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The competitive effect of heterogeneous subjects dominant environmental regulations on environmental quality and its asymmetric strategies

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Introduction: Based on the heterogeneity of participants, current research generally categorizes environmental regulations into three types, government-, market-, and public-dominant environmental regulations, but neglects their intricate real-world interactions.

Methods: To bridge this gap, this study employs panel data spanning 30 Chinese provinces from 2010 to 2021, based on employing the introduced synergy intensity variable (HSP_Synergy), the objective is to investigate the combined effects of these regulations on environmental quality and develop an asymmetric political strategy for optimizing environmental benefits.

Results and discussion: Key findings include: (1) The heterogeneous subjects participation synergy index (HSP_Synergy) effectively integrates diverse heterogenous subjects dominant environmental regulations into a unified research framework. (2) By analyzing the interaction among heterogeneous subjects environmental regulations, using the environmental administrative, environmental tax, and public environmental concern as proxy variables, competitive rather than cooperative effects on environmental quality are identified. An incremental unit of synergy intensity corresponds to a decline of approximately 22%–25% in environmental quality. Notably, regions with lower synergy degrees exhibit 36%–42% higher environmental quality compared to those with higher synergy degrees. (3) This study introduces "asymmetric strategy" as an effective mode for maximizing environmental effects. Introducing both environmental administrative penalty and public environmental concern in environmental management leads to 6%–17% higher environmental benefits compared to introducing environmental administrative penalty and environmental tax, and 21%–23% higher benefits compared to environmental tax and public environmental concern combined participation.

KEYWORDS

environmental regulations, environmental quality, competition effects, asymmetric strategy, synergy index

1 Introduction

The escalating severity of environmental issues has prompted active participation from diverse sectors of society in environmental governance (Cheng et al., 2017; Li et al., 2022). As a result, a wide array of environmental regulations, each dominated by different social sectors, has emerged. One crucial aspect worth considering is the categorization of the current environmental regulations based on their participation subjects. This classification reveals three main types: government-dominant, market-dominant, and public-dominant environmental regulations (Tang et al., 2020). Government-dominant environmental regulations have consistently shown effectiveness in achieving environmental objectives (Wang A. et al., 2023), including biodiversity conservation (Zhao Q. et al., 2023), sustainable resource management (Zhao X. et al., 2023), and climate change mitigation (Luo et al., 2022). Similarly, research has shed light on the positive outcomes associated with market-dominant environmental regulations, which spur technological innovation (Zhang and Zhao, 2023), cleaner technology adoption (Cai et al., 2023), and cost-effective emission reductions (Cheng et al., 2017). Furthermore, public-dominant regulations positively impact environmental outcomes, enhancing public awareness (Todaro et al., 2023), mobilizing community-driven initiatives (Holston and Greene, 2023), and empowering citizens in decision-making (Guerola-Navarro et al., 2023).

However, the current body of research on the interplay of different environmental regulations has specific constraints. Currently, the focus is mainly on each type of environmental regulation in isolation, leading to dispersed research models that do not fully represent the reality of their coexistence. In practice, governments often adopt a combination of various environmental instruments, actively implementing measures from different categories. However, the existing corpus of literature primarily examines the effects of each subject-dominant environmental regulation, often utilizing separate observation models. Another compelling study incentive emerges from the need to further explore the optimization of political strategies to maximize environmental effects. Among various subjects dominant environmental regulations. Over the years, numerous policy discussions have been conducted, focusing on different types of environmental regulations. However, critical questions regarding how to improve collaboration and overall effectiveness of these diverse environmental regulations, and what constitutes the most appropriate policy strategy, remain largely unsolved.

Therefore, it is imperative to understand whether these different environmental regulations exhibit cooperative or competitive effects on the environment and how they can be effectively synergized to maximize their overall environmental impact. Answering these fundamental questions is extremely important for developing optimal and efficient solutions for environmental governance strategies that can effectively tackle the urgent environmental concerns faced by our society. So this study investigated the overall impact of three diverse dominating environmental legislation on environmental quality and provided an effective political strategy to maximize environmental effects.

This paper contributes to the field of environmental regulations by addressing several key research gaps. First of all, this study integrates various heterogeneous subjects dominant environmental regulations into an integrated research framework, addressing the constraints of prior studies that segregated these instruments into separate analysis methodologies. Through this integrated approach, the study explores the dynamic interactions among these diverse environmental regulations, revealing their synergistic effects and interplay. Furthermore, this study delves into the competition effects among heterogeneous subjects dominant environmental regulations on environmental quality, presenting novel insights into this area of research. At now, there is a widely held belief that implementing more environmental regulations results in better environmental outcomes, without fully acknowledging the significance of a balanced and proportionate policy approach. Lastly, this study introduces the "asymmetric strategy" as the optimal environmental management model for maximizing environmental effects. By exploring the synergistic potential among various types of environmental regulations, this research identifies a policy framework that ensures effective and efficient environmental governance.

The research flow chart is summarized in Figure 1.

2 Literature review

2.1 Effects of government-dominant environmental regulations on environmental quality

Government-dominant environmental regulations represent a crucial aspect of environmental governance and policy-making. As one of the most common regulatory approaches, government-dominant regulations involve immediate interference and enforcement by government authorities to tackle environmental challenges (Sun et al., 2023). Government-dominant environmental regulations involve the implementation of regulations or directives by environmental agencies to restrict the release of environmental contaminants produced during business operations. This strategy is typically characterized by its simplicity and straightforwardness, as it establishes explicit and unambiguous environmental objectives (Tang et al., 2016c; Zhang and Jiang, 2019; Zhang et al., 2018).

Extensive empirical research has explored the effectiveness of government-dominant environmental regulations in achieving environmental objectives. Studies have examined their impact on air and water quality, biodiversity conservation (Zhao Q. et al., 2023), sustainable resource management (Zhao X. et al., 2023), and climate change mitigation (Luo et al., 2022). Numerous theoretical frameworks and analytical methods have been employed to assess the impacts of government-dominant environmental regulations. These include cost-effectiveness analysis, regulatory impact assessment, public policy analysis, and environmental governance frameworks.

While government-dominant environmental regulations have shown promise, they are not immune to challenges. Studies have identified issues such as regulatory compliance costs, administrative burdens, and the potential for regulatory capture or lack of enforcement in some cases. Government-dominant environmental regulations often interact with other types of environmental regulations, such as market-based instruments and

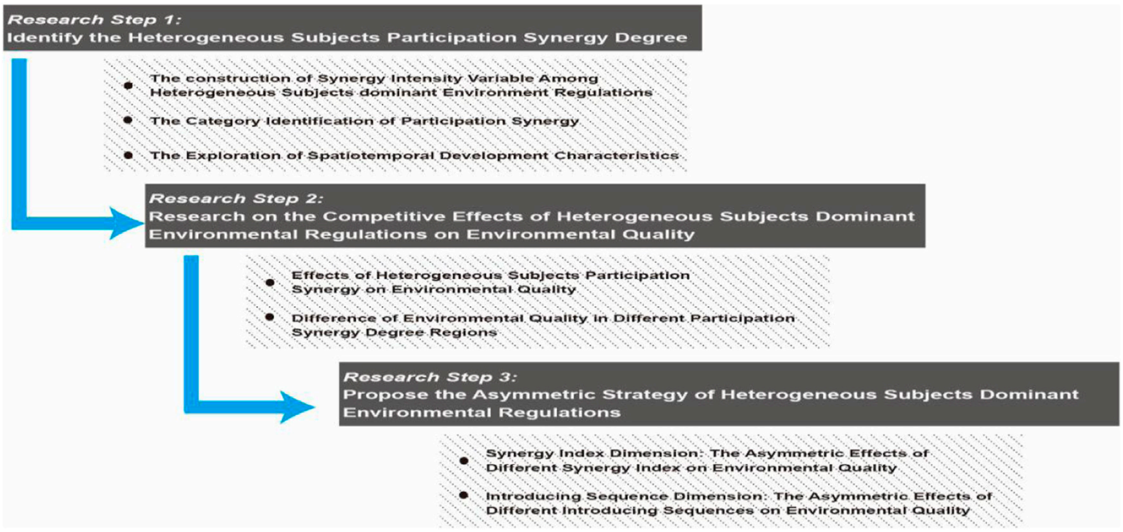

FIGURE 1
Research flow chart.

community-driven initiatives (O'Rourke and Macey, 2003). Understanding these interactions is essential to design effective and integrated environmental policies.

