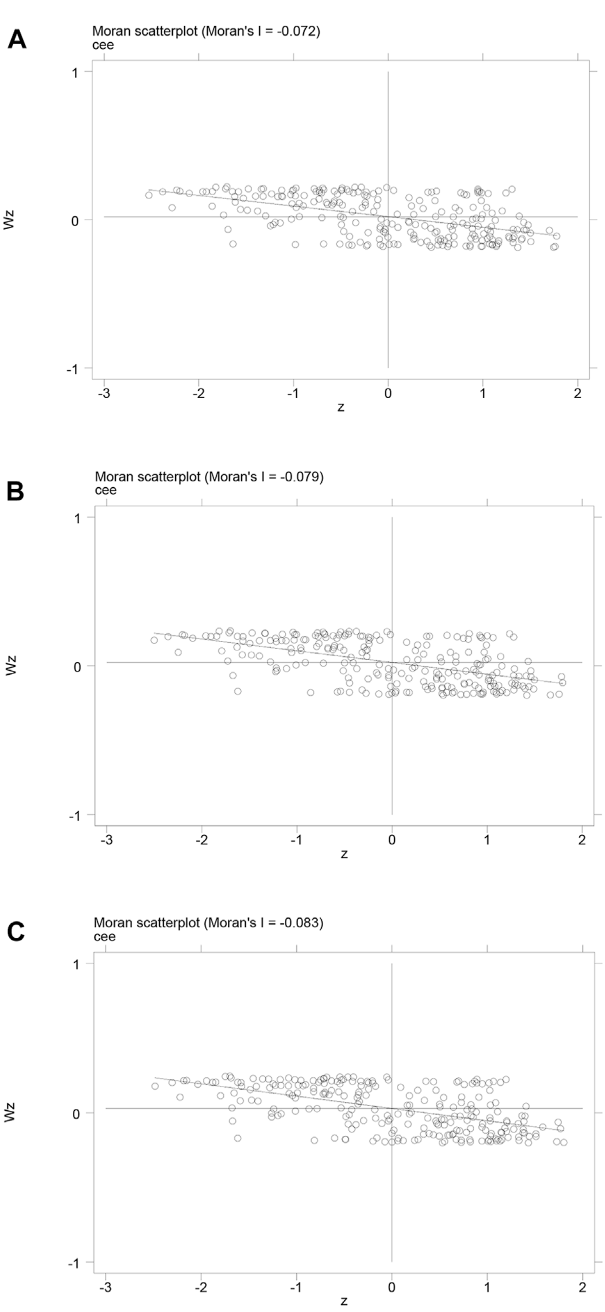


FIGURE 3
Moran scatterplot of urban carbon emission performance. **(A)** denotes the Moran scatterplot in 2010, **(B)** denotes the Moran scatterplot in 2010 in 2015, and **(C)** denotes the Moran scatterplot in 2010 in 2019.

the region firstly, and significantly contribute to the carbon emission performance of other regions. Thus, the average effect of ICP on carbon emission performance is all elevated, which is consistent with the study of Xu et al. (2021). However, the study of Xu et al. (2021) ignored the spatial spillover effect of ICP. This paper holds that the contribution of ICP policy to the

TABLE 3 Calculation of Moran's I index of urban carbon emission performance.

| | Moran's I | Z-value |
|---|---|---|
| 2008 | −0.061*** | −24.206 |
| 2009 | −0.061*** | −24.247 |
| 2010 | −0.072*** | −28.834 |
| 2011 | −0.073*** | −29.448 |
| 2012 | −0.073*** | −29.432 |
| 2013 | −0.074*** | −29.702 |
| 2014 | −0.075*** | −30.458 |
| 2015 | −0.079*** | −31.884 |
| 2016 | −0.081*** | −32.869 |
| 2017 | −0.083*** | −33.516 |
| 2018 | −0.082*** | −33.201 |
| 2019 | −0.083*** | −33.521 |

Note: ***, **, and * denote significant at the 1% level, 5% level and 10% level.

carbon emission performance of the region is greater than that for other regions. In addition, some studies use fiscal innovation spending or carbon taxes to measure government innovation support and find that the improvement in carbon performance is not significant (Fu et al., 2022; Yıldırım et al., 2022). This paper argues that the assessment results based on the above indicators may be subject to endogenous interference. In contrast, this paper uses ICP to measure government innovation support, which can reduce the potential interference from endogenous. In conclusion, the government should also pay attention to the demonstration role of pilot cities, which can improve the radiation efficiency by enacting policies such as inter-regional collaboration (De Noni et al., 2017; Tang D et al., 2022). Such policies can promote the overall improvement of carbon emission performance in a larger scale.

## 5.4 Parallel trend test

Figure 4 reports the results of the parallel trend test. None of the regression coefficients passed the significance test before the implementation of the ICP policy. This shows that there is no significant difference between the control and experimental groups before the implementation of the policy. The hypothesis of parallel trend was satisfied. In addition, after the implementation of ICP policy, the regression coefficients showed a trend of in-creasing and then decreasing. This shows that the innovative city pilot policy has the strongest effect in the first 2 years of implementation. And as time passes, the effect of the policy on carbon emission performance starts to decline. This means that in the short term, the pilot innovative cities can bring about an improvement in carbon emission performance, but the effect will gradually diminish. The

TABLE 4 Impact of innovative city pilots on urban carbon emission performance.

| Variables | *FE* | *SLM* | *SEM* | *SDM* |
|---|---|---|---|---|
| ICP | 0.009*** | 0.017*** | 0.012*** | 0.013*** |
| | (0.002) | (0.002) | (0.002) | (0.002) |
| lnrgdp | −0.015*** | −0.004*** | −0.008*** | −0.013*** |
| | (0.002) | (0.001) | (0.002) | (0.002) |
| is | −0.081*** | −0.020*** | −0.061*** | −0.044*** |
| | (0.009) | (0.008) | (0.008) | (0.009) |
| gov | −0.085*** | −0.039*** | −0.062*** | −0.075*** |
| | (0.009) | (0.010) | (0.010) | (0.010) |
| fin | 0.009*** | 0.006*** | 0.010*** | 0.008*** |
| | (0.002) | (0.002) | (0.002) | (0.002) |
| fdi | −0.126 | −0.085 | −0.062 | 0.074 |
| | (0.185) | (0.198) | (0.191) | (0.188) |
| wICP | | | | 0.033*** |
| | | | | (0.004) |
| wlnrgdp | | | | 0.023*** |
| | | | | (0.003) |
| wis | | | | 0.127*** |
| | | | | (0.015) |
| wgov | | | | 0.111*** |
| | | | | (0.024) |
| wfin | | | | −0.023*** |
| | | | | (0.004) |
| wfdi | | | | −0.736 |
| | | | | (0.453) |
| City FE | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y |
| Obs | 2856 | 2856 | 2856 | 2856 |
| Log-L | 98.384 | 8231.978 | 8239.058 | 8265.711 |
| $R^2$ | 0.391 | 0.155 | 0.036 | 0.066 |

Note: 1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. 2) City FE, and Year FE, denote the city fixed effects and year fixed effects. 3) City-level cluster robust standard errors are reported in parentheses.

government should improve the effectiveness of the ICP policy more in the long term while ensuring the short-term performance of the policy.

## 5.5 Further analysis

### 5.5.1 Mechanism of innovative city pilots affecting urban carbon emission performance

To test hypothesis 1, this paper constructs the following mediating effect model to explore the mechanism of the innovative city pilots affecting urban carbon emission performance:

$$CEP_{it} = \alpha + \beta ICP_{it} + \lambda Con_{it} + \varepsilon_{it} \tag{11}$$

$$M_{it} = \alpha + \beta ICP_{it} + \varepsilon_{it} \tag{12}$$

$$CEP_{it} = \alpha + \beta ICP_{it} + \gamma M_{it} + \lambda Con_{it} + \varepsilon_{it} \tag{13}$$

where $M_{it}$ denotes the mediating variable, including total factor productivity, green innovation, and industrial upgrading. Total factor productivity is measured through the extended SFA model, where total GDP is the dependent variable and population, government expenditure and foreign investment are the independent variables. Green innovation is measured by the logarithm of the total number of green invention patents and green applicable patents in city $i$ in year $t$. This paper measures industrial upgrading through the following equation according to the study of Jie and Qian (2016):

$$iu_{it} = \sum_{m=1}^{3} y_{imt} \times m, m = 1, 2, 3 \tag{14}$$

where a denotes the share of industry $m$ of city $i$ in the GDP at time $t$. This indicator denotes the evolution of the proportional relationship between the three major industries in China from the dominance of the primary industry to the dominance of the secondary and tertiary industries. Higher value of this indicator means the higher level of industrial upgrading. If the coefficients of ***ICP*** in Eqs. 11 and $M$ in Eq. 12 pass the significance test, it indicates that ICP affects urban carbon emission performance through promoting labor productivity, green innovation, and industrial upgrading. Table 6 reports the regression results for this model.

According to the results in Table 6, the impact of ICP on *tfp*, *green_inn* and *iu* are 0.252 ($p < 0.01$), 1.376 ($p < 0.01$) and 0.191 ($p < 0.01$), which all pass the 1% significance test. This shows that government innovation support can significantly improve the urban total factor productivity, green innovation, and industrial upgrading, which are consistent with the study of Xu et al. (2021)

TABLE 5 Direct effect, indirect effect, and total effect of SDM in Table 4.

| | ICP | Lnrgdp | is | Gov | Fin | Fdi |
|---|---|---|---|---|---|---|
| Direct effect | 0.033*** | 0.023*** | 0.127*** | 0.111*** | −0.023*** | −0.736 |
| | (0.004) | (0.003) | (0.015) | (0.024) | (0.004) | (0.453) |
| Indirect effect | 0.014*** | −0.012*** | −0.038*** | −0.071*** | 0.007*** | 0.056 |
| | (0.002) | (0.002) | (0.009) | (0.009) | (0.002) | (0.191) |
| Total effect | 0.048*** | 0.026*** | 0.155*** | 0.122*** | −0.028*** | −0.935 |
| | (0.005) | (0.003) | (0.019) | (0.031) | (0.006) | (0.620) |

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City-level cluster robust standard errors are reported in parentheses.

TABLE 6 Mechanisms of innovative city pilots affecting urban carbon emission performance.

| | *tfp* | *cep* | *green_inn* | *cep* | *iu* | *cep* |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| ICP | 0.252*** | 0.024*** | 1.376*** | 0.008*** | 0.191*** | 0.011*** |
| | (0.014) | (0.002) | (0.082) | (0.002) | (0.014) | (0.002) |
| tfp | | 0.018*** | | | | |
| | | (0.006) | | | | |
| green_inn | | | | 0.008*** | | |
| | | | | (0.001) | | |
| iu | | | | | | 0.033*** |
| | | | | | | (0.004) |
| Control | Y | Y | Y | Y | Y | Y |
| City FE | Y | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y | Y | Y |
| Observation | 2856 | 2856 | 2856 | 2856 | 2856 | 2856 |
| F | 326.475 | 31.785 | 278.610 | 102.345 | 184.184 | 96.233 |
| $R^2$ | 0.111 | 0.079 | 0.096 | 0.415 | 0.066 | 0.387 |

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

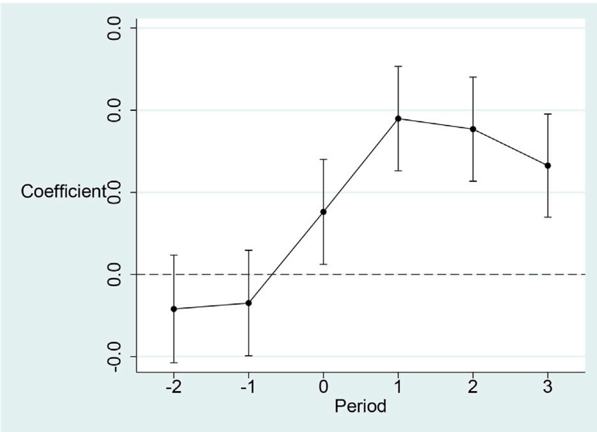


FIGURE 4
Results of Parallel Trend Test. The X-axis denotes the window period for ICP implementation. The Y axis represents the regression coefficient of ICP implementation. The year before ICP is implemented as the base period.

and Zheng and Ge (2022). In addition, the results hold that the coefficients of ***tfp***, *green_inn* and *iu* are 0.018 ($p < 0.01$), 0.008 ($p < 0.01$) and 0.033 ($p < 0.01$). This means that there are significant mechanisms for ICP to improve urban carbon emission performance through the promotion of urban total factor productivity, green innovation, and industrial upgrading, that is, the results support hypothesis 1. Therefore, the government should not only strengthen its support for technological innovation, but also further improve the market allocation of production factors and strengthen the positive impact of the above three mechanisms (Shen et al., 2021; Xi and Mei, 2022).

### 5.5.2 Heterogeneity analysis

There are huge differences in development between different regions in China. In terms of economic development level, the eastern region is higher than the western region in the central region (Dai and Mischke, 2014). As a government-led financial support policy, there may be differences in the intensity and effectiveness of ICP implementation in different economic development regions. Therefore, it is necessary to analyze the differences in the impact of ICP on different regions. Second, the impact effect of ICP is also related to the size of cities. The larger the city has a more complex and well-developed industrial system, the higher the scale effect of ICP implementation will be (Pan A et al., 2022). Therefore, the differences in the impact of ICP on the carbon emission performance of cities of different sizes should be further explored. Finally, the resource-dependent cities of cities are also factors to be considered. Compared with resource-based cities, non-resource-based cities consume less energy and have lower upside of carbon emission performance from ICP (Sun et al., 2022). Therefore, this paper further evaluates the differences in the impact of ICP on cities of different resource types.

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TABLE 7 Heterogeneity analysis.

| Variables | Region | Size | Resource Type |
|---|---|---|---|
| ICP | 0.019*** | 0.009*** | −0.001 |
| | (0.002) | (0.002) | (0.003) |
| ICP×Central | −0.018*** | | |
| | (0.004) | | |
| ICP×Western | −0.005 | | |
| | (0.004) | | |
| ICP×Big | | 0.008*** | |
| | | (0.003) | |
| ICP×Res | | | 0.020*** |
| | | | (0.003) |
| lnrgdp | −0.013*** | −0.013*** | −0.012*** |
| | (0.002) | (0.002) | (0.002) |
| is | −0.048*** | −0.044*** | −0.043*** |
| | (0.009) | (0.009) | (0.009) |
| gov | −0.078*** | −0.073*** | −0.076*** |
| | (0.009) | (0.009) | (0.009) |
| fin | 0.008*** | 0.008*** | 0.008*** |
| | (0.002) | (0.002) | (0.002) |
| fdi | 0.159 | 0.091 | 0.085 |
| | (0.188) | (0.188) | (0.188) |
| wICP | 0.020*** | 0.046*** | 0.030*** |
| | (0.005) | (0.006) | (0.007) |
| wICP×Central | 0.075*** | | |
| | (0.011) | | |
| wICP×Western | −0.009 | | |
| | (0.010) | | |
| wICP×Big | | −0.024*** | |
| | | (0.007) | |
| wICP×Res | | | 0.001 |
| | | | (0.009) |
| wlnrgdp | 0.023*** | 0.022*** | 0.022*** |
| | (0.003) | (0.003) | (0.003) |
| wis | 0.123*** | 0.127*** | 0.126*** |
| | (0.015) | (0.015) | (0.015) |
| wgov | 0.112*** | 0.111*** | 0.107*** |
| | (0.024) | (0.024) | (0.024) |
| wfin | −0.026*** | −0.023*** | −0.023*** |
| | (0.004) | (0.004) | (0.004) |
| wfdi | −0.924** | −0.762* | −0.576 |
| | (0.454) | (0.451) | (0.451) |
| City FE | Y | Y | Y |
| Year FE | Y | Y | Y |
| Obs | 2856 | 2856 | 2856 |
| $R^2$ | 0.056 | 0.076 | 0.105 |

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

Table 7 reports the results of the heterogeneity analysis of ICP policies on carbon emission efficiency. The first row of Table 7 is the baseline row, and the effects of ICP policies on carbon emission performance are reported from left to right for eastern regional cities, small cities, and non-resource cities, respectively. In terms of geographic location, the impact of ICP policy on carbon emission performance for eastern cities is 1.9%. The effect of ICP policy on carbon emission performance in central cities is significantly lower compared to eastern cities, which is only 0.1%. And the improvement effect of ICP policy on carbon emission performance in western cities is not significantly different from that in eastern cities. This indicates that the government should pay attention to the efficiency of the role of ICP policies in central cities, while ensuring the continued improvement of carbon emission performance in the east and west. The synergistic green development of the country's eastern, central, and western cities should be advocated. The size of cities al-so makes a difference in the impact of ICP policies on carbon emission performance. For small cities, ICP policies can significantly improve carbon emission performance by 0.9%. This improvement is more pronounced in large cities. The level of improvement in carbon emission performance for ICP policies in large cities is 1.7%, which is nearly twice as high as in small cities.

The results indicate that the country should pay attention to the radiative effect brought by large cities while paying attention to the development of green innovation in large cities. The large cities should be the center of a more efficient synergy of policy implementation in the surrounding small cities (Li X et al., 2022). Which will promote the synergistic enhancement of technological innovation and green development in a wider range of cities through the extensive layout of ICP policies. The difference between resource-based cities and non-resource-based cities is obvious. The specific setting of resource-based cities is based on the total amount of carbon emissions. Here we set the cities with higher total carbon emissions as resource-based cities using the data of total carbon emissions of different cities. Conversely, the remaining ones are non-resource-based cities. The study of Kang et al. (2022) points out that the focus of energy efficiency and emission reduction is on less efficient regions, but does not further assess the differences in the impact of government innovation support on cities with different resource types. The effect of ICP policy for non-resource-based cities on carbon emission performance is insignificant. In contrast, the ICP policy of resource-based cities has a 2% enhancement effect on carbon emission performance. On the one hand, this indicates that resource-based cities are uniquely positioned to improve their carbon emission performance based on improved technological innovation, which is consistent with the findings of Zheng and Ge (2022). On the other hand, this paper suggests that government

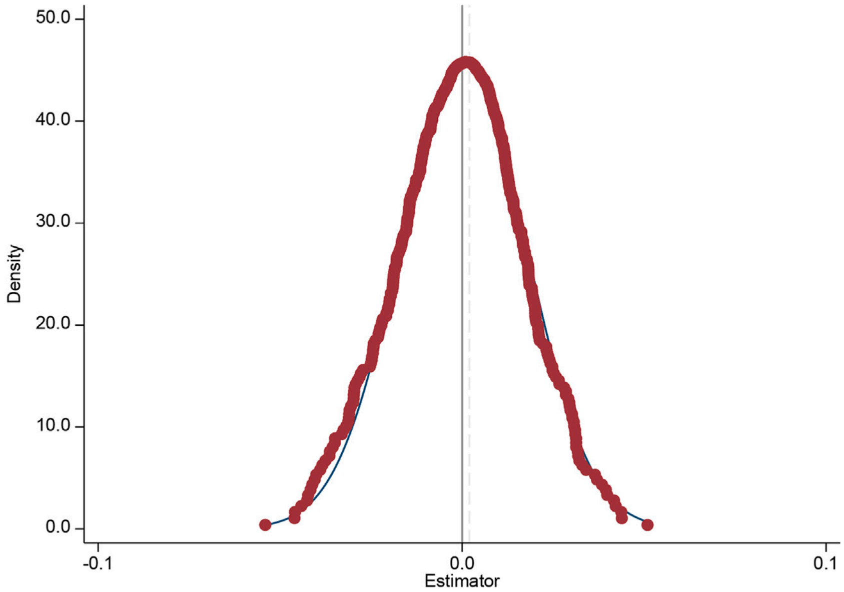


FIGURE 5
Results of placebo test. Treatment groups were randomly drawn 500 times in the control group by Monte Carlo simulation and DID regression was performed. Plot the obtained regression coefficients as a distribution graph. This figure reports the results of carbon emission performance of non-pilot cities as a dependent variable, presenting a normal distribution with an average value of 0.

needs to improve the effectiveness of ICP policies in non-resource-based cities. According to the study of Kang et al. (2022), better policy guidance and implementation are needed to promote the carbon emission performance of all types of cities.

## 5.6 Robustness test

### 5.6.1 Placebo test

Considering ICP policies may also affect the carbon emission performance of non-pilot cities, this would lead to unreliable estimation results. In this paper, a placebo test is conducted using Monte Carlo simulation. Firstly, we randomly selected samples from the control group multiple times as the treatment group. Then, based on this we then perform PSM-DID regression analysis and estimate the parameters. If the estimated parameters are normally distributed with a mean value of 0, then the results of the analysis in this paper are reliable. Figure 5 gives the estimated coefficient distributions and kernel density curves after 500 randomly drawn samples. As expected from the placebo test, the estimated coefficients show a normal distribution, and the mean value is around 0. This shows that the change in carbon emission performance of the real treated group originates from the implementation of the ICP policy.

### 5.6.2 Re-estimation using PSM-DID

In our previous study, we used a spatial panel regression. Based on this paper we obtained a positive result and concluded that the contribution of ICP policy on carbon emission performance is significant. To strengthen the robustness of the study, here we modify the methodology. Instead of using a spatial panel, we use the PSM method for post-matching regressions. In applying the PSM method, we used two conventional matching methods, namely 1:1 nearest neighbor matching and kernel density matching. Table 8 reports the regression results after matching using these two methods. The results show that the ICP policy can significantly improve the carbon emission performance of cities by either using nearest neighbor matching or kernel density matching. This is consistent with the results of the previous study using spatial panels. The results of this paper are robust.

### 5.6.3 Re-estimation of different dependent variable

To avoid the potential influence of variable settings on the estimation results, this paper also chooses to measure the carbon emission performance of cities by taking the logarithm of GDP per unit of carbon emissions. Table 9 reports the re-estimation results for the replaced dependent variables. Table 9 shows that the effects of ICP policy on urban

TABLE 8 Re-estimation using PSM-DID.

| | Neighbor matching (n = 1) | Kernel matching |
|---|---|---|
| ICP | 0.016** | 0.010*** |
| | (0.008) | (0.002) |
| lnrgdp | −0.053*** | −0.014*** |
| | (0.008) | (0.002) |
| is | −0.070* | −0.077*** |
| | (0.038) | (0.010) |
| gov | −0.310*** | −0.085*** |
| | (0.073) | (0.010) |
| fin | −0.006 | 0.010*** |
| | (0.004) | (0.002) |
| C | 1.183*** | 0.637*** |
| | (0.080) | (0.022) |
| City FE | Y | Y |
| Year FE | Y | Y |
| Obs | 469 | 2302 |
| F-static | 23.595 | 28.098 |
| Adj-$R^2$ | 0.371 | 0.314 |

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

TABLE 9 Re-estimation of different dependent variable.

| Variables | FE | SLM | SEM | SDM |
|---|---|---|---|---|
| ICP | 0.049*** | 0.037*** | 0.038*** | 0.034*** |
| | (0.010) | (0.009) | (0.009) | (0.009) |
| wICP | | | | 1.365*** |
| | | | | (0.397) |
| Control | Y | Y | Y | Y |
| City FE | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y |
| Obs | 2856 | 2856 | 2856 | 2856 |
| Log-L | 1161.54 | 2932.872 | 2948.328 | 3038.752 |
| $R^2$ | 0.884 | 0.064 | 0.056 | 0.079 |

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

carbon emission performance under the fixed effects model, SLM model, SEM model and SDM model are 4.9%, 3.7%, 3.8%, and 3.4%, respectively. And all the coefficients passed the 1% significance test. This implies the regression results of replacing individual explanatory variables remain consistent with those of the previous paper. The conclusions of this paper are relatively re-liable.

TABLE 10 Re-estimation excluding contemporaneous policy disturbances.

| Variables | (1) | (2) |
|---|---|---|
| ICP | 0.009*** | 0.009*** |
| | (0.001) | (0.002) |
| LCCP | 0.001 | |
| | (0.001) | |
| CETP | | 0.011*** |
| | | (0.002) |
| Control | Y | Y |
| City FE | Y | Y |
| Year FE | Y | Y |
| Obs | 2856 | 2856 |
| F | 92.88 | 96.43 |
| $R^2$ | 0.391 | 0.403 |

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

### 5.6.4 Re-estimation excluding contemporaneous policy disturbances

To exclude the interference of other contemporaneous policies on the analysis results of this paper, this paper further controls for low carbon city pilot (LCCP) and carbon emission trading pilot (CETP) policy shocks in the model (Chen et al., 2021; Cui et al., 2021). After adding the above two policy shocks, the results of the impact of ICP on urban carbon emission performance are shown in Table 10. According to the results in Table 10, the coefficients of ICP and LCCP are 0.009 ($p < 0.01$) and 0.001 ($p > 0.1$) in column (1). The coefficients of ICP and CETP are 0.009 ($p < 0.01$) and 0.011 ($p < 0.01$) in column (2). The above results show that controlling for LCCP and CETP separately, ICP still has a significant positive effect on carbon emission performance. This shows that the conclusion that government innovation support enhances carbon emission performance is robust.

### 5.6.5 Re-estimation based on an expanded SDID approach

Chagas et al. (2016) proposed a spatial DID method that can decompose the treatment effects of the spatial weight matrix. We used this method for re-estimation to ensure the reliability of the analytical results in this paper. The results are shown in the following Table 11.

According to the results in Table 11, the coefficients of ICP and wICP in restricted model are 0.016 ($p < 0.01$) and 0.067 ($p < 0.01$), which both passes the 1% significance test. In addition, the coefficients of $W_{T,T}$ICP and $W_{NT,T}$ICP in restricted model are 0.028 ($p < 0.01$)

TABLE 11 Re-estimation based on an expanded SDID approach.

| Variables | Restricted model | Unrestricted model |
|---|---|---|
| ICP | 0.016*** | 0.027*** |
| | (0.002) | (0.003) |
| wICP | 0.067*** | |
| | (0.005) | |
| $W_{T,T}$ICP | | 0.028*** |
| | | (0.009) |
| $W_{NT,T}$ICP | | 0.081*** |
| | | (0.005) |
| Control | Y | Y |
| City FE | Y | Y |
| Year FE | Y | Y |
| Obs | 2856 | 2856 |
| Log-L | 64.25 | 60.65 |
| $R^2$ | 0.182 | 0.165 |

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses. (4) According to the study of Chagas et al. (2016), the matrix w can be decomposed as $w = w_{T,T} + w_{T,NT} + w_{NT,T} + w_{NT,NT}$., The restricted model reports the results based on matrix w. Since $w_{T,NT}$, and are $w_{NT,NT}$, 0-vectors matrix, the unrestricted model reports the results based on matrix $w_{T,T}$ and are $w_{NT,T}$.

and 0.081 ($p < 0.01$), which also passed the 1% significance test. This means that the implementation of ICP policy not only significantly improves the local carbon emission performance, but also enhance the carbon emission performance of the surrounding areas. Consistent conclusions are obtained based on the extended SDID model estimation proposed by Chagas et al. (2016), indicating the robustness of the analytical results in this paper.

# 6 Conclusion and recommendations

## 6.1 Conclusion

This paper uses a spatial DID model to assess the effect of government innovation support on urban carbon emission performance based on a quasi-natural experiment of ICP from China. The main findings of this paper can be summarized in the following three points.

First, this paper measures urban carbon emission performance through the extended SFA model proposed by (Kumbhakar et al., 2014). The measurement results indicate that the average urban carbon emission in China from 2008 to 2019 is 49.7%, and there is still much room for improvement. In addition, our findings indicate that there is a significant spatial correlation in urban carbon emission performance, and that the carbon emission performance in northern and coastal regions is much higher than that in central and western regions.

Second, the estimation results of the spatial DID indicate that the implementation of ICP leads to a 1.3% improvement in the urban carbon emission performance. Meanwhile, the implementation of ICP also leads to a 3.3% improvement in the urban carbon emission performance of the surrounding areas. The total effects of carbon emission performance improvement from ICP implementation are 4.8%. The results shows that government innovation support not only significantly improves local carbon emission performance, but also has a positive spatial spillover effect.

Third, the results of mechanism analysis show that government innovation support enhances urban carbon performance mainly through three mechanisms, namely total factor productivity improvement, green innovation, and industrial upgrading. This paper also conducts a heterogeneity analysis for cities of different regions, sizes, and resource dependencies. The results show that there is no significant difference in the contribution of ICP to carbon performance between eastern and western cities, while the effect of ICP in central cities is relatively low. Meanwhile, the increase of ICP on carbon performance in large cities reaches almost twice that of small cities. In addition, we also observe that ICP in resource-based cities have a significant increase on carbon performance, while ICP in non-resource-based cities have no significant effect on carbon performance.

Finally, a series of robustness tests were conducted to ensure the reliability of the analysis results. The parallel trend test showed that there was no significant difference between the carbon emission performance of the treatment group and the control group before the implementation of ICP, while the carbon emission performance of the treatment group was significantly higher than that of the control group after the implementation of ICP. Therefore, the assessment results of spatial DID are relatively reliable. Meanwhile, the placebo test, re-estimation based on PSM-DID and re-estimation by replacing the dependent variable all yielded more consistent conclusions. This paper further controls for two policies, low-carbon pilot cities and carbon emissions trading pilot, respectively. The results show that after controlling for the above two policies ICP still has a significant positive impact on urban carbon emission performance.

This paper highlights the important role of government innovation support in improving urban carbon performance. Future research can further explore whether the effect of government innovation support differs across firms with different characteristics through micro data of firms. In addition, there is necessary to provide more assessments of the emission reduction effects of different types of government innovation support.

### 6.2 Recommendations

Based on the findings of the study, this paper puts forward the following recommendations.

First, government innovation support should be increased to improve carbon emission performance. China has become the country with the highest total carbon emissions in the world. The key to achieving peak and neutral carbon targets lies in the control of total emissions from high carbon sectors and the control of overall sectoral emissions performance. The findings of this paper suggest that the implementation of ICP not only significantly improves local carbon emission performance, but also has significant spillover effects on neighboring regions. Therefore, the role of innovation support in pollution control should be better utilized. On the one hand, government innovation support should focus on traditional sectors such as oil, steel and construction. Promote the improvement of carbon emission performance of traditional sectors through financial subsidies and tax incentives. On the other hand, government innovation support also needs to foster frontier industries such as carbon capture and storage. These industries can absorb carbon emissions from traditional sectors, thus effectively improving the overall carbon performance of the region.

Then, for economies with differences in regional development, such as China, differentiated innovation support policies should be developed for different regions. China's economic development is characterized by a more developed eastern coastal region and a more backward central and western region. As a result, the eastern region has been the first to complete industrial upgrading and transformation and has higher carbon performance. While the central and western regions have taken over part of the industrial transfer from the eastern regions, and their carbon emission performance is low. If the similar innovation support policy is adopted nationwide, it will inhibit the willingness of the central and western regions to improve their carbon emission performance through green innovation. Therefore, it is necessary for the government to give stronger incentives to the central and western regions to gather innovation factors to improve their carbon emission performance. The findings of this paper show that ICP has no significant enhancing effect on carbon emission performance in the western region. There are also differences in the effects of ICP with different city sizes and resource dependence. Therefore, the government should consider its own geographic environment, city size and resource dependencies when providing innovation support. For example, for western cities such as Xining and Lanzhou, the implementation of ICP may not be effective in improving carbon emission performance. In contrast, for cities such as Shanghai, Nanjing, or Hangzhou, ICP can significantly improve carbon emission performance. In addition, government can balance such regional differences through the setting of carbon emission trading allowances. For heavy industries in resource-based cities, such as mining and smelting, allow them to obtain higher carbon quotas through green technology innovation. This would further amplify the effect of government innovation support on the carbon performance of such regions.

### 6.3 Limitations

The study in this paper also has limitations, and further research can be extended in the following ways. First, due to the lack of firm-level carbon emission data, this paper only assesses the impact of government innovation support on carbon emission performance at the city level. Further research can explore the impact of government innovation from a more microscopic perspective by quantifying firm-level carbon emissions. Second, this paper focuses on the impact of government innovation support in a sample of developing countries represented by China. Further research can compare the differences in the impact of government innovation support on carbon performance across countries at different stages of development.

## Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.nies.go.jp/doi/10.17595/20170411.001-e.html.

## Author contributions

CY: Conceptualization; Data curation; Methodology; Writing—original draft. CT: Funding acquisition; Supervision; Validation; Project administration. HL: Writing—review and editing; Software; Resources. YT: Writing—review and editing. YZ: Writing—review and editing. CZ: Writing—review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Appendix A

Table A1 reports the regression results for the stochastic frontier function. The regression coefficients of economic aggregate (∅lngdp), total population (∅ln**pop**) and industrialized output (∅ln**ind**) are 0.045, 0.119 and 0.083, respectively. This means that the increase of these factors significantly raises the urban carbon emissions. In addition, the coefficient of government expenditure (∅ln**gov**) on urban carbon emissions is -0.057, which indicates that the increase of government expenditure can reduce urban carbon emissions. Based on the regression results, this paper extracts the residuals and transforms them through the extended SFA model to finally obtain the urban carbon emission performance.