2.2 Effects of market-dominant environmental regulations on environmental quality

Among various types of environmental regulations, market-dominant environmental regulations have garnered significant attention in recent years. Market-dominant environmental regulations are policies and initiatives that predominantly utilize market mechanisms, economic incentives, and pricing tactics to tackle environmental concerns (Khan et al., 2021; Nenavath, 2022; Zhou and Tang, 2022). These regulations are often based on the premise that economic incentives can effectively promote favorable environmental outcomes by harnessing the power of market forces.

Many studies have reported positive outcomes associated with market-dominant environmental regulations. These regulations have been found to promote technological innovation (Zhang and Zhao, 2023), encourage industries to adopt cleaner technologies (Cai et al., 2023), and achieve cost-effective emission reductions (Cheng et al., 2017). Various theoretical frameworks and analytical methods have been employed to investigate the effects of market-dominant environmental regulations. These include cost-benefit analysis, environmental economics, game theory, and environmental impact assessment, among others. A plethora of empirical studies have explored the impact of market-dominant environmental regulations on environmental quality. These studies have focused on different sectors, industries, and regions, examining the effectiveness of market-based approaches in reducing pollution, resource consumption, and greenhouse gas emissions (Zhou et al., 2020).

Despite the potential benefits, market-dominant environmental regulations are not without challenges. Some studies have raised concerns about the potential for market failures, adverse environmental impacts in specific contexts, and issues of equity and distributional effects (Hao et al., 2018; Wu et al., 2020). Understanding the trade-offs and synergies between market-dominant and other regulatory approaches is critical for designing effective environmental policies.

2.3 Effects of public-dominant environmental regulations on environmental quality

Public-dominant environmental regulations play a pivotal role in environmental governance, involving active participation and engagement of the public in addressing environmental challenges. Public-dominant environmental regulations encompass a range of policies and initiatives that involve the active involvement and collaboration of the public, including citizens, communities, and non-governmental organizations, in environmental protection and conservation efforts (Chess, 2000). In addition, compared to regulations characterized by command and control, public-dominant environmental regulations such as public opinion and citizen participation provide incentives rather than authorization for pollution control (Li et al., 2012).

Research suggests that public-dominant environmental regulations have led to several positive outcomes. These include increased public awareness of environmental issues (Todaro et al., 2023), mobilization of community-driven environmental initiatives (Holston and Greene, 2023), and the empowerment of citizens in environmental decision-making processes (Guerola-Navarro et al., 2023). The assessment of the impacts of public-dominant environmental regulations draws upon various theoretical frameworks and analytical approaches. Participatory governance models, social capital theory, and stakeholder engagement analysis are among the methods employed to evaluate their effectiveness. Numerous empirical studies have examined the outcomes of public-dominant environmental regulations in different contexts.

While public-dominant environmental regulations hold great promise, they also face challenges. Studies have identified issues such as the need for effective communication and coordination among stakeholders, resource constraints, and the potential for unequal participation and representation. Understanding these interactions is crucial to foster effective collaboration and synergies in environmental governance.

2.4 Effects of multi-environmental regulations synergy on environmental quality

Research on the interaction effects among the three main types of environmental regulations—government-dominant, market-dominant, and public-dominant—is still limited. While several studies have explored the interactions between two types of regulations, such as government and market-based instruments, or market and public-driven initiatives, these interactions are not often the primary focus of research. Moreover, most studies have not conducted in-depth quantitative analyses to evaluate the combined effects of these regulatory approaches. Instead, existing literature tends to discuss these interactions in more general terms, without exploring the underlying synergies or competitive dynamics between the three types of regulations. This gap highlights the need for a more comprehensive, quantitative study that examines how these regulations work together, either competitively or cooperatively, to affect environmental quality.

Several studies have explored the complementary effects of government regulations and market-based mechanisms. Government regulations, such as emissions standards or bans on certain pollutants, provide a framework for baseline environmental performance, while market-based tools, such as carbon pricing or emissions trading systems, incentivize industries to reduce emissions cost-effectively. Research by Slunge and Alpizar (2019) found that carbon taxes and cap-and-trade systems can complement government regulations by providing financial incentives for compliance. However, the success of these synergies often depends on the alignment and robustness of the regulatory frameworks.

The combination of government regulations and public-driven initiatives has been studied in the context of enhancing environmental compliance and awareness. Public participation in environmental governance—such as community-driven projects, public awareness campaigns, or citizen science—can significantly improve the effectiveness of government regulations. Guo et al. (2021) show that public involvement in environmental decision-making helps to reinforce the enforcement of government policies, leading to better environmental quality outcomes.

The interaction between market mechanisms and public-driven environmental policies has received less attention. However, some studies, such as those by Wang Y. et al. (2024), suggest that public pressure for stricter environmental policies can lead to more stringent market regulations. When market-driven incentives, such as taxes or pollution fees, align with public demand for greener policies, it can lead to more sustainable environmental outcomes. However, when these forces are misaligned, they may create inefficiencies or conflict, limiting the overall effectiveness of the policies.

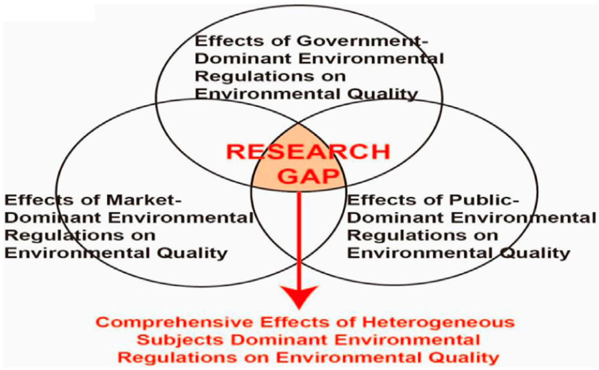

FIGURE 2
The research gap in the current literature.

2.5 Research gaps and contributions

Despite the growing body of work on individual regulatory instruments, there is a significant gap in the literature regarding the combined effects of government-, market-, and public-dominant regulations on environmental quality. The existing research has focused primarily on the isolated impact of each type of regulation, and the potential for their combined effects remains underexplored. The lack of integrated models that account for the interplay of these regulations presents a key challenge in environmental policy research. Figure 2 provides a visual representation of the logic behind this research gap in the current literature.

This gap serves as the motivation for the current study. The study introduces the Heterogeneous Subjects Participation Synergy Index (HSP_Synergy), which aims to capture the interactions among government, market, and public regulations in a unified framework. By considering the competitive and cooperative dynamics among these regulatory approaches, the study offers valuable insights into how they can be optimized for better environmental outcomes.

The primary contribution of this study lies in its ability to integrate three distinct types of environmental regulations into a single framework. It highlights the importance of understanding the interactions between these regulations, whether competitive or cooperative, and provides an innovative approach to optimize their effects through the "asymmetric strategy". This strategy, focusing on government and public involvement, is shown to yield higher environmental benefits than other regulatory combinations, offering a practical guide for policymakers aiming to improve environmental governance.

3 Sample and variables

3.1 Samples

A panel sample is employed in this study for comprehensive analysis. In terms of the spatial dimension, it includes a sample of 30 provinces and municipalities, encompassing all regions in China except for Taiwan, Hong Kong, Macao, and Tibet. Regarding the time dimension, the study covers the period from 2010 to 2021, considering data availability from resources when performing this research, the research observation period is updated to the year 2021.

TABLE 1 The input and output indexes of environmental efficiency.

Primary index	Secondary index	Unit
Input index	Physical capital stock	100 Mio Yuan
	Employed population	10 K
	Energy consumption	10 KTCE
Expected output index	Real GDP	100 Mio Yuan
Unexpected output index	Carbon dioxide emission	10 KT
	Sulfur dioxide emission	10 KT
	Industrial solid waste emission	10 KT
	Industrial wastewater emission	10 KT

3.2 Variables

3.2.1 Environmental quality variables (EQ)

Consistent with the mainstream, the variable of environmental quality is measured from the comprehensive environmental efficiency index, which includes both input and output perspectives of environmental quality (Tang et al., 2023). Compared with the traditional method that uses pollutants emissions as a proxy for environmental quality, the efficiency could reflect the environmental quality (environmental output) level under fixed environmental input conditions, which, thereby, is more comprehensive and accurate. Increased environmental efficiency corresponds to improved environmental quality, resulting in reduced emissions of pollutants while maintaining the same level of economic input.

Specifically, following the literature on calculating environmental efficiency (Xie et al., 2021; Dong et al., 2022; Zhao et al., 2022), the SSBM-DEA method is used in this study. To meet the calculation requirements of the SSBM-DEA method, input indexes (physical capital stock, employed population, energy consumption), expected output indexes (real GDP), and unexpected output indexes (carbon dioxide emission, industrial sulfur dioxide emission, industrial wasted water emission, and industrial solid waste) are added into SSBM-DEA model.

Moreover, the non-oriented SSBM-DEA method could effectively solve the problem of relaxation variables faced by the normal SSBM-DEA method, which, therefore, is also performed in this study to construct another environmental quality variable (*EQ2*) to serve as robustness evidence. The input and output indexes system is listed in Table 1.

3.2.2 Heterogeneous subjects dominant environmental regulations variables

Based on the heterogeneity of environmental governance participants, it is generally accepted that current environmental regulations could be divided into three kinds, government-dominated environmental regulation, market-dominated environmental regulation, and public-dominated environmental regulation (Tang et al., 2020). Since the sources and power owned by heterogeneous environmental government participants are way different, three kinds of environmental regulations, thus, show plenty of different characteristics (Ji et al., 2022; Li et al., 2023).

As environmental concerns grow, a multitude of environmental regulation instruments continue to emerge. When selecting observing variables in this study, the objective of the research is primarily considered, which is to investigate and compare the overall effects among heterogeneous subjects dominated environmental regulations on environmental quality. Thus, the three most representative environmental tools are identified from various environmental instruments to measure three kinds of environmental regulations, and the selection logic is as Figure 3 (Xu et al., 2018).

3.2.2.1 Government-dominant environmental regulation (Government_DER)

Government-dominated environmental regulation behaves as the most commanding and controlling feature, which typically refers to a mandatory environmental policy that restricts pollution emissions by managing the process of production, usage of materials, or other enterprise activities involved with the environment at a particular time or in a specific area (Tang et al., 2020). Typical Government-dominated environmental regulation tools include discharge standards, permits, quotas, and restricted use (Pan et al., 2019).

Typically, the registered amount of environmental administrative penalty cases is the most common and straightforward index used to measure the intensity of government-dominated environmental regulation. Nevertheless, there is a notable flaw in this measurement, namely, the lack of clarity regarding the ultimate cause of registered cases, which might be attributed to either the stringent enforcement measures or the presence of a substantial number of pollution firms. Hence, in order to circumvent the inadequacy of the abstract index, this study employs the relative indicator. The original abstract index is modified by incorporating the energy consumption technology index. Consequently, the variable of government-dominated environmental regulation could be derived using Equations 1 and 2 as shown below.

$$Government\_DER_{i,t} = CASE_{i,t} \times rt_{i,t} \tag{1}$$

$$rt_{i,t} = \frac{M_t / y_t}{M_{i,t} / y_{i,t}} \tag{2}$$

where, $Government\_DER_{i,t}$ denotes the intensity degree of government-dominated environmental regulation of province i at year t; $CASE_{i,t}$ denotes the registered amount of environmental pollution cases of province i at year t; M_t denotes the nationwide energy consumption level at year t, M_t denotes the energy consumption level of province i at year t; y_t denotes the nationwide GDP level at year t, y_t denotes the GDP level of province i at year t; $rt_{i,t}$ denotes the relative technical level of energy consumption of province i at year t, $t > 1$ stands for the higher degree of technical level in province i than the nationwide at year t, the environmental enforcement variable, thus, could be effectively captured by the corrected index of environmental pollution cases.

3.2.2.2 Market-dominant environmental regulation (Market_DER)

Market-dominated environmental regulation is distinguished by its robust incentive mechanism, which

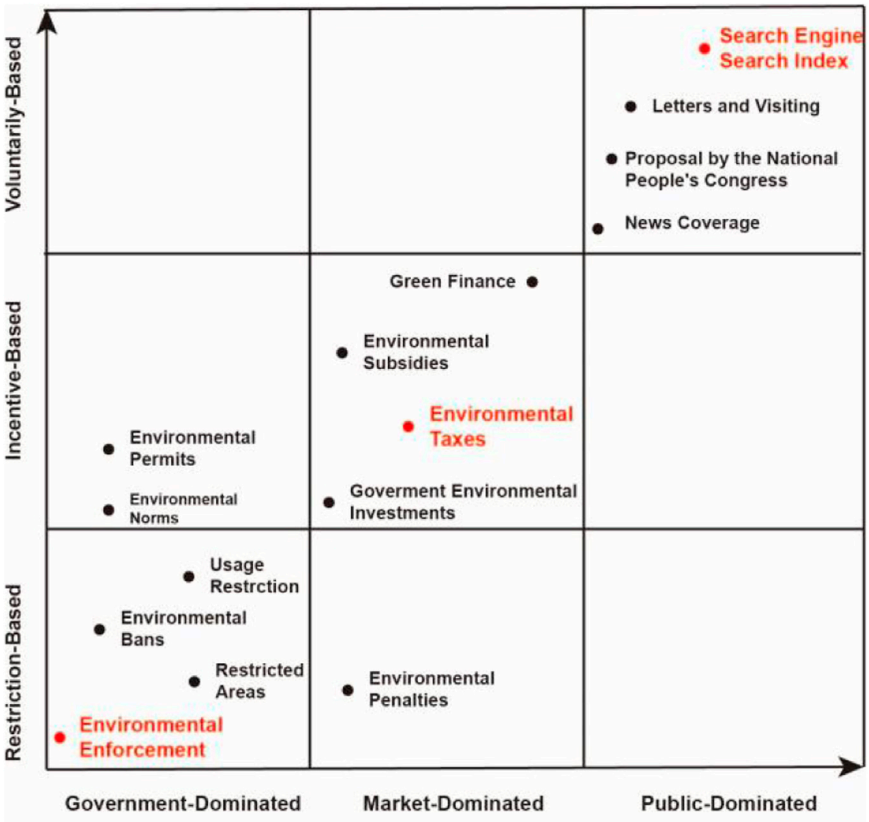

FIGURE 3
Variables selection logic of heterogeneous subjects dominated environmental regulations.

encourages businesses to decrease pollution emissions via market indicators (Cheng et al., 2017; Tang et al., 2016a). In this approach, the government can establish a market, such as an emission trading system, or leverage existing markets, such as pollution discharge fees and environmental taxes, to effectively coordinate the environmental behavior of enterprises (Tang et al., 2018; Tang et al., 2016b).