TABLE A1 Results of energy demand stochastic frontier model.

| Variable | Coeff | T-value |
|---|---|---|
| *Basic Regression* | | |
| ∅ln*gdp* | 0.045*** | 2.250 |
| ∅ln*pop* | 0.119*** | 12.910 |
| ∅ln*gov* | −0.057*** | −2.580 |
| ∅ln*ind* | 0.083*** | 6.480 |
| *constant* | 13.432*** | 99.810 |
| *Inefficiency and error term* | | |
| $\mathbf{C_u}$ | −5.108*** | −85.090 |
| $\mathbf{C_v}$ | −6.306*** | −109.420 |
| Log likelihood | 3872.048 | |

Note: $\mathbf{C_u}$ and $\mathbf{C_v}$ are the unconstrained parameters, where $exp(C_\mu) = \sigma_\mu^2, exp(C_v) = \sigma_v^2$

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# Regional differences and influencing factors of the carbon emission efficiency from public buildings in China

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The rapid development of the tertiary industry has made the energy consumption of public buildings grow too fast during the operation stage, which has become a key area of energy conservation and emission reduction in China's construction industry. This study uses the Minimum Distance to Strong effective Frontier function (MinDS) and Malmquist-Luenberger (ML) index analysis methods to measure the public building carbon emission efficiency (PBCEE) of 30 provincial-level units in China's eight economic regions from 2010 to 2019, and analyze regional differences and evolution. Then, the influencing factors of PBCEE in different regions were analyzed using the fixed-effect panel data model. The results show that: 1) China's PBCEE is generally low, with an average efficiency value of only 0.74, and there are great differences among regions, showing the spatial characteristics of "high in the east and low in the west." 2) Relying on the positive impact of technological progress, the PBCEE in the eight regions increased year by year, with an annual growth rate of 1.82%. 3) The influence results and degrees of various factors on PBCEE are different in different economic zones, but increasing the proportion of electricity consumption has a certain positive effect on improving PBCEE. The same influencing factor has obvious threshold characteristics for PBCEE in different regions, so the government needs to consider the actual situation of the region when formulating carbon emission reduction policies for public buildings.

KEYWORDS

**public buildings, carbon emission efficiency, minimum distance to strong effective frontier function, Malmquist-Luenberger index, panel data model**

## Introduction

Sustainable development and global warming are still the main issues affecting world development. In recent years, the frequent occurrence of extreme weather and energy crises has brought great challenges to human society (Shan and Hwang, 2018). As one of the three major energy-consuming industries in China, the construction industry not only promotes economic development but also emits a large amount of carbon dioxide. In 2018, the total carbon emission of China's construction industry was 4.93 billion tons, accounting for 51.2% of the country's total carbon emissions (China Building Energy Consumption Research Report, 2021). To this end, the Chinese government has pledged to reduce carbon emissions per unit of gross domestic product (GDP) by around 65% by 2030 compared with 2005 (UNFCCC, 2016). To achieve this binding target, efforts are required to reduce carbon emissions by various industries, especially the construction industry (Lai et al., 2019), where the key to carbon emission reduction is to improve carbon emission efficiency.

Public buildings, also known as commercial buildings, as a typical part of the construction industry, and undertake most of the production activities of the tertiary industry. Therefore, the rapid development of the tertiary industry has made the carbon emissions of public buildings soar, accounting for more than 30% of the carbon emissions of the construction industry in 2018. In the whole life cycle of carbon emissions from public buildings, the proportion of carbon emissions generated in the operation stage is the largest (Building Energy Conservation Research Center of Tsinghua University, 2020). It is foreseeable that with the development of the tertiary industry, public buildings will also lead to a continuously high level of carbon emissions during operation. The newly promulgated "China's Carbon Neutral Strategy and Path to Peak Carbon" point out that the priority concept of energy saving is adhered to, and the energy efficiency of the whole society is continuously improved to facilitate the green transformation of production and life. Therefore, the improvement of carbon emission efficiency of related industries with public buildings as the main body (public building industry) plays an important role in realizing China's carbon peak in 2030.

Most studies on carbon emission efficiency focus on single-factor efficiency and total factor efficiency. The former defines carbon emission efficiency as the ratio of carbon emission to a certain factor of production. Such as Song et al. (2018) calculated the carbon emission intensity of China's construction industry; Li et al. (2021) analyzed that the change in intermediate input structure caused the change in the carbon intensity of the construction industry. However, this indicator does not consider the actual connection with other production factors, so it cannot be accurately measured (Hu and Wang, 2006). The commonly used methods in total factor efficiency research are the non-parametric method represented by Data Envelopment Analysis (DEA) and the parametric method represented by Stochastic Frontier Analysis (SFA). Compared with SFA, DEA has the advantages of multiple inputs and multiple outputs and has become the mainstream model for evaluating carbon emission efficiency. But under the traditional DEA model, the optimal value obtained is the maximum efficiency ratio, leading to the accuracy of efficiency measurement suffering. Relevant scholars are currently paying more attention to which model can better reflect the essence and significance of efficiency evaluation.

In the study of public buildings, related scholars have carried out work from different perspectives. Xiang et al. (2022a) used a structural decomposition approach to assess the progress of decarbonization of commercial buildings in 16 countries between 2010 and 2019, and the decarbonization efficiency of 16 economies was 10.1%. Soonsawad et al. (2022) calculated the material consumption and carbon emission of commercial buildings during the construction stage. Xiang et al. (2022b) estimated peak emissions from the commercial building sector at 1,264.81 MtCO2 using the LASSO-WOA method, with the peak year of 2030. Xiang et al. (2022c) developed a carbon emission index decomposition tool for the construction industry—PyLMDI. Du et al. (2022) discussed the spatiotemporal distribution of carbon emissions from public buildings in 30 provinces in China using the GTWR model and believed that there were east-west differences in the carbon emissions of public buildings in various provinces in China. Li G J. et al. (2022) studied the commercial buildings in China from 2001 to 2016 changes in carbon emission reduction in the operation phase and established an evaluation framework for emission reduction intensity, emission reduction amount, and carbon emission reduction rate for the decomposition of carbon intensity. Liu L. Q et al. (2021) evaluated the static environmental efficiency of the public building industry but did not analyze the dynamic analyze it from an angle. So far, scholars have done a lot of research on public buildings, but there is still less research on the carbon emission efficiency of provincial public buildings in the operation stage, and the imbalance of regional economic development and differences in resource endowments will increase the carbon emission efficiency of public buildings (PBCEE). The big difference is not in line with China's strategy of coordinating regional development. Therefore, it is necessary to study the PBCEE from a regional perspective.

This paper evaluates the PBCEE of 30 provinces in China from 2010 to 2019, divides the 30 provinces into eight economic zones according to the criteria of the Development Center of The State Council, then discusses the regional differences in PBCEE, and analyzes the PBCEE in each region main driver. Finally, through the analysis of PBCEE and its influencing factors, the corresponding emission reduction measures in each region are proposed. The main contributions of this study are as follows: 1) Research the subject of public buildings, and calculate the PBCEE of China from the provincial level, to fill the gap in the current evaluation of total factor carbon emission efficiency. 2) Selected efficiency calculation model overcomes the inherent defects of the traditional DEA model and makes the PBCEE more consistent with the actual situation. The calculation results can provide a better basis for the government to make decisions. 3) The combination of static and dynamic dual perspectives is more helpful to reveal the evolution law and influencing factors of PBCEE differences, and can provide decision-making references for improving PBCEE in various regions and accelerating energy conservation, emission reduction and coordinated development.

## Literature review

The carbon emission efficiency research and sustainable development of public buildings need to attract global attention, and DEA is widely used in the current carbon emission efficiency evaluation. DEA evaluates the relative efficiency of the decision-making unit (DMU) with multiple input and output indexes based on linear programming. Thus a nonparametric production frontier is constructed (Charnes et al., 1978). Hu and Liu (2015) used the traditional DEA model to measure the carbon emission efficiency of the Australian construction industry, and the results show that the carbon emission efficiency has improved in most regions. Han et al. (2022) also used the DEA model to measure the static energy efficiency of buildings. Zhou and Yu (2021) evaluated the carbon dioxide emission efficiency of the construction industry using three-stage DEA and found that environmental factors and random errors are serious in its carbon emission efficiency. To eliminate the influence of environmental factors. Zhang et al. (2018) adopted a three-stage DEA model to measure the carbon emission efficiency of China's construction industry, thereby improving the objectivity of the results. Simar and Wilson (2007) later developed the dual-bootstrap DEA method to measure environmental efficiency and improve the statistical efficiency of the second-stage regression.

These models are all radial DEA models, and the inefficiency level of DMU can only cover the part that the input-output index can be reduced or increased in equal proportion, which is inconsistent with the actual situation and effects the accuracy of efficiency measurement (Yu, 2020). Tone (2001) proposed the SBM model to more effectively study the redundancy of input indexes and the deficiency of output indexes of each DMU. The SBM model can not only solve the problem of slack variables but also solve the problem of DMU efficiency evaluation under the existence of undesirable outputs. Zhou et al. (2019) measured the total-factor carbon emission efficiency of the construction industry from 2003 to 2016 by applying the Super-SBM DEA approach, the results show that the carbon emission efficiency of the construction industry is declining year by year. Considering environmental and technological heterogeneity, Du et al. (2021) employed a meta-frontier method to measure carbon emission efficiency. To remove the influence of environmental factors and statistical noise, Li K et al. (2022) used the super-efficiency SBM model combined with the three-stage DEA model to calculate the green building efficiency value and obtain a value closer to the actual situation.

However, the SBM model also has an obvious disadvantage, that is, the objective function minimizes the efficiency value, and the projection point is the farthest point from the evaluation object on the front plane, which leads to the overestimation of the improvement potential of DMU (Song and Cong, 2016). In contrast, the Minimum Distance to Strong effective Frontier function (MinDS) proposed by Aparicio et al. (2007) was adopted to effectively solve the inherent defects of the SBM model, and make carbon emission efficiency evaluation results closer to the real situation. Guo et al. (2022) used the super-efficiency MinDS model to measure China's eco-efficiency, providing a reliable basis for the improvement of the carbon emissions trading market. Therefore, considering the undesired output, this study combined with the MinDS model to measure the total factor PBCEE during operation.

The above efficiency analysis model is a static evaluation model, which can make a horizontal comparison of the efficiency of DMUs. To analyze PBCEE more completely, a dynamic evaluation of PBCEE is needed to observe whether the efficiency improves in different periods. The most common dynamic efficiency evaluation models are the Malmquist index model and the Malmquist-Luenberger (ML) index model. As the basic Malmquist index model cannot deal with the situation containing unintended outputs, Chung et al. (2007) extended the study on the index and constructed the ML model. This not only inherited the advantages of the Malmquist model, and when calculating the change rate of carbon emission efficiency, it is required to obtain a larger expected output with smaller unexpected output. Many scholars used the above two models to measure the change in total factor productivity of carbon emissions. Fernández et al. (2018) used DEA-Malmquist to evaluate industrial energy efficiency. Ran et al. (2018) studied the growth capacity and convergence of agricultural energy efficiency through the ML index decomposition model; Wang and Guo (2018) used the combination of the super-efficiency SBM model and ML index model to evaluate the carbon emission efficiency of Beijing public transportation. Therefore, based on the MinDS model and combined with the ML model, this study conducted a dynamic evaluation of the PBCEE.

To further study the influencing factors of carbon emission efficiency, many scholars have combined the DEA model with the econometric model for analysis. Wang et al. (2019) used the DEA model to measure the carbon emission efficiency of 30 provinces in China and combined the Tobit regression model to analyze the influencing factors of carbon emission efficiency. Considering the bad output of carbon emissions, Kuang et al. (2020) used the SBM model to measure the cultivated land-use efficiency in China and used the Tobit regression model to analyze the influencing factors of the difference in cultivated land-use efficiency. It is worth noting that when using the Tobit regression model to analyze, the efficiency value needs to be between 0 and 1, but the carbon emission efficiency value calculated by the MinDS model overcomes the defect that the traditional efficiency value can only be 1 at most. Therefore, this paper chooses a panel data model that is more suitable for the MinDS model to analyze the influencing factors of carbon emission efficiency.

Although the research methods are different, scholars' research on the driving factors of carbon emission efficiency shows that industrial structure, the urbanization process, FDI, economic development, energy structure, *etc.* are the main factors affecting efficiency changes. As a low-carbon and environmentally friendly industry with high added value, the tertiary industry has a much lower energy consumption per 10,000 yuan of added value than the secondary industry (Ma et al., 2017), from the perspective of development trends, it is the industry that is most conducive to energy conservation. Xiang et al. (2022a) believed that the industrial structure is the key to decarbonization in the operation stage of public buildings. But Jiang and Zhao (2018) believed that the optimization of the industrial structure will lead to an increase in carbon emissions. The acceleration of urbanization may accelerate the generation of agglomeration effects, reduce energy consumption, and improve carbon emission efficiency (Su et al., 2018). It may also be that cities, as agglomeration areas of population and industries, will lead to an increase in carbon emissions (Qi et al., 2020). Scholars at home and abroad have different views on the impact of FDI on carbon emission efficiency. Li and Qi (2016) believe that foreign investment is still mainly in energy-intensive industries, ignoring the improvement of development technology, resulting in low efficiency, which means that FDI is not conducive to carbon emission efficiency. Ntom and Selin (2021) and Liu X. W et al. (2021) believe that when a region is closely connected with the rest of the world, it is easier to introduce advanced foreign technology and management experience, reduce the consumption of energy-intensive products, and improve carbon emission efficiency. From the perspective of economic growth, Li (2021) believed that under China's extensive economic development model, its economic growth will significantly promote the growth of its carbon emissions, and Zhong et al. (2020) have shown through empirical research that GDP has the highest correlation with carbon emissions. While Chen et al. (2021) believed that economic development also helps to invest more in environmental protection and improves carbon emission efficiency. The optimization of the energy structure will slow down the generation of carbon emissions (Sun and Ren, 2021), and the energy consumption dominated by coal will lead to more carbon emissions, which is not conducive to the improvement of carbon emission efficiency.

In addition to the above factors, public building areas can also be used as another factor effecting carbon emission efficiency. On the one hand, the increase in public building areas will promote the development of the tertiary industry, but it will also increase the electricity consumption of the tertiary industry (Chen et al., 2016). Ma et al. (2017) analyzed the driving factors of carbon emissions from the operation of public buildings in China and believed that the per capita floor area of public buildings is the main driving force for the increase in carbon emissions. However, few related studies use the public building area as an influencing factor of carbon emissions efficiency.

# Methodology and data

## MinDS model

In this study, PBCEE was calculated by applying the MinDS model of undesired output. This model limits all the evaluated DMU reference benchmarks to the same hyperplane by adding constraints. After all the effective DMUs are determined through the SBM model, use the effective subset as the reference set to solve the planning model.

Let's say the number of DMUs is $n$, Each DMU has $m$ inputs, $q_1$ expected outputs and $q_2$ unexpected outputs,$\lambda$ is the weight of DMU, $s^-$, $s^+$, and $s^{z-}$ represents the relaxation variables of input, expected output and unexpected output respectively, $\nu_i$, $\mu_r$, and $\mu_b$ are the weights of input, expected output and unexpected output respectively, $\rho$ is the efficiency value of DMU.

Firstly, find the effective DMU set of DEA through the SBM model, and record it as set E.

$$Min\rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m} s_i^- / x_{ik}}{1-\frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1} s_r^+ / y_{rk} + \sum_{b=1}^{q_2} s_b^{z-} / z_{bk}\right)} \tag{1}$$

$$s.t.\begin{cases} \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^- \le x_{ik}, \quad \sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j + s_r^+ \ge y_{rk}, \\ \sum_{j=1,j\neq k}^{n} z_{bj}\lambda_j - s_b^{z-} \ge z_{bk}, \lambda \ge 0, s^- \ge 0, s^+ \ge 0 \end{cases} \tag{2}$$

Where, $i = 1,2,3,\cdots,m;\ j = 1,2,3,\cdots,n;\ j \neq k;\ r = 1,2,3,\cdots,q_1;\ b = 1,2,3,\cdots,q_2.$

Secondly, using set E as the initial reference set, the following mixed linear programming is solved to obtain the MinDS efficiency value. Among them, $\rho_k$ represents the carbon emission efficiency value of the $K$th province; $b_j$is expressed as a variable between 0–1, if $b_j = 0$, then $d_j = 0$, at this time $DMU_j$ is the reference benchmark of $DMU_k$; if $b_j = 1$, then$d_j \le M$, at this time $DMU_j$ is not the reference bar of $DMU_k$. It can be concluded from the following formula that if the evaluated DMU wants to reach the best efficiency, the necessary and sufficient condition is that all slack variables are zero.

$$Max\,\rho_k = \frac{1}{m}\sum_{i=1}^{m}\left(1-\frac{s_i^-}{x_{ik}}\right) \Big/ \left[1+\frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^+}{y_{rk}}+\sum_{b=1}^{q_2}\frac{s_b^{z-}}{z_{rk}}\right)\right] \tag{3}$$

$$s.t.\begin{cases} \sum_{j\in E} x_{ij}\lambda_j + s_i^- = x_{ik}, i = 1,2,\cdots,m \\ \sum_{j\in E} y_{rj}\lambda_j - s_r^+ = y_{rk}, r = 1,2,\cdots,q_1 \\ \sum_{j\in E} z_{bj}\lambda_j + s_b^{z-} = z_{bk}, b = 1,2,\cdots,q_2 \\ \sum_{r=1}^{q_1}\mu_r y_{rj} + \sum_{b=1}^{q_2}\mu_b y_{bj} + d_j = \sum_{i=1}^{m}\nu_i x_{ij} \\ \sum_{j\in E}\lambda_j = 1; d_j \le Mb_j, \lambda_j \le M\left(1-b_j\right) \\ \lambda, s_i, s_r, s_b, d_j \ge 0 \\ \nu_i, \mu_r, \mu_b \ge 1 \\ b_j \in \{0,1\}, j \in E \end{cases} \tag{4}$$

## ML index model

This paper draws on the ML index model proposed by Chung et al. (2007) that considers undesired output to measure the PBCEE. The ML index constructed based on the MinDS model is:

$$ML_t^{t+1} = \sqrt{\frac{1+\vec{E}_0^{t+1}(i^t, r^t, b^t; r^t, -b^t)}{1+\vec{E}_0^{t+1}(i^{t+1}, r^{t+1}, b^{t+1}; r^{t+1}, -b^{t+1})} \times \frac{1+\vec{E}_0^{t}(i^t, r^t, b^t; r^t, -b^t)}{1+\vec{E}_0^{t}(i^{t+1}, r^{t+1}, b^{t+1}; r^{t+1}, -b^{t+1})}} \quad (5)$$

Furthermore, the ML index can be further decomposed into the product of the technical efficiency change index $EC_t^{t+1}$ and the technology change index $TC_t^{t+1}$ to explore the main reasons for the changes in PBCEE. The function expression is as follows:

$$ML_t^{t+1} = EC_t^{t+1} \times TC_t^{t+1} = \frac{1+\vec{E}_0^{t}(i^t, r^t, b^t; r^t, -b^t)}{1+\vec{E}_0^{t+1}(i^{t+1}, r^{t+1}, b^{t+1}; r^{t+1}, -b^{t+1})} \times \sqrt{\frac{1+\vec{E}_0^{t+1}(i^t, r^t, b^t; r^t, -b^t)}{1+\vec{E}_0^{t}(i^t, r^t, b^t; r^t, -b^t)} \times \frac{1+\vec{E}_0^{t+1}(i^t, r^t, b^t; r^t, -b^t)}{1+\vec{E}_0^{t}(i^{t+1}, r^{t+1}, b^{t+1}; r^{t+1}, -b^{t+1})}} \quad (6)$$

Among them, EC measures the change of the production possibility boundary of technical efficiency from period t to period t+1. The degree of closeness between its observations and the production frontier represents the change in the level of DMU management organization capabilities in the two periods, also known as the "catch-up effect." When the EC is greater than 1, it means that technological advancement contributes to the growth of PBCEE; if it is less than 1, the opposite is true. TC measures the degree of advancement of the technological frontier in two periods, reflecting the degree of technological change or technological innovation, and is called the "frontier movement effect." TC greater than 1 indicates the improvement of PBCEE and technological progress, while less than 1 indicates the deterioration of efficiency and technological regression.

To further explore the source of the technical efficiency change index, Fare et al. (1994) decompose the technical efficiency change index into a pure efficiency change index and a scaling efficiency change index. The expression is:

$$EC_t^{t+1} = PEC_t^{t+1} \times SEC_t^{t+1} \quad (7)$$

## Panel data model

This paper takes the influencing factors as independent variables and PBCEE derived from the MinDS model as dependent variables to establish a panel data model, to judge the influence degree of independent variables on PBCEE.

Hausman statistical test results were used to determine whether to build a random effect model or a fixed-effect model. The original hypothesis of its test is that individual effects are independent of explanatory variables. If true, the random effect estimation results are more valid. In addition, the fixed-effect model is better. The basic measurement model set is:

$$EE = \beta_0 + \beta_1 IS_{it} + \beta_2 URB_{it} + \beta_3 FDI_{it} + \beta_4 ED_{it} + \beta_5 ES_{it} + \beta_6 PBA_{it} + \varepsilon_{it} \quad (8)$$

To eliminate the heteroscedasticity existing between the variables and enhance the stability of the panel data, all variables are processed logarithmically, and the final regression model constructed is:

$$\ln EE = \beta_0 + \beta_1 \ln(IS)_{it} + \beta_2 \ln(URB)_{it} + \beta_3 \ln(FDI)_{it} + \beta_4 \ln(ED)_{it} + \beta_5 \ln(ES)_{it} + \beta_6 \ln(PBA)_{it} + \varepsilon_{it} \quad (9)$$

Where, $EE$ is the PBCEE, $IS_{it}$, $URB_{it}$, $FDI_{it}$, $ED_{it}$, $ES_{it}$, $PBA_{it}$ are constant terms, representing 6 independent variables,$\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$, $\beta_5$, $\beta_6$ are the regression coefficients of the respective variables, $i$ stands for province or city,$t$means year,$\varepsilon_{it}$ is the residual.

## Variables and data

Based on the total factor productivity theory and input-output model, this paper calculates the PBCEE of 30 provinces in China from 2010 to 2019 and selects relevant indicators to analyze the influencing factors of PBCEE. The basic data of the related variables are mainly derived from the "China Statistical Yearbook" (2011–2020) and the "China Energy Statistical Yearbook" (2011–2020). For individual data missing and outliers, the mean is used to correct.

There are three input indicators in this paper, namely capital input, labor input, and energy consumption; the value-added of related industries is selected as the expected output; the carbon emission of public buildings is the undesired output. The specific indicators are explained as follows, and the descriptive statistics of each indicator are shown in Table 1.

### Capital input

This study adopts the perpetual inventory method (Goldsmith, 1951; Shan, 2008) to estimate the capital investment in the public buildings industry (Wu, 2016), and then uniformly adjusts it to the constant price based on 2010.

### Labor input

Since the labor time invested in the actual production process cannot be obtained (Feng et al., 2014), the labor force indicator represents the number of people engaged in social labor and obtained reasonable remuneration, reflecting the utilization of labor resources in actual production during a certain period (Zhang and Jia, 2019). Therefore, following Lin and Wang (2016), this article regards 90% of the number

TABLE 1 Descriptive statistics of Input-Output indicators.

| Indicators | Variables | Unit | Min | Max | Mean | Std. |
|---|---|---|---|---|---|---|
| Input | Capital stock | 100 million Yuan | 616.71 | 36402.15 | 10697.38 | 6,902.03 |
| | Labor | ten thousand persons | 99.18 | 3,040.22 | 919.97 | 566.93 |
| | Energy | ten thousand tce | 147.07 | 4,104.87 | 1,109.24 | 727.74 |
| Desirable output | Added value of related industries | 100 million Yuan | 506.12 | 41552.81 | 8,084.08 | 7,116.23 |
| Undesirable output | $CO_2$ emissions | ten thousand tons | 247.12 | 7,528.76 | 2,487.94 | 1,617.83 |

of employees in the tertiary industry as the number of employees in the public building industry.

### Energy consumption

This paper adopts the macro model of building energy consumption based on an energy balance table to measure the energy consumption of public buildings. It can be seen from Cai et al. (2017) that the energy consumption of public buildings are concentrated in the three major industries "Transport, Storage and Post," "Wholesale, Retail Trade and Hotel, Restaurants" and "Others." Therefore, the energy consumption of public buildings is based on these three items, and the energy consumption of transportation is deducted from them. The deduction method of transportation energy consumption refers to the method of Wang (2007) and Zhao (2008). This paper selects eight types of energy for calculation, respectively raw coal, gasoline, diesel oil, fuel oil, kerosene, liquefied petroleum gas, natural gas, heat, and electricity, and converts the processed energy consumption into standard coal equivalent. The energy consumption of public buildings in 2019 is shown in Table A1.

### Value added of related industries

Since the value added of the transportation industry does not occur in public buildings, the value added of the relevant industries calculated in this article is the value added of the tertiary industry in each province from 2010 to 2019 minus the value added of the transportation industry (Lin and Wang, 2016), and converted it into the constant price in 2010, excluding the impact of inflation.

### Carbon emissions from public buildings

Carbon emission refers to the emission of greenhouse gases such as $CO_2$ and methane. For the convenience of calculation, carbon emission from public buildings is specifically referred to as $CO_2$ emission in this paper. The carbon emission coefficient method is used to calculate the $CO_2$ emissions during the operation phase of public buildings. The calculation formula is:$C = \sum_{i=1}^{n} E_i \times EF_i$, where $E_i$ is the $i$th energy consumed by public buildings, and $EF_i$ is the $CO_2$ emission coefficient of the $i$th energy. Among them, the carbon emission factors of electricity and heat refer to the data given in the document "Guidelines for Accounting Methods and Reporting of Greenhouse Gas Emissions for Public Building Operators."

Based on previous studies, this article selects indicators of Industrial Structure, Urbanization Level, Foreign Direct Investment, Development Level, Energy Structure, and Public Building Area, combined with the characteristics of the public building industry, to conduct an empirical analysis of the influencing factors of PBCEE. The meaning of each variable is shown in Table 2.

## Study area

This paper conducts PBCEE research according to the eight comprehensive economic regions classified in the report "Strategies and Policies for Regional Coordinated Development" by the Development Research Center of the State Council. The specific classifications are shown in Table 3.

## Analysis of empirical results

### Static efficiency analysis of PBCEE

This study uses MAXDEA 8 Ultra software to calculate the super-efficiency MinDS model considering undesired output, and obtains the PBCEE in various provinces from 2010 to 2019, as shown in Table 4 and Figure 1.

Table 4 shows that there is a large difference in PBCEE between provinces, the maximum PBCEE is about 2.5 times the minimum, indicating that quite a few provinces still have a large improvement and chasing space, and the overall PBCEE in China could be further improved.

From Figure 1, among the eight economic zones, the first echelon of PBCEE during the study period is the coastal areas, eastern coastal > southern coastal > northern coastal; the second echelon is the southern inland region, the middle reaches of the Yangtze River> the southwest region, and around the national average carbon emission level fluctuate up and down; the third echelon is the northern inland region, the middle reaches of the Yellow River > the northwest region; the fourth echelon has the lowest efficiency value in the northeast region. This result is consistent with the study by Li et al. (2019). It can be seen that PBCEE is consistent with the level of economic development. Specifically, the analysis is:

(1) The southern and eastern coastal areas represented by Guangdong and Jiangsu have the highest carbon emission efficiency values. On the one hand, due to the open geographical location and the support of national preferential policies, they have accumulated capital and technological advantages. On the other hand, the tertiary industry accounts for a large proportion, has high technical proficiency, and is in the forefront of production, resulting in an increase in PBCEE (Niu et al., 2020).

(2) From the northern coastal areas, Beijing and Tianjin are municipalities directly under the Central Government, enjoying more policy dividends, a relatively developed economy, a higher degree of popularization in the concept of low-carbon development, and higher energy efficiency (Lin and Wang, 2016). As a part of the coordinated development of Beijing-Tianjin-Hebei Province, Hebei has accepted a large number of enterprises that have moved out of Beijing, with high energy demand and low carbon emission efficiency, and is facing huge pressure to reduce emissions.

(3) In the middle reaches of the Yangtze River, the PBCEEs of the four provinces were the same. The highest is Hunan and the lowest is Hubei. During the study period, the PBCEEs increased the fastest in Jiangxi Province, with an increased value of 0.4125. As one of the first provinces in China to be included in the construction of the first demonstration zone for ecological civilization, Jiangxi Province adheres to the concept of "ecology first and green development," and continuously promotes the adjustment of industrial structure and energy structure. The efficiency calculation results confirm that Jiangxi has made great progress in low-carbon development, but there is still room for improvement.

(4) In the southwest region, except for Guizhou, the average PBCEE of other provinces is 0.7724, which exceeds the national average. As one of the important development regions for China to implement the "Western Development Strategy" since the 21st century, the tertiary industry led by the tourism economy has made considerable development, and the introduction of foreign capital investment is an important factor in reducing the intensity of carbon emissions (Zhang et al., 2019). Among them, Guangxi and Chongqing have the fastest growth in PBCEE in the southwest region, with growth values exceeding 0.3. For example, the output value of Chongqing's tertiary industry accounted for 49% of GDP in 2015, which has become the main driving force for Chongqing's economic growth. 92.5% of Guizhou's geomorphic structure is mountainous and hilly, which severely restricts the development of the local tertiary industry and makes the PBCEE the lowest.

(5) From the perspective of the economic zone in the middle reaches of the Yellow River, Henan has the fastest increase in the PBCEE during the study period, with a growth value of 0.4105. The vigorous development of tourism and service industries has brought great economic output to related industries that rely on public buildings. The growth rate of the added value of economic output in related industries was 138% between 2010 and 2019, making Henan's economic development level rank first in Chinese central and western. In addition, due to the backward development of the tertiary industry in Shanxi and Inner Mongolia, and the use of raw coal as the main energy consumption, the PBCEE is at the end of the country, with an average value of only 0.5404.

(6) The PBCEE of Northwest China is Ningxia, Xinjiang, Gansu, and Qinghai in order from the highest to the bottom. The efficiency values of the four provinces are not much different, fluctuating around 0.6070. The reason for the low PBCEE may be that on the one hand, the geographical location is relatively remote, far from the political and economic center, and it is difficult to access advanced foreign technology and capital investment; on the other hand, the infrastructure construction is not perfect and the economic development is relatively backward. Among them, the PBCEEs in Gansu and Qinghai have a reciprocal ranking. These areas have large land areas, sparse populations, large proportions of mountainous plateaus, and extremely underdeveloped economies.

(7) As a traditional old industrial base in China, the Northeast mostly consumes raw coal as the main energy source, while the tertiary industry accounts for a relatively small proportion. This has led to lower public buildings' energy-saving effects and the lowest PBCEE.

## Dynamic efficiency analysis of PBCEE

On the basis of analyzing the static characteristics and prosperity of PBCEE in various provinces and cities, the dynamic characteristics of PBCEE are further analyzed, and the ML index and its decomposition value of the public building industry by time period are obtained as shown in Table 5 by using MAXDEA 8 Ultra software.

As can be seen from table 5, the PBCEE is showing a trend of continuous improvement. During the study period, the average annual growth rate of PBCEE was 1.82%, and the fastest growth rate of PBCEE in 2015–2016 was 3.61%. Generally, the development of China's PBCEE is showing a good momentum of steady progress.

Moreover, the TC index indicating that the average annual growth rate of the production technology frontier of public buildings is 2.92% considering carbon emission; the EC index showing that

TABLE 2 Influencing factors and variable description of PBCEE.

| Variables | Abbr. | Processing | References | Data sources |
|---|---|---|---|---|
| Industrial Structure | IS | Since the activities of the tertiary industry mainly occur in public buildings, it is expressed as the proportion of the added value of the tertiary industry in GDP | Ma et al. (2017) | China Statistical Yearbook |
| Urbanization Level | URB | Urbanization rate is used to represent the urbanization level | Wu et al. (2020) | China Statistical Yearbook |
| Foreign Direct Investment | FDI | The proportion of direct investment comes from foreign enterprises in Chinese enterprises to GDP | Li et al. (2019) | China Statistical Yearbook |
| Economic Development Level | ED | Economic development is measured by the impact of GDP per capita on PBCEE | Liu et al. (2020) | China Statistical Yearbook |
| Energy Structure | ES | Electricity is the main energy consumed in the public building industry, so the ratio of electricity to terminal energy consumption is used to represent the energy structure | Lin and Wang, (2016) | China Energy Statistical Yearbook |
| Public Building Area | PBA | The completed area of public buildings is taken as the newly added area to illustrate the influence of public building areas on PBCEE | Ma et al. (2017) | China Construction Industry Statistical Yearbook |

TABLE 3 Division of eight major economic regions in China.

| Economic region | Provinces included | Economic region | Provinces included |
|---|---|---|---|
| Northeast | Liaoning, Jilin, Heilongjiang | Middle Yellow River | Shanxi, Inner Mongolia, Henan, Shaanxi |
| Northern coastal | Beijing, Tianjin, Hebei, Shandong | Middle Yangtze River | Anhui, Jiangxi, Hubei, Hunan |
| Eastern coastal | Shanghai, Jiangsu, Zhejiang | Southwest | Guangxi, Chongqing, Sichuan, Guizhou, Yunnan |
| Southern coastal | Fujian, Guangdong, Hainan | Northwest | Gansu, Qinghai, Ningxia, Xinjiang |

PBCEE's catching-up speed on the production frontier has an average annual growth rate of 0.27%. This also means that the improvement of the overall PBCEE mainly depends on technological progress, while PBCEE's catch-up of the production frontier is advancing in volatility, and the "catch-up effect" has slowed down.

Further breakdown, the average annual growth rate of the PEC index is 0.46%, and the SEC index is -0.06%. This shows that changes in technical efficiency are mainly affected by changes in pure technical efficiency, while changes in scale efficiency reflect that there is a gap between the level of production input in public buildings and the amount of input under the optimal production scale, and the ratio of input and output needs to be further coordinated.

Figure 2 show the dynamic changes in the PBCEE of the eight economic regions. Especially the PBCEE in the middle reaches of the Yangtze River has made the fastest progress, with a growth rate of 2.42%. Followed by the northern coast and the middle reaches of the Yellow River regions, the growth rates were 2.27% and 2.09% respectively. The PBCEE of the northwest, southwest, and northeast regions ranks behind, the growth rate is low, and there is plenty of room for improvement.

Combining the ML index, TC index, and EC index measured above, the development of PBCEE from 2010 to 2019 can be studied, and targeted measures can be formulated for the problems in each region. For example, the ML index in the middle reaches of the Yellow River ranks third, the TC index ranks first, and the EC index ranks fourth. It can be seen that the PBCEE of this region has improved significantly, and technological progress is the most important reason for the improvement of PBCEE. At the same time, its carbon emission efficiency has slightly lagged in catching up with the production frontier. In other words, the rapid technological advancement in the region can drive the rapid development of the production frontier, but the PBCEE catching up with the production frontier is relatively slow, causing the industry's production frontier to advance faster than the region's own PBCEE improvement speed. To further increase the PBCEE in the region, it is necessary to start with the EC index. It is recommended to strengthen the absorption and utilization of high-tech by the public building industry and increase the degree of knowledge conversion.