Environmental tax is widely recognized as a prominent example of market-based environmental instruments due to its utilization of economic mechanisms to shape behavior and stimulate environmental conservation (Tan et al., 2022). Through the imposition of taxes on activities that cause environmental harm or pollution, environmental tax effectively raises the costs associated with these activities, making them economically less desirable. As a result, businesses are incentivized to explore alternative, greener options that align with environmental goals (Tan et al., 2022). In line with the prevailing approach in current literature, this study adopts environmental tax as the representative observing variable for market-dominant environmental regulation.

3.2.2.3 Public-dominant environmental regulation (Public_DER)

Public-dominated environmental regulation has the most voluntary feature, which reflects the demand of the public for environmental quality and thus becomes the core reflection of informal and voluntary environmental regulation (Yu and Jin, 2022).

Existing studies mainly use questionnaire surveys to evaluate the public-dominated environmental regulation intensity, however, significant intervention bias and random sampling errors exist in the above method. In contrast, online search data is based on real search behavior, which is essentially an electronic trace left by human behavior. Its data accumulation is a nonintrusive process, thus, the "Hawthorne effect" could effectively be avoided by the feature of online data (Yu and Jin, 2022). In recent years, the practice of using online search data to reflect public environmental demands has also been recognized by scholars (Wang L. et al., 2023). Following the method in the mainstream (Wang L. et al., 2023), the Baidu Index of keywords related to the environment is adopted in this study as the measurement of the degree of public-dominated environmental regulation.

3.2.3 Heterogeneous subjects participation synergy index variable (HSP_Synergy)

Given that the focus of this study is to examine the synergistic and coordinated effects of environmental regulations, which are predominantly influenced by heterogeneous subjects, on environmental quality, the variable of heterogeneity subject participation synergy degree is introduced. This variable aims to capture the synergistic and coordinated extent to which different subjects with varying interests and perspectives participate in environmental governance. The measurement of the heterogeneity subjects participation synergy degree variable is conducted using the coupling coordination method, which provides a quantitative assessment of the level of synergy and coordination achieved among the heterogeneous subjects involved.

3.2.4 Control variables

The STIRPAT model is widely acknowledged as one of the most suitable models in the field of environmental economics, representing a stochastic extension of the conventional environmental IPAT model (York et al., 2003; Gani, 2021). The IPAT model takes into account three key factors: affluence, population size, and technological progress, which are widely recognized as pivotal elements influencing environmental performance in practical scenarios (Wang et al., 2017; Wu et al., 2021). In line with this concept, three control variables have been developed to capture these fundamental factors, as outlined below.

3.2.4.1 Affluence factor: green finance (*GF*)

The significant interplay between affluence factors and environmental quality has been widely supported in the existing literature (Yuan et al., 2020). As people's income levels increase, the expanded consumption of energy and resources resulting from higher national wealth inevitably contributes to environmental degradation and higher pollutant emissions. However, on the other hand, the accumulation of affluence can also stimulate green innovation and the advancement of environmentally friendly technologies (Wang and Wang, 2021). Considering the specific focus of this study, the green dimension of affluence factors, represented by green finance, is adopted as an observed control variable. In line with the prevailing approach, the measurement of the green finance index aligns with the methodology used in the study by Zhou and Tang (2022).

3.2.4.2 Population factor: employment rate (*EPR*)

The higher employment rate often aligns with heightened economic development and increased industrial activities, which can be attributed to rapid industrialization and economic growth (Yuan et al., 2020). However, it is crucial to acknowledge that these factors may lead to a rise in pollution and environmental degradation, primarily due to amplified energy consumption, resource extraction, and waste generation. Consequently, this scenario could potentially explain the observed negative impact on environmental quality. Within the scope of this study, the employment rate is utilized as a control variable to examine its influence on environmental outcomes.

3.2.4.3 Technological factor: green innovation patent amount (*GIPA*)

Technological progress plays a complex and multifaceted role, presenting both opportunities and challenges in the realms of development and production, as well as the potential for ecological damage and environmental pollution (Yuan et al., 2020). It serves as a double-edged sword, as advancements in technology offer the potential for economic growth and improved living standards, but also pose risks to the natural environment and ecological balance. In the vast landscape of technological advancements, it is noteworthy that green innovation patents hold a particularly significant relationship with environmental quality. By focusing on green innovation patents as a key control variable, this study aims to capture the distinctive contribution of technological factors to environmental outcomes.

3.2.5 Descriptive statistics

The distribution characteristics of the variables are analyzed by examining boxplots and distribution plots, as depicted in Figure 4. The data distribution for all variables exhibits a normal pattern without any significant outliers or extreme values. This demonstrates the strength and dependability of the chosen variables for this research. Therefore, all of these variables are deemed appropriate for further study and interpretation.

Furthermore, as all the dependent variables in this study are selected based on their relevance to environmental regulations, they share similar characteristics. Therefore, it is essential to examine the potential issue of collinearity among these variables. To assess collinearity, the Variance Inflation Factor (VIF) tests are conducted, and the results are presented in Table 2. Since the dependent variables are added to the regression models one by one, the VIF tests are repeated multiple times. The results in Table 2 reveal that the VIF values for all variables are well below 10, which is a commonly accepted threshold for detecting collinearity problems. This indicates the absence of severe multicollinearity issues among the variables and confirms the feasibility of including all the explanatory variables in the same regression model.

3.2.6 Summarizing of variables

To account for the potential influence of inflation over time, the inflation-adjusted GDP index based on the year 2010 is employed to deflate price fluctuations. Furthermore, in order to ensure the comparability of empirical results, a mean normalization technique is applied to the data of all variables. The summarizing of all variables is listed in Table 3, including abbreviations, descriptions, and resources.

4 Heterogeneous subjects participation synergy index

In response to the limitations in existing literature, where various environmental regulations are often studied in isolation, this study introduces the variable of heterogeneous subjects participation synergy (*HSP_Synergy*). This variable serves as a crucial link, connecting the heterogeneous subjects dominant environmental regulations by quantifying their synergy and collaboration degree. By constructing this variable, it provides a quantitative measure to investigate how the synergy and coordination among these subjects influence environmental quality and the effectiveness of environmental regulations.

4.1 Construction process

The coupling coordination method is a quantitative approach that assesses the degree of coordination and synergy among different elements or factors in a complex system (Xing et al., 2019). The main idea behind the coupling coordination method is to evaluate how

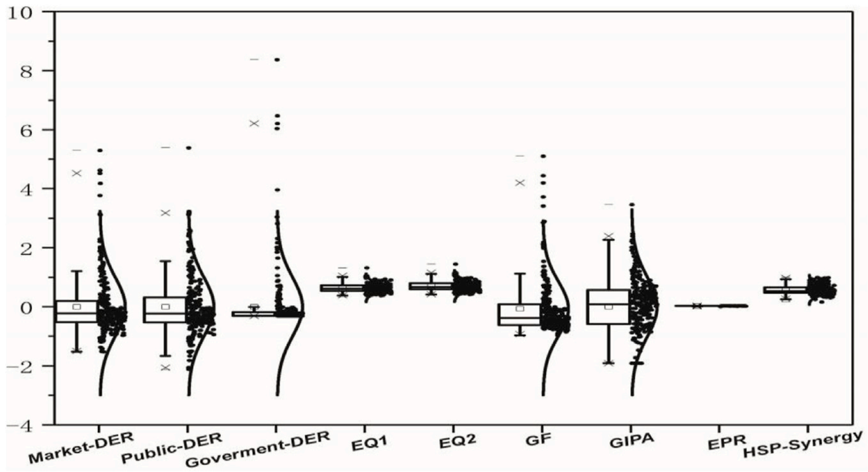

FIGURE 4
Descriptive statistics.

TABLE 2 Results of VIF tests.

Variable	Government_DER	Market_DER	Public_DER	HSP_Synergy	GF	EPR	GIPA
1/VIF	0.54				0.62	1.30	1.14
VIF	1.83				1.59	0.76	0.87
1/VIF		0.97			0.82	0.76	0.85
VIF		1.03			1.21	1.30	1.18
1/VIF			0.98		0.82	0.87	0.75
VIF			1.01		1.21	1.15	1.32
1/VIF				0.68	0.61	0.76	0.86
VIF				1.46	1.61	1.30	1.15

well different elements within a system work together and complement each other (Liu et al., 2018). It aims to measure the level of coordination and synergy among these elements, which can offer useful perspectives on the general efficacy and efficiency of the system (Liu et al., 2018).

In the context of this research, this method helps measure the level of collaboration and coordination among the three kinds of heterogeneous subjects dominant environmental regulation. Government-, market-, and public-dominant environmental regulations, thereby, are regarded as observing elements in the whole environmental management complex system. Therefore, the coupling coordination method is used to construct heterogeneous subjects participation synergy index variable (*HSP_Synergy*), the calculation equation is shown in Equation 3 below.

$$HSP\_Synergy_{i,t} = \left[\prod_{j=1}^{n} U_j \bigg/ \left(\frac{1}{n}\prod_{j=1}^{n} U_j\right)^{n}\right]^{\frac{1}{n}} \tag{3}$$

where, $HSP\_Synergy_{i,t}$ denotes the heterogeneous subjects participation synergy degree of province i at tth year, which is designed to measure the degree of synergy and coordination among the three kinds of heterogeneous subjects dominant environmental regulations; U_j denotes the jth observing element in the complex coupling system, in this study, which are variables of government-dominant environmental regulations (*government-DER*), market-dominant environmental regulations (*market-DER*), and public-dominant environmental regulations (*public-DER*); n denotes the amount of observing element, which equals three in this study.

4.2 Participation synergy category identification

Furthermore, this study categorizes provinces based on the degree of participation synergy among heterogeneous subjects dominant environmental regulations. Referring to relevant research (Liu et al., 2018; Xing et al., 2019), the coupling and coordination between these regulations are classified into three distinct stages: the coordinated, transiting, and maladjustment and declining stages. These stages are determined by analyzing the level of cooperation and synergy among the different

TABLE 3 Summarizing of variables.

	Variable	Abb.	Description	Data resource
Independent Variables	Government-Dominant Environmental Regulation	$Government\_DER_{i,t}$	The degree of corrected registered amount of environmental administrative penalty cases of province i at year t	Data is from the PKULAW Database
	Market-Dominant Environmental Regulation	$Market\_DER_{i,t}$	The amount of environmental tax of province i at year t	Data is from China Environmental Statistical Yearbook
	Public-Dominant Environmental Regulation	$Public\_DER_{i,t}$	The degree of environmental-related Baidu search index of province i at year t	Data is from Baidu Search Engine
	Heterogenous Subjects Participation Synergy Degree	$HSP\_Synergy_{i,t}$	The development of synergistic and coordinated degrees among three kinds of heterogenous subjects environmental regulations	Calculated by this study, data is from the PKULAW Database, China Environmental Statistical Yearbook, and Baidu Search Engine
	Government and Market Participation Synergy Degree	$GM\_Synergy_{i,t}$	The development of synergistic and coordinated degrees among government- and market-dominant environmental regulations	Calculated by this study, data is from the PKULAW Database and China Environmental Statistical Yearbook
	Government and Public Participation Synergy Degree	$GP\_Synergy_{i,t}$	The development of synergistic and coordinated degrees among government- and public-dominant environmental regulations	Calculated by this study, data is from the PKULAW Database, China Environmental Statistical Yearbook, and Baidu Search Engine
	Market and Public Participation Synergy Degree	$MP\_Synergy_{i,t}$	The development of synergistic and coordinated degrees among market- and public-dominant environmental regulations	Calculated by this study, data is from the PKULAW Database, China Environmental Statistical Yearbook, and Baidu Search Engine
	Dummy variable to distinguish between high and low degree synergy regions	$REGION\_DUMMY_i$	The dummy index of province i, province i is with a high level of heterogenous subjects participation synergy when dummy variable equals 1; province i is with the low level of heterogenous subjects participation synergy when the dummy variable equals 0	Calculated by this study
Dependent Variables	Environmental Quality	$EQ1_{i,t}$	The degree of environmental quality calculated by the SSBM-DEA method of province i at year t	Calculated by this study, data are from China Environmental Statistical Yearbook, China Statistical Yearbook, and the WIND database
	Environmental Quality	$EQ2_{i,t}$	The degree of environmental quality calculated by the non-oriented SSBM-DEA method of province i at year t	Calculated by this study, data are from China Environmental Statistical Yearbook, China Statistical Yearbook, and the WIND database
Control Variables	Green Finance	$GF_{i,t}$	The development degree of green finance of province i at year t	Calculated by this study, data are from China Environmental Statistical Yearbook, China Statistical Yearbook, and the WIND database
	Employment Rate	$EPR_{i,t}$	The degree of the employment rate of province i at year t	Data is from the WIND database
	Green Innovation Patent Amount	$GIPA_{i,t}$	The amount of green innovation patents of province i at year t	Data is from the WIND database

environmental regulations within each province. The specific criteria for categorization are presented in Table 4, which enables a more targeted and tailored policy approach for each province, taking into account its unique dynamics of environmental regulations. Understanding these different stages helps to identify areas that require targeted interventions and policy adjustments to promote better environmental outcomes.

Based on the division results presented in Figure 4, the 30 observed provinces can be categorized into three distinct stages. Among these, five provinces are currently at the maladjustment and declining stage, indicating that the synergy degree among three heterogeneous subjects dominant environmental regulations is still low, and the coordination development of various environmental regulations is close to collapse. On the other hand, 24 provinces fall into the transiting stage, signifying that the synergy degree among three heterogeneous subjects dominant environmental regulations is at a median level. In this stage, the coordination development of various environmental regulations is transitioning from a non-synergistic state to a more synergized state. In contrast, only one province has achieved the most optimal situation, known as the coordinated stage. This stage indicates that various environmental regulations have developed in a balanced and synergistic manner, maximizing their combined environmental effects.

As depicted in Figure 5, it is evident that a substantial proportion of provinces are currently positioned within the crucial transiting stage. In this pivotal phase, proactive endeavors are underway to reinforce and bolster the synergy and coordination among diverse environmental regulations. Given the importance of this stage, policymakers and stakeholders are diligently striving to bridge the gaps and foster effective collaboration between heterogeneous subjects' dominant environmental regulations. This strategic focus

TABLE 4 Coupling coordination stages categorizations standards.