The significance of the further decomposition of the EC index is to be able to find the deep-seated reasons for the changes in the PBCEE, to propose more targeted improvements and promotion measures. For example, the EC index in Southwest China is 1.0056, the PEC index is 1.0100, and the SEC index is 0.9978. This shows that the improvement of the technical efficiency of the public building industry is mainly caused by the improvement of pure technical efficiency, that is, the public building industry has realized the rapid promotion and application of high-tech as a whole, but because the industry scale is not at the optimal scale, the scale efficiency change index

TABLE 4 Estimation results of PBCEE in China.

| Province | Max | Min | Mean | Ranking |
|---|---|---|---|---|
| Guangdong | 1.2195 | 1.1202 | 1.1341 | 1 |
| Jiangsu | 1.1173 | 1.0379 | 1.1006 | 2 |
| Beijing | 1.1115 | 1.0782 | 1.0971 | 3 |
| Shanghai | 1.0748 | 0.9351 | 0.9822 | 4 |
| Zhejiang | 1.0020 | 0.9120 | 0.9339 | 5 |
| Fujian | 1.0129 | 0.8042 | 0.8626 | 6 |
| Chongqing | 1.0469 | 0.7238 | 0.8167 | 7 |
| Tianjin | 0.8825 | 0.7805 | 0.8006 | 8 |
| Henan | 1.0303 | 0.6199 | 0.8006 | 9 |
| Guangxi | 1.0456 | 0.6545 | 0.7850 | 10 |
| Shandong | 1.0106 | 0.6532 | 0.7711 | 11 |
| Hunan | 0.8654 | 0.7293 | 0.7707 | 12 |
| Yunnan | 0.9010 | 0.6441 | 0.7604 | 13 |
| Jiangxi | 1.0305 | 0.5383 | 0.7489 | 14 |
| Anhui | 0.8117 | 0.6560 | 0.7375 | 15 |
| Sichuan | 0.7871 | 0.6275 | 0.7274 | 16 |
| Hubei | 0.8571 | 0.6064 | 0.7002 | 17 |
| Hainan | 0.7463 | 0.6237 | 0.6887 | 18 |
| Shaanxi | 0.7672 | 0.5973 | 0.6561 | 19 |
| Ningxia | 0.7136 | 0.6073 | 0.6548 | 20 |
| Liaoning | 0.7287 | 0.6057 | 0.6313 | 21 |
| Xinjiang | 0.6842 | 0.5659 | 0.6241 | 22 |
| Jilin | 0.7881 | 0.5773 | 0.6206 | 23 |
| Hebei | 0.6928 | 0.5916 | 0.6133 | 24 |
| Gansu | 0.6532 | 0.5529 | 0.5913 | 25 |
| Qinghai | 0.5847 | 0.5362 | 0.5579 | 26 |
| Shanxi | 0.5746 | 0.5292 | 0.5493 | 27 |
| Inner Mongolia | 0.6533 | 0.4479 | 0.5315 | 28 |
| Heilongjiang | 0.6679 | 0.3771 | 0.4914 | 29 |
| Guizhou | 0.4853 | 0.4045 | 0.4490 | 30 |
| Mean | 0.8516 | 0.6713 | 0.7396 | |

is less than 1, which harms the change in technical efficiency. Therefore, the adjustment proposal of this study for the development of the public building industry in the region is that in the future development process, the overall scale of the industry should be appropriately increased, the scale efficiency of the industry should be improved, and then drive the improvement of carbon emission efficiency level.

## Analysis of driving factors of PBCEE

This paper uses Eviews10.0 statistical software to analyze the influencing factors of PBCEE. First, the $p$-value is 0 from the Hausman test results, so it is determined that the fixed-effects model should be selected in this paper. The results obtained by incorporating all explanatory variables into the fixed-effects model are shown in Tables 6 and 7.

By analyzing the regression results in Tables 6 and 7, the following conclusions can be obtained.

(1) IS inhibited the increase of PBCEE in the southeast coast, northwest, northeast, and the middle Yellow River, but the north coast and the southwest area have the promotion effect. This is consistent with the findings of Zheng et al. (2020), that is, the impact of IS on carbon emissions has regional differences. There are three reasons for the analysis:

The first is that the tertiary industry in the southeastern coastal area has a relatively high degree of maturity. The

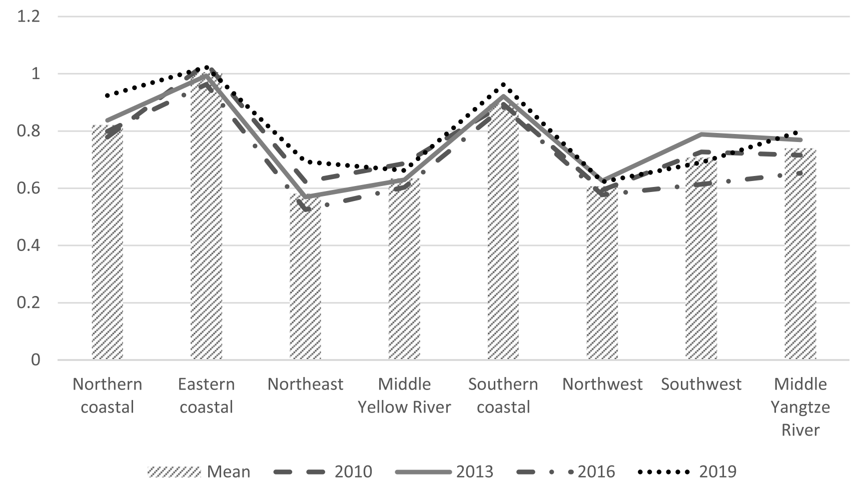


FIGURE 1
Carbon emission efficiency values of public buildings in China's eight economic zones.

TABLE 5 The ML index decomposition results of PBCEE in 2010–2019.

| Period | TC index | EC index | PEC index | SEC index | ML index |
|---|---|---|---|---|---|
| 2010–2011 | 1.0104 | 1.0010 | 0.9960 | 1.0067 | 1.0069 |
| 2011–2012 | 1.0252 | 0.9948 | 0.9952 | 0.9998 | 1.0192 |
| 2012–2013 | 0.9948 | 1.0332 | 0.9861 | 1.0499 | 1.0211 |
| 2013–2014 | 1.1220 | 0.9244 | 0.9999 | 0.9248 | 1.0215 |
| 2014–2015 | 0.9596 | 1.0722 | 0.9774 | 1.1019 | 1.0167 |
| 2015–2016 | 1.1227 | 0.9318 | 0.9553 | 0.9745 | 1.0361 |
| 2016–2017 | 0.9103 | 1.1356 | 1.1287 | 1.0061 | 1.0176 |
| 2017–2018 | 1.1069 | 0.9307 | 1.0036 | 0.9274 | 1.0145 |
| 2018–2019 | 1.0106 | 0.9999 | 0.9989 | 1.0032 | 1.0102 |
| Mean | 1.0292 | 1.0027 | 1.0046 | 0.9994 | 1.0182 |

proportion of IS in most provinces has already exceeded 50%, and the growth rate of the added value of the tertiary industry is gradually slowing. The positive driving effect of economic growth on PBCEE is less than the negative driving effect of carbon emissions.

Second, in the northwest, northeast, and middle reaches of the Yellow River, the increase in the share of the tertiary industry hurts the increase of PBCEE. The reason is that in the development process of the tertiary industry, the energy structure dominated by coal consumption is unreasonable, and the demand for energy consumption is huge. Increasing the added value of the tertiary industry will generate more carbon emissions, thereby reducing PBCEE.

The third category is the southwest and northern coastal areas. Combined with the above ML index analysis, it can be seen that the rapid development of the tertiary industry in the two places is due to the improvement of pure technical efficiency, the realization of the promotion and application of emerging technologies, the reduction of energy consumption rate, and the improvement of PBCEE.

(2) The URB does not have a significant impact on PBCEE in half of the region. It only has a 1% significant negative impact on the PBCEE on the northern coast, the middle reaches of the Yangtze River, and the southwest region, while it has a 10% significant level of positive impact on PBCEE in Northwest China. This shows that the impact of URB on PBCEE is not always a driving or inhibiting effect, but has obvious threshold characteristics. Different levels of urbanization have different impacts on internal mechanisms, leading to different impacts on carbon emission efficiency.

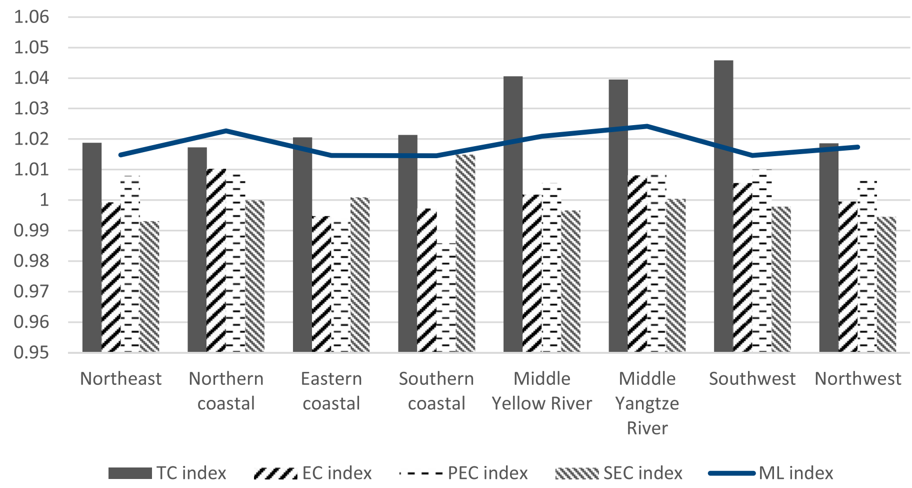


FIGURE 2
Dynamic average growth rate in the PBCEE of the eight economic regions.

TABLE 6 Fixed effects model regression results (1).

| Variables | Northeast | | Northern coastal | | Eastern coastal | | Southern coastal | |
|---|---|---|---|---|---|---|---|---|
| | Coefficients | t-Statistic | Coefficients | t-Statistic | Coefficients | t-Statistic | Coefficients | t-Statistic |
| lnIS | −0.30* | −1.56 | 0.16* | 1.65 | −0.69*** | −2.78 | −0.98*** | −3.71 |
| lnURB | −0.02 | −0.13 | −0.18*** | −1.00 | −0.03 | −0.27 | 0.20 | 1.32 |
| lnFDI | 0.13 | 0.12 | −0.23 | 3.09 | 0.97*** | 2.70 | −0.02 | −1.17 |
| lnED | 0.15*** | 3.54 | 0.28*** | −4.31 | 0.57*** | 2.64 | 0.34*** | 3.56 |
| lnES | 0.31*** | 3.14 | 0.07*** | 2.76 | 0.01 | 0.17 | −0.34*** | −6.29 |
| lnPBA | 0.07* | 1.61 | 0.05 | 1.34 | −0.01 | −0.06 | −−0.09** | −2.23 |
| Adjusted $R^2$ | 0.82 | | 0.99 | | 0.94 | | 0.96 | |

TABLE 7 Fixed effects model regression results (2).

| Variables | Middle yellow river | Middle yangtze river | Southwest | Northwest | | | | |
|---|---|---|---|---|---|---|---|---|
| | Coefficients | t-Statistic | Coefficients | t-Statistic | Coefficients | t-Statistic | Coefficients | t-Statistic |
| lnIS | −0.14* | −1.86 | −0.14 | −0.53 | 0.19*** | 2.52 | −0.39*** | −5.74 |
| lnURB | 0.04 | 1.04 | −1.74*** | −2.99 | −1.39*** | −3.85 | 0.18* | 1.89 |
| lnFDI | 0.05 | 0.84 | 0.15*** | 2.76 | 0.18*** | 4.62 | 0.02 | 1.29 |
| lnED | −0.01 | −0.25 | 0.54*** | 2.83 | 0.17 | 1.20 | 0.04 | 0.75 |
| lnES | 0.27*** | 3.34 | 0.26*** | 3.91 | 0.22*** | 2.95 | 0.08** | 2.27 |
| lnPBA | −0.06* | −1.86 | −0.03 | −0.54 | 0.13** | 1.90 | 0.04* | 1.72 |
| Adjusted $R^2$ | 0.86 | | 0.82 | | 0.98 | | 0.89 | |

*, **, and *** represent significant at 10%, 5%, and 1% significance level, respectively.

(3) The FDI has a relatively small degree of impact on PBCEE in most regions and only has a significant positive impact of 1% on PBCEE in the eastern coastal, southwestern and middle reaches of the Yangtze River, especially the positive effect on PBCEE in the eastern coastal is stronger. This conclusion supports the analysis of the static efficiency results of the above-mentioned relevant regions. On the one hand, this situation arises because of the capital and technological advantages brought by foreign businessmen. On the other hand, although foreign capital has advanced management models and advantages in carbon emission reduction, investment in China is often high energy consumption and high pollution projects. Therefore, the impact of FDI on PBCEE has a dual nature, namely, the pollution halo hypothesis and the pollution haven hypothesis.

(4) The ED has a relatively small impact on the PBCEE in the middle reaches of the Yellow River, southwest and northwest, and has a positive impact of 1% significant level in other regions. The tertiary industry activities based on public buildings are closely related to the level of local economic development. On one hand, the more the economy develops, the more carbon dioxide is produced in economic activities; but on another, as the economic level improves, there will be more capital and technology to deal with carbon emissions, to a certain extent, offset the carbon emissions brought about by economic development. This analysis is in line with the conclusions of the environmental Kuznets curve.

(5) The ES, as the most influential factor of regional PBCEE, has a positive impact of 1% on PBCEE in most regions, a negative impact of 1% in the southern coastal, and no impact on the eastern coast. Increasing the proportion of electricity consumption has a positive effect on increasing PBCEE to a certain extent in most regions. However, for the southeast coastal areas, increasing the proportion of power consumption in the final energy consumption is not an absolute advantage. It is necessary to take advantage of local resources and increase the use of clean energy such as hydropower and nuclear power to further increase PBCEE.

(6) The influence of PBA on PBCEE can be roughly divided into two categories. One is that the southern coastal area and the middle reaches of the Yellow River have significant negative influence on PBCEE at 5% and 10%, respectively. In addition, the southwest had a significant positive effect on PBCEE at a level of 5%, the northwest and northeast only had a positive effect at a level of 10%. Therefore, the impact of the increase of public building area on PBCEE also has regional differences. The increase of public building areas lead to the increase of corresponding public building activities, which leads to the overuse of corresponding facilities and intensifies the generation of carbon dioxide.

# Conclusion and policy recommendations

## Conclusion

Based on the total factor productivity theory and panel data of eight economic regions in China from 2010 to 2019, this study evaluates PBCEE from static and dynamic perspectives by using MinDS and ML index models. On this basis, a fixed-effect panel data model is established to analyze the influencing factors of PBCEE. On the one hand, this paper makes up for the relative deficiency of PBCEE research in China's eight economic regions; On the other hand, suggestions can be put forward for the sustainable development of economic zones and carbon emission reduction of public buildings. The main conclusions are as follows:

Firstly, from the analysis of static results, there are large differences in the PBCEE in different regions, which makes the overall level in China relatively low. The PBCEE is 0.74 during the study period. From the point of the eight areas, PBCEE present the space of the "east high west low" characteristics, the eastern coastal area efficiency value is greater than the coastal areas of southern and northern coastal areas, the second is the area in the middle reach of Yangtze river and the southwest area fluctuating around the national average level, the performance of the middle reaches of the Yellow River and the northwest are a bit times, and the northeast is the lowest. The PBCEE is consistent with the level of economic development.

Secondly, from the analysis of dynamic results, the PBCEE level of eight regions in China is further improving, with an average annual growth rate of 1.82%. The improvement of PBCEE mainly depends on technological progress. The reason why the change of technological efficiency has a low positive impact on PBCEE is that the scale efficiency is low. There is a gap between the input level of the public building industry and the input amount under the optimal production scale, which needs further coordination. It is worth noting that the PBCEE in the northwest, southwest and northeast regions is not only backward, but also has a low growth rate, and there is still a lot of room for improvement.

Lastly, as for the internal driving factors of PBCEE, due to the different degrees of development in different regions, the impact result and degree of each factor on each region are different, and there is an obvious threshold effect. For the northern coastal region and the middle reaches of the Yangtze River, the energy structure and local economic development level have a positive impact on PBCEE, and the urbanization process has a restraining effect. For the eastern and southern coastal areas, the regional industrial structure has a restraining effect on PBCEE, and the level of economic development will promote PBCEE. Foreign investment can promote PBCEE in the middle reaches of the Yangtze River and eastern coastal. In southwest China, the industrial structure, foreign investment and energy structure have a significant positive effect on

PBCEE, and only the urbanization level has a negative effect on PBCEE. For the northwest region and the middle reaches of the Yellow River, the energy structure has a significant promoting effect on PBCEE, while the industrial structure has a negative effect on PBCEE. For northeast China, regional economic development and energy structure have promoted PBCEE significantly. But in general, increasing the share of electricity in final energy consumption will improve the national PBCEE.

## Policy recommendations

Based on the above conclusions and under the guidance of China's regional coordinated and sustainable development strategy, this paper puts forward the following policy recommendations.

There are great differences in geographical location, level of economic development, and degree of openness among different regions, leading to great differences in PBCEE in different regions at present. Given this situation, it is suggested to make different policies and emission reduction targets according to the actual situation of different regions.

The eastern and southern coastal areas should increase the proportion of modern service industries, mainly finance and information, in the tertiary industry, and continue to enhance the level of high-tech and independent innovation. Reduce the use of secondary energy such as electricity in local public buildings, make more use of local natural conditions, increase the proportion of renewable clean energy, and reduce carbon emissions from public buildings. In addition, the government should establish a public building energy consumption monitoring platform, promulgate high carbon emission standards for public buildings, and take measures such as mandatory renovation and fines for buildings that meet high carbon emissions.

In the middle reaches of the Yangtze River and the southwest region, play the pivotal role of the Yangtze River Economic Belt, realize the joint reorganization of the overall service industry, promote the development of the knowledge-intensive tertiary industry, and enhance the scale economy of the industry. It is suggested that the focus of this area is to continuously improve the ability of technological progress. On the one hand, the electrical equipment in public buildings can be significantly improved, and on the other hand, public building facilities can be upgraded to energy-saving facilities to improve energy efficiency.

For the middle reaches of the Yellow River and the northwest region, the proportion of coal consumption in the operation of public buildings should be reduced, and the use of electricity and wind energy should be increased. Pay attention to the rational allocation of the existing resource element structure and technical level, and seek the continuous improvement of the scale economy of public buildings. It can also create an environment conducive to the low-carbon operation of public buildings by promoting energy-saving technology innovation and advocating low-carbon energy-saving consumption methods.

For the northern coastal and northeastern regions, it is necessary to increase the proportion of the tertiary industry, speed up the transformation of traditional industries, and promote local economic development. At the same time, clean and low-carbon power supply technology should be developed to reduce the carbon emissions of public buildings during the use stage. Perhaps setting reasonable energy prices can foster good energy use habits in public building operators.

## Deficiencies and the next research direction

This study calculates the PBCEE and the influencing factors of efficiency change, providing the theoretical basis for formulating energy saving and emission reduction measures and coordinating regional development. However, the calculation results of this study are all carried out at the provincial level, while the analysis of the results is carried out at the regional level, ignoring the heterogeneity between different cities. Therefore, the results of theoretical analysis and policy making can be further refined. In the future, the research scope should be narrowed, focusing on the PBCEE of different prefecture-level cities in the region, and trying to expand the selection of input indicators. Or the combined method of DEA and SFA can also be used to measure PBCEE to improve the objectivity and pertinence of efficiency analysis. In addition, this study found that the same factor has different driving effects on different regions, and the focus of future research should also be to explore the mechanism of influence of different factors on PBCEE.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

Y-KW: grasp the theme and research direction, YL: empirical research and data, L-SS: data.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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TABLE A1 The energy consumption of public buildings in 2019.

| Province | Raw Coal($10^4$ tons) | Gasoline ($10^4$ tons) | Diesel Oil ($10^4$ tons) | Fuel Oil ($10^4$ tons) | Kerosene ($10^4$ tons) | Electricity ($10^8$ kWh) | Heat($10^{10}$kJ) | Liquefied petroleum Gas($10^4$ tons) | Natural Gas($10^8$ cu.m) |
|---|---|---|---|---|---|---|---|---|---|
| Beijing | 1.32 | 2.03 | 14.03 | 0.01 | 0.57 | 417.17 | 9,328.45 | 2.32 | 23.35 |
| Tianjin | 39.02 | 1.70 | 41.92 | 2.64 | 0.00 | 165.38 | 2,617.94 | 13.67 | 13.50 |
| Hebei | 150.00 | 2.04 | 13.13 | 0.00 | 0.00 | 534.02 | 8,893.99 | 0.00 | 28.33 |
| Shanxi | 327.06 | 1.41 | 5.36 | 0.00 | 0.26 | 211.31 | 3,260.87 | 0.37 | 20.35 |
| Inner Mongolia | 669.85 | 3.71 | 41.42 | 0.00 | 0.00 | 227.97 | 7,644.68 | 4.55 | 11.94 |
| Liaoning | 10.87 | 7.96 | 110.64 | 0.00 | 0.00 | 316.13 | 2,866.41 | 60.07 | 7.18 |
| Jilin | 122.76 | 3.13 | 12.88 | 0.00 | 0.00 | 147.33 | 5,972.86 | 4.49 | 10.08 |
| Heilongjiang | 1,072.93 | 3.90 | 50.77 | 0.00 | 0.00 | 158.39 | 9,657.28 | 0.00 | 5.33 |
| Shanghai | 3.62 | 7.76 | 104.97 | 0.16 | 0.00 | 493.71 | 50.24 | 17.00 | 10.50 |
| Jiangsu | 3.69 | 0.80 | 4.86 | 0.00 | 0.00 | 856.50 | 244.51 | 1.83 | 19.56 |
| Zhejiang | 22.57 | 4.30 | 18.85 | 3.55 | 0.00 | 663.41 | 5,623.27 | 38.02 | 7.92 |
| Anhui | 0.36 | 6.04 | 16.82 | 0.00 | 0.00 | 350.09 | 3.14 | 0.03 | 15.28 |
| Fujian | 10.20 | 1.62 | 6.05 | 0.00 | 0.00 | 336.13 | 0.00 | 3.72 | 3.27 |
| Jiangxi | 52.03 | 2.40 | 27.95 | 0.00 | 0.00 | 234.41 | 0.00 | 15.96 | 5.31 |
| Shandong | 90.72 | 3.36 | 37.19 | 2.40 | 0.00 | 593.48 | 9,983.30 | 20.12 | 28.01 |
| Henan | 30.40 | 8.33 | 39.77 | 0.00 | 4.65 | 475.89 | 5,631.70 | 26.27 | 20.68 |
| Hubei | 543.06 | 8.52 | 60.74 | 2.45 | 0.00 | 351.37 | 1,073.70 | 53.35 | 16.09 |
| Hunan | 950.07 | 8.79 | 24.86 | 3.25 | 2.58 | 310.15 | 4.78 | 36.70 | 9.09 |
| Guangdong | 52.78 | 8.71 | 100.69 | 15.91 | 0.04 | 1,255.85 | 2.97 | 83.50 | 7.50 |
| Guangxi | 0.37 | 0.85 | 16.48 | 0.00 | 0.00 | 220.76 | 0.00 | 16.10 | 6.65 |
| Hainan | 0.00 | 2.50 | 2.36 | 0.00 | 0.00 | 119.66 | 0.00 | 2.62 | 1.31 |
| Chongqing | 9.93 | 3.39 | 9.91 | 0.00 | 0.00 | 230.53 | 0.00 | 14.15 | 13.76 |
| Sichuan | 25.85 | 9.54 | 88.17 | 0.00 | 0.50 | 410.57 | 0.00 | 13.21 | 25.59 |
| Guizhou | 1,354.61 | 10.10 | 156.00 | 0.00 | 0.00 | 155.00 | 0.00 | 7.00 | 17.00 |
| Yunnan | 166.89 | 3.58 | 14.98 | 0.00 | 0.13 | 217.84 | 3.13 | 45.04 | 1.60 |
| Shaanxi | 142.47 | 1.99 | 16.93 | 1.70 | 1.03 | 278.95 | 2,858.03 | 11.34 | 11.83 |
| Gansu | 62.20 | 3.04 | 14.30 | 0.00 | 0.00 | 129.77 | 2,151.00 | 1.60 | 15.20 |
| Qinghai | 26.10 | 0.55 | 10.90 | 0.00 | 0.00 | 38.36 | 171.23 | 9.31 | 12.54 |
| Ningxia | 24.72 | 0.11 | 0.62 | 0.00 | 0.00 | 48.79 | 1,348.17 | 0.32 | 4.49 |
| Xinjiang | 101.35 | 0.90 | 13.33 | 0.00 | 0.00 | 215.35 | 8,401.88 | 2.41 | 18.94 |
| Sum | 6,067.80 | 1,064.34 | 2002.09 | 978.89 | 957.25 | 10804.19 | 87793.53 | 1,418.44 | 1,333.16 |

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# Assessing the effect of the joint governance of transboundary pollution on water quality: Evidence from China

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The joint governance of transboundary river pollution is an important means to resolve disputes between upstream and downstream, to achieve regional coordinated development and water environment governance. In this paper, dissolved oxygen, chemical oxygen demand and ammonia nitrogen are used to measure water quality. Regarding the joint governance of transboundary water pollution as a quasi-natural experiment, this paper employs a difference-in-differences model of causal judgment to assess the effect of the policy on transboundary water quality based on the water quality monitoring week data from 2004 to 2016 in China. The results show that compared with non-trans-provincial rivers, the joint governance of water pollution at the provincial boundary could significantly promote the rise of dissolved oxygen, while reducing the chemical oxygen demand and ammonia nitrogen emissions. Additionally, the long-term dynamics based on the dynamic trend suggests that the implementation of this policy has fluctuations in the improvement of dissolved oxygen, but has a strong continuous effect on the reduction of chemical oxygen demand and ammonia nitrogen. These results stand up to robustness tests. Moreover, the green promotion pressure of officials and stakeholder supervision are important influence mechanisms of transboundary joint pollution control on improving transboundary water quality. An important implication is to provide a long-term way for collaborative water pollution control and solving transboundary water pollution disputes.

KEYWORDS

**transboundary water pollution, joint governance, water quality, difference-in-differences model, China**

## 1 Introduction

While enjoying rapid economic development, China is also facing more and more serious pressure on the ecological environment with respect to its river's pollution. Rivers provide an important guarantee for the social and economic development of the upstream and downstream areas and for the people to live and work in peace and contentment (Duda and Hume, 2013). However, as the "clear flow becomes turbid water," the important ecological functions of the river are gradually weakened. Due to the nature of rivers as quasi-public goods, negative externalities make upstream areas prone to promoting "beggar-thy-neighbour" pollutant discharge behaviour, whereas positive externalities of pollution control make downstream areas prone to the "free-rider" psychology. A situation that leads to the transboundary pollution of rivers, is an environmental problem commonly faced by the international community (Sigman, 2002). The fact is that not only developing countries have serious transboundary water pollution problems, but developed countries as well (Lipscomb and Mobarak, 2017). Actually, the annual economic loss caused by water pollution in China is as much as 240 billion RMB. More specifically, the central government spent 430 billion RMB in 2016 and 300 billion RMB in 2017 on water pollution control. Approximately 80% of China's oil and chemical projects are along rivers, and as many as 20% of these companies are in trans-provincial areas (Cai et al., 2016). Accordingly, frequent outbreaks of water pollution across river basins have caused serious regional disputes. Since 1995 in China, there have been about 11,000 water environmental emergencies that have resulted in substantial negative impacts on people's lives and productivity. As the issue of transboundary water pollution involves the management boundaries and interest relationships of different administrative divisions, it is difficult to solve the problem solely through negotiations between upstream and downstream local governments. Therefore, the central government urgently needs to introduce some polices to define the responsible subjects, regulate the behaviour of the various subjects, and establish joint governance mechanisms.

Although the environmental protection laws (in 1998 and 2000) stipulated transboundary pollution in China, the effect is not significant. The local protectionism is an important factor in addressing the problem of transboundary pollution in the river basins. However, each administrative region has its own war-style pollution control measures, which are unable to fundamentally reverse the increasingly serious trend of transboundary water pollution. Only by breaking the administrative division and adopting cross-regional joint governance can it be possible to curb this trend. To this end, the State Environmental Protection Administration in China issued the "Notice on Strengthening the Prevention and Control of River Pollution" on 29 December 2007, focusing on solving the serious river water pollution problem in China and proposing to improve the water quality monitoring of transboundary rivers. On this basis, on 7 July 2008, the Ministry of Environmental Protection of the People's Republic of China further issued a policy to solve the transboundary pollution of rivers, that is, the guiding opinions on the prevention and disposal of disputes over trans-provincial water pollution. This policy stipulates the establishment of a cross-provincial joint prevention and control mechanism in key rivers to reduce the level of transboundary water pollution in the basin and resolve regional disputes caused by transboundary water pollution. Therefore, this paper uses a difference-in-differences (DID) model to evaluate the effect of the implementation of the policy on transboundary water pollution in river basins. This is also a test of whether the policy can effectively solve the problem of local environmental pollution. As expected, the results of this paper show that the implementation of this policy has a positive impact on river water pollution, resulting in significant improvements in river water quality in transboundary areas, and the improvement effect is sustainable to a certain extent.

The possible marginal contribution of this paper is as follows. First, this paper takes the implementation of the joint governance policy as a natural experiment, and studies the policy effect of transboundary water pollution control from the water quality of two different watersheds, trans-provincial and non-trans-provincial. This enriches the empirical identification of the relevant literature in the content of water pollution control in transboundary basins. Second, this paper collects the weekly monitoring data of the water quality of the cross-section of the river by the national regulatory authorities, and the time span is long. Most studies use regional or annual data. Therefore, the long-term observation point data in this paper is conducive to using the DID method to evaluate the implementation effect of the policy. This allows for a more accurate assessment of the causality of the policy's impact on transboundary water pollution in the basin, and endogeneity issues are well addressed. Of course, this also provides data support for us to study the long-term dynamic policy effect. Third, few studies have quantitatively analysed the impact mechanism of transboundary governance of water pollution. This paper explores the mechanism from two aspects of official green promotion pressure and stakeholder supervision. This provides effective evidence for the further improvement of upstream and downstream joint governance of river transboundary water pollution.

The rest of this paper is structured as follows. Section 2 reviews the relevant literature. Section 3 expounds the policy background of trans-provincial water pollution control. Section 4 describes the data and empirical strategy used in this paper. Section 5 analyses the empirical results. Mechanistic analysis is in Section 6. Section 7 concludes this paper.

## 2 Literature review

The prevalence of transboundary pollution indicates the inefficiency of unilateral action. Increasingly more scholars and policy makers have realized that only cooperation between local governments and countries can fundamentally solve the problem of transboundary water pollution (Du et al., 2022). By adding emissions trading and learning-by-doing mechanism to the game model, Chang et al. (2018) used numerical simulation to prove that cooperation is an effective way to solve transboundary pollution. Most literatures only analyse transboundary pollution from the perspective of government governance, and few involve industrial enterprises. Yeung (2007) confirmed that the cooperation between upstream and downstream governments, and between governments and enterprises can achieve a radical cure for transboundary pollution by using game models. The assumption of these studies is that in order to realize cooperative pollution control in the upstream and downstream regions, it is necessary to ensure the ecological environment of the downstream regions without compromising the development opportunities of the upstream regions. However, it is difficult to achieve the symmetrical incentive of joint pollution control in upstream and downstream areas due to the great differences in economic development, pollution control costs and losses caused by pollution. The upstream and downstream regions can effectively solve the problem of transboundary water pollution only by negotiating an agreement on the cost-sharing of pollution control costs (Chander and Tulkens, 1992; Dong et al., 2012; Alcalde-Unzu et al., 2015). Fernandez (2009) took the Tijuana River, a transboundary river between the United States and Mexico as an example, and found that the two governments reached an agreement through negotiation to jointly bear the cost of pollution control such as environmental infrastructure construction. This joint pollution control not only mobilized Mexico's enthusiasm for pollution control, but also effectively reduced the harm of upstream pollution in the United States (Fernandez, 2009).

Addressing transboundary water pollution requires coordinated action by upstream and downstream regions, while the reality is that upstream and downstream regions are often uncooperative due to the indifference of the central government (Duda, 2016). The central government can improve this situation and promote cooperation between upstream and downstream regions by introducing some policies. Hence, it is important for the central government to introduce regional environmental policies to reduce transboundary pollution (Tomkins, 2005). In this regard, it is helpful to investigate the role of these policies in the field of air pollution control in the United States (Greenstone, 2004). The Clean Air Act of 1990 also encourages the building of cooperative governance relationships between and among the federal, state and local governments and actively guides the public to participate in environmental governance, thus achieving obvious improve (Greenstone, 2004; Auffhammer et al., 2009). For the governance of river pollution, Chakraborti (2016) took the clean water act in United States as an example, proved that when the water environment around the factory is improved, the factory could increase the discharge of pollutants, and conversely when the quality of the surrounding water environment is degraded, the discharge of pollutants could be reduced. Schiff (2014) believed that the Clean Water Act in the United States has played an important role in controlling point source pollution from large industrial equipment and sewage treatment plants. However, as river pollution increases on a spatial scale and ocean water quality continues to deteriorate, the policy has not played its role in addressing these two types of pollution. With respect to some policies on air and water pollution in India, Greenstone and Hanna (2014) demonstrated that these policies significantly improve air quality and reduce infant mortality, but water pollution-related policies have not worked. Wunder (2005, 2006) proposed a new direction for marketization to address environmental externalities: payment for environmental services (PES). PES is a market mechanism or public policy to reach a transaction agreement through voluntary negotiation and negotiation on the basis of clarifying the property rights of ecological products (Jing and Du, 2022).

Although the above studies provide useful references for the river transboundary water pollution control and policy evaluation, there are still some deficiencies worth exploring. First, most of the literature is theoretically deduced from the perspective of game theory, proving that upstream and downstream regional cooperation is the best strategy for controlling transboundary water pollution in river basins. However, there is little empirical identification on transboundary water pollution control, especially China's policy effects in addressing transboundary water pollution. Second, some studies have shown that the environmental assessment mechanism for the promotion of officials in China in recent years has had a positive effect on transboundary water pollution control. Water pollution control is a long-term systematic project, and there may be a lag effect. Therefore, after the implementation of the policy, the government implemented environmental assessments on officials. The fact that the level of transboundary water pollution in rivers has decreased since then. Without considering the impact of the joint pollution control policy, it is inevitable that there could be certain policy biases when examining the impact of official promotion assessment on transboundary water pollution alone. Third, the existing evaluations of water environment governance policies rarely use the DID method, and fail to effectively eliminate the impact of other factors on river transboundary water pollution, which may lead to overestimation of regression results. Accordingly, this paper takes the joint governance of transboundary water pollution in China as a quasi-natural experiment, and uses the DID model to empirically evaluate whether the policy has significantly improved the transboundary water quality of rivers.

## 3 Context of transboundary governance policy

When the level of economic development is low and the degree of water pollution does not exceed the self-purification capacity of the river, the river belongs to the nature of public goods. However, with the rapid development of the economy and the excess of river sewage discharge capacity, the pollution carrying capacity of rivers becomes a scarce resource and gradually evolve into a quasi-public good with competitiveness and non-exclusivity. Moreover, with the aggravation of river pollution, the transboundary water pollution would gradually cause disputes between upstream and downstream regions. Cross-border water pollution not only causes the transboundary transfer of pollutants, but it also has a serious impact on production in the downstream area and on the living conditions of those residing there. Additional issues, such as international disputes, arise if the pollutants cross the national border. Transboundary water pollution poses a new challenge for China’s fragmented local governments to control water pollution not only by focusing on their “An acre of three points” but also by promoting collective participation between central and local governments through new regulations.

The rivers are being increasingly polluted in China as a result from the extensive economic development mode, unreasonable industrial layout and backward pollution control technology in the past. On 29 December 2007, the state environmental protection administration issued a notice to strengthen river pollution prevention and control clearly stipulates those further efforts should be made to strengthen river pollution prevention and control and accelerate the improvement of river water quality in China. With the aim to improve trans-provincial water quality, the notice proposes to improve the urban sewage treatment rate, strengthen the river water quality supervision, improve early warning mechanisms, increase treatment capacity, and improve the trans-provincial water quality monitoring and assessment system. Furthermore, it was proposed that by the end of 2010, the trans-provincial water quality would be improved significantly and the corresponding guiding measures were put forward. With respect to the local governments’ interest disputes regarding upstream and downstream transboundary pollution, the notice puts forward the guideline but is less concerned with the concrete measures.

To manage the increasingly serious cross-border water pollution and the resulting upstream and downstream disputes and to promote the continuous improvement of river water quality across the country, the Ministry of Environmental Protection promulgated a policy on the joint governance of transboundary river pollution, including 13 specific implementation measures in 2008. This policy requires the adjacent areas of the inter provincial boundary basin, especially the upstream areas, to optimize the regional layout, adjust the industrial structure, strictly control the environmental access, strictly control the generation of new pollution sources, and prevent the occurrence of inter provincial water pollution from the source according to the environmental capacity and outbound water quality objectives. In addition, this policy also pointed out that it is necessary to establish a long-term working mechanism for the prevention and disposal of cross-provincial water pollution disputes. These mechanisms include regular joint consultations, information sharing, joint sampling and monitoring, joint law enforcement supervision, early warnings during sensitive periods, coordinated emergency responses, coordinated handling of disputes, and joint rectification supervision.

The policy provides a comprehensive guide to improves the river pollution environment by the upstream and downstream river basin provinces engaging in cooperative governance in China. The goal is to establish cooperative governance regarding pollution between upstream and downstream provinces and the long-term mechanism of resolving disputes, containing transboundary pollution, improving water quality in the cross section of the provinces, improving the river’s ecosystem service functions and the welfare level of the coastal residents. If the policy is implemented, it would affect the provincial boundary section’s river water quality, but it would not affect the water quality of the provincial non-boundary rivers or areas removed from the boundary transition section. Then, compared with the latter, the water quality of the former provincial boundary section is likely to have a significant improvement. Therefore, it is necessary to use the method of causal judgment to identify the impact of the implementation of this policy on the water quality of the provincial boundary section.

## 4 Data and empirical strategy

### 4.1 Data description

The data in this paper were collected from data sources such as China National Environmental Monitoring Centre, China Statistical Yearbook, and China Environmental Statistical Yearbook. The time span is the period 2004–2016. These variables mainly involve water pollution indicators in the weekly water quality monitoring reports of 62 state-controlled sections of China’s river basins and other provincial-level data indicators. The name of the station provided in the weekly water quality monitoring report of key sections of major river basins in China shows whether the station is located at the junction of administrative divisions. Among them, 24 monitoring stations are located at the provincial boundary, and the administrative division is set as the dummy variable in this paper. If the water quality monitoring point of the national control section is located at the administrative Boundary, the value is 1, otherwise it is 0. The 62 state-controlled sections are mainly located in the Heilongjiang River basin, Liaohe River basin, Haihe River basin, Yellow River basin, Huaihe River Basin, Yangtze River basin, Pearl River basin and Southwest River basin.

The explained variables in this paper are three water pollution indicators that measure water quality (*WQ*), which are derived from the weekly reports on water quality monitoring of key sections in major river basins across the country. The three water quality indicators are dissolved oxygen (DO), chemical oxygen demand (COD) and ammonia nitrogen (NH), respectively. This paper sorts out the monitoring point indicators since 2004 (deleting the revoked Dongsongmen monitoring point in Cangzhou, Hebei), including water pollution indicators at the provincial boundary and non-provincial boundary water pollution indicators. The weekly reports of automatic water quality inspection of 62 state-controlled sections of major river basins in China show whether the monitoring points are monitoring points at provincial boundaries.

The explanatory variable of interest in this paper is treatment, that is, the interaction term between the two variables of *treat* and *post*. This paper uses the year of policy promulgation as the critical point of the period to describe the changes in water quality before and after the policy was promulgated. Specifically, the variable *post* is defined as one for every week in 2008 and later, and 0 otherwise. The variable *treat* is generated according to whether the water quality monitoring points are located at the inter-provincial boundary, and is used to measure the changes in the water quality of the rivers in the treatment group and the control group. To be specific, the rivers of the provincial boundary section are listed as the treatment group, that is, the variable *treat* is defined as 1. While the non-provincial boundary sections are classified as the control group, that is, the variable *treat* is defined as 0.

The control variables cover variables for river, season, and provincial characteristics. The season dummy variable (*Season*) is based on the flood seasons of each river. If the river is in flood season, the value of *Season* is 1, otherwise 0. The variables of river characteristics are dummy variables of the main and tributary stream (*Mainstream*), the upstream and downstream (*Upstream*) and the north-south rivers (*Northstream*). Specifically, the variable *Mainstream* is one if the monitoring point is at the mainstream, otherwise 0. If the monitoring point is located upstream, the variable *Upstream* takes the value of 1, otherwise 0. The variable *Northstream* is defined as one if the monitoring point is located in the northern rivers, otherwise 0. The provincial-level control variables include gross domestic product (*GDP*), industrial structure (*IS*), foreign direct investment (*FDI*), total population (*Pop*), highway mileage (*Road*), and waste water emissions (*Water*). The industrial structure is measured by the ratio of the added value of the tertiary industry to the gross domestic product. Among them, the variables of *GDP*, *FDI*, *Pop*, *Road*, and *Water* are all processed logarithmically in the regressions. The statistical descriptions of these non-dummy variables are presented in Table 1.

## 4.2 Empirical strategy

The changes of the transboundary water environment in the basin mainly result from three factors. One is the time effect caused by economic development, improvements in the enterprise's environmental protection, improvements in the agricultural non-point source pollution and improvements in the sewage treatment equipment. A second factor is the cumulative effect of pollution caused by the unidirectional characteristics of the rivers. The third factor is policy effects brought about by law enforcement that the impact of coordinated measures on water pollution by provincial governments. The purpose of this paper is to evaluate the policy effects on the changes in transboundary water pollution in watershed areas. The DID method effectively eliminates the time effect and pollution accumulation effect and identifies the influence of the policy effects. Therefore, this paper constructs the following the difference-in-differences model to evaluate the effect of the joint water pollution control policy on water quality improvement.

$$WQ_{it} = \alpha + \beta treat_i \cdot post_t + \delta treat_i + \gamma post_t + \varphi X_{itp} + \theta_t + \mu_p + \varepsilon \tag{1}$$

Where the subscripts $i$, $t$, and $p$ represent the monitoring point, the year-week and the province, respectively. $\beta$, the regression coefficient of interest, reflects the net effect of the implementation of the joint governance policy on the transboundary water quality of the basins. With respect to dissolved oxygen, if $\beta$ is significantly positive, the implementation of the joint governance significantly improves the water quality of the watershed transboundary water. Regarding chemical oxygen demand and ammonia nitrogen, if $\beta$ is significantly negative, the implementation of the joint governance effectively reduces cross-border water pollution and improves the water quality in the basins. $\delta$ is a regression coefficient that denotes that the water qualities of the treatment and control rivers do not change over time. $\gamma$ is a regression coefficient that reflects the change in water quality of the treatment group over time. $X$ represents a series of control variables, and is logarithmically converted. $\varepsilon$ is a random error term.

TABLE 1 Descriptive statistics for non-dummy variables.

| Variables | Mean | S.D. | Median | Obs | Data source |
|---|---|---|---|---|---|
| DO | 7.7780 | 2.6370 | 7.7300 | 39959 | China National Environmental Monitoring Centre |
| COD | 4.3680 | 8.4760 | 3.0000 | 39959 | |
| NH | 0.7670 | 2.2070 | 0.2700 | 39959 | |
| GDP | 19000 | 15000 | 15000 | 299 | China Statistical Yearbook, and China Environmental Statistical Yearbook |
| IS | 39.8100 | 8.0350 | 38.4000 | 299 | |
| FDI | 1000 | 1500 | 428.6000 | 299 | |
| Pop | 5600 | 2500 | 5600 | 299 | |
| Road | 140000 | 70000 | 140000 | 299 | |
| Water | 260000 | 160000 | 240000 | 299 | |

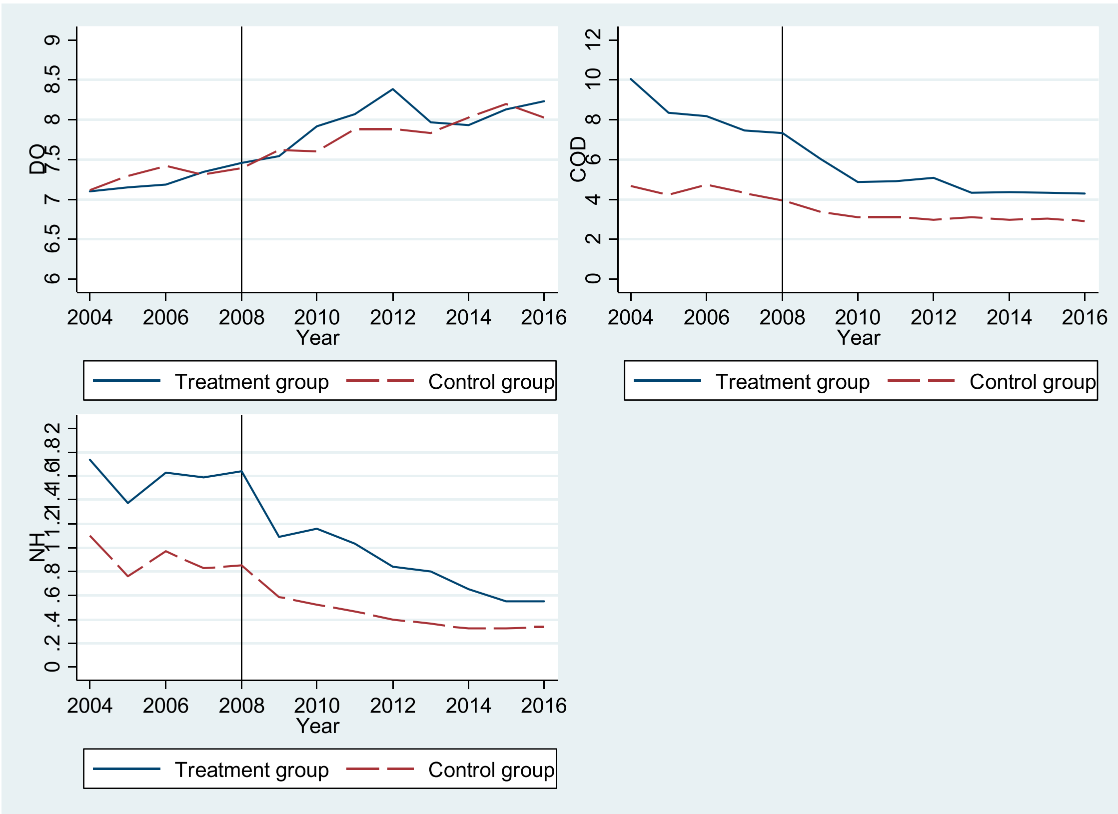


FIGURE 1
Parallel trends for DO, COD, and NH.

## 5 Empirical results

### 5.1 Parallel trend test

The premise of using the DID strategy is that there is no significant difference in the water pollution indicators between the treatment group and the control group before the implementation of the joint governance policy, which means that the two have a parallel trend. As displayed in Figure 1, the three water pollution indicators exhibit the same change trend before the implementation of the policy, while after the implementation of the policy, the changes in the

TABLE 2 Regression results of the policy on the impact of transboundary water pollution in China's river basins.

| Variables | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Panel A: DO | | | | |
| *treat·post* | 0.1336*** | 0.0792 | 0.1064** | 0.0952* |
| | (0.0508) | (0.0508) | (0.0509) | (0.0509) |
| Constant | 7.3310*** | 11.7591*** | 9.1819*** | 56.2139*** |
| | (0.2148) | (2.0274) | (0.3024) | (3.5089) |
| Within $R^2$ | 0.0157 | 0.0328 | 0.2048 | 0.2154 |
| Observations | 39959 | 39959 | 39959 | 39959 |
| Panel B: COD | | | | |
| *treat·post* | −1.2709*** | −1.1282*** | −0.9045*** | −0.7068*** |
| | (0.1321) | (0.1323) | (0.1645) | (0.1604) |
| Constant | 4.3383*** | 33.7301*** | 0.9780 | −10.3329 |
| | (0.7332) | (5.5945) | (0.9766) | (11.0419) |
| Within $R^2$ | 0.0182 | 0.0333 | 0.0361 | 0.0554 |
| Observations | 39925 | 39925 | 39925 | 39925 |
| Panel C: NH | | | | |
| *treat·post* | −0.2384*** | −0.1558*** | −0.1399*** | −0.0937** |
| | (0.0339) | (0.0338) | (0.0421) | (0.0412) |
| Constant | 0.8461*** | 2.6689* | 0.5587** | −21.1439*** |
| | (0.1926) | (1.4654) | (0.2498) | (2.8385) |
| Within $R^2$ | 0.0231 | 0.0424 | 0.0881 | 0.1023 |
| Observations | 39975 | 39975 | 39975 | 39975 |
| Control variables | No | Yes | No | Yes |
| Year-week fixed effect | No | No | Yes | Yes |
| Province fixed effect | No | No | Yes | Yes |

Notes: *, **, and *** denote statistical significance at 10%, 5%, and 1% levels respectively. Standard errors in parentheses.

treatment group were more obvious than that of the control group. The DO in the treatment group rises faster than that in the control group, while the COD and NH indicators in the treatment group decline faster than that in the control group. This indicates that the water quality of the treatment group affected by the policy improves faster than the water quality of the control group. Hence, the implementation of this policy has a positive impact on the improvement of cross-border water quality, and the three water quality monitoring indicators in this paper meet the parallel trend assumption of the DID strategy.

## 5.2 Benchmark regression results

The benchmark regression results of DID estimation are presented in Table 2. The regression results for column (1) exclude control variables and fixed effects. The results in column (2) add control variables to the regression in column (1). The results in column (3) add the year-week and province fixed effects to the regression in column (1). The regression results in column (4) include both control variables and fixed effects. As can be seen from column (1) of Table 2, all treatment effects are significant at the 1% level. The signs of these coefficients remain the same when the control variables and fixed effects are added to columns (2) and (3), respectively. From column (4), it can be found that the coefficient of *treat·post* in Panel A for DO is statistically significant at 0.0952. This indicates that the joint governance policy helps to improve the dissolved oxygen content in the watersheds along the provincial boundary. In terms of COD in Panel B, the coefficient for *treat·post* is statistically significant at −0.7068. This suggests that this policy is beneficial to reduce the chemical oxygen demand in the trans-provincial watershed. With respect to NH in Panel C, the coefficient for *treat·post* is statistically significant at −0.0937. This implies that this policy helps reduce ammonia nitrogen levels in watersheds across provincial boundaries. In summary, compared with non-transprovincial watersheds, the joint management of water pollution in interprovincial watersheds can indeed improve water quality. These findings are consistent with the results of Fernandez (2009) on transboundary river governance.

TABLE 3 Dynamic trend test results.

| Variables | (1) | (2) | (3) |
|---|---|---|---|
| | DO | COD | NH |
| *treat·trend09* | −0.0786 | −0.2535 | −0.1965*** |
| | (0.0919) | (0.2909) | (0.0743) |
| *treat·trend10* | 0.2608*** | −1.0730*** | −0.0248 |
| | (0.0911) | (0.2884) | (0.0735) |
| *treat·trend11* | 0.1363 | −1.0372*** | −0.1203 |
| | (0.0909) | (0.2881) | (0.0733) |
| *treat·trend12* | 0.3126*** | −0.7117** | −0.2160*** |
| | (0.0913) | (0.2891) | (0.0737) |
| *treat·trend13* | 0.0307 | −1.5535*** | −0.2189*** |
| | (0.0907) | (0.2873) | (0.0731) |
| *treat·trend14* | −0.0620 | −1.2373*** | −0.3154*** |
| | (0.0912) | (0.2888) | (0.0736) |
| *treat·trend15* | −0.0538 | −1.0019*** | −0.3770*** |
| | (0.0922) | (0.2921) | (0.0745) |
| *treat·trend16* | 0.1845* | −1.5011*** | −0.5146*** |
| | (0.0950) | (0.3010) | (0.0765) |
| Constant | 56.3927*** | −15.3872 | −23.7917*** |
| | (3.5069) | (11.1079) | (2.8177) |
| Control variables | Yes | Yes | Yes |
| Year-week fixed effect | Yes | Yes | Yes |
| Province fixed effect | Yes | Yes | Yes |
| Within $R^2$ | 0.2160 | 0.0575 | 0.1033 |
| Observations | 39959 | 39925 | 39975 |

Notes: *, ** and *** denote statistical significance at 10%, 5%, and 1% levels respectively. Standard errors in parentheses.

## 5.3 Dynamic trend results

The above results indicate that the implementation of the joint governance policy has significantly reduced the cross-provincial water pollution. However, the DID estimation results can only measure the effect of the policy on cross-border water pollution compared with that before the promulgation. This average effect does not reflect the dynamic effect of the implementation of the policy on transboundary water pollution or whether there is a lag effect. Therefore, we rewrite the benchmark regression Eq. 1 as an equation that measures the dynamic effect of the policy on transboundary water pollution:

$$WQ_{it} = \alpha + \beta\sum_{tt=09}^{16} treat_i \cdot trend_{tt} + \delta treat_i + \gamma trend_{tt} + \varphi X_{itp} + \theta_t + \mu_p + \varepsilon \tag{2}$$

where $treat_i \cdot trend_{tt}$ represents the time effect of the implementation of the policy. $trend_{tt}$ represents the dummy variable of the year after the policy is implemented, including *trend09*, *trend10*, . . . , *trend16*. These values are one in a certain year after the promulgation, and 0 in other years.

Table 3 reports dynamic trend results of the implementation effect of this joint governance policy. With regard to DO in column (1), the coefficient of *treat·trend09* in 2009 is negative but not significant. From 2010 to 2013, the regression coefficients are positive and are significant in 2010 and 2012. However, the sign of the regression coefficients gradually changes from positive to negative and there is no significant difference between the period 2014–2015. The regression coefficient is significantly positive in 2016. These results indicate that the implementation of this policy has a certain volatility on the improvement of DO. As for COD in column (2), the regression coefficient is not significantly negative in 2009, but it is significantly negative at 1% level after 2010, which means that the implementation of the policy has a significant continuous effect on the reduction of COD. With respect to NH in column (3), the regression coefficient is negative at the significance level of 1% in 2009, but they are not significant in 2010 and 2011. However, the regression coefficients are negative at the significance level of 1% after 2012. This shows that the improvement of NH in the policy may have a lag of about 3 years. To sum up, the joint governance policy for transboundary water pollution has long-term dynamic effects in improving water quality.

## 5.4 Robustness tests

To further verify the benchmark regression results, some robustness tests are conducted in this section, including eliminating political cycles, replacing the sample and placebo test.

### 5.4.1 Eliminating political cycles

Party committees or governments generally change every 5 years in China. In this case, local governments may temporarily shut down water polluters due to political pressure to avoid major environmental pollution incidents. Therefore, political changes may also affect the results of the econometric estimates. The 18th National Congress of the Communist Party of China (CPC) was held in Beijing in November 2012. Thus, this paper conducts a regression analysis again after excluding major national political events in 2012. Column (1) of Table 4 presents the results of eliminating political cycles. These results show that the joint governance of water pollution can promote dissolved oxygen, and effectively reduce chemical oxygen demand and ammonia nitrogen, which are consistent with the benchmark results.

### 5.4.2 Replacing the sample

Some state-controlled sections are set at sea estuaries and borders, and their water quality is affected by more complex factors. Therefore, this paper deletes the statistical data of monitoring points located at sea estuaries and national

TABLE 4 Robustness test results.

| Variables | (1) Eliminating political cycles | (2) Replacing the sample | (3) Placebo test (2006) | (4) Placebo test (2007) |
| --- | --- | --- | --- | --- |
| Panel A: DO | | | | |
| *treat·post* | 0.1425*** | 0.1596*** | 0.1078 | 0.1688 |
| | (0.0523) | (0.0510) | (0.0908) | (0.1137) |
| Panel B: COD | | | | |
| *treat·post* | −1.1327*** | −1.1142*** | −0.1054 | −0.0888 |
| | (0.1750) | (0.1672) | (0.2273) | (0.2822) |
| Panel C: NH | | | | |
| *treat·post* | −0.1105** | −0.1176*** | 0.0662 | −0.0067 |
| | (0.0440) | (0.0425) | (0.0767) | (0.0698) |
| Control variables | Yes | Yes | Yes | Yes |
| Year-week fixed effect | Yes | Yes | Yes | Yes |
| Province fixed effect | Yes | Yes | Yes | Yes |

Notes: *, ** and *** denote statistical significance at 10%, 5%, and 1% levels respectively. Standard errors in parentheses.

borders for further testing. As shown in column (2) of Table 4, the results indicate that the impact of this policy on NH is more significant and the benchmark results are generally validated to be robust.

### 5.4.3 Placebo test

Because there may be missing variables and unobservable data that have a systematic impact on the empirical results, this paper uses a placebo test for the robustness test. Specifically, the implementation time of the policy is advanced to 2006 and 2007, respectively, as the time when the pseudo-policy is implemented. If the pseudo-policy has no significant effect on the improvement of transboundary water quality, then the policy plays a key role in the improvement of cross-border water quality and the empirical results are not affected by systematic errors or missing variables. The results of the placebo test in columns (3)–(4) of Table 4 reveal that the implementation of the pseudo-policy has no significant effect on transboundary water quality.

## 6 Mechanism identification

The above results suggest that after the implementation of the cross-border joint pollution control by upstream and downstream local governments, the level of water pollution in rivers across provincial boundaries decreases significantly. However, how the implementation of the policy improves the water quality of transboundary rivers requires further discussion. This policy stipulates that the distribution of water quality monitoring sites in cross-provincial cross-sections should be improved and the target accountability system should be implemented for cross-provincial cross-sections. The implementation of the policy is one way to perfect the supervision mechanism and realize water pollution environmental governance. The supervision mechanism is not only needed in the official assessment of the water quality target, but that it is also needed to ensure the diversity of supervision and the compactness of the interest relationship. Accordingly, this paper examines the corresponding mechanism from two aspects of the official green promotion pressure and the stakeholder supervision. Referring to Ruan et al. (2014) and Li et al. (2015), the mechanism identification is presented in Eqs 3, 4.

$$pressure_{it} = \alpha + \beta treat_i \cdot post_t + \delta treat_i + \gamma post_t + \varphi X_{itp} + \theta_t + \mu_p + \varepsilon \tag{3}$$

$$stakehol_{it} = \alpha + \beta treat_i \cdot post_t + \delta treat_i + \gamma post_t + \varphi X_{itp} + \theta_t + \mu_p + \varepsilon \tag{4}$$

Where *pressure* denotes a green promotion pressure on officials, and *stakehol* stands for the stakeholder supervision. This paper constructs the green promotion pressure by sulphur dioxide emissions, dust emissions, total waste water emissions, solid waste emissions and environmental emergencies. The annual sub-indexes of each province are compared with the annual averages of the corresponding indexes at the provincial level. If the sub-indexes of each province are greater than the mean value, the value is 1, otherwise 0. Five indexes are then added together to obtain the promotion pressure of the environmental protection assessment. The higher the value, the greater the green promotion pressure on local officials. The stakeholder supervision indicator is obtained through principal component analyses of the number of suggestions from National People's

TABLE 5 Mechanism identification results.

| Variables | (1) | (2) |
|---|---|---|
| | Green promotion pressure | Stakeholder supervision |
| *treat·post* | 0.3652*** | 0.0819*** |
| | (0.0153) | (0.0126) |
| *post* | 5.5471*** | −3.3571*** |
| | (0.1689) | (0.1399) |
| *treat* | −0.2483*** | −0.0554*** |
| | (0.0212) | (0.0175) |
| Constant | −0.3956 | 27.8154*** |
| | (1.1190) | (0.9269) |
| Control variables | Yes | Yes |
| Year-week fixed effect | Yes | Yes |
| Province fixed effect | Yes | Yes |
| Within $R^2$ | 0.2459 | 0.6946 |
| Observations | 37386 | 37386 |

Notes: *, ** and *** denote statistical significance at 10%, 5%, and 1% levels respectively. Standard errors in parentheses.

Congress (NPC), proposals proffered by the Chinese People's Political Consultative Conference (CPPCC), letters, visiting batches and the total number of public complaints and proposals in the field of environmental protection as counted by provinces between 2004 and 2016. Table 5 reports the regression results for mechanism identification.

## 6.1 Green promotion pressure

Political tournaments centered on GDP have caused officials to only pay attention to economic growth while ignoring environmental protection in the process of pursuing promotion, resulting in serious environmental pollution (Qian and Roland, 1998; Jin et al., 2016). Therefore, scholars propose to improve the performance evaluation system of officials, increase the weight of indicators such as environmental protection, and gradually realize the transition from the GDP tournament to the environmental protection tournament. The central government first introduced a "one vote vote" system for evaluating officials in 2005. In 2009, targets for environmental protection and ecological improvement were added to the evaluation system for officials. In 2012, it was made clear that officials should not be judged solely on GDP. Since then, the environmental protection assessment system for officials has been gradually improved. The 11th Five-Year plan included chemical oxygen demand, which involves water pollution indicators, in the assessment set for officials, and the 12th Five-Year Plan included ammonia nitrogen in the assessment set. The GDP championship is gradually transitioning to the environmental protection championship. By increasing the assessment weight of environmental protection, the baton role of the environmental protection championship can be played to influence the behavioural preferences of officials. Only by increasing the investment in environmental protection can we get more promotion opportunities.

Based on the promotion pressure (Qian et al., 2011), this paper constructs the promotion pressure of environmental protection assessment, including five indicators of sulfur dioxide emission, dust emission, total wastewater discharge, solid waste discharge and emergency environmental events. The annual sub-indicators of each province are compared with the average of corresponding indicators at the provincial level. If the corresponding indicators are greater than the mean, the value is 1, otherwise, it is 0. Then, the promotion pressure of environmental protection assessment is obtained by adding up the five indicators. The higher the number, the greater the pressure on local officials to assess environmental protection. From column (1) of Table 5, it can be seen that the coefficient of official green promotion pressure is 0.3652 at the significance level of 1%, indicating that this policy promotes the increase of the green promotion pressure of officials and then improves the transboundary water quality of the river basins. This is mainly due to the fact that through the pressure of the downstream local government on the upstream local government, the upstream government is encouraged to actively implement source treatment and adjust the industrial structure to improve the water environment quality and reduce the pollution of the cross-section water. Therefore, the implementation of the joint governance further encourages local officials to actively participate in environmental governance through official assessment indicators and gradually develops the environmental protection championship pattern of official promotion, finally improves the river water environment.

### 6.2 Stakeholder supervision

The failure of the government in environmental governance is usually due to the form of environmental decentralization adopted by the government, which will lead to serious information asymmetry between the central government and local governments, and then lead to the "principal-agent" problem in environmental governance. The objective function of the central government includes ecological environmental protection. However, the behaviour preference of local governments, especially the "top leaders" of local governments, may prefer "personal promotion caused by economic growth," and the supervision cost of the central government to local governments is relatively high, leading to the failure of the government in environmental governance. On the other hand, fiscal decentralization leads to the tendency of local governments to obtain their own fiscal revenue, which is more likely to lead to the collusion between government and enterprises under local protectionism, and environmental governance becomes more "an armchair strategy". The resulting environmental pollution is ultimately paid by residents. Therefore, improving public appeal channels can effectively reduce the degree of information asymmetry between the central government and local governments and play a good supervisory role (Nie et al., 2013). First, the central government holds the key to the promotion of local officials, so this form of political centralization provides more powerful support for public demands. The public demand for environmental protection is more manifested in major environmental pollution incidents, and the central government's assessment of local governments has implemented the "one vote veto" system in the field of environmental protection (Lin and Shen, 2021), which puts a "restraint" on the environmental protection behaviour of local officials through the public demand. Secondly, the public's demand for good water quality and environment can improve the local government's efforts to control water pollution and strengthen the enforcement of relevant laws (Zheng et al., 2014). Finally, public demand data is a mirror reflecting local officials' efforts in environmental governance. If public environmental demand is high, it indirectly indicates that officials do not implement policies to improve the environmental level in the process of local environmental governance, thus lowering the assessment scores of officials. On the premise that the mechanisms of "voting with hands" (Harsman and Quigley, 2010) and "voting with feet" (Tiebout, 1956) are not perfect, the establishment and improvement of public appeal channels can bring citizens into the environmental governance process of governments and enterprises, and truly realize the "triangle" of environmental governance. And it can change the top-down "unidirectional" of China's environmental governance, realize the "responsibility from below" of China's environmental governance, and improve the ecological environment.

According to Yu (2014), this paper calculates the number of people's congresses' suggestions, CPPCC proposals, total number of letters, batches of visitors and total number of visitors in the field of environmental protection from 2004 to 2016 in provinces (autonomous regions and municipalities directly under the Central Government) through principal component analysis, and obtains the public environmental demand index. As shown in column (2) of Table 5, the regression coefficient of *treat·post* is 0.0819 at a significance level of 1%, indicating that stakeholder supervision effectively reduces the degree of river transboundary water pollution and improves water quality. On the one hand, the petition work of the NPC, the CPPCC and related personnel can promote local governments to strengthen the implementation of cross-border joint law enforcement and information sharing. The proposals of the NPC and the CPPCC represent the requirements of a good water environment. This kind of supervision can standardize and institutionalize a good way of cross-border joint pollution control, thereby strengthening the effect of cross-border joint pollution control. On the other hand, the public's demands for environmental protection are more manifested in major environmental pollution incidents. Through the supervision mechanism of petition, the environmental protection behaviour of local officials is put on a "curse." If the number of petitions is frequent, it indirectly indicates that officials do not effectively implement the policy of improving the environmental level in the process of local environmental governance, thus lowering the evaluation scores of officials. Therefore, under the premise that the mechanisms of "voting with your hands" and "voting with your feet" are not sound, incorporating stakeholder supervision into the environmental governance process of the government and enterprises could truly realize the "triangle" of environmental governance, which is conducive to improving river water quality.

## 7 Conclusion

Only the cooperation between upstream and downstream can better solve the problem of river transboundary water pollution. The key to the effect of joint water pollution control is whether it can promote cooperation between upstream and downstream. To this end in this paper, the weekly monitoring data of 62 state-controlled sections between the period 2004–2016 are used to assess the policy effect of the joint governance on transboundary water pollution by using a difference-in-differences strategy in China. Further, this paper examines the dynamic effect of the implementation of the joint governance on the improvement of transboundary water pollution in watersheds and proves the robustness of the results by deleting the political cycle, replacing the control group and placebo test. The Ministry of Environmental Protection hopes to improve the target of transboundary water pollution in the basins through joint prevention and control of upstream and downstream areas in China. Only when both upstream and downstream regions adopt a cooperative attitude can they avoid the free-rider problem of public goods to the greatest extent. Therefore, this paper also provides evidence from China for the theory of cooperative governance of environmental pollution.