Interval value	Coupling coordination degree	Stages categorizations
(0, 0.1)	Extremely Disordered	Maladjustment and Declining Stage
[0.1, 0.2)	Severe Disordered	
[0.2, 0.3)	Moderate Disordered	
[0.3, 0.4)	Mild Disordered	
[0.4, 0.5)	On the Verge of Disordered	Transiting Stage
[0.5, 0.6)	Barely Coordinated	
[0.6, 0.7)	Junior Coordinated	Coordinated Stage
[0.7, 0.8)	Intermediate Coordinated	
[0.8, 0.9)	Well Coordinated	
[0.9, 1.0)	Highly Coordinated	

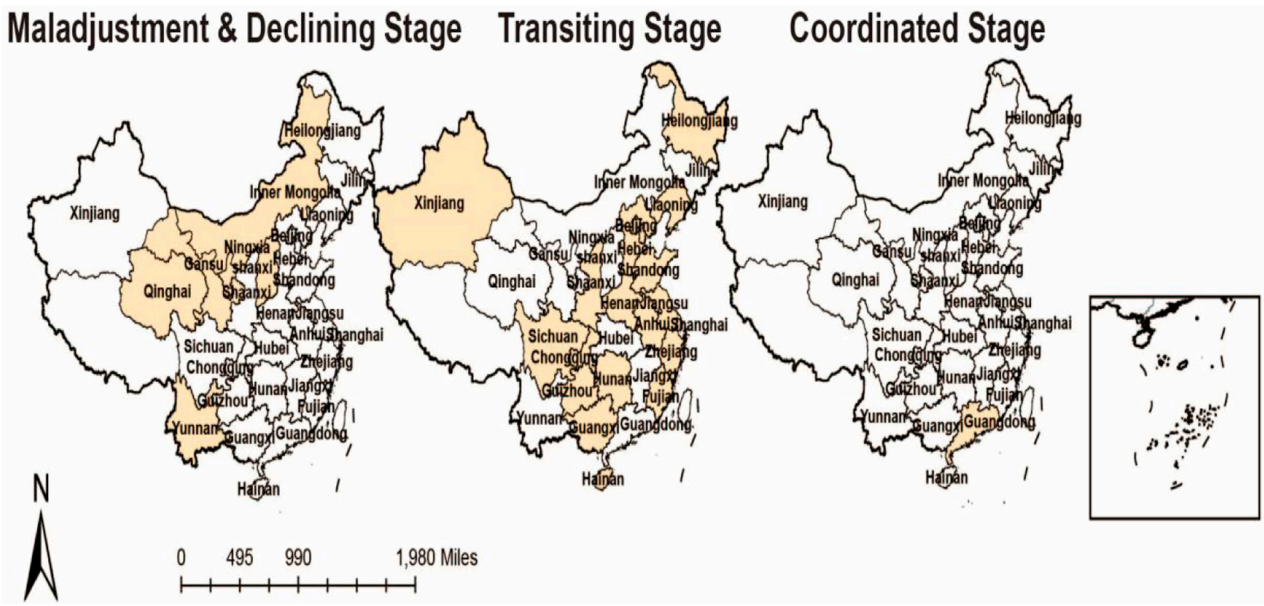

FIGURE 5
Coupling coordination stages categorizations.

on enhancing coordination at the transiting stage reflects a collective commitment to achieving more harmonious and synergistic outcomes in environmental governance across these provinces.

4.3 Spatiotemporal development characteristics

Based on the natural breakpoint classification method, the temporal and spatial distribution, as well as the evolution of the constructed variable of heterogeneous subjects participation synergy (*HSP_Synergy*) in 30 provinces observed in this study, are drawn as the map version in Figure 6. The spatiotemporal evolution characteristics of heterogeneous subjects participation synergy are captured as three aspects in the past decade.

Firstly, there has been a gradual increase in synergy among heterogeneous subjects in environmental governance over the past decade. This indicates an increasing inclination towards cooperation and collaboration among different entities engaged in environmental regulation, which could result in more efficient policy implementation and enhanced environmental results. Secondly, the new growth in *HSP_Synergy* is predominantly observed in provinces located in the central region, such as Sichuan and Shaanxi. This spatial pattern indicates that central regions are witnessing significant progress in fostering synergy and coordination among different environmental regulations and

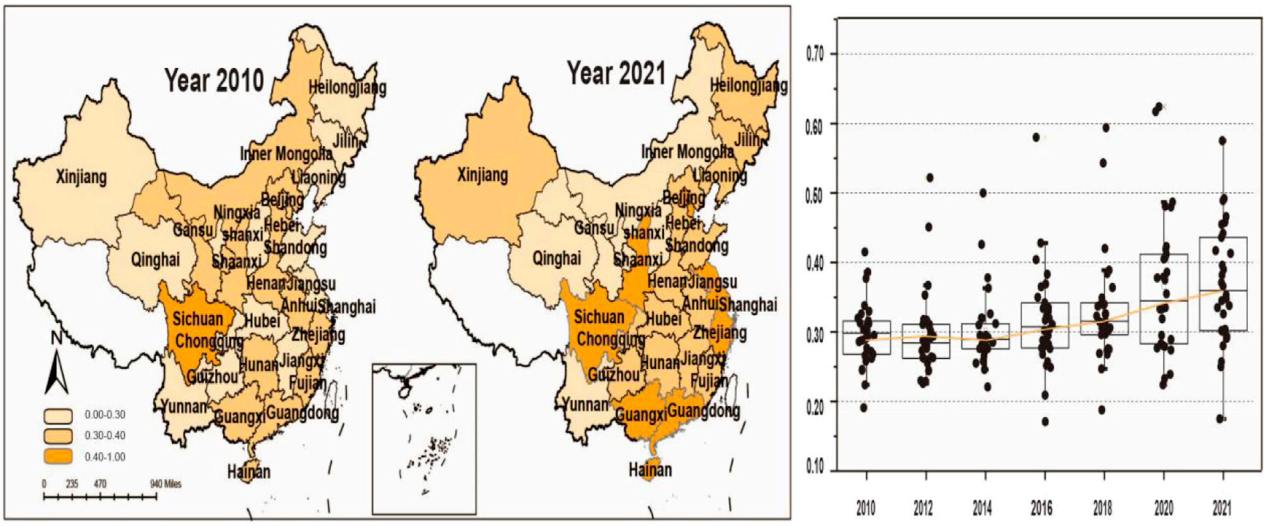

FIGURE 6
Spatiotemporal development characteristics.

stakeholders. This may be attributed to specific regional policies, resource allocation, or local initiatives that promote cooperation among diverse actors. Thirdly, the HSP_Synergy variance is exhibiting a rising pattern, and there is a distinct division across the provinces. Certain provinces are witnessing significant enhancements in synergy, while others are falling behind with lower levels of cooperation across heterogeneous subjects. The increasing divergence highlights the significance of tackling regional inequalities and difficulties in promoting cooperation in environmental governance.

4.4 Coordinated stage of Guangdong province

Among the various provinces analyzed in this study, Guangdong is the only region that reached the coordination stage in terms of integrating government-dominant, market-dominant, and public-dominant environmental regulations. This achievement is due to several key factors that distinguish Guangdong from other provinces, which include its comprehensive regulatory framework, the effective use of market-based instruments, and the active participation of the public.

The provincial government of Guangdong has been proactive in setting and enforcing stringent environmental standards across various sectors, particularly in high-pollution industries such as manufacturing, transportation, and energy production. Guangdong's regulatory framework is not only comprehensive but also enforced with strong penalties for non-compliance. The government's active role in regulating industrial emissions and its focus on green development initiatives have created a solid foundation for environmental governance. This robust enforcement capacity ensures that government regulations are adhered to, which is a critical step in achieving coordination between the three regulatory types.

In addition to government regulations, Guangdong has integrated market-based instruments, such as emissions trading systems (ETS) and environmental taxes, into its regulatory approach. These market-driven mechanisms incentivize businesses to reduce emissions and adopt cleaner technologies by providing financial rewards for compliance. Research has shown that the success of market-based instruments is largely dependent on the alignment with government policies, and Guangdong has successfully linked these tools to its environmental goals. The province's emissions trading system is one of the first and most successful in China, promoting cost-effective emissions reductions while supporting sustainable economic growth.

A defining feature of Guangdong's success is the high level of public participation in environmental governance. Public involvement in environmental issues is fostered through community-driven initiatives, citizen science projects, and widespread environmental education programs. Guangdong has also implemented public consultations during policy formulation, ensuring that local communities have a say in environmental decision-making. This public engagement has reinforced the regulatory framework, ensuring that environmental policies are not only top-down but also have strong grassroots support. By involving citizens in policy processes, Guangdong has fostered a culture of compliance and public accountability, which has contributed significantly to its success in reaching the coordination stage.