Based on empirical results, in general, it has a significant impact on the reduction of transboundary water pollution in the basins since the promulgation of the joint governance policy. Also, as long as the upstream and downstream areas continue to deepen the cooperation between the two sides, the level of transboundary water pollution in the basins can be significantly reduced. What's more, official green promotion pressure and stakeholder supervision play an important role in promoting this policy in transboundary governance of water pollution. To solve the problem of motivation, we should build a market-oriented environmental governance mechanism. First, at present, the joint governance of transboundary pollution is mainly used for water quality improvement, and does not involve the treatment of forests, grasslands and wetlands. This will not systematically achieve stable improvement of water quality. Forests and grasslands can better fulfil ecological functions such as soil and water conservation, flood prevention, climate regulation and biodiversity maintenance. The management of "mountains, rivers, forests, fields, lakes and grasses" and the unified management of cities, villages, industries and agriculture can improve and maintain river water quality more effectively.

Second, choosing the water quality breakpoint of the provincial boundary section for monitoring can promote better joint monitoring of the upstream and downstream provinces, so as to achieve fair and transparent water quality monitoring. In addition, a third-party independent institution can be introduced to follow up the implementation of water quality, improve the water quality evaluation index system and upgrade the evaluation technology. Since the joint prevention and control measures promulgated by the Ministry of Environmental Protection have played a certain role in reducing river transboundary water pollution, but a long-term mechanism for joint prevention and control of transboundary water pollution has not yet been formed. The regular joint prevention and control system can not only effectively prevent transboundary water pollution, but also reduce disputes caused by water pollution in upstream and downstream areas.

Third, when assessing the environmental protection performance of officials, it is not only necessary to establish a "one vote veto" system, but also to establish a set of scientific green evaluation index system. As China is still a large developing country with uneven regional development and arduous task of poverty alleviation, it also needs a certain economic growth rate to improve people's living standards, so economic development and environmental protection should not be neglected. Different assessment indicators are set according to different regions and different development stages, so as to not only adapt measures to local conditions, but also achieve the goal of environmental protection. For example, China has implemented the ecological function zoning system, which can increase the proportion of environmental assessment in the promotion assessment index of officials in key ecological function zones and restricted development zones, and reduce or cancel the proportion of GDP assessment, so as to provide important indicator guidance for officials to implement ecological and environmental protection.

## Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## Author contributions

SJ: Software, validation, data curation, writing—original draft. LL: Formal analysis, conceptualization, supervision, visualization. MD: Methodology, writing—review and editing, project administration, funding acquisition. ES: Conceptualization, writing—review and editing, funding acquisition.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Collaborative governance of municipal solid waste in urban agglomerations: The case of Yangtze River Delta

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As the by-product of modern life, the accelerating amount of municipal solid waste remains a wicked environmental and social problem that burdens megacities or populated cities in large. Apart from enhancing dexterity and proficiency in the intracity handling of waste, efficient and effective management needs to go beyond administrative boundaries and seek regional cooperation. Previous studies featuring Chinese regional waste management have paid scant attention to such endeavors. A SWOT analysis of the strengths and weaknesses of provinces and municipalities within the Yangtze River Delta, one of the country's top urban agglomerations, justifies the opportunities for further intra-region collaboration. This research analyzed the status quo of waste management in the region and laid out the enabling institutions, challenges, and policy suggestions for enhanced collaborations.

KEYWORDS

**collaborative governance, municipal solid waste management, SWOT analysis, urban governance, Yangtze River Delta, China**

## Introduction

Waste generation is increasing at a higher growth rate due to rapid urbanization, industrialization, and improved community living standards. This phenomenon occurred primarily in China and other emerging economies (Zhang et al., 2010; Guerrero et al., 2013). For example, national statistics show that in 2019 alone, 196 large and medium-sized cities in China reported generating about 1.8 billion tons of solid waste[1]. The increased volume of solid waste threatens the cities' sustainable development due to land scarcity issues and has thus attracted the lavish attention of local governments. The waste problem pressures megacities and large cities that usually generate more waste per capita. At the same time, efficient waste management is conducive to achieving the Carbon Peak and Carbon Neutral Targets (Li et al., 2021). The entire process of solid waste

1 Data source: 2020 Annual Report on Prevention and Control of Environmental Pollution by Solid Waste in Large and medium Cities of China.

management produces greenhouse gas emissions and affects cities' energy consumption and carbon cycle, including collection, transportation, compost, digestion, incineration, and landfill (Zhou et al., 2015). It is estimated that approximately 4,984.71 kg $CO_2$ will be produced per 8,500 ton of fully treated solid waste (Nabavi-Pelesaraei et al., 2017). Improving solid waste disposal efficiency can recover valuable recyclable materials and mitigate adverse environmental impacts (Gundupalli et al., 2017).

This study discusses the potential for collaborative governance of municipal solid waste among different provinces and municipalities in the Yangtze River Delta to achieve higher levels of management efficiency and effectiveness. The Yangtze River Delta covers 41 cities in Jiangsu, Zhejiang, and Anhui provinces and the Shanghai municipality, covering an area of 3,58,000 square kilometers. It is an essential engine for China's economic transformation and upgrading and a model for regional coordination. The region has become the sixth-largest urban agglomeration in the world (Xu and Yin, 2021). However, due to the economic growth and population increase, solid waste generation in the Yangtze River Delta is enormous and increasing annually (Zhou et al., 2022), causing severe social and environmental problems. The imbalance of solid waste production and disposal capacity among cities has affected the daily operations of cities and sometimes led to the illegal dumping of solid waste across regions. In recent years, although the central governments have repeatedly proposed to build collaborative governance institutions for solid waste in the Yangtze River Delta, local governments lack the motivation to break the limits of administrative divisions and seek cooperation. Up to now, the integrated management of solid in the Yangtze River Delta is only at the level of oral consensus. Formal institutions for the joint prevention and disposal of solid waste have not been established.

In this paper, we conduct a SWOT analysis of solid waste governance in different types of cities, i.e., central and non-central. Then, we analyze the necessity, feasibility, and current difficulties of collaborative governance in the region, exploring the policy measures and discussing enabling institutions for collaborative governance.

## Strength, weakness, opportunity, and threat analysis of waste management in different types of cities

### Waste management in the Yangtze River Delta

Cities in the Yangtze River Delta generate huge amounts of waste every year. The types of solid waste are extensive, including general industrial, hazardous, and domestic waste (Gupta et al., 2015). Industrial, hazardous, and domestic waste, respectively, account for about 9%, 17%, and 21% of the national total[2]. There are also disparities within the region. Notable features are: Waste generation of industrial solid waste in Jiangsu and Anhui Provinces accounts for a high proportion of the regional total (about 40% respectively); The output of hazardous waste in the four administrative areas is relatively small, but the regional distribution is highly uneven; Shanghai's annual domestic waste output exceeds that of Anhui, accounting for about 20 percent of the regional total (Figure 1).

There are also divergence in solid waste generation and solid waste bearing capacity per unit area among cities. Some cities are faced with severe difficulties in solid waste management due to their high waste output and high bearing strength per unit area, such as Shanghai, Nanjing, Suzhou, Ma'anshan (Figure 2).

With-region comparison of the current status of waste disposal reveals a severe imbalance between the region's solid waste generation and disposal capacities. Taking hazardous waste, for example, according to the data published by the Departments of Ecology and Environment in four administrative regions, Shanghai's hazardous waste disposal capacity is lower than its annual generation, with a gap of about 3,30,000 tons. At the same time, Anhui, Zhejiang, and Jiangsu have far more hazardous waste disposal capacity than the annual output, with a surplus capacity of about 3.42 million tons, 6.7 million tons, and 8.14 million tons, respectively (Figure 3).

Solid waste management in different cities has different characteristics (Kurniawan et al., 2021). The Yangtze River Delta urban agglomeration includes many cities, among which the difference in industrial development is large (Zhang et al., 2018; Ye et al., 2019; Xue et al., 2020), and solid waste management also presents different characteristics. Scholars divide the constituent cities of the region into central cities and surrounding cities, leading cities and other cities, or central cities and other cities judging by the industrial evolution, price spillover, and population flow and migration (Wang et al., 2020; Niu et al., 2020; Lan et al., 2021). Based on these existing typologies, this research divides central and non-central cities by comparing the cities' solid waste generation and disposal capacity. If the solid waste generation exceeds its disposal capacity, the city is considered a central city; otherwise, it is considered a non-central city. The classification of central and non-central cities is based on the current situation. They are interchangeable in the future, provided that the gaps in generation and disposal capacities change.

Central and non-central cities have advantages and disadvantages in solid waste management and face different development situations. This research provides a comparative

2 Data source: China Statistical Yearbook 2020.

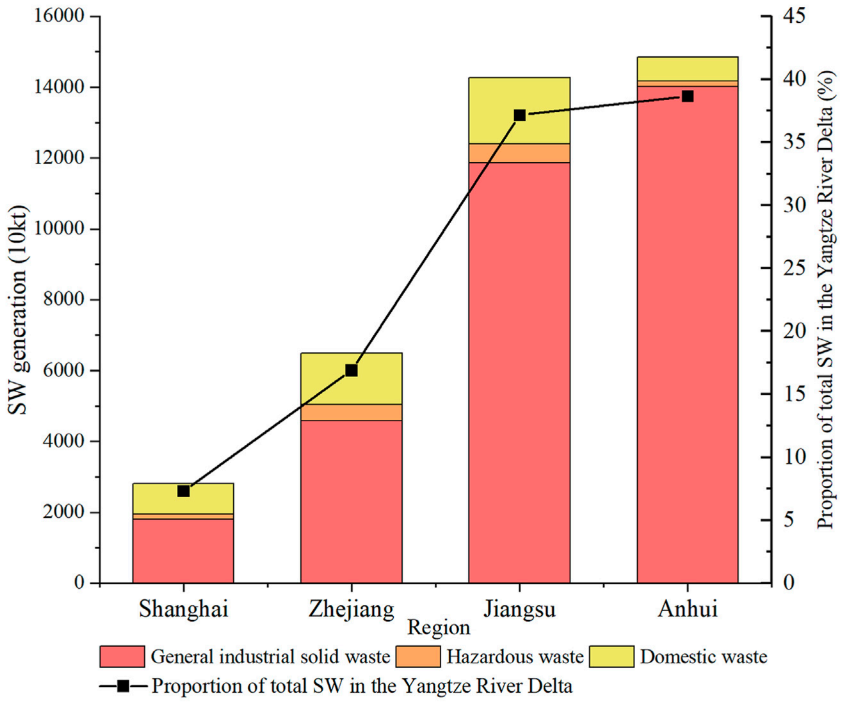


FIGURE 1
Municipal solid waste generation in different provinces or municipalities in the Yangtze River Delta in 2020.

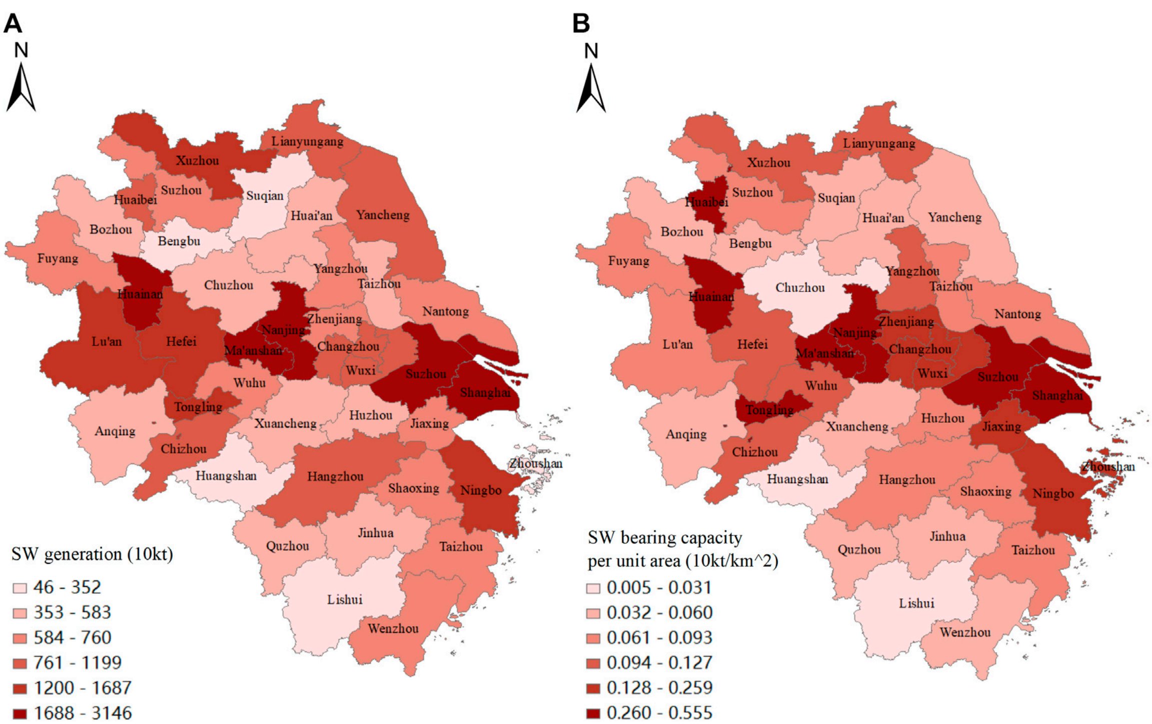


FIGURE 2
**(A)** Solid waste generation in different cities in the Yangtze River Delta in 2020. **(B)** Solid waste bearing strength per unit area in different cities in the Yangtze River Delta in 2020.

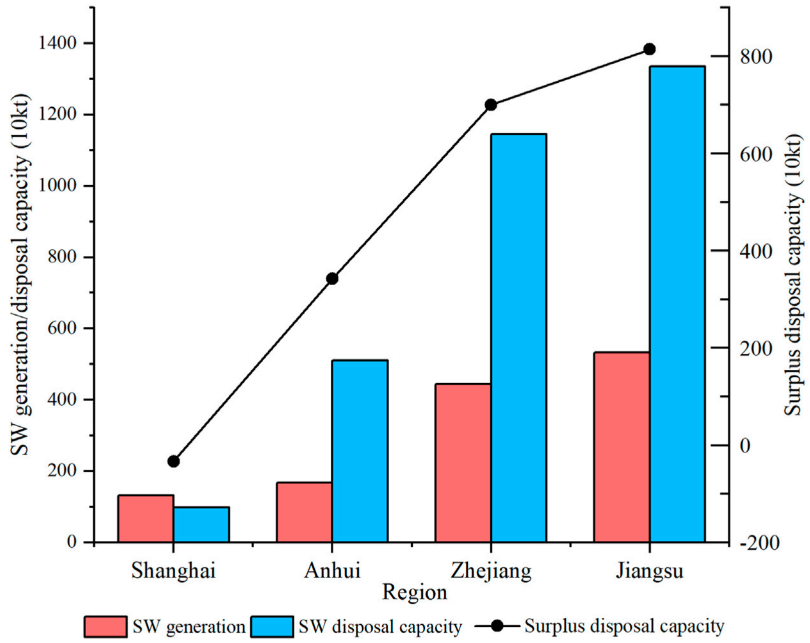


FIGURE 3
Municipal solid waste generation and disposal capacities in different provinces or municipalities in the Yangtze River Delta in 2020.

analysis using the Strength, Weakness, Opportunity, and Threat (SWOT) matrix as an analysis framework. This analysis method adopts a systematic perspective to assess the object's internal strengths and weaknesses and the external opportunities and threats to help the action subjects choose strategies (Chen et al., 2014; Phadermrod et al., 2019; Longhurst et al., 2020). Tables 1 and 2 present the analytical results of solid waste management in central and non-central cities in the Yangtze River Delta. Driven by mutual external conditions, i.e., the national zero-waste city strategy, the difference between central and non-central cities lies in internal advantages and disadvantages. Central cities are usually large cities and most probably the capital city. They share favorable policies, good governing capacity, and advanced technology, precisely the disadvantage of non-central cities. By contrast, surplus solid waste disposal capacity and vast available land in non-central cities are also lacking in central cities. The complementarity between the advantages and disadvantages is the basis of the collaborative governance of solid waste in the Yangtze River Delta.

## Towards an integrated regional waste management collaboration

The SWOT analysis indicates the region's huge potential to move towards an integrated regional waste management collaboration. Firstly, the mismatch between the disposal

TABLE 1 SWOT analysis of solid waste management in central cities.

| Strengths | Weaknesses |
|---|---|
| • Strong policy support from local governments<br>• Adequate financial support<br>• Agglomeration of leading enterprises and strong technical expertise<br>• High level of social governance and rich experience in solid waste management<br>• Pronounced garbage classification effect and smooth process of solid waste management | • High production of solid waste<br>• Limited land spaces for building new waste disposal facilities |
| **Opportunities** | **Threats** |
| • Special city status and more attention given by the upper-level government<br>• Reference of excellent experience available at home and abroad | • Strong awareness of NIMBY among residents |

TABLE 2 SWOT analysis of solid waste management in non-central cities.

| **Strengths** | **Weaknesses** |
|---|---|
| • Relatively lower production of solid waste<br>• Adequate solid waste disposal facilities<br>• Abundantly available land resources | • Immature technology and rudimental disposal methods<br>• Weak financial support for the solid waste disposal industry<br>• Lack of operational policies and standards<br>• Incomplete industrial chain and low utilization of solid waste resources<br>• Unsound solid waste classification and recovery system |
| **Opportunities** | **Threats** |
| • Driving pressure of national environmental assessment<br>• Spillover of technology and experience from central cities | • Frequent illegal dumping incidents of solid waste<br>• Residents' NIMBY awareness |

demand and disposal capacity of solid waste in different cities is crucial in establishing a cooperative disposal institution. The volume of waste generated is closely related to the types and intensities of human activities in different cities (Das et al., 2021). The utilization and disposal capacity of solid waste is also confined by multiple factors such as city scale, technological level, and land use. Therefore, making a significant adjustment in a short time is challenging. The Not In My Back Yard (NIMBY) effect has also caused significant obstacles to implementing relevant projects (He et al., 2021). This mismatch leads to pressure on solid waste disposal in central cities, while waste disposal in non-central cities has surplus capacity. The central cities have been exerting their own strength to reduce solid waste in the region. For example, Shanghai has been actively building several solid waste utilization and disposal facilities, striving to build a terminal disposal pattern of "one master and multiple points" in the municipal area, and reducing source quantity by promoting green consumption and implementing waste classification, along with some solid waste transfer outsourcing to solve the problem. However, low land use efficiency, difficulty in promoting the site selection of facilities, and unstable cooperative relationships have become new dilemmas to be faced. If trans-regional treatment of solid waste can be achieved, it can solve the urgent need of central cities. Non-central cities also benefit from the improvement of solid waste disposal and resource utilization technologies. The collaboration also boosts their industrial development and local employment.

Secondly, waste treatment and utilization involve multiple streams and require a good separation of labor. The most appropriate disposal techniques for different kinds of solid waste exhibit noticeable differences (Aich and Ghosh, 2015). It is hardly possible for any single city to include all types of disposal facilities within its jurisdiction. Cities in the Yangtze River Delta share distinctive industrial structures (Zhang et al., 2019; Zhou et al., 2021) and may deploy treatment plants based on their comparative advantage. Also, transportation to specific areas for centralized disposal will bring economies of scale for small and scattered solid waste generation spots.

Lastly, it is conducive to establishing a joint prevention and control institution of solid waste and regulating the illegal behavior of trans-regional dumping with this scientific transfer institution. In recent years, there have been several illegal dumping cases of solid waste in the region and even formed a close collaboration black industry chain, which seriously polluted the ecological environment of the dumped sites. For example, in the case of Suzhou's Wujiang district in recent years, law enforcement officers have repeatedly intercepted large quantities of industrial solid waste and construction waste shipped from the nearby Qingpu district of Shanghai and Jiashan County in Zhejiang. Despite a strong crackdown on illegal dumping in the region, the very low cost of illegal dumping has made it more prevalent. Moreover, to save operating costs, some enterprises hand over solid waste to unqualified companies for disposal or directly dump it in other jurisdictions. As a result, some inter-provincial and inter-municipal adjacent areas have become vulnerable areas of illegal dumping.

## Feasibility assessment

Cities in the region are very much prepared for such joint action. Firstly, laws and regulations in both environmental protection and regional documents of the Yangtze River Delta have proposed to promote the establishment of a trans-regional solid waste disposal institution. Specific provisions can be found in the Solid Waste Law, the Plan for the Integrated Development of the Yangtze River Delta, and documents of the Ministry of Environmental Protection and other ministries. These documents ensure its implementation through legality and authority.

Secondly, the experience of joint control of air pollution and river basin pollution in the Yangtze River Delta provides a cooperative foundation for the collaborative governance of solid waste. The region has made some valuable explorations on air and water pollution under the mode of trans-regional and multi-entity participation (Hu et al., 2014; Wang et al., 2020). In this process, some scientific trans-regional cooperation measures have also been introduced, including leaders' joint meeting systems, regional environmental cooperation institutions, regional environmental cooperation agreements, and horizontal ecological compensation mechanisms. Although there are differences in specific management methods and technical means between solid waste management and the other two, the core problem of collaborative governance of municipal solid waste is still how to go beyond administrative boundaries and achieve cross-regional cooperation. Therefore, the experiences in joint control of air pollution and river basin pollution could provide references for the collaborative governance of solid waste. Meanwhile, the regular consultation and mutual assistance relationship established by local ecological and environmental protection departments in the long-term cooperation will also benefit regional waste management.

Finally, collaborative regional waste management has proved successful in other urban agglomerations globally. For example, Germany's Rhin-Ruhr urban agglomeration has established a waste exchange system, which summarizes the trading intention information of different regions to meet the demand and supply of solid waste in different markets. The Tokyo metropolitan area has developed an efficient solid waste disposal mode: The surrounding areas of Tokyo have formed a clear industrial chain of solid waste disposal, which jointly eliminates the solid waste generated in the region through the division of labor. There are also quite a few attempts domestically. For example, Sichuan and Chongqing have established a safelist for the trans-regional transfer of hazardous waste, which has improved the disposal capacity of hazardous waste in both places. Guangdong and Macao have also set up environmental protection groups to solve Macao's environmental problems.

However, despite those favoring factors, there are also challenges that policy designers might consider. The transregional disposal of solid waste brings about the transfer of environmental pollution and management risk. Local government leaders face the pressure of the increasingly stringent target responsibility system and performance evaluation system in environmental protection. The jurisdiction's environmental protection situation is closely related to their promotion (Wu et al., 2018), which will unavoidably affect their policy choices. This exacerbates the mismatch between supply and demand for solid waste disposal in the Yangtze River Delta: Governments in central cities such as Shanghai and Hangzhou are eager to release excess solid waste from their jurisdictions; Northern Anhui, Northern Jiangsu, and other places have vast inland hinterland and idle disposal capacity, but they are not willing to receive solid waste from other administrative areas. Administrative barriers make it difficult to form a consensus on bilateral cooperation between cities. Meanwhile, there is a big gap between the actual cooperation situation and the policy assumption. Even though the restrictions on the trans-regional transfer of solid waste are gradually relaxed in the recently issued new policies, the local government's mindset has not changed in time, which is reflected in the fact that the approval and inspection process is complicated and time-consuming.

## Actionable recommendations

Based on the analysis above, it is essential to establish institutions for the collaborative governance of solid waste in the Yangtze River Delta. Central cities have the opportunity to transfer the solid waste that cannot be disposed of to the non-central cities and the latter would get compensations in various forms. However, at the same time, we should choose the most efficient solid waste flow direction according to the structural differences of solid waste output and types in different cities and if necessary, relocate the disposal facilities or transfer advanced technologies among different cities. We have offered four actionable recommendations that may facilitate the collaborative governance of waste in the Yangtze River Delta.

Firstly, we need to strengthen the top-level design to provide organizational and institutional guarantees for the cooperative governance of solid waste. Under the background of the integrated development of the Yangtze River Delta, local governments should strengthen environmental cooperation and promote regional solid waste collaborative management by formulating regional policies, laws, and regulations. The Yangtze River Delta should also establish a robust organizational institution with precise functions and smooth operation to coordinate the work of solid waste cooperative management, which should cover all departments related to solid waste management in each city. Based on full consultation, each city's common goals and interests should be clarified, and regional cooperation agreements on solid waste management should be reached. At the same time, the Yangtze River Delta should establish a positive expert advice system. Domestic and overseas experts should be invited to conduct investigations and studies to provide decision-making references for government cooperation from a professional perspective.

Secondly, a reasonable ecological compensation institution needs to be developed. Ecological compensation is an essential means to adjust the relationship between stakeholders of environmental protection and has been widely used in many fields of environmental governance (Pan et al., 2017; Fu et al., 2018). The trans-regional disposal of solid waste is not only the market behavior of waste producers and disposers but also closely related to local environmental pollution and governance risks. Therefore, in addition to paying the specific disposal cost according to the market principle, the production government should also pay ecological compensation fees to the disposal government for the adverse external effects such as exacerbating solid waste pollution, occupying the ecological environment resources, and causing NIMBY conflicts. Cities should establish a stable cooperative relationship. Governments should agree on compensation standards in advance based on careful consideration of short-term benefits and long-term development. They can use diversified compensation means, including special fund compensation, project compensation, and technology compensation. For the regional transfer of large-scale or multiple-type solid waste, specific cooperation matters can be negotiated case by case.

Thirdly, the local governments need to attach importance to the role of enterprises and promote technological innovation and industrialization development in the solid waste industry. Enterprises play the role of responsible persons (Yang et al., 2020) or contractors (Corvellec et al., 2012) in environmental protection and pollution prevention. Their market behaviors affect the quality and efficiency of solid waste disposal. Therefore, the government should promote the formation of a healthy market competition environment, encourage enterprises to improve their technical level and explore a more efficient business model of solid waste co-management. Local governments should overcome the dependence on low labor and environmental cost of small workshops, actively introduce or cultivate leading enterprises in the field of solid waste disposal by building industrial parks, strive to achieve breakthroughs in core technologies, and eventually improve the total level of solid waste disposal in the Yangtze River Delta. At the same time, it should also be noted that technological innovation may change the structure of coordinated solid waste management in the Yangtze River Delta and then timely change the disposal flow.

Lastly, both central and local governments need to take multiple measures to ensure the integration of solid waste governance with other industries. The suitable disposal of solid waste is a complex system involving multiple highly correlated processes. Therefore, unified standards and rules should be formulated at the beginning to ensure a smooth transition during the processes. Local governments could invest and build them proportionally for the site selection and construction of solid waste disposal facilities. They can also learn from the experience of the Superfund Law of the United States to create a green investment and financing system to ensure its operation in a market-oriented way. When COVID-19 has strongly impacted all industries (Donthu and Gustafsson, 2020), it is more important to give full play to the solid waste disposal industry's positive role in boosting the economy and stimulating employment. By extending the industrial chain, the solid waste raw materials after resource disposal can be put into related industries for use, and ecotype and park-type resource recycling bases can be built to drive the industrial development of surrounding areas.

## Conclusion

Municipal solid waste management is becoming an increasingly complicated task in large cities in the Yangtze River Delta. The SWOT analysis provides the legitimacy for formulating regional collaborative governance institutions on waste management. Potential future stances include the transformation in the legal (a safelist system for illegal dumping), political (an integrated regional waste management strategy), economical (a formal ecological compensation system for extra-territorial waste disposal), and technological (synergizing waste management with other emerging industries) aspects. The case has also sought to serve as an instructive example to other urban agglomerations during the process of urbanization.

## Author contributions

JZ: conceptualization, writing-review and editing, funding acquisition, supervision. MZ: methodology, investigation, writing original draft.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Transformation and development of resource-based cities in China: A review and bibliometric analysis

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With increasingly serious environmental and resource problems, resource-based cities have attracted unprecedented attention at home and abroad. In recent years, resource-based cities have become a hot research topic that has produced fruitful results. However, few articles have comprehensively and systematically reviewed the research on resource-based cities, which makes it difficult to carry out further research. This study introduces the influencing factors of the urban transformation of resource-based cities, the path of urban transformation, and the evaluation index system of urban transformation in detail. At the same time, a total of 2,182 articles related to resource-based cities in the CNKI and WOS from 2002 to 2022 were taken as the research objects. CiteSpace software was used to conduct statistical analysis of publication dates, journals of publication, institutions, and highly cited literature. Using the co-occurrence network of literature keywords and the analysis of emergent words, the research status of resource-based cities at home and abroad is visually analyzed. It is found that Chinese universities attach the most importance to research on resource-based cities. Chinese-language journals focus on urban and economic transformation, while English-language journals focus on sustainable development and the circular economy, which are quite different. The overall research content of Chinese journals is scattered, the co-occurrence ability of keywords is weak, and the duration of hot research topics is short. In contrast, the overall research trend of English-language journals is more concentrated, the key words' emergence intensity is high, and the duration is long. This study aims to systematically sort out the theories and research related to resource-based city development in China and internationally, clarify the key issues of resource-based city research and the shortcomings of existing research, and put forward feasible suggestions for future research.

KEYWORDS

**resource-based city, bibliometrics, urban transformation, sustainable development, visualization**

# 1 Introduction

Resource-based cities are a typical kind of city in China's urban system. Their development mainly depends on the exploitation and processing of nonrenewable resources such as minerals, forests, and oil in the region. Resource-based cities have played a vital role in China's economic development. According to the National Sustainable Development Plan for Resource-Based Cities (2013–2020) issued by the State Council in 2013, 262 resource-based cities were identified, accounting for 40% of the total number of cities in China, including 126 prefecture-level administrative regions. These resource-based cities were further divided into four types: growth (31), mature (141), declining (67), and regeneration (23). The principal resource types of these resource-based cities include coal, metal, oil, and forestry resources. Cities with coal as the main resource are mainly distributed in central China, such as Datong in Shanxi Province; resource-based cities with metal as the main resource are mainly distributed in northwest China, such as Baiyin in Gansu Province and Tongchuan in Shanxi Province; and oil and forestry resources are scattered. With the continuous exploitation of resources, the recoverable reserves of some cities have reached 70% of the recoverable reserves, which has a huge impact on the local environment, population, and economy. These cities have become resource-exhausted cities. In 2008, 2009, and 2012, China identified 69 resource-exhausted cities in three batches, including 37 coal cities, 14 nonferrous metal cities, 6 ferrous metal cities, 3 oil cities, and 9 other cities, involving a population of 154 million.

For many years, the extensive development mode of resource-based cities in China inevitably faced a series of problems, such as gradual depletion of resources, a single industrial structure, an abnormal economic structure, and serious damage to the ecological environment (Yu et al., 2015; He et al., 2017). Miachel (2015) showed that the excessive dependence on natural resources makes resource-based cities depend on a single industrial structure; that is, the secondary industry accounts for too much of the economy. The lock-in and crowding-out effect caused by such an industrial structure not only excludes the expansion of the manufacturing industry but also restricts the development of primary and tertiary industries (Fan and Zhang, 2021). Due to the large scale of operations, low technical level, and short industrial chain, economic accumulation is mainly based on the exploitation of a large number of raw materials. When resource stocks fall to a certain level, production declines, which further affects the local economy. Resource-based cities gradually lose their investment attraction in the process of resource depletion and economic growth slowdown, which further hinders economic development (Takatsuka et al., 2015; Liu and Meng., 2018). This phenomenon is known as the "Dutch disease" or the "resource curse." Shao and Qi (2009) explained the negative relationship between resource development and economic growth through China's interprovincial panel data from 1991 to 2006, proving the phenomenon of a serious resource curse in China.

Urban shrinkage is also an important feature of resource-based cities, which is manifested by population loss caused by low fertility rates, aging, and out-migration (He, 2014; Long et al., 2015). Due to technological change and product market transfer, resource-based industries will lose their competitiveness in the market. Another cause of the contraction of resource-based cities is the weak connection between resource-based industries and other businesses, such as knowledge and innovation transfer, which isolates resource-based cities from global knowledge networks (He et al., 2017).

Promoting the industrial transformation and upgrading of China's resource-based cities is a path to overcoming the historical fate of mine exhaustion and urban decline and is also an important part of guiding the transformation of China's economic development from high-speed growth to high-quality growth. Therefore, it has become urgent to promote the industrial transformation of resource-based cities and accelerate the transformation of the new economic development mode. Research on resource-based cities covers a wide range and involves many fields, which is of great significance for national development. The purpose of this study is to clarify the existing research context and hotspots of resource-based cities to help researchers carry out more targeted research on resource-based cities.

In recent years, discussions on the influencing factors of the industrial transformation of resource-based cities have been intensified. It has always been the focus of government and academic circles to help resource-based cities escape the predicament of the "resource curse" and undergo urban transformation. Van der Ploeg (2011) pointed out that resource-based cities' excessive dependence on resources creates rigid economic structures, underlying the resource curse. Bai et al. (2014) found that the adjustment of the industrial structure, attention to scientific education, and development of the ecological economy are conducive to the transformation of resource-based cities. Shao and Yang (2014) showed that the lack of human capital is an important factor hindering the sustainable development of resource-based cities. The government plays an important role in the process of urban transformation and is a key factor in the ability of a region to reduce or eliminate the negative impact of resource dependence (He et al., 2017). Local governments will be subject to many constraints in the process of urban transformation, which will lead to large externalities in the process of urban transformation; for example, the financial pressure on local governments will increase the emission of air pollutants (Hui et al., 2022). The transformation efficiency of resource-exhausted cities depends on local political incentives. Local government officials play an important role in the process of urban transformation (Zhang et al., 2018). Government policies can promote the industrial transformation of resource-based cities through economic simplification and diversification (Li et al., 2020).

Most studies on the transformation of resource-based cities and resource-depleted cities take specific cities as cases for targeted analysis. For example, Zhu (2013) studied the Wan Sheng district of Chongqing and found that resource-depleted cities should focus on geological structures and groundwater hazards in agricultural transformation. Based on the carbon emission data of Xuzhou, Jiangsu Province, Guo et al. (2019) showed that there is a decoupling phenomenon between the urbanization transformation of resource-depleted cities and the environment. Yin (2020) studied the ecological transformation of six resource-depleted cities in Jilin Province and found that the level of science and technology plays a role in promoting ecological efficiency. In addition, education investment (Zeng et al., 2016), trade structure, and the tax system (Li et al., 2018) have an impact on the transformation of resource-exhausted cities. Wang et al. (2022) researched Benxi (a typical mineral resource-based city in China) to understand the economic and environmental performance and existing problems in the process of local transformation and compared it with the successful transformation model of the global mineral resource-based city.

Urban transformation can be divided into two main approaches: active adaptation to contraction and growth-oriented sustainable transformation. China's urban transformation is mainly led by multilevel governments (Li et al., 2015). The central government makes special annual transfer payments to resource-exhausted cities to help them carry out transformation strategies. He et al. (2017) summarized three strategies for the sustainable transformation of foreign mining cities, namely, industrial substitution, industrial chain extension, and a combination of the first two. For example, transforming mining heritage into tourism destinations is a popular industrial alternative strategy in many post-mining cities worldwide (Armis and Kanegae, 2020). Yu et al. (2016) identified the tension between the difficulties in industrial transformation and environmental policies and the limited impact of the circular economy in the process of sustainable transformation.

The transformation path of resource-based cities has always been the focus of both Chinese and international scholars (Sliuzas et al., 2015; Huang et al., 2017). Li et al. (2020) concluded that the transformation path has three types: industrial substitution mode, industrial chain extension, and a combination of the first two. Regions such as Lorraine (France), Kitakyushu (Japan), and Pittsburgh (United States) mainly applied the industrial substitution model (Liu, 2013). In Pittsburgh, the industrial structure changed from heavy industry to a high-end service economy, with an emphasis on health care and higher education. Houston (United States) presents a restructuring pattern characterized by the extension of the industrial chain. By developing its machinery, cement, steel, electric power, transportation, and paper industries, Houston has gradually been transformed from an oil-based city into an integrated technology city, and NASA's location in Houston has facilitated high-tech industries related to aerospace, such as electronics, precision machinery, and instruments. Zaozhuang (China) also adopted the industry chain extension transformation mode, relying on scientific and technological progress and innovation, and promoted the development of greater benefits and added value of science and technology industries that rely on resources and geographical advantages to develop new energy sources, new building materials, ecological tourism, and other alternative industries to adjust and optimize the industrial structure. By accelerating the construction of infrastructure, optimizing the urban spatial pattern, creating a good ecological environment, and improving the functional level of the city, an appropriate environment was created for urban transformation (Wang and Li, 2012). Ruhr (Germany) is a good example of the third model, which combines the first two types. In the early stages, the Ruhr region adopted the method of industrial chain extension and changed the leading industry from mining to processing. Later, it began efforts to develop new industries and diversify and enrich its economic structure.

Jiao et al. (2021) pointed out that both industrial substitution and industrial extension should follow several basic principles. First, according to the profit principle, new industries need to be high-tech or market-oriented to ensure high economic profits. The second is the linkage principle, according to which a new industry should have extensive and firm connections with other industries to form industrial agglomerations and create new sectors (Zhu and Qiang, 2012). Connectivity between different regions can improve industrial dexterity and proficiency (Zhang and Zhu, 2022). The third is the adaptation principle, according to which industry should be competitive and make full use of various local resources to adapt to the actual and objective conditions at the local and regional levels. Last, based on the environmentally friendly principle, development must be environmentally friendly, consume little energy or resources, and help ease the local pressure of resource extraction.

The development of a circular economy is also an important link in the path of urban economic transformation (Andersen, 2007; Zhu et al., 2010; Mathews and Tan, 2011). The circular economy is a closed-loop process that transforms resource processing waste into inputs to another process. Since the circular economy promotes more efficient use of resources, it should be widely applied in resource-based cities to reduce resource extraction, improve resource utilization, and reduce waste disposal and waste stock. The traditional resource-based urban development model that relies on extensive resource development to realize industrialization and modernization is unsustainable. By adopting energy-efficient and clean technologies, the circular economy is an effective way to address these challenges (Fan and Zhang, 2021).

Methods to evaluate the effects of industrial transformation in resource-based cities can be roughly divided into three categories. The first is the direct evaluation method, which uses one or more indicators to evaluate the development of urban industries. Guo et al. (2016) used four indicators to analyze the impact of technological progress on the transformation of China's energy consumption structure. Chen et al. (2018) evaluated the industrial transformation efficiency of resource-based cities in Shanxi Province from three dimensions: economic, social, and environmental. The second is data envelopment analysis (DEA), which is commonly used to estimate efficiency. Sun et al. (2012) used the DEA method to study the differences in urban efficiency among different types of resources. Li and Dewan (2017) used it to measure the efficiency of resource-based cities, analyze the differences in efficiency levels among cities, and identify the main determinants. Zhang et al. (2020) used data envelopment analysis with a slack-based model (DEA-SBM) to evaluate the efficiency of China's green transition. On this basis, Zhao et al. (2021) used a model based on system dynamics to evaluate the transformation effect in Jiaozuo city. The third is a comprehensive evaluation method that identifies the characteristics of the evaluation object through the system. Yu et al. (2005) constructed an index system including resources, economy, society, environment, and other factors to evaluate the sustainable development of mineral resources in Huangshi, China. Chen et al. (2018) evaluated the industrial transformation and upgrading level of six resource-based cities in Shanxi Province from 2001 to 2015 using the improved TOPSIS method and sequential weighting method.

At present, there are few studies that have systematically analyzed the development of resource-based cities in China. With the help of CiteSpace as a bibliometric analysis tool, this study sorted out the publishing trends, journals, authors' relevant information, and keywords in the field of resource-based city transformation and development in the past 20 years (2002–2022), summarized their development context and research hotspots, and then provided guidance for the future construction of resource-based cities in China. The structure of the study is as follows. The first section expounds the mainstream hot issues in the current research on resource-based cities. The second section explains the data and methods used in the research, the third section uses graphs to show the analysis results, the fourth section shows the correlation between the studies through visualization, and the last section summarizes the shortcomings of the existing research and identifies future research prospects.

# 2 Data and methods

## 2.1 Data

In this study, the China National Knowledge Infrastructure (CNKI) and Web of Science (WOS) databases were used as the main data sources. In CNKI, "resource-based city" and "resource-exhausted city" were used as the search terms. The search scope was Peking University core and CSSCI, the time range was 2002–2022, and the deadline was 9 June 2022. A total of 1,750 Chinese articles were retrieved, and 18 articles without authors were manually eliminated to obtain 1,732 valid Chinese articles. In the Web of Science database, the search formula "TS = resource-based cities or TS = resource-exhausted cities" was constructed. The search range was the core collection, the time range was 2002–2022, and the deadline was 9 June 2022. Finally, 450 valid English-language studies were retrieved, of which the title, abstract, keywords, author, reference, and other full records of the search results were exported to construct the research dataset.

## 2.2 Methods

Bibliometric analysis combines visualization, graphics, and scientometrics to research evolving scientific knowledge (Niu et al., 2014). It is used to quantitatively assess the quality of research results, research trends, and tacit knowledge structures to gain a comprehensive and in-depth understanding of the academic literature (Chen, 2006). Since keywords indicate the central content of research, high-frequency co-occurrence keywords reflect popular research topics, which can be further aggregated into higher levels of abstraction. The frequency changes of keywords in a given period of time reflect hot spots. The importance of keywords not only depends on their high frequency but also depends on the intensity of their frequency change in a given period. The rapid growth of keyword frequency in a specific period reflects that the research topic may become a research hotspot and new trend (Lin et al., 2015). These keywords, known as burst terms, reflect a sudden increase in research interest and buzz. Therefore, the detection of keywords with high frequency and rapid frequency change in a specific period reveals different aspects of research trends. The former indicates an important research topic, while the latter reflects a new research trend.

This study mainly adopted the bibliometric analysis method and content analysis method, using the visual analysis software CiteSpace developed by Dr. Chen to conduct in-depth analysis and research on the retrieved articles on resource-based cities. Bibliometric analysis objectively evaluates the research history, current state, and future development of a research field among different countries, regions, scientific research institutions, and scholars based on quantitative research methods such as mathematical statistics. The visual analysis method can explain the internal relationship of different studies more intuitively to predict the trend of future research. Content analysis is a research method that effectively combines qualitative and quantitative analyses. It conducts statistical analysis of the content of the research object to draw qualitative conclusions. By combining the aforementioned

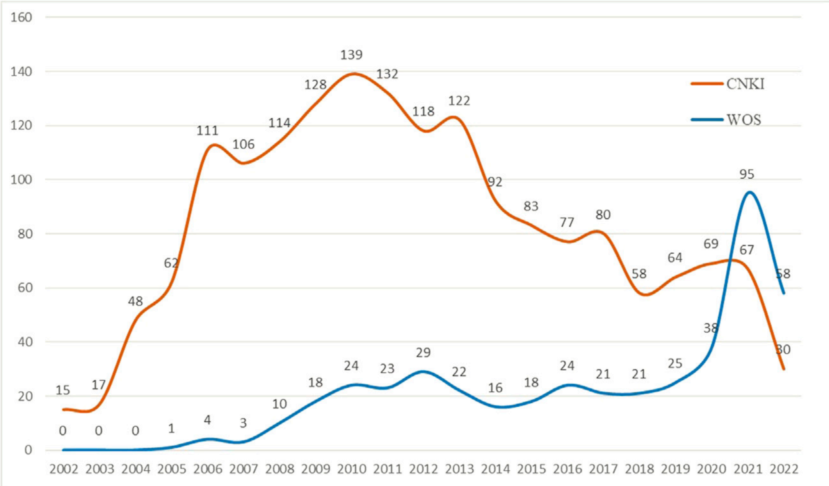


FIGURE 1
The number of articles in resource-based cities changes with time.

TABLE 1 Journal of resource-based city research (top 10).

| Rank | Journal (CNKI) | Number of articles | Journal (WOS) | Number of articles |
|---|---|---|---|---|
| 1 | China Population Resources and Environment | 33 | Sustainability | 31 |
| 2 | Economic Geography | 28 | Advanced Materials Research | 19 |
| 3 | Journal of Natural Resources | 23 | Journal of Cleaner Production | 16 |
| 4 | Geographical Studies | 16 | Resources Policy | 15 |
| 5 | Geographical Sciences | 16 | Environmental Science and Pollution Research | 14 |
| 6 | Reform | 11 | Applied Mechanics and Materials | 11 |
| 7 | Journal of Ecology | 9 | Frontiers in Environmental Science | 8 |
| 8 | Chinese Soft Science | 6 | Advances in Social Science Education and Humanities Research | 7 |
| 9 | Acta Geographica Sinica | 5 | Chinese Geographical Science | 7 |
| 10 | Chinese Land Science | 5 | Ecological Indicators | 7 |

three methods and referring to the relevant practices of Wei et al. (2014) and Li et al. (2014), the literature on resource-based cities is analyzed to objectively and scientifically identify the status of research and development trends related to resource-based cities in China and around the world.

# 3 Dynamic data analysis

## 3.1 Published dating analysis

When the bibliometric method is used to analyze the development process of a research field, according to the growth and aging laws of the literature, annual statistical analysis of the number of relevant articles reveals the current development status of the field and predicts future research prospects and development trends. In the early stages of research studies in a certain field, due to the lack of relevant theories and foundations, the number of relevant articles published is low. As in-depth research studies increases, the number of scholars and institutions entering the field of research studies grows. As a result, the number of articles published grows rapidly, and after the research becomes mature, the number of articles published tends to be stable. Figure 1 is based on the analysis of the chronological distribution of 1,732 Chinese and 450 English articles retrieved from CNKI and WOS.

In Figure 1, the horizontal axis is the publication date, and the vertical axis is the publication volume. The red curve represents

TABLE 2 Number of publications published by research institutions in resource-based cities (top 10).

| Rank | Institution (CNKI) | Number of articles | Institution (WOS) | Number of articles |
|---|---|---|---|---|
| 1 | Northeast Normal University | 60 | Chinese Academic of Science | 38 |
| 2 | China University of Mining and Technology | 51 | China University of Mining and Technology | 35 |
| 3 | China University of Geosciences (Beijing) | 41 | China University of Geosciences | 29 |
| 4 | Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences | 40 | University of Chinese Academy of Sciences | 17 |
| 5 | Peking University | 35 | Wuhan University | 17 |
| 6 | Lanzhou University | 35 | Ministry of Natural Resources | 10 |
| 7 | China University of Geosciences | 32 | Shanghai University of Finance and Economics | 10 |
| 8 | Jilin University | 29 | Jiangsu Normal University | 9 |
| 9 | Sichuan University | 26 | Northeast Petroleum University | 9 |
| 10 | Henan Polytechnic University | 26 | China University of Mining and Technology (Beijing) | 8 |

TABLE 3 Highly cited Chinese studies on resource-based cities (top 10).

| Rank | Title (CNKI) | Source publication | Publish time | Citation times |
|---|---|---|---|---|
| 1 | Definition and classification of resource-based cities in my country | Macroeconomics | 2002.11 | 520 |
| 2 | Research on environmental regulation, resource endowment, and urban industrial transformation: a comparative analysis based on resource-based cities and non-resource-based cities | Economic Research Journal | 2018.11 | 363 |
| 3 | Problems and strategic exploration of economic transformation of resource-based cities in China | China Population, Resources and Environment | 2007.01 | 272 |
| 4 | A review of the research progress on the development of resource-based cities in my country | Urban Development Studies | 2006.05 | 228 |
| 5 | Empirical analysis of influencing factors of sustainable development of resource-based cities | China Population, Resources and Environment | 2014.07 | 227 |
| 6 | Efficiency and changes of Chinese resource-based cities based on DEA model | Geographical Research | 2010.12 | 222 |
| 7 | Analysis on the current situation and countermeasures of sustainable development of resource-based cities in China | Journal of Central China Normal University (Humanities and Social Sciences) | 2002.04 | 222 |
| 8 | Practice, theory, and enlightenment of industrial transformation of foreign resource-based cities | Research on Financial and Economic Issues | 2005.12 | 218 |
| 9 | Analysis of sunk cost and transformation of resource-based cities | China Industrial Economics | 2004.06 | 201 |
| 10 | Urban space development model of intensive land use | Urban Planning Forum | 2006.01 | 187 |

the variation trend of the volume of Chinese publications in CNKI, and the blue curve represents the variation trend of English publication volume in WOS. The number of Chinese documents published in the past 20 years can be divided into three stages: the rapid rise stage from 2002 to 2006, the high fluctuation stage from 2007 to 2013, and the mature development stage from 2014 to the present. The number of articles published in the rapid rise stage increased annually, and the research content was mainly focused on the transformation of a single city or a city with the same resource type. At the stage of high fluctuation, the state began to gradually identify resource-exhausted cities and issued special transfer payments to support urban transformation. The research content during this stage was carried out around the transformation of resource-exhausted cities and the evaluation of resource-based cities, which was the golden period in the field. The number of publications in the mature development stage began to decline. Due to the accumulation of historical data, the focus of research

TABLE 4 Highly cited English studies on resource-based cities (top 10).

| Rank | Title (WOS) | Source publication | Publish time | Citation times |
|---|---|---|---|---|
| 1 | The impact of low-carbon city construction on ecological efficiency: Empirical evidence from quasi-natural experiments | Resources Conservation and Recycling | 2020.06 | 104 |
| 2 | Effects of urbanization on ecosystem service values in a mineral resource-based city | Habitat International | 2015.04 | 104 |
| 3 | Shrinking cities and resource-based economy: The economic restructuring in China's mining cities | Cities | 2017.02 | 102 |
| 4 | Analyzing and modeling land use land cover change (LUCC) in the Daqing City, China | Applied Geography | 2011.04 | 90 |
| 5 | Economic transition policies in Chinese resource-based cities: An overview of government efforts | Energy Policy | 2013.04 | 89 |
| 6 | Heterogeneous green innovations and carbon emission performance: Evidence at China's city level | Energy Economics | 2021.07 | 77 |
| 7 | Research on sustainable development of resource-based cities based on the DEA approach: A case study of Jiaozuo, China | Mathematical Problems in Engineering | 2016.01 | 66 |
| 8 | Energy structure, digital economy, and carbon emissions: Evidence from China | Environmental Science and Pollution Research | 2021.12 | 64 |
| 9 | The determinants of urban sustainability in Chinese resource-based cities: A panel quantile regression approach | Science of the Total Environment | 2019.10 | 64 |
| 10 | Fiscal spending and green economic growth: Evidence from China | Energy Economics | 2020.01 | 59 |

at this stage turned to the impact of policies on the transformation of resource-based cities. At the same time, the number of articles published in English started in 2005 and slowly increased until 2008. From 2009 to 2018, the number of articles remained stable, and starting in 2019, the number of articles increased sharply, with an increasing number of articles using quantitative methods to study the transformation of resource-based cities began to emerge.

## 3.2 Analysis of journals

A statistical study of the journals that published studies on resource-based cities illustrates the importance of different journals for the issue of resource-based cities, allowing scholars to identify the journals with the greatest number of published articles. In Table 1, we summarize the top 10 journals with the largest number of resource-based city articles in CNKI and WOS. From 2002 to 2022, the journal with the largest number of articles on resource-based cities in CNKI was China Population Resources and Environment, with a total of 33 articles. The journal with the second largest number was Economic Geography, with a total of 28 articles. The third was the Journal of Natural Resources, with a total of 23 articles. From the top three journals, journals with themes of resources, environment, and economy are more willing to accept articles on resource-based cities. From 2002 to 2022, the journal with the largest number of articles on resource-based cities in WOS was Sustainability (31 articles), the second was Advanced Materials Research (19 articles), and the third was Journal of Cleaner Production (16 articles), and their themes are mainly around sustainability, materials, clean production, and environmental science. Compared with the journals in CNKI and WOS, the Chinese research articles paid more attention to the economic development of resource-based cities, while the English-language research articles paid more attention to the sustainable development of resource-based cities. At the same time, in terms of the number of articles published, Chinese journals

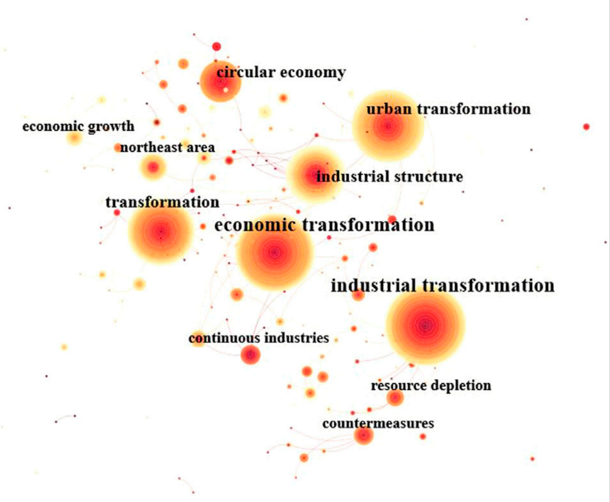


FIGURE 2
Co-occurrence network of high-frequency keywords in the CNKI literature.

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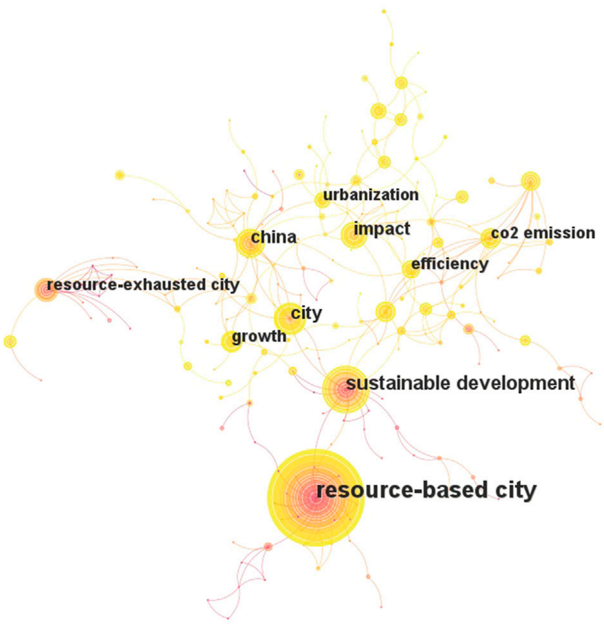


FIGURE 3
High-frequency keyword co-occurrence network in the WOS literature.

showed a trend of polarized development. The top few journals include the vast majority of articles, while the journals after the seventh place have only a small number of articles with no obvious difference between them. In contrast, the development of English-language journals is relatively balanced, with an equitable number of publications across journals, with the exception of sustainability.

## 3.3 Analysis of the issuing agency

Statistical analysis can also help readers understand where the main institutions that produce research on resource-based cities are distributed. As seen in Table 2, the institution with the largest number of publications in Chinese journals is Northeast Normal University, which has published a total of 60 articles on resource-based cities from 2002 to 2022. The second is the China University of Mining and Technology. Other institutions, such as the China University of Geosciences (Beijing), the Institute of Geographical Sciences and Natural Resources Research, the Chinese Academy of Sciences, Peking University, the Commission University, and the China University of Geosciences, also showed strong research capabilities, with more than 20 articles published in each institution. Most of them specialize in humanities and social sciences. From 2002 to 2022, the Chinese Academic of Science and the China University of Mining and Technology published 38 and 35 English-language articles on resource-based cities, respectively. The China University of Geosciences, the University of the Chinese Academy of Sciences, and Wuhan University each have more than 15 articles published. A comparison of the published institutions in both Chinese and English shows that the research on resource-based cities is mostly conducted by Chinese scientific research institutions, and no foreign scientific research institutions are listed. This shows the scientific research strength of China's institutions and indicates that China attaches great importance to the research on resource-based cities.

## 3.4 Analysis of highly cited literature

A statistical analysis of highly cited literature helps readers quickly understand the important literature in this field. Table 3 and Table 4 show the top 10 most highly cited Chinese and English articles on the theme of resource-based cities, respectively. In the Chinese literature, as of 9 June 2022, the article "Definition and Classification of Resource-based Cities in My Country" has been cited 520 times total. It defined resource-based cities for the first time, and it established the principles of determining resource-based cities in China and the classification of resource-based cities, which laid the foundation for the study of resource-based cities. The second most cited is "Research on Environmental Regulation, Resource Endowment, and Urban Industrial Transformation: A Comparative Analysis Based on Resource-based Cities and Non-resource-based Cities," published in the Economic Research Journal in 2018. This article explains that industrial transformation is the key to the transformation of resource-based cities and analyzes the influence mechanisms of environmental regulation and resource endowment on industrial transformation (Li and Zou, 2018). In just 4 years, the citation volume of this article climbed to the second place, which indicates its significance for the study of resource-based cities and to be of referenced and studied by scholars in related fields. Until 9 June 2022, "The Impact of Low-Carbon City Construction on Ecological Efficiency: Empirical Evidence from Quasi-Natural Experiments," published in 2020, topped the list with 104 citations in the English literature. The heterogeneity analysis between resource-based cities and non-resource-based cities indicated that cities with high natural resource dependence tend to develop resource-based industries and fall into the "resource curse," which makes the effects of low-carbon city pilot policies not obvious (Song et al., 2020). The article "Effects of Urbanization on Ecosystem Service Values in a Mineral Resource-based City," published in 2015, also topped the list. Huaibei (a mining resource-based city in China) is taken as an example to illustrate the impact of the urbanization process on resource-based ecological service systems and residents' quality of life (Wan et al., 2015). A comparison of the citations of Chinese and English literature indicates that the Chinese literature has obvious advantages, that it is more macroscopic and provides a better reference value for research on resource-based cities.

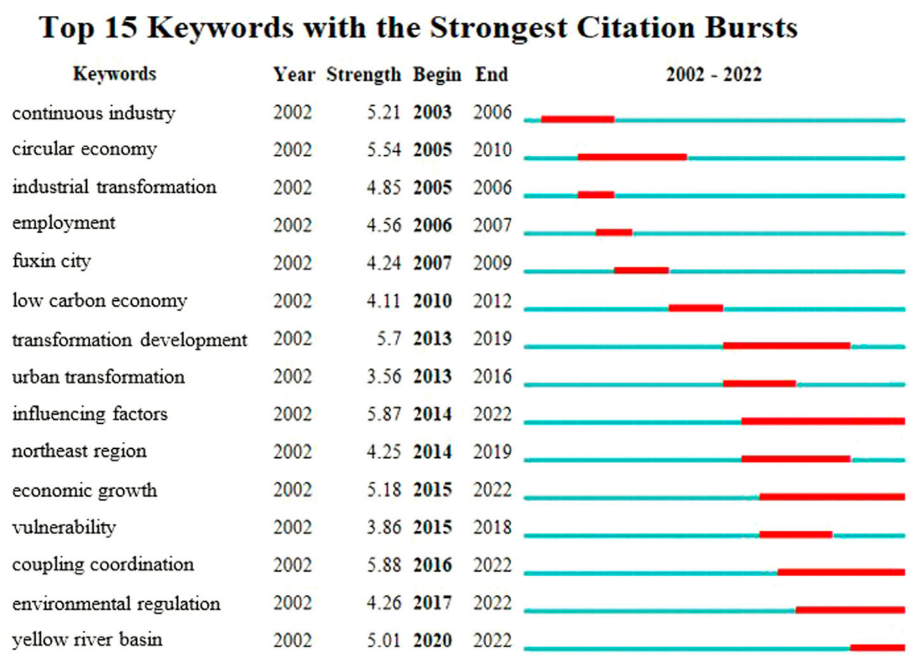


FIGURE 4
Analysis of keyword emergence in the CNKI literature.

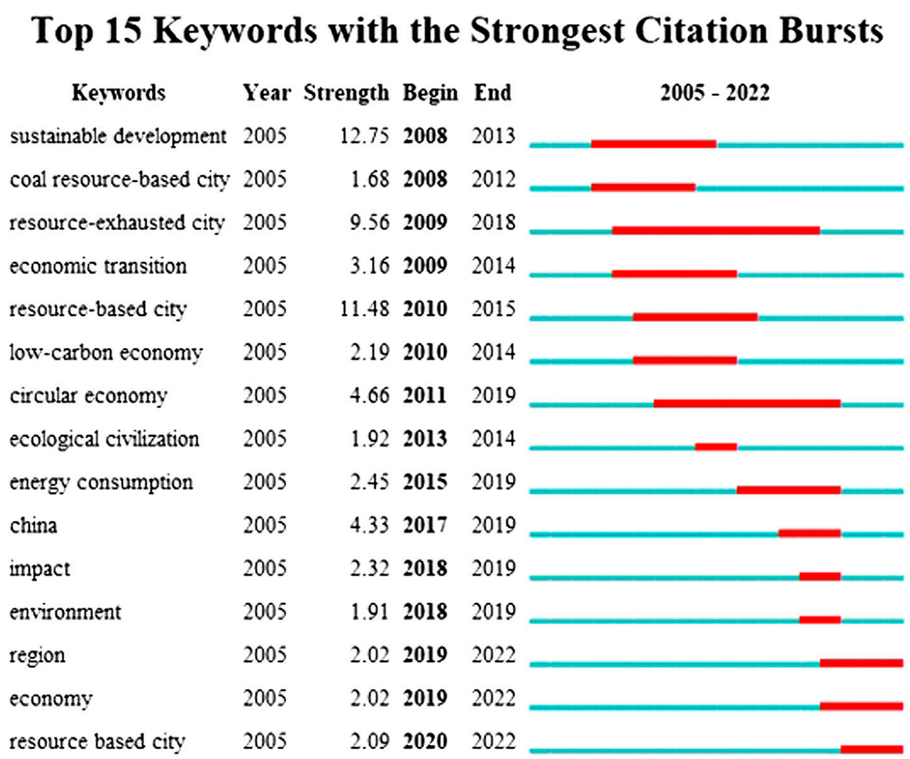


FIGURE 5
Analysis of keyword emergence in the WOS literature.

# 4 Analysis of research hotspots

Keywords summarize the whole study, and their frequency provides an important basis for judging whether a research direction is a research hotspot in the field, which is one of the means to analyze the research focus of a field. To show the frequency, centrality, and evolution trend of keywords in studies on resource-based cities, this study uses CiteSpace software to analyze keyword co-occurrence and keyword emergence.

## 4.1 Keyword co-occurrence analysis

Keyword co-occurrence analysis visually shows the research hotspots in a research field through the frequency of keywords. We conducted keyword co-occurrence analysis on the Chinese literature on resource-based cities in the CNKI database and the English literature in the WOS database and drew the keyword co-occurrence network, as shown in Figure 2 and Figure 3 (we translated the Chinese display results in Figure 2 into English). The larger the circle of the node in the figure, the larger the word frequency of the keyword, which indicates a research topic hotspot. The thicker the connection between nodes, the greater they appear in the same article together. A different color in each layer of the circle represents a different year, with darker colors representing earlier years and lighter colors representing later years.

Figure 2 shows that words such as industrial transformation, economic transformation, urban transformation, and industrial structure are at the core of the whole network. It is an important network node and has been the focus of ongoing research since 2002. Although the theme of industrial structure is not dominant in terms of keyword frequency, it can be seen from the color analysis of the outer circle that it has been the focus of scholars in recent years and has very strong characteristics. Because northeast China is rich in natural resources, including coal, minerals, and forest resources, and the old industrial base of northeast China is a very typical resource-dependent region, the northeast area is also a keyword that often appears in the research on resource-based cities. In addition, the circular economy, continuous industries, countermeasures, and resource depletion are important nodes in the network, which readers can learn about.

Figure 3 is a keyword co-occurrence network diagram of relevant literature in the WOS database. Resource-based cities occupy the core position in the network, followed by cities, sustainable development, China, impact, carbon dioxide emissions, and other words. This shows that foreign journals pay more attention to sustainable development and carbon emissions in the transformation process of resource-based cities. By comparing the network diagram of co-occurrence of keywords in China and internationally, it can be seen that the connection between nodes in Figure 3 is more significant. English journals are more systematic in the co-occurrence of keywords and content focus. However, except for a few core nodes of Chinese journals, the connection between the other nodes is not significant, indicating scattered research content.

## 4.2 Keyword emergence analysis

The keyword frequency spike is a phenomenon worthy of attention in the field of research, which reflects an interest by researchers and a general academic concern with a specific period of time. CiteSpace generates a keyword emergence network map by extracting the uprush of keywords in a particular timeframe, which becomes keyword emergence analysis. Figure 4 and Figure 5 are plotted to show the temporal changes in keyword emergence in both Chinese and English literature, respectively (we translated the Chinese analysis results in Figure 4 into English). The red lines in the figure represent the temporal regions with significant changes.

As shown in Figure 4, scholars paid more attention to the transformation and development of resource-based cities before 2013, including industrial transformation focusing on the economy and the successor industry in terms of employment. Since 2014, "influencing factors" have become an important topic, with the mutation intensity reaching 5.87, which also indicates that the research focus on resource-based cities has changed from how to develop to how to evaluate. In recent years, an increasing number of environment-related keywords have emerged, such as "vulnerability" in 2015, "coupling coordination" in 2016, and "environmental regulation" in 2017. The emergence of these keywords indicates that scholars paid attention to the impact of urban transformation on the environment in their research on resource-based cities.

Since the English literature on resource-based cities started in 2005, the starting year in Figure 5 was changed to 2005. In Figure 5, from the analysis of mutation intensity, sustainable development, resource-based cities, and resource-exhausted cities exhibit intensities of 12.75, 11.48, and 9.56, respectively, indicating that these three keywords occupy a core position in the research field and that sustainable development is the core content of English journals. Resource-exhausted city and circular economy are two keywords that have persisted over time. From 2009 to 2018, resource-exhausted cities were the focus of attention, which coincided with the period when China began to identify resource-depleted cities in 2007. The popularity of the circular economy lasted from 2011 to 2019, becoming a popular research hotspot. The mutation intensity of the circular economy also reached 4.66.

# 5 Conclusion

First, this study introduces the basic concept of resource-based cities and expounds the domestic and international research on the development of resource-based cities, including the influencing factors of urban transformation, the path of urban transformation, and the evaluation index of urban transformation. Through data analysis and visual analysis of 1,732 Chinese articles included in CNKI Peking University Core and CSSCI journals and 450 English articles in WOS from 2002 to 2022, the important indicators in the field of resource-based city research are visually displayed. The key topics of Chinese literature mainly focus on urban transformation, including economic, industrial, and environmental dimensions. The evolution of research can be divided into three stages: rapid rise, high fluctuation, and mature development. Future research will focus more on the coupling between low-carbon development and urban transformation. The main theme of the English-language literature is sustainability, supplemented by a circular economy and a low-carbon economy, and the number of articles has increased rapidly since 2017, indicating that research on resource-based cities has received increasing attention from English journals in recent years. In terms of publications, Chinese institutions are the absolute leaders of both Chinese- and English-language journals, indicating that China attaches great importance to the issue of resource-based cities.

However, China's research on resource-based cities still has the following problems. 1) The research scope is uneven. According to the keyword co-occurrence network diagram of CNKI and WOS, it can be seen that, except for a few core nodes, most nodes are small, indicating that the research has focused on the main core points in the past 20 years and has not undergone more extensive development. 2) The focus of the research is scattered. Although the frequency of core keywords in Chinese journals is high, the co-occurrence among keywords is weak, and most keywords have no relation to each other. Meanwhile, in the analysis of keyword emergence, the intensity of the top 15 keywords in Chinese journals is between 4 and 5. In contrast, the intensity of keyword emergence in English journals is obviously differentiated, which indicates that the current research published in domestic journals has not formed a clear system, each topic is popular for a short period of time, and the research content is not thorough enough. 3) Quantitative research is lacking. Among the top 10 most highly cited Chinese and English studies, few have studied the efficiency and policy effects in the transformation process of resource-based cities through quantitative research. This shows that the research on resource-based cities still lacks the support of mathematical models, and the results obtained are mostly based on qualitative analysis and historical information. 4) The evaluation indicators are not unified. In many articles evaluating the transformation effects of resource-based cities, scholars have proposed a variety of indicators and evaluation methods, and the evaluation effects obtained are quite different. Multiple indicators are not helpful to government analysts; it will be difficult and inefficient for the government to carry out work in this field.