While Guangdong has reached the coordination stage, other provinces have not achieved the same level of synergy. For instance, Beijing and Shanghai have strong governmental controls, but these regions lack the same level of public engagement seen in Guangdong. Jiangsu and Zhejiang have utilized market-based mechanisms such as emissions trading, but their regulatory frameworks do not integrate public participation to the same extent. These differences in regulatory integration explain why Guangdong's model has been more successful in achieving full coordination between government, market, and public regulations. The success of Guangdong provides valuable lessons for other provinces and regions looking to improve their environmental governance. Key takeaways include the importance of integrating government, market, and public

TABLE 5 Effects of heterogeneous subjects participation synergy on environmental quality.

	Coef	Std. Err	z	P > |z|	[Confi. Int.]
Model 1 OLS Dependent Variable = *EQ1*					
HSP_Synergy	−0.22***	0.06	−3.30	0.00	[−0.35, −0.09]
EPR	2.43	1.58	1.54	0.12	[−0.66, 5.53]
GF	0.05***	0.01	4.27	0.00	[0.02, 0.07]
GIPA	−0.00	0.00	−0.95	0.34	[−0.02, 0.01]
Constant	0.69***	0.06	10.45	0.00	[0.56, 0.82]
Wald chi2	21.91***				
*R*_square	0.14				
Model 2 OLS Dependent Variable = *EQ2*					
HSP_Synergy	−0.24***	0.07	−3.33	0.00	[−0.39, −0.10]
EPR	2.68	1.73	1.54	0.12	[−0.72, 6.09]
GF	0.06***	0.01	4.27	0.00	[0.03, 0.08]
GIPA	−0.00	0.01	−0.95	0.34	[−0.03, 0.01]
Constant	0.76***	0.07	10.45	0.00	[0.62, 0.90]
Wald chi2	21.91***				
*R*_square	0.14				
Model 3 GLS Dependent Variable = *EQ1*					
HSP_Synergy	−0.21***	0.06	−3.33	0.00	[−0.35, −0.09]
EPR	2.43	1.56	1.54	0.12	[−0.63, 5.50]
GF	0.05***	0.01	4.31	0.00	[0.02, 0.07]
GIPA	−0.00	0.00	−0.95	0.33	[−0.02, 0.01]
Constant	0.69***	0.06	10.55	0.00	[0.56, 0.82]
Wald chi2	22.33***				
*R*_square	0.21				
Model 4 GLS Dependent Variable = *EQ2*					
HSP_Synergy	−0.22***	0.07	−3.33	0.00	[−0.39, −0.10]
EPR	2.68	1.72	1.56	0.12	[−0.69, 6.05]
GF	0.05***	0.01	4.31	0.00	[0.03, 0.08]
GIPA	−0.00	0.01	−0.96	0.33	[−0.03, 0.01]
Constant	0.76***	0.07	10.55	0.00	[0.62, 0.90]
Wald chi2					
*R*_square	0.21				
Model 5 SDM Dependent Variable = *EQ1*					
HSP_Synergy	−0.23***	0.06	−3.33	0.00	[−0.35, −0.09]
EPR	2.42	1.56	1.55	0.12	[−0.64, 5.50]
GF	0.05***	0.01	4.29	0.00	[0.02, 0.07]
GIPA	−0.00	0.00	−0.96	0.33	[−0.02, 0.00]
Constant	0.68***	0.09	7.45	0.00	[0.50, 0.86]

(Continued on following page)

TABLE 5 (*Continued*) Effects of heterogeneous subjects participation synergy on environmental quality.

	Coef	Std. Err	z	P > |z|	[Confi. Int.]
Wald chi2	0.02***	0.00	11.62	0.00	[0.01, 0.02]
*R*_square	0.14				
Model 6 SDM Dependent Variable = *EQ2*					
HSP_Synergy	−0.25***	0.07	−3.33	0.00	[−0.39, −0.10]
EPR	2.66	1.72	1.55	0.12	[−0.71, 6.05]
GF	0.05***	0.01	4.29	0.00	[0.03, 0.08]
GIPA	−0.00	0.01	−0.96	0.33	[−0.03, 0.01]
Constant	0.75***	0.10	7.45	0.00	[0.55, 0.95]
Wald chi2	0.02***	0.00	11.62	0.00	[0.02, 0.02]
*R*_square	0.14				

Note: 1. The symbols *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
2. Econometric methods of Ordinary Least Squares (OLS), Generalized Least Squares (GLS), and Spatial Durbin Model (SDM) are adopted in this research. OLS is the most basic econometric method, performed to reflect baseline associations among heterogeneous subjects dominant environmental regulations and environmental quality. GLS is performed to avoid the influence of observation data with different variances on empirical results by weighting the error term. SDM is introduced to reflect the spatial influence and dependence between environmental regulations and environmental quality. Models 1 and 2 are conducted using the OLS method; Models 3 and 4 are conducted using the GLS method; Models 5 and 6 are conducted using the SDM method; Models 1, 3, and 5 are conducted using the *EQ1* as the dependent variable; Models 2, 4, and 6 are conducted using the *EQ2* as the dependent variable.

policies into a cohesive regulatory framework, fostering public participation to enhance policy effectiveness, and adapting policies to local conditions. These elements, when combined, have the potential to create a synergistic effect that enhances environmental quality across multiple sectors.

5 The competitive effects of heterogeneous subjects dominant environmental regulations on environmental quality

5.1 Effects of heterogeneous subjects participation synergy on environmental quality

How do heterogeneous subjects dominant environmental regulations interact with each other? Do they exhibit a competitive or cooperative pattern when they come to improving environmental quality? To address and investigate these inquiries, the constructed variable of heterogeneous subjects participation synergy degree is included in the regression model to assess the impact of participation synergy on environmental quality. The results of the regression model examining the effect of heterogeneous subjects participation synergy degree on environmental quality are presented in Table 5, and for enhanced comprehension, the statistical outcomes are visually depicted in Figure 7 for comparative analysis.

In contrast to conventional expectations, this study has confirmed that, using the environmental administrative, environmental tax, and public environmental concern as proxy variables, the participation synergy among heterogeneous subjects undermines rather than fosters environmental quality. And the observed interaction pattern among heterogeneous subjects dominated environmental regulations leans towards competition rather than cooperation. As the level of heterogeneous subjects participation synergy increases, there is a significant decrease in environmental quality. Each incremental unit of synergy intensity is associated with a decline of approximately 22%–25% in environmental quality. Importantly, this negative impact of increased synergy degree on environmental quality is consistent across heterogeneous dependent variables and econometrics methodology.

Specially, when utilizing the OLS method in Models 1 and 2, each unit synergy degree among heterogeneous subjects dominant environmental regulations (*HSP-Synerg*) leads to 22% and 24% unit declines in two observing dependent variables of environmental quality (*EQ1* and *EQ2*), respectively, the significance level of which are both at the 1% level. When utilizing the GLS method in Models 3 and 4, each unit synergy degree among heterogeneous subjects dominant environmental regulations (*HSP-Synerg*) leads to 21% and 22% unit declines in two observing dependent variables of environmental quality (*EQ1* and *EQ2*), respectively, the significance level of which are both at the 1% level. When utilizing the SDM method in Models 5 and 6, each unit synergy degree among heterogeneous subjects dominant environmental regulations (*HSP-Synerg*) leads to 23% and 25% unit declines in two observing dependent variables of environmental quality (*EQ1* and *EQ2*), respectively, the significance level of which are both at the 1% level.