Nevertheless, we provide corresponding prospects for future research work. Researchers can further deepen the existing research conclusions in terms of topic selection and conduct a more thorough analysis and discussion on the existing topics. Qualitative content can be quantified by establishing mathematical models or data-driven methods to make the conclusions more robust. To increase the co-occurrence of keywords in the knowledge network, it is necessary to explore the connections between existing topics and the internal relations between each topic instead of making each topic independent. The existing relevant indicators should be sorted out to form a more systematic evaluation system, and the theoretical content should be implemented to help governments at all levels effectively improve the problems encountered in the transformation process of resource-based cities.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

## Author contributions

DX conceived the idea and outlined in brief. DX and QG collected the data used in the study. ZW participated in the whole discussion and produced all the figures and tables in the study. QG put forward targeted improvement suggestions based on the results. QG and ZW assisted in polishing the manuscript. All authors contributed to study revision and have both read and approved the submitted version.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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# Coupling coordination and spatial-temporal characteristics of resource and environmental carrying capacity and high-quality development

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The high-quality development of society needs the support of resource and environmental carrying capacity, and the improvement of resource and environmental carrying capacity is driven by the process of high-quality development. Therefore, how to realize the dynamic coordination of the two is an urgent problem to be solved. Different from previous studies which mainly focused on economic development and the environment, this paper considers all aspects of society and analyzes the interactive relationship between high-quality development and resource and environmental carrying capacity for the first time. Based on the panel data of 30 provinces in China from 2005 to 2020, a comprehensive evaluation index system is constructed, and the information entropy method, coupling coordination degree, and kernel density estimation model are applied to explore the coupling coordination relationship and spatial-temporal characteristics between resource and environmental carrying capacity and high-quality development. The results show that there are four nonlinear relationships between the resource and environmental carrying capacity and high-quality development, including simultaneous increase, first increase and then decrease, first decrease and then increase, and alternating fluctuation; Water resources per capita and the green coverage rate of the built-up area contributed the most to the resource and environmental carrying capacity subsystem, and GDP per capita and urbanization rate contributed the most to the high-quality development subsystem. From the time series, the coupling relationship between the two shows an upward trend over time. From the spatial series, the coupling relationship between the two is in a state of spatial aggregation. This paper discusses the results and puts forward policy recommendations, hoping to provide a reference for the coordinated development of the region. Moreover, this study provides a new perspective for the scientific construction of the relationship between resource and environmental carrying capacity and high-quality development on a global level.

KEYWORDS

**resource and environmental carrying capability, high-quality development, coupling degree, kernel density estimation, spatial-temporal characteristics**

## 1 Introduction

With the rapid development of global urbanization and industrialization, the contradiction between social-economic development and resources and the environment is gradually prominent (Bao et al., 2020; Zou and Ma, 2021). The cities and regions are facing major challenges related to the environment and resources due to the development of urbanization and industrialization, including increased energy consumption, pollution, resource consumption, and other issues (Bibri et al., 2020). These have created enormous pressure on the environment and great demand for natural resources. Resource and environmental carrying capacity is not only a regional issue, but a global issue (Fu et al., 2020; Zou and Ma, 2021).

Since the reform and opening up, China's economy has been developing rapidly. However, in pursuit of rapid economic growth, many regions have paid the price of ecological damage. In some fast-developing areas in China, there is a huge conflict between the needs for social and economic development and the carrying capacity of the resource and environment system (Cheng et al., 2016). In these areas, a large number of environmental resources are exploited, and economic growth is driven by enterprises with high pollution, high energy consumption, low quality, and low output. Due to the lack of awareness of sustainability, these behaviors promote the development of extensive growth models and put enormous pressure on natural resources and the ecological environment. Excessive grazing and unreasonable mining of arid land in northwest China have accelerated the expansion of desertification and eventually made water resources scarcer. Many studies have pointed out that China's current economic growth rate is unbalanced with the resource and environmental carrying capacity (RECC), and green development is insufficient (Huang et al., 2020). Due to the lack of experience in resource development in China and the unreasonable utilization of resources, the climate is gradually warming and the coverage of grassland has decreased linearly, the problems of environmental pollution and soil erosion are very prominent, and resource constraints are becoming increasingly tense. Therefore, changing the mode of economic development and improving the quality of development have become the inevitable choice for China's future development (Guan and Zhang, 2022). Under this circumstance, China put forward the expression of high-quality development (HQD) for the first time in 2017, not only focusing on economic growth but also achieving sustainable growth under the condition of low consumption and high efficiency, avoiding blind expansion and extensive methods.

High-quality development requires the support of resource and environmental carrying capacity, and only development that meets the requirements of resource and environmental carrying capacity can be sustained. The carrying capacity of various natural resources and environment, including water, land, energy, and air, in the process of urbanization and industrialization is called RECC (Liao et al., 2020). Resources are the "food" and "blood" of development and the foundation of social development. The coordination between the social economy, resources, and the environment can promote the sustainable development of the economy (Sun et al., 2018). From the perspective of the economic growth model, economic development is inseparable from the input of supply factors such as land, energy, and the environment, as well as the investment of innovative factors such as technological progress (J. K. Wang et al., 2022). Efficient use of resources and high-level environmental protection is conducive to promoting high-quality development (Liao et al., 2020). If the quality and efficiency of the supply of elements such as resources and the environment are effectively improved, the effect of technological progress will be difficult to show in the short term, but it is in line with the eternal concept of long-term sustainable development, and is consistent with the "low energy consumption, low environmental pollution, and high economic benefits" model required for high-quality development (Xiao and Wen, 2021). If a region has prominent resource and environmental problems and blindly increases resource input and environmental pollution output, economic growth in the short term may be at a relatively high level (Wu et al., 2022). However, with the excessive consumption of resources and the environment, it is bound to bring resource constraints, and the RECC reaches the upper limit, which makes it difficult to withstand rapid economic growth. Some scholars have researched the constraints of resources and the environment on economic growth (Andersen et al., 2013; Barbier, 1999; Eriksson, 2018). The continuous reduction of resources will cause their prices to rise, attracting a flood of investment. These investments have a "crowding-out effect" on human and physical capital investments, hindering long-term economic growth in the region (Kang et al., 2021). Environmental hazards such as acid rain, land desertification, and the greenhouse effect have led to less and less available arable land and resources, increasing the disposal costs of the government and enterprises, and reducing economic benefits. Once the pollution that exceeds the environmental capacity continues to increase, it will have side effects on economic development and reduce the sustainability of economic development (Chen et al., 2022).

To solve these resource and environmental problems and reduce the constraints of resources and the environment on society and the economy, it is necessary to promote high-quality development (Zhu et al., 2020; Song et al., 2022). Rational planning under the requirements of high-quality development can ensure the effective use of environmental resources (Jia et al., 2019). High-quality development puts forward the goals of improving the RECC, such as land reclamation, mine geological environment management, land remediation, and coastal zone protection (Song et al., 2022). To achieve these goals, China's high-quality development has adopted the means of industrial structure optimization and adjustment, technological progress, and green development (Wang and Li, 2019). After analyzing the "short plank" of RECC through the degree of coupling coordination, Wang et al. (2017) pointed out that due to the mobility of resources, under the conditions of limited resources, the formulation of economic development plans should consider transforming traditional technologies and optimizing the industrial layout. However, the unreasonable industrial structure and production layout will also make the existing problems of resources and the environment increasingly prominent (Meng, 2021). It can be seen that HQD and RECC are not only complementary but also infiltrate and interact with each other. Coordination involves benign interactions between multiple elements in a subsystem and can describe the sustainable development of interactions (Sun et al., 2018). Therefore, analyzing the coordination between RECC and HQD is of great significance for regional planning and development. The goal of the coordinated development of the two is to create a sustainable city with a solid economic foundation, ecological livability, and abundant natural resources (Song et al., 2022).

The existing literature on HQD and RECC focuses on two aspects, including their assessment and the interplay of social, economic, resource, and environmental impacts. On the one hand, many scholars have evaluated the high-quality economic development level and RECC of the region. Scholars evaluate the city's high-quality economic development level on topics such as mining (Xu et al., 2022), ocean (Li et al., 2020), and urbanization (Cheng, 2022). Some scholars also analyze HQD from the perspective of carbon emissions (Liu and Hu, 2021; Zhang et al., 2021). The means of high-quality development, such as industrial structure upgrading, can achieve energy conservation and emission reduction, thereby improving environmental quality. Different from the traditional concept of economic development, high-quality development pays more attention to the comprehensive development of politics, economy, society, culture, and ecology. To achieve this comprehensive development, the government and its measures play a key role. Yang et al. (2019) discussed the role of the government in high-quality innovation development, and pointed out that government governance needs to be adapted to local conditions. In the case of environmental governance, the impact of environmental regulations varies for different regions (Ma and Xu, 2022). Appropriate environmental regulations can promote high-quality and sustainable economic development (L. Chen et al., 2022a), but overly stringent regulatory measures can be counterproductive (Yang et al., 2022).

Meanwhile, the evaluation of RECC has always been a hot topic of research. The existing literature has adopted frameworks such as the Pressure-State-Response model (Zou and Ma, 2021), the Driver-Pressure-State-Impact-Response model (A. Y. Wang et al., 2022), and Planetary Boundaries (Fang et al., 2015), etc. to study RECC. To cope with the disturbance of ecosystems caused by resource and environmental pressure, scholars use the results of RECC measurements to plan and manage the carrying capacity of regional ecosystems in advance. By assessing the water-carrying capacity of water-scarce countries, Ait-Aoudia and Berezowska-Azzag (2016) identified the population that can be sustained based on water resources and domestic consumption patterns. After evaluating the RECC of China's mining economic zones, Wang et al. (2017) found that most economic zones lack water resources and need some policy leadership. Zhang et al. (2019) constructed the support-pressure index to assess the RECC level of cities, and pointed out that the pressure of human activities on resources and environment is gradually increasing, but the growth rate is slowing down. These scholars have studied the level of urban quality development and the status of the resource environment from different perspectives. HQD and RECC, as two independent subsystems, have their own connotations and focus. But the interaction between the two has a coupling and coordination relationship, which enables them to form a brand-new system. Therefore, it is necessary to study the coupling relationship between them.

On the other hand, the coupling between HQD and RECC subsystems can be distilled into interactions between society, economy, resources, and environment. Scholars have studied the economic-resource (Chen and Chen, 2019), economic-environmental (Li et al., 2022), economic-ecological (Liao et al., 2019), economic-energy-environmental (Wang et al., 2020), economic-resource-environmental (Zhu et al., 2020), socio-economic-environmental (Yang et al., 2015), and socio-economic-ecological (Wan et al., 2021; Bao et al., 2022) perspectives. Most of the studies on these issues are empirical studies covering multiple countries and provinces, and they all demonstrate the interconnectedness of subsystems. In other words, social and economic development and the natural resource environment are mutually influential and interactive. In addition to the study of cities, scholars from different fields are also studying the marine economy (Yu and Di, 2020), industrial economy (J. K. Wang et al., 2022), and mineral resources (X. H. Chen X. H. et al., 2022b). The coordination evaluation was achieved by using models such as coupling models (Li et al., 2022), system dynamics (Bao et al., 2022), and structural equation models (Chen and Chen, 2019). However, no scholars have carried out research from the level of HQD and RECC. As the goal of regional development, HQD includes not only the economic dimension but also the social and cultural level of the region. RECC is the ability of resources and the environment to sustain human socio-economic activities. Exploring the coupling relationship between HQD and RECC can not only fully reflect the interconnection between society, economy, resources and environment, but also synergistically promote HQD of human society and high-level protection of the ecological environment.

TABLE 1 The index system of resource and environmental carrying capacity (RECC).

| Criterion | Number | Index | Calculation | Unit | Direction | Index weight | Reference |
|---|---|---|---|---|---|---|---|
| Resources carrying capacity | N1 | Per capita cultivated land area | Cultivated land area/total population | Thousand hectares per ten thousand people | + | 0.168 | Tan et al. (2022) |
| | N2 | Water resources per capita | Water resources/total population | $m^3$ per capita | + | 0.285 | Zhu et al. (2020) |
| | N3 | The proportion of nature reserves in the area under the jurisdiction | Nature reserve area/Jurisdiction area | % | + | 0.156 | Huang et al. (2020) |
| | N4 | Forest coverage rate | Forest area/total land area | % | + | 0.121 | Chen and Chen (2019) |
| | N5 | Total consumption of coal | Direct access to statistical yearbooks | Ten thousand tons | – | 0.021 | Wang et al. (2020) |
| | N6 | Total consumption of crude oil | Direct access to statistical yearbooks | Ten thousand tons | – | 0.008 | Wang et al. (2020) |
| | N7 | Electricity consumption per capita | Electricity consumption/total population | kWh per capita | – | 0.017 | Wang et al. (2020) |
| Environmental carrying capacity | N8 | Urban sewage treatment rate | Sewage treatment volume/sewage production volume | % | + | 0.026 | Wang et al. (2020) |
| | N9 | Per capita sulfur dioxide emissions | Sulfur dioxide emissions/total population | Tons per capita | – | 0.024 | Huang et al. (2020) |
| | N10 | Harmless treatment rate of domestic waste | Amount of harmless treated domestic waste/amount of domestic waste generated | % | + | 0.031 | Zhu et al. (2020) |
| | N11 | The comprehensive utilization rate of industrial solid waste | Comprehensive utilization of industrial solid waste/production of industrial solid waste | % | + | 0.058 | F. Zhang et al. (2022) |
| | N12 | The green coverage rate of the built-up area | The green coverage area of the built-up area/built-up area | % | + | 0.085 | Wang et al. (2020) |

"+" indicates the indicator is a position index, and "–" indicates the indicator is a negative index.

After reviewing the existing literature, we found that the research on the relationship between RECC and HQD in recent years mostly focuses on economic development and the environment, and rarely considers other dimensions of "high-quality development". The connotation of high-quality development needs to jump out of the economic field and expand to all aspects of society, to better promote overall social progress. At present, no scholars have analyzed the interaction relationship and interaction mechanism between RECC and HQD. This paper provides a new idea for coordinated development. Therefore, this paper uses the coupling coordination degree and kernel density estimation model to measure the coupling degree and coordination degree of RECC and HQD systems in 30 provinces in China from 2005 to 2020, and identify the temporal and spatial evolution characteristics of the coupling relationship between RECC and HQD. The contributions of this paper are as follows: (1) The interactive relationship between HQD and RECC is analyzed, which opens up a new way for coordinated development; (2) Based on the existing theoretical framework, a comprehensive evaluation index system of RECC and HQD is constructed; (3) Through the information entropy method, coupling and kernel density estimation model, the spatial-temporal evolution characteristics of the coupling relationship between RECC and HQD are analyzed, and corresponding suggestions are put forward. The other parts of this paper are: the second part introduces the methods and data sources in detail; the third part analyzes the obtained results in detail; the fourth part discusses the results, and the last part concludes.

# 2 Materials and methods

## 2.1 Indicators and data

To study the coupling relationship between RECC and HQD coupling degree subsystems, a set of evaluation indicators should be established first. Through the literature search, expert interviews, and reference to relevant indices used in China's national planning, 24 indices were identified, as shown in Tables

TABLE 2 The index system of high-quality development (HQD).

| Criterion | Number | Index | Calculation | Unit | Direction | Index weight | Reference |
|---|---|---|---|---|---|---|---|
| Economy | N1 | GDP index | Direct access to statistical yearbooks | % | + | 0.008 | Z. Y. Zhang et al. (2022) |
| | N2 | GDP per capita | GDP/total population | Ten thousand yuan per capita | + | 0.060 | Z. Y. Zhang et al. (2022) |
| | N3 | Public budget revenue per capita | Public budget revenue/total population | Ten thousand yuan per capita | + | 0.104 | Wang et al. (2020) |
| Coordination | N4 | Urbanization rate | Urban population/total population | % | + | 0.024 | Z. Y. Zhang et al. (2022) |
| | N5 | The proportion of output value of secondary and tertiary industries in GDP | The output value of secondary and tertiary industries/GDP | % | + | 0.009 | Wang et al. (2020) |
| Green | N6 | Parkland area per capita | Parkland area/total population | $m^2$ per capita | + | 0.020 | Huang et al. (2020) |
| | N7 | Consumption of chemical fertilizers | Direct access to statistical yearbooks | Ten thousand tons | – | 0.011 | Wang et al. (2017) |
| Innovation | N8 | The proportion of science, technology and education in GDP | Science, technology and education spending/GDP | % | + | 0.040 | Z. Y. Zhang et al. (2022) |
| | N9 | The number of students in higher education per 10,000 persons | The number of students enrolled in higher education/total population | Person | + | 0.030 | Wang et al. (2020) |
| | N10 | The number of patent applications granted | Direct access to statistical yearbooks | Piece | + | 0.233 | Zhong et al. (2021) |
| Openness | N11 | Openness to the outside world | Total imports and exports/GDP | % | + | 0.125 | L. Chen et al. (2022) |
| | N12 | FDI (Foreign Direct Investment) | Direct access to statistical yearbooks | Ten thousand dollars | + | 0.126 | L. Chen et al. (2022) |
| Sharing | N13 | Public library collections per 10,000 persons | Public library collections/total population | Thousand copies | + | 0.096 | Huang et al. (2020) |
| | N14 | The number of doctors per 10,000 persons | Number of doctors/total population | Person | + | 0.043 | F. Zhang et al. (2022) |
| | N15 | Public finance expenditure per capita | Public finance expenditure/total population | Ten thousand yuan per capita | + | 0.072 | Zhong et al. (2021) |

"+" indicates the indicator is a position index, and "–" indicates the indicator is a negative index.

1, 2. This paper establishes an index system for RECC from two aspects: resource carrying capacity and environmental carrying capacity (Tan et al., 2022), and analyzes HQD from six aspects: economy, coordination, green, innovation, openness, and sharing.

The data in this study include urban data, environmental data, and resource data. The data comes from relevant statistical yearbooks, including the China Statistical Yearbook (2006–2021), China Statistical Yearbook on Environment (2006–2021), China City Statistical Yearbook (2006–2021), and statistical yearbooks of various provinces. The missing data were filled by interpolation, and the data from Tibet, Hong Kong, Macau, and Taiwan were not included due to the difficulty of data availability. The drawing software is ArcGIS10.8.

Since different evaluation indices have different measurement units and dimension levels, it is difficult to compare with each other, so Eqs. 1, 2 are used to standardize the index data to eliminate the influence of dimensions and positive and negative directions (Liao et al., 2020):

$$X_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} positive, \quad (1)$$

$$X_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} negative, \quad (2)$$

where $x_{ij}$ is the value of index $i$, $X_{ij}$ is the normalized value, $\max(x_{ij})$ is the maximum, $\min(x_{ij})$ is the minimum.

## 2.2 Information entropy method

This paper uses the information entropy method (Tan et al., 2022) to calculate the weights of different indicators, and objectively reflects the importance of the indicators according to the difference between the observed values of the indicators, to obtain a comprehensive index of RECC and HQD in each province. The specific calculation steps are as follows:

The calculation for the ratio of each indicator value to the total number of standard values in the sample year:

$$e_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \tag{3}$$

The calculation for the information entropy weight of the index $j$:

$$h_j = -\frac{1}{In(n)}\sum_{i=1}^{n} e_{ij} Ine_{ij} \tag{4}$$

The calculation for the final weights of indicator $j$:

$$w_{ij} = \frac{1-h_j}{n-\sum_{j=1}^{n} h_j} \tag{5}$$

Calculation for the HQD development index and RECC development index for the sample:

$$U_i = \sum_{j=1}^{m} w_j X_{ij} \tag{6}$$

where $n$ is the number of samples, $m$ is the number of evaluation indicators, $i = 1, 2, \ldots, n$, $j = 1, 2, \ldots, m$, and $0 \le w_j \le 1$, $\sum w_j = 1$.

## 2.3 Coupling degree model

According to the coupling degree model of multiple subsystems, the coupling model of the two subsystems used in this paper is Eq. 7 (Nasrollahi et al., 2020), where $U_a$ represents the high-quality development system, and $U_b$ represents the resource and environmental carrying capacity system:

$$C_{ab} = 2\left[\frac{U_a U_b}{(U_a + U_b)^2}\right]^{(1/2)} \tag{7}$$

where $0 \le C \le 1$, the larger the $C$, the greater the degree of coupling between the two subsystems, and *vice versa*.

## 2.4 Coupling coordination degree model

The coupling degree can only express the degree of interaction between the two subsystems, and cannot express the quality of coordination. Therefore, this paper constructs a coupling coordination degree model (J. K. Wang et al., 2022) based on coupling degree to reflect the virtuous cycle relationship between HQD and RECC. The formula is shown below:

$$T_{ab} = \alpha U_a + \beta U_b \tag{8}$$

$$D_{ab} = \sqrt{C_{ab} \times T_{ab}} \tag{9}$$

where $T$ is the annual comprehensive mean of the HQD and RECC systems, $D$ is the coupling coordination degree, $\alpha$ and $\beta$ represent the weights of the two subsystems on the comprehensive coordination effect, respectively. Since HQD and RECC are equally important in this study, $\alpha = \beta = 0.5$. The coupling degree and coupling coordination degree are classified according to the value of $C$ and $D$, and the judgment criteria are shown in Table 3 (Tan et al., 2022).

## 2.5 Kernel density estimation model

The kernel density estimation model can use the density curve to reflect the distribution of the observed variables. In this paper, the development and distribution of the coordination degree and coordination coupling degree of HQD and RECC in 30 provinces in China are described and analyzed by the kernel density curve. The weight function is obtained based on the results of the index weight calculation, and then the obtained results are compared with 0 to analyze the Gaussian function kernel function density values. Assuming that the random variable $x_i$ is identically distributed, $\widehat{f_h}(x)$ is used as a density function, and there are n unknowns x (observed values). The kernel density estimate can be expressed as (Bond and Hui, 1996):

$$\widehat{f_h}(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x_i - \bar{x}}{h}\right) \tag{10}$$

where $K(\cdot)$ is the kernel function, the Gaussian kernel function is used in this paper, and $h$ is the bandwidth.

# 3 Results

## 3.1 Comprehensive evaluation of high-quality development and resource and environmental carrying capacity

### 3.1.1 Index system analysis

Each indicator weight and dominant factor in the HQD and RECC subsystems (Table 1) can be determined. The factors that contribute the most to resource carrying capacity and environmental carrying capacity are water resources per capita and the green coverage rate of the built-up area, respectively. The factors that contribute the most to the economy, coordination, green, innovation, openness, and sharing are public budget revenue per capita, urbanization rate, parkland area per capita, number of patent applications granted, FDI (Foreign Direct Investment), and public library collections per 10,000 persons. In the HQD subsystem, the index weights are sorted as follows: the number of patent applications granted > FDI > openness to the outside world > public budget revenue per

TABLE 3 Level division of the coupling degree and coupling coordination degree between RECC and HQD.

| Serial number | Coupling degree (C) | Coupling type | Coupling coordination degree (D) | Coordination type | Level |
|---|---|---|---|---|---|
| 1 | $0.00 \le C < 0.10$ | Low-level coupling | $0.00 \le D < 0.10$ | Extremely maladjusted | 1 |
| 2 | $0.10 \le C < 0.20$ | Low-to-medium level coupling | $0.10 \le D < 0.20$ | Seriously maladjusted | 2 |
| 3 | $0.20 \le C < 0.30$ | High-level antagonistic coupling | $0.20 \le D < 0.30$ | Moderately maladjusted | 3 |
| 4 | $0.30 \le C < 0.40$ | Moderately antagonistic coupling | $0.30 \le D < 0.40$ | Slightly maladjusted | 4 |
| 5 | $0.40 \le C < 0.50$ | Low-level antagonistic coupling | $0.40 \le D < 0.50$ | Near maladjusted | 5 |
| 6 | $0.50 \le C < 0.60$ | Low-level running-in coupling | $0.50 \le D < 0.60$ | Barely coordinated | 6 |
| 7 | $0.60 \le C < 0.70$ | Intermediate level running-in coupling | $0.60 \le D < 0.70$ | Primary coordination | 7 |
| 8 | $0.70 \le C < 0.80$ | High-level running-in coupling | $0.70 \le D < 0.80$ | Intermediate coordination | 8 |
| 9 | $0.80 \le C < 0.90$ | Intermediate to high-level coupling | $0.80 \le D < 0.90$ | Good coordination | 9 |
| 10 | $0.90 \le C < 1.00$ | High-level coupling | $0.90 \le D < 1.00$ | High-quality coordination | 10 |

capita > public library collections per 10,000 persons > public finance expenditure per capita > GDP per capita > the number of doctors per 10,000 persons > the proportion of science, technology and education in GDP > the number of students in higher education per 10,000 persons > urbanization rate > parkland area per capita > consumption of chemical fertilizers > the proportion of output value of secondary and tertiary industries in GDP > GDP index. In the RECC subsystem, the indicator weights are sorted as follows: water resources per capita > per capita cultivated land area > proportion of nature reserve in the area under jurisdiction > forest coverage rate > the green coverage rate of the built-up area > comprehensive utilization rate of industrial solid waste > harmless treatment rate of domestic waste > urban sewage treatment rate > per capita sulfur dioxide emissions > electricity consumption per capita > total consumption of coal>total consumption of crude oil. The number of patent applications granted and water resources per capita contribute the most to HQD and RECC. The possible reason is that the number of patent applications granted can reflect the technical capabilities of a province, and advanced technologies are more conducive to high-quality development; It has an irreplaceable important position in social development.

### 3.1.2 Curve fitting

According to the formulas and index systems above, this paper calculates the changes in the comprehensive development index of RECC and HQD in the 30 provinces from 2005 to 2020, respectively (Figures 1, 2). In recent years, the improvement of resource utilization efficiency and the level of production technology has made the RECC and HQD indices of most provinces show an upward trend. While the upward trend of RECC is not as obvious as that of HQD. The possible reasons are: China has intensified efforts to build infrastructure and open to the outside world in recent years, and established coastal economic open areas (Li et al., 2021). The implementation of some policies, such as the Belt and Road, has effectively promoted the improvement of RQD in coastal regions, while the development of RECC in various coastal regions is relatively underpowered.

There is a large gap in the RECC of each province (Figure 1). Inland cities such as Inner Mongolia, Heilongjiang, Yunnan, and Qinghai stand out. In the western region, through the establishment of ecological compensation mechanisms, environmental problems such as grasslands, wetlands, and desertification have been repaired, and the resources and environment have been gradually restored. This, coupled with the unique resources and regional location of these provinces, has driven their RECC development. In comparison, coastal cities such as Tianjin, Shanghai, and Shandong have a lower RECC composite index. Generally speaking, coastal cities have many types of resources and abundant reserves, and their RECC values should perform well. This result shows that their social and economic structure during this period is not reasonable enough, which affects the effective allocation of resources and the effective protection of the environment.

The HQD composite index of all provinces increased steadily during this period, which is inseparable from the achievements of China's new development concept leading to economic development. The development trend of HQD in various regions is uneven to a certain extent. The best-performing provinces are Beijing, Tianjin, Shanghai, Zhejiang, and Guangdong. It can be seen that, except for the capital Beijing, all other provinces are coastal cities. Compared with the results of the RECC index, it shows that the objective level of economic development in China's coastal areas is better, but the regional linkage effect is not strong, and the development between regions is not balanced.

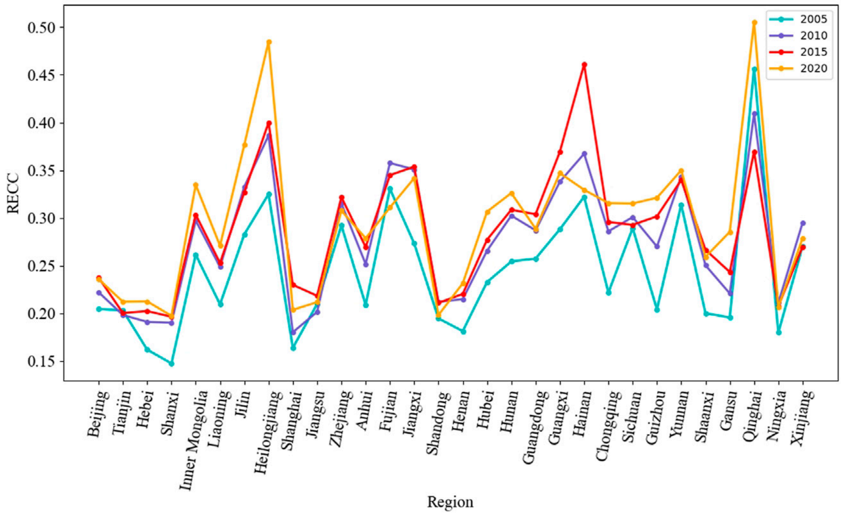



**FIGURE 1**
RECC temporal line chart of 30 provinces.

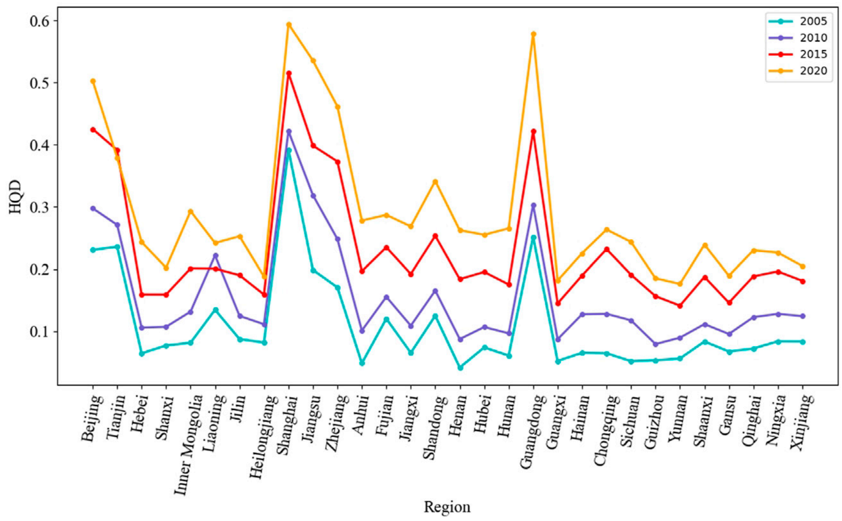



**FIGURE 2**
HQD temporal line chart of 30 provinces.

The HQD and RECC fitting curves of 30 provinces in China from 2005 to 2020 are nonlinear. To explore the nonlinear relationship between them, this paper chooses different functions for fitting, and finally finds that the polynomial function has the best effect on fitting the nonlinear relationship. The results show that there are 4 nonlinear relationships between HQD and RECC in 30 provinces (Figure 3).

The first type is that HQD increases with the increase of RECC, including 12 provinces of Beijing, Hebei, Shanxi, Jilin, Heilongjiang, Anhui, Henan, Hubei, Hunan, Guizhou, Yunnan, and Shaanxi. The second type is that HQD first decreases and then increases with the increase of RECC, including 4 provinces of Inner Mongolia, Fujian, Gansu, and Qinghai. The third type is that HQD first increases and then decreases with the increase of RECC, including

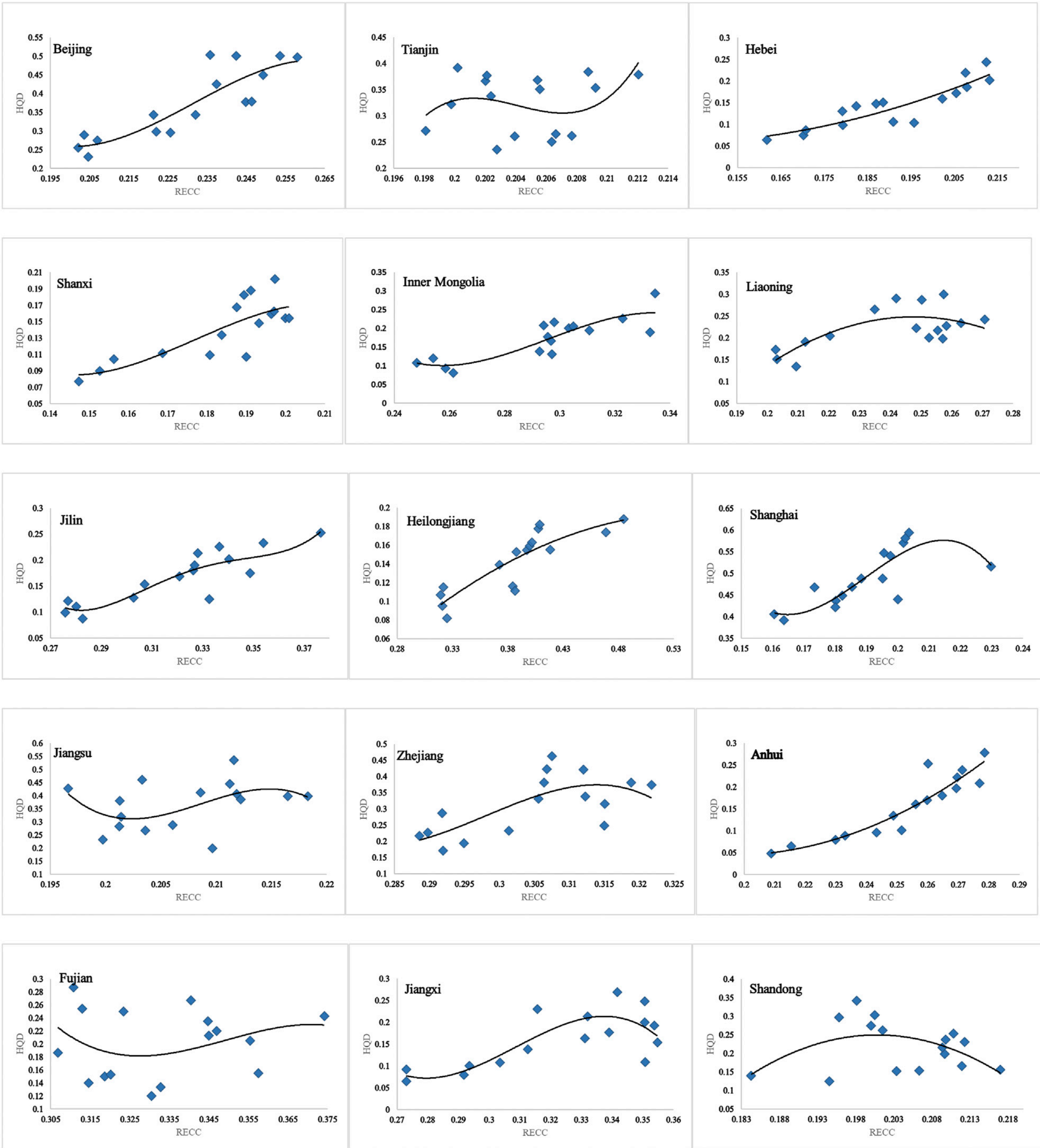



FIGURE 3
(Continued)

Liaoning, Shandong, Zhejiang, and Ningxia. The fourth type is that HQD fluctuates between increasing and decreasing with the increase of RECC, including Tianjin, Shanghai, Jiangsu, Guangdong, Guangxi, Jiangxi, Hainan, Chongqing, Sichuan, and Xinjiang, a total of 10 provinces. Different provinces have different degrees of development in various aspects, and the factors that their development depends on are also different. Except for Beijing, most of the provinces in which HQD and

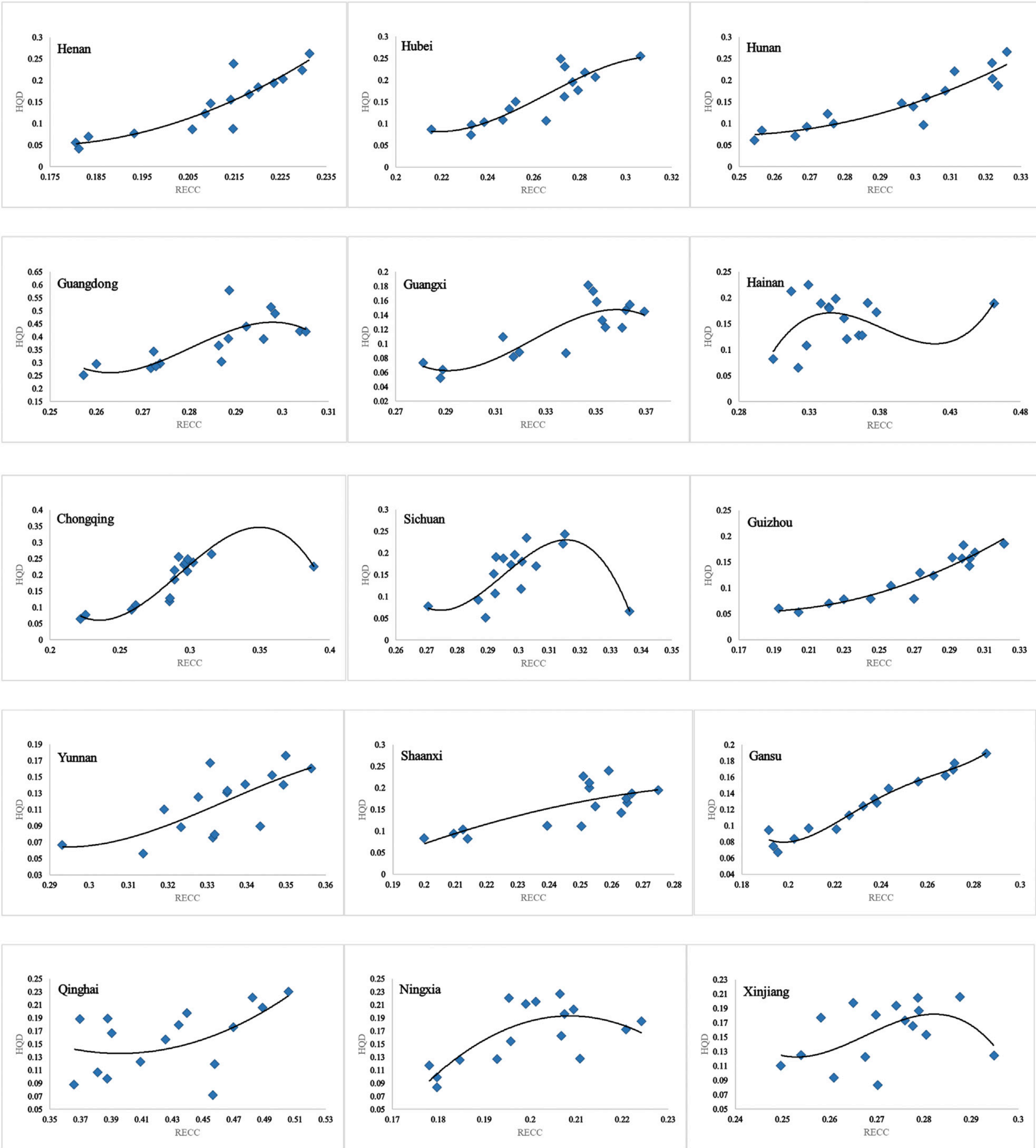



FIGURE 3
(Continued). The fitting curve of HQD and RECC in 30 provinces.

RECC have developed steadily together are those with relatively backward economies. These provinces have had slower economic growth, but they are not overly dependent on resources for development. The economic growth of some western provinces depends on infrastructure construction and resource output, such as Chongqing, Sichuan, Guangxi, etc. Therefore, the relationship between their HQD and RECC is not simply a simultaneous growth.

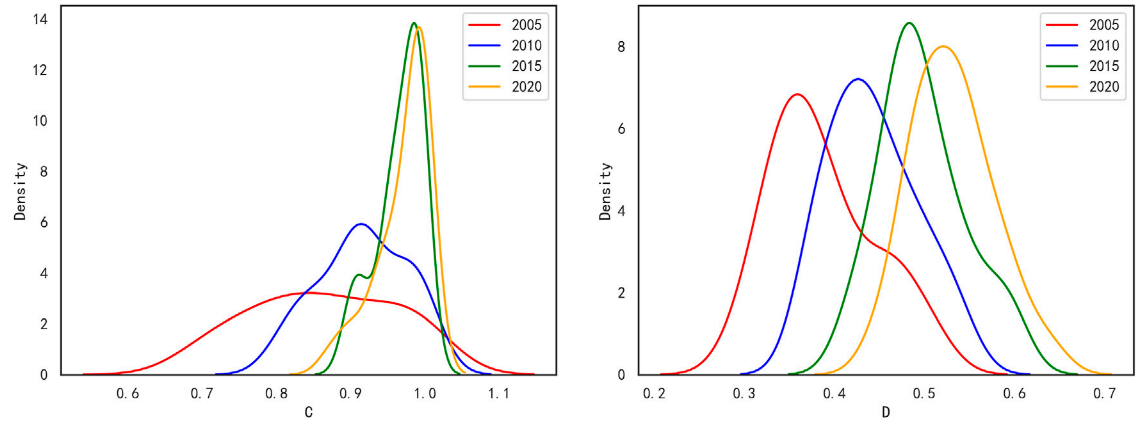
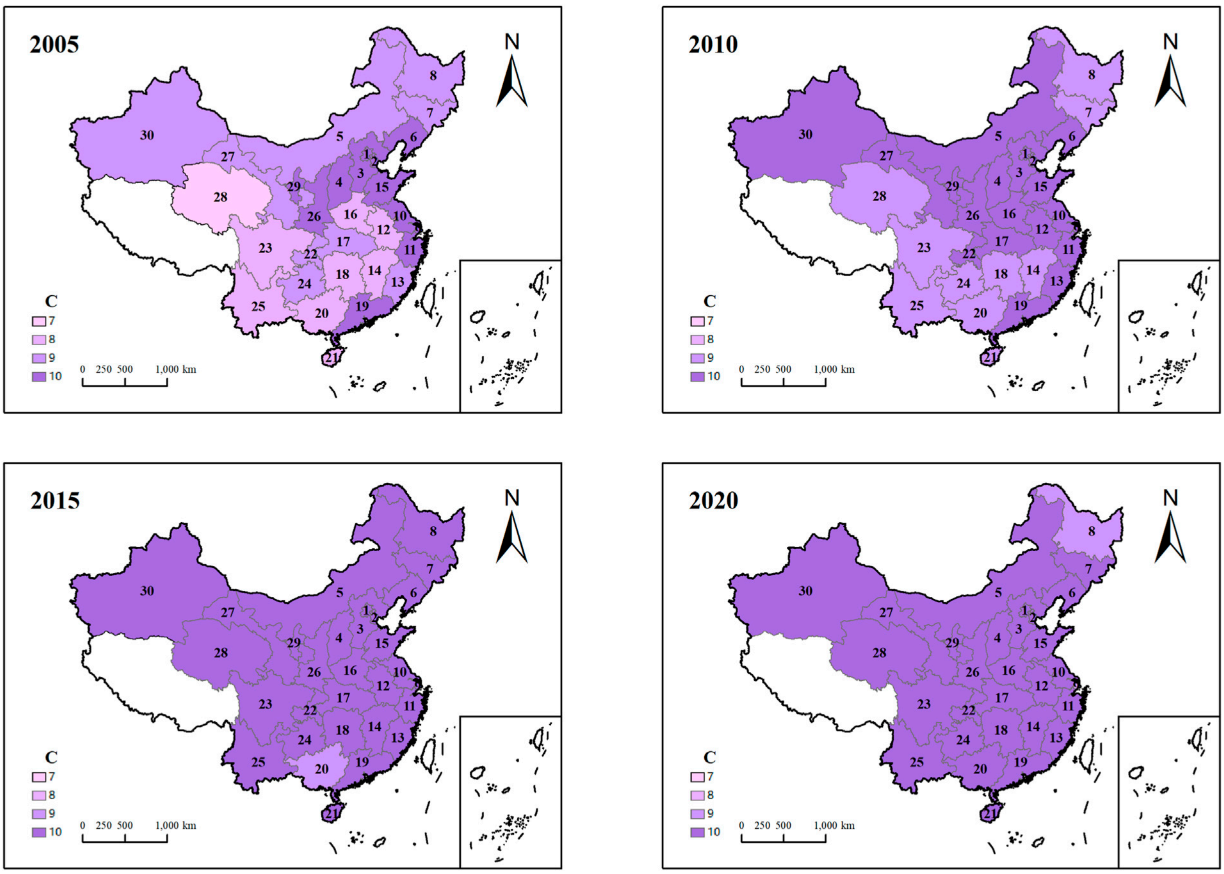


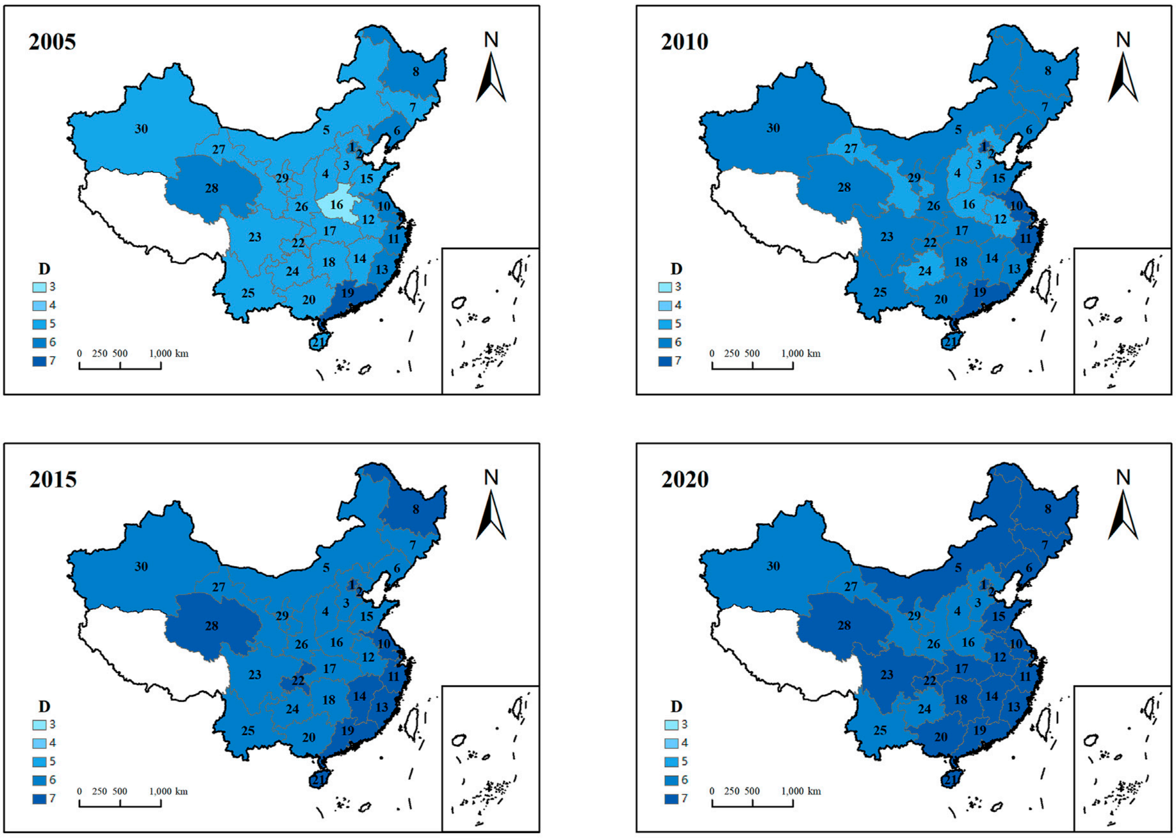

FIGURE 4
Kernel density curves of coupling and coordination degrees of HQD and RECC in 30 provinces.




Note: On the map, 1-Beijing, 2-Tianjin, 3-Hebei, 4-Shanxi, 5-Inner Mongolia, 6-Liaoning, 7-Jilin, 8-Heilongjiang, 9-Shanghai, 10-Jiangsu, 11-Zhejiang, 12-Anhui, 13-Fujian, 14-Jiangxi, 15-Shandong, 16-Henan, 17-Hubei, 18-Hunan, 19-Guangdong, 20-Guangxi, 21-Hainan, 22-Chongqing, 23-Sichuan, 24-Guizhou, 25-Yunnan, 26-Shaanxi, 27-Gansu, 28-Qinghai, 29-Ningxia, 30-Xinjiang,

7-10 represents the coupling level according to Table 3.

FIGURE 5
Spatial evolution of coupling level between HQD and RECC of 30 provinces.




Note: On the map, 1-Beijing, 2-Tianjin, 3-Hebei, 4-Shanxi, 5-Inner Mongolia, 6-Liaoning, 7-Jilin, 8-Heilongjiang, 9-Shanghai, 10-Jiangsu, 11-Zhejiang, 12-Anhui, 13-Fujian, 14-Jiangxi, 15-Shandong, 16-Henan, 17-Hubei, 18-Hunan, 19-Guangdong, 20-Guangxi, 21-Hainan, 22-Chongqing, 23-Sichuan, 24-Guizhou, 25-Yunnan, 26-Shaanxi, 27-Gansu, 28-Qinghai, 29-Ningxia, 30-Xinjiang,
3-7 represents the coupling coordination level according to Table 3.

FIGURE 6
Spatial evolution of coupling coordination level between HQD and RECC of 30 provinces.

## 3.2 Temporal evolution

### 3.2.1 Kernel density estimation

The result (Figure 4) shows the kernel density curves of the coupling degree and coupling coordination degree of the HQD and RECC subsystems changing with time. As far as the coupling degree is concerned, the overall kernel density curve shows a right-shifting trend, but there is no obvious right-shifting from 2015 to 2020, indicating that from 2005 to 2015, the overall coupling degree of HQD and RECC in China has increased, while the level of coupling did not change much in 2015; The kernel density curve in 2005 has a weak double peak, indicating that the coupling degree of HQD and RECC has a certain polarization phenomenon at this time. The peak value of the curve gradually increases, and the width of the wave peak gradually decreases, indicating that the coupling degree gap between regions is decreasing, until the curve has an obvious peak form. In terms of coupling coordination degree, the peak value of the nuclear density curve does not change significantly, but the overall curve shifts to the right year by year, indicating that the overall HQD and RECC coupling coordination degree in China has gradually increased from 2005 to 2020. The gradual improvement of China's economic development structure is conducive to the utilization of resources, and the economical use of environmental resources will also promote economic development. The crest width did not change significantly, indicating that the difference in the coordination degree between regions did not change much, but the crest width increased to a certain extent from 2005 to 2010, that is, the regional disparity in the coordination degree in 2010 widened slightly. There is no double peak in the kernel density curve of coordination degree, indicating that the phenomenon of polarization does not exist.

### 3.2.2 Spatial evolution of coupling degree

The result (Figure 5) shows the process of the spatial evolution of coupling degree between HQD and RECC in 30 provinces in China. The proportion of spaces with high coupling degree levels gradually increased, and the spatial distribution of coupling degree types gradually gathered, that is, the degree of interaction between HQD and RECC in adjacent areas did not differ much, and eventually maintained stable development.

In 2005, Qinghai belonged to the intermediate level running-in coupling area [0.6, 0.7], accounting for 3.33%. The high-level running-in coupling area [0.7, 0.8] includes 8 provinces including Sichuan, Guangxi, and Hainan, accounting for 26.67%. The intermediate to high-level coupling area [0.8, 0.9] includes 9 provinces including Guizhou, Fujian, Jilin, Xinjiang, and Chongqing, accounting for 30%. The high-level coupling area [0.9, 1.0] includes 12 provinces including Guangdong, Jiangsu, Beijing, Tianjin, and Liaoning, accounting for 40%. At this time, the resource advantages of western regions such as Yunnan, Qinghai, and Sichuan, and northeastern regions such as Jilin and Heilongjiang have not yet been transformed into economic advantages. The coastal provinces, such as Guangdong and Jiangsu, took advantage of the reform and opening-up policy and other policies to give full play to their advantages in resources and geographical location, and turned them into economic advantages.

In 2010, no provinces belonged to the intermediate level running-in coupling area [0.6, 0.7] and the high-level running-in coupling area [0.7, 0.8]. The intermediate to high-level coupling area [0.8, 0.9] includes 10 provinces including Sichuan, Jilin, Hainan, and Hunan, accounting for 33.33%. The high-level coupling area [0.9, 1.0] includes the remaining 20 provinces such as Hubei, Fujian, Shaanxi, and Henan, accounting for 66.67%. Compared with 2005, Qinghai changed from the intermediate level running-in coupling area to the intermediate to high-level coupling area. Sichuan, Hainan, Hunan, Jiangxi, Yunnan, and Guangxi became the intermediate to high-level coupling areas. Chongqing, Inner Mongolia, Fujian, Gansu, Xinjiang, Henan, Hubei, and Anhui became the high-level coupling area. The remaining 15 provinces maintained the same coupling type as in 2005. At this time, the spatial distribution and aggregation of coupling degree types began to be obvious. Most of the western regions and parts of northern regions were in the intermediate to high-level coupling area, and most of the coastal areas and central areas were in the high-level coupling area.

In 2015, only Guangxi was in the intermediate to high-level coupling area [0.8, 0.9], accounting for 3.33%. Guangxi's advantage lies in the coastal area, but from 2010 to 2015, Guangxi's RECC increased significantly more than HQD. In this period, Guangxi has not given full play to its geographical advantages and needs to increase its economic development efforts. The remaining 29 provinces were all in the high-level coupling area [0.9, 1.0], accounting for 96.67%, indicating that the development during this period is less dependent on the large supply of natural resources.

In 2020, only Shanghai and Heilongjiang were reduced to the intermediate to high-level coupling area [0.8, 0.9]. The remaining 28 provinces were all in the high-level coupling area [0.9, 1.0], accounting for 93.33%. As a province with rapid economic development, Shanghai has played a leading role in China's economic development. Therefore, it is difficult to avoid increasing resource consumption and causing certain impacts on ecology and the environment. The growth rate of HQD in Heilongjiang is not as fast as that of RECC, indicating that Heilongjiang needs to pay more attention to social and economic development, and can take advantage of resources and the environment at an appropriate time.

### 3.2.3 Spatial evolution of coupling coordination degree

The result (Figure 6) shows the process of the spatial evolution of coupling coordination degree between HQD and RECC in 30 provinces in China. The proportion of regions with a high degree of coordination is an upward trend, showing spatial aggregation. However, there is still a certain gap in the overall state of high-quality coordination.

In 2005, Henan was moderately maladjusted [0.2, 0.3], accounting for 3.33%. 19 provinces including Guizhou, Chongqing, Ningxia, and Gansu were slightly maladjusted [0.3, 0.4], accounting for 63.33%. 8 provinces including Beijing, Qinghai, Fujian, Zhejiang, and Liaoning were near maladjusted [0.4, 0.5], accounting for 26.67%. Guangdong and Shanghai were near maladjusted areas [0.4, 0.5], accounting for 6.67%. The coordination degree in the central region was relatively low, showing a trend of gradually increasing coordination degree from the central region to the coast. The natural resources in central China are not as good as those in coastal cities and western regions, so it is difficult to convert resources into economic advantages. The overall quality of their development is lower, and the level of their coordinated development is also relatively low.

In 2010, Henan became a slightly maladjusted area [0.3, 0.4]. Jilin, Hainan, Jiangxi, Xinjiang, Chongqing, and other 14 provinces became near maladjusted areas [0.4, 0.5]. Beijing, Zhejiang, and Jiangsu became barely coordinated [0.5, 0.6]. The remaining 12 provinces maintained the same coordination level as in 2005. The northern and central regions saw the most significant increases in coordination degree, with little change in the western and southern provinces. Overall, 6 provinces including Anhui, Guizhou, Gansu, and Shanxi were slightly maladjusted [0.3, 0.4], accounting for 20%. 19 provinces including Fujian, Liaoning, Tianjin, and Qinghai were near maladjusted [0.4,0.5], accounting for 63.33%. The remaining 5 provinces were barely coordinated, accounting for 16.67%.

In 2015, 18 provinces including Sichuan, Shandong, Yunnan, and Guangxi were near maladjusted [0.4, 0.5], accounting for 60%. Twelve provinces including Jilin, Jiangxi, Heilongjiang, and Jiangsu were at the level of barely coordinated [0.5, 0.6], accounting for 40%. Anhui, Guizhou, Henan, Gansu, Hebei, and Shanxi became near maladjusted areas. Hainan, Fujian, Tianjin, Qinghai, Chongqing, Jiangxi, and Heilongjiang became barely coordinated regions. The remaining 17 provinces maintained the same level of coordination as in 2010. It can be seen that the overall coordination degree in China has an obvious upward trend, and the coordination degree of many provinces has increased by one level. This also shows the determination and measures of the Chinese government to enhance the resource and environmental carrying capacity in the process of high-quality development, to ensure the coordinated development of regional environmental development and regional economy.

In 2020, 9 provinces including Guizhou, Tianjin, Shandong, and Shaanxi were near maladjusted [0.4, 0.5], accounting for 30%. 19 provinces including Liaoning, Anhui, Henan, and Hubei were at the level of barely coordinated [0.5, 0.6], accounting for 63.33%. Guangdong and Zhejiang were at the level of primary coordination [0.6, 0.7], accounting for 6.67%. Inner Mongolia, Jilin, Hunan, Hubei, and the other 9 provinces became barely coordinated regions. Guangdong and Zhejiang became the primary coordination area. The remaining 19 provinces maintained the same coordination level as in 2015. Compared with 2015, the improvement of coordination in 2020 is not outstanding, but the overall development is more coordinated and orderly, and the differences between regions are narrowed.

Based on the above analysis, it can be found that the spatiotemporal evolution of the coupling coordination of HQD and RECC in each province had the following characteristics. The overall level of development of coupling coordination was on the rise, but there was still a certain gap from high-quality coordination. This also reflected China's efforts to promote urban economic development and ecological protection. From a regional perspective, the coordination level of HQD and RECC showed a downward trend from the eastern region to the central and western regions, and the coordination level of the southeastern provinces was generally higher. This was related to more active economic development and richer natural resources in coastal provinces. Since 2010, the coordination level in the northern region was also better. Many cities in the north take the road of green and high-quality development, relying on the advantages of resources and the environment. This choice not only strengthened the ecological environment protection but also developed the characteristic economy, which gradually improved the coupling and coordination of HQD and RECC in the northern region in recent years.

## 3.3 Discussion

The coordinated development between HQD and RECC will help cities improve the sustainable utilization of resources in the process of high-quality development. This paper provides a reference for the scientific formulation of resource planning and environmental management policies in different regions.

The number of patent applications granted, FDI, and openness to the outside world are the most crucial factors for HQD, and the possible reason is that the important positions the number of patent applications granted, FDI, and openness to the outside world hold for social and economic development. The number of patents granted is used to measure the level of innovative development, driving high-quality development. FDI and openness to the outside world play a significant positive role in high-quality development (Li et al., 2021). We should adhere to the policy of opening up to the outside world. Moreover, the results of this study show that indicators such as per capita cultivated land area, the proportion of nature reserves in the area under the jurisdiction, and forest coverage rate are relatively important determinants in the RECC subsystems. Among them, water resources per capita contributes the most to RECC, which is similar to the argument of most research (Bian et al., 2019; Tan et al., 2022). Therefore, while attaching importance to economic development, relevant managers and policymakers need to pay attention to the utilization of cultivated land and water resources, and strengthen the protection of nature and forests, achieving coordinated development (Long et al., 2019; Yang et al., 2021).

The results of the HQD and RECC composite indices reflect the variability among Chinese provinces. The RECC performance of inland provinces is better, and the HQD index of coastal provinces is generally higher than that of inland cities. Contrary to the expected results (Zhang et al., 2019), the RECC performance of the resource-rich coastal region was inferior to that of the interior. The possible reasons are as follows. The western inland areas have complex landform types and climates, and the ecological environment is fragile and changeable. Therefore, China has been focusing on the environmental quality of the western region for a long time. At the same time, the public's awareness of environmental protection has increased, which has promoted the improvement of its RECC. However, due to the constraints of natural conditions in inland areas, the performance of its HQD did not reach the level of RECC. Coastal areas pay too much attention to economic development, and lose their original resource advantages. This may be due to the unreasonable social and economic structure during this period. To promote the improvement of the economy and comprehensive level, the developed regions have to pay the cost of the destruction of resources and the environment, leading to prominent ecological problems, and the performance of RECC is not as good as expected.

This phenomenon also leads to a certain gap between China's overall coordination level and high-quality coordination. In the time dimension, the overall coupling level and coordination level of the 30 provinces are gradually improving. Spatially, the spatial distribution of coupling degree types gradually gathered, and the differences in coupling coordination types between regions gradually decreased. These basic features of this study are similar to the findings of (Zhu et al., 2020; Zhong et al., 2021; Ding et al., 2022) in Guangxi province, southwest China and urban agglomeration in middle reaches of the Yangtze River. So far, the vast majority of China's poor population is still distributed in the western region, and the western region still faces severe challenges from the imbalance of resources, environment, and social and economic development. In developed areas such as coastal provinces, despite their rapid economic development, they are densely populated and have limited terrain. The fundamental reason is that China's social and economic structure is not rational enough, the regional linkage effect is not strong, and the development between regions is not balanced. Therefore, the coordinated development of HQD and RECC is an urgent problem that China needs to solve at present. The optimization of industrial structure, technological progress, and green development under the connotation of high-quality development can offset the damage to resources and the environment caused by the increase in economic scale (Wang and Li, 2019). The government needs to "prescribe the right medicine". For inland backward areas, the government should promote technological progress and talent attraction to achieve strong social and economic development. For developed areas, the government should increase the implementation of environmental protection policies, adhere to sustainable development, and ultimately achieve coordinated regional development.

# 4 Conclusion and policy suggestions

## 4.1 Conclusion

It has always been the focus of people to realize the win-win between social and economic development and resource protection. Extensive economic development needs to pay the price of resource depletion and environmental degradation. Therefore, the realization of sustainable HQD has become an inevitable path for future development. Under China's sustainable development goal, coordinated development is the ultimate pursuit. In this context, this study analyzed the interaction between HQD and RECC for the first time, opening up a new path for synergistic development. Based on the existing theoretical framework, this paper constructs the evaluation index system of RECC and HQD. Relevant researchers can evaluate and analyze the coupling characteristics of different regions based on this system. In this paper, the coupling degree, coupling coordination degree, and nuclear density model are used to analyze the temporal and spatial evolution characteristics between them, and the interaction relationship between HQD and RECC is confirmed. This study measures the coupling coordination level of HQD and RECC from the provincial spatial scale, and finds the regional differentiation law of high coupling coordination degree in developed areas and low coordination degree in backward areas. The obtained results provide a theoretical and empirical basis for the coordinated development of resources, environment, and social economy, and have great policy implications for the sustainable development of developing countries such as China. The main conclusions can be summarized as follows:

1. Among the subsystems of RECC, water resources per capita and the green coverage rate of the built-up area contribute the most to RECC. Among the subsystems of HQD, GDP per capita, urbanization rate, parkland area per capita, number of patent applications granted, FDI, and public library collections per 10,000 persons contribute the most to HQD. Over time, the comprehensive development indices of RECC and HQD in most provinces have shown an upward trend, but the upward trend of RECC is not as obvious as that of HQD. The RECC performance of inland regions is generally better than that of coastal provinces, but the HQD development index is not as good as that of coastal provinces. There are four nonlinear relationships between RECC and HQD, including simultaneous increase, first decrease and then increase, first increase and then decrease, and alternating fluctuation. During this period, the social and economic structure is not reasonable enough, which affects the effective allocation of resources and the effective protection of the environment.
2. From the perspective of time series, the coupling relationship between RECC and HQD shows an overall upward trend over time. The coupling degree and coupling coordination degree between them are gradually improving, gradually evolving to high-level coupling types, and low-level coupling types gradually decreasing or even disappearing. The coupling degree between RECC and HQD has reached the highest level, but the coupling coordination degree between them is still a certain gap from the state of high-quality coordination. This reflects the role of China's resource and environmental policies and departments in achieving coordinated development.
3. From the perspective of spatial sequence, the coupling relationship between RECC and HQD is in a state of spatial aggregation as a whole. The distribution range of the high coupling area and high coordination area gradually expanded. There is a certain gap in the coupling level between coastal and inland regions, but the overall spatial gap between adjacent regions is narrowing. The

polarization of the coupling degree changes from weak to insignificant, and there is no polarization phenomenon in the coordination degree. Overall, the coupling stage of the interaction between HQD and RECC in Chinese provinces is consistent with their social and economic development level.

## 4.2 Policy suggestion

Under the goal of high-quality development, the harmonious coexistence of nature and humans requires more effort. Therefore, from the research in this paper, the following policy recommendations can be put forward. First, the government needs to improve the environmental protection system. By increasing the cost burden of the production environment of enterprises, local enterprises are forced to improve their technical level. High-quality development is not overly dependent on resources, but on technological progress (Pan et al., 2021). The government should strictly carry out environmental protection supervision and promote the implementation of industrial greening in various places. Localities can accelerate the elimination of industries with high emissions, high pollution, and low efficiency, and reduce unnecessary consumption of resources. Second, the government should promote the differentiation mechanism of environmental policies and promote high-quality and balanced development among regions. When local governments carry out urban planning and construction, they need to consider the pressure and carrying capacity of local resources and the environment. After the national overall strategic policy is formulated, regional urban factors will lead to differences in effects. The government can formulate corresponding green development strategies based on the resource endowments and industrial bases of various regions. For the damaged environment, it is necessary to implement a zonal and classified ecological protection and restoration system. Finally, the government can pay attention to the developmental strengths of various places, define characteristic resources and technologies, and form complementary advantages. Although natural resources such as land and protected areas are difficult to flow, talents and technologies can be shared in many places. Therefore, the government should focus on promoting the flow of advantageous elements in various regions, amplifying comparative advantages, and promoting the transformation of resource advantages into development advantages. Focusing on pillar industries, all regions continue to improve the level of corresponding resource reserves and factor guarantees, and gather advantages to form a surging development momentum.

However, this paper also has certain limitations. The indicators of this study refer to the existing literature and relevant indicators mentioned in China's national planning, but there are still some indicators that are not considered due to unavailability. The socio-economic development among regions in China is unbalanced, and the evaluation indicators cannot be one-size-fits-all. Future researchers can further refine and modify the indicators. In addition, this paper studies and analyzes the time and space sequences of RECC and HQD, but does not study the driving mechanism, which still needs to be further explored in the future [Wang et al., 2022].

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

## Author contributions

LZ designed the study, played the guiding role in the study, and completed the writing of the manuscript; YC were responsible for data collection and processing, and mainly took charge of the revision of the manuscript; LZ completed the analysis of the results and the writing; WW contributed to the data processing and the revision of the manuscript; JW contributed to the analysis of the results and the writing of the manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.971508/full#supplementary-material

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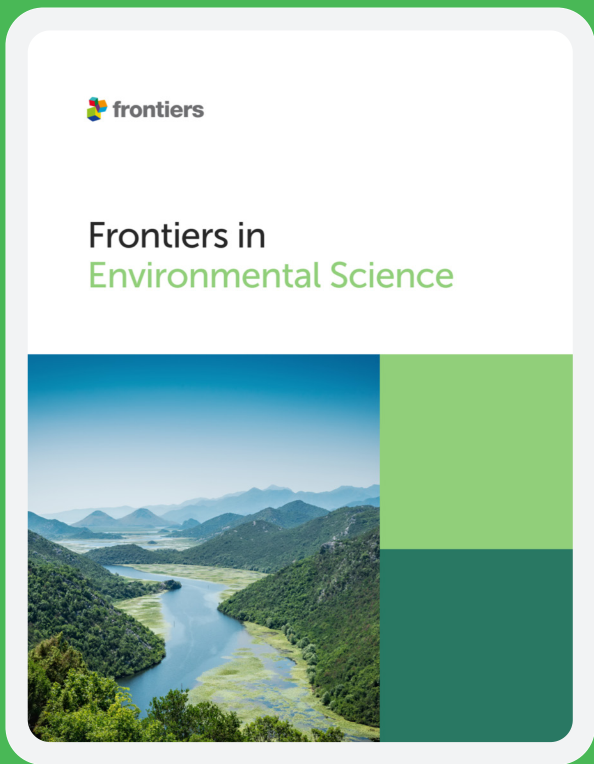


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