5.2 Difference of environmental quality in different participation synergy degree regions

In addition, this study further investigates the impact of the heterogeneous subjects participation synergy in real-world scenarios. Specifically, this study examines the differences in environmental quality between regions with high synergy degrees

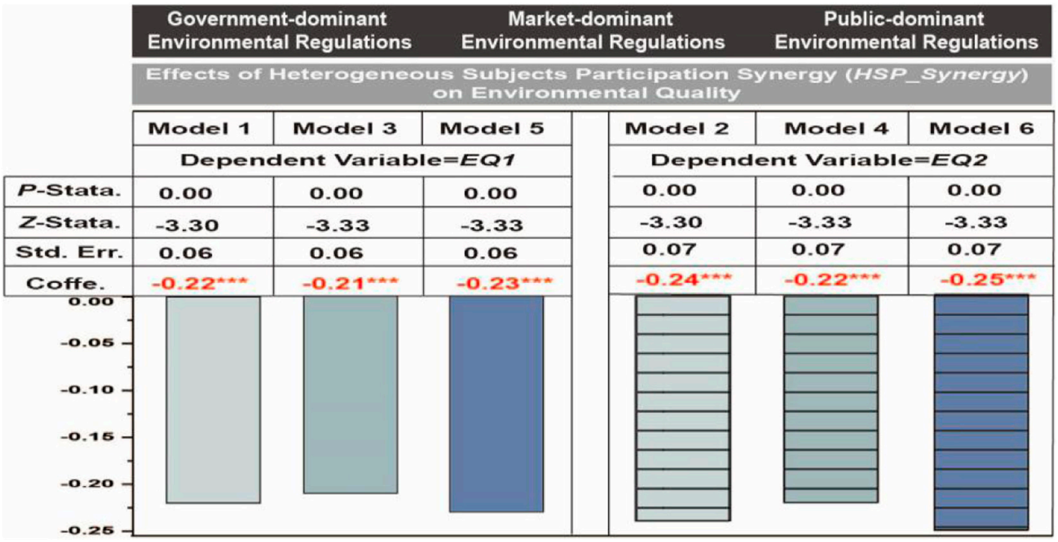

FIGURE 7
Comparison of environment effects of heterogeneous subjects participation synergy.

and those with low synergy degree. To analyze this, a dummy variable is introduced to distinguish between high synergy degree regions (*REGION_DUMMY* = 1) and low synergy degree regions (*REGION_DUMMY* = 0) in the regression model. The results of this analysis are presented in Table 6, and the visualization results are presented in Figure 8. These findings provide robust evidence supporting the previously identified competitive effects among heterogeneous subjects dominant environmental regulations.

From Table 6 and Figure 8, it can be proved that there are significant differences in environmental quality in regions with different participation synergy degrees, based on real situations in China, environmental quality is higher by 36‰–42‰ in regions with low synergy degrees than in regions with high synergy degree.

Specifically, in models performed by the method of the OLS (Models 7 and 8), environmental quality (*EQ1* and *EQ2*) is higher by 37‰–41‰ in regions with low synergy degree (*REGION_DUMMY* = 0) than in regions with high synergy degree (*REGION_DUMMY* = 1), and the significance of the statistics values are both less than at least 10%. In models performed by the method of the GLS (Models 9 and 10), environmental quality (*EQ1* and *EQ2*) is higher by 38‰–42‰ in regions with low synergy degree (*REGION_DUMMY* = 0) than in regions with high synergy degree (*REGION_DUMMY* = 1), and the significance of the statistics values are both less than at least 10%. In models performed by the method of the SDM (Models 11 and 12), environmental quality (*EQ1* and *EQ2*) is higher by 36‰–40‰ in regions with low synergy degree (*REGION_DUMMY* = 0) than in regions with high synergy degree (*REGION_DUMMY* = 1), and the significance of the statistics values are both less than at least 10%.

5.3 Robustness test

To ensure the robustness of the results, we incorporate additional control variables reflecting factors that could influence the effectiveness of environmental regulations, such as regional industrial structures, local government fiscal capacity, and public awareness. By accounting for these variables, we assess whether the main conclusions of this study are influenced by regional variations or structural differences in environmental governance. The following additional control variables are included in the regression models to account for the factors might affecting research conclusions.

5.3.1 Industrial structure (*IS*)

Differences in the industrial structure and economic priorities of each province may influence both the level of environmental regulation and its effectiveness. Provinces with a higher proportion of heavy industries, such as mining, manufacturing, and energy production, may face greater challenges in implementing environmental regulations and may prioritize industrial growth over environmental protection (Huang et al., 2021). To capture this variation, we include a variable that represents the share of heavy industries in each province's GDP. This allows us to control for regional differences in economic structures that may influence how market-dominant regulations, such as environmental taxes or emissions trading systems, are implemented and their effectiveness.

5.3.2 Local government fiscal capacity (*LGFC*)

The willingness and capacity of local governments to enforce environmental regulations can differ significantly across regions, influenced by fiscal capacity and the relationships between local and central governments (Wang F. et al., 2024). As highlighted in research on fiscal decentralization, local governments with higher fiscal autonomy may have greater resources and incentives to implement environmental policies effectively (Zhang et al., 2022). To account for this, we introduce a variable reflecting the fiscal capacity of local governments, based on measures of fiscal decentralization. This variable helps to control for the potential

TABLE 6 Difference of environmental quality in participation synergy degree regions.

	Coef	Std. Err	z	P > |z|	[Confi. Int.]
Model 7 dependent variable = *EQ1*					
REGION_DUMMY	−0.037*	0.02	−1.71	0.08	[−0.08, 0.01]
EPR	2.45	1.60	1.53	0.12	[−0.69, 5.59]
GF	0.04***	0.01	3.43	0.00	[0.01, 0.06]
GIPA	−0.01	0.00	−1.09	0.27	[−0.02, 0.01]
Constant	0.57***	0.05	10.60	0.00	[0.47, 0.68]
Wald chi2	13.61***				
*R*_square	0.14				
Model 8 OLS dependent variable = *EQ2*					
REGION_DUMMY	−0.041*	0.02	−1.71	0.08	[−0.08, 0.00]
EPR	2.69	1.76	1.53	0.12	[−0.76, 6.15]
GF	0.04***	0.01	3.43	0.00	[0.01, 0.07]
GIPA	−0.01	0.01	−1.09	0.27	[−0.03, 0.00]
Constant	0.63***	0.06	10.60	0.00	[0.51, 0.75]
Wald chi2	13.61***				
*R*_square	0.14				
Model 9 GLS Dependent Variable = *EQ1*					
REGION_DUMMY	−0.038*	0.02	−1.72	0.08	[−0.08, 0.01]
EPR	2.45	1.59	1.54	0.12	[−0.66, 5.56]
GF	0.04***	0.01	3.46	0.00	[0.01, 0.06]
GIPA	−0.01	0.00	−1.10	0.27	[−0.02, 0.00]
Constant	0.57***	0.05	10.70	0.00	[0.47, 0.68]
Wald chi2	13.87***				
*R*_square	0.14				
Model 10 GLS Dependent Variable = *EQ2*					
REGION_DUMMY	−0.042*	0.02	−1.72	0.08	[−0.08, 0.00]
EPR	2.69	1.74	1.54	0.12	[−0.73, 6.12]
GF	0.04***	0.01	3.46	0.00	[0.02, 0.07]
GIPA	−0.01	0.01	−1.10	0.27	[−0.03, 0.00]
Constant	0.63***	0.05	10.70	0.00	[0.52, 0.75]
Wald chi2	13.87***				
*R*_square	0.14				
Model 11 SDM Dependent Variable = *EQ1*					
REGION_DUMMY	−0.036*	0.02	−1.72	0.08	[−0.08, 0.00]
EPR	2.44	1.59	1.53	0.12	[−0.67, 5.56]
GF	0.04***	0.01	3.44	0.00	[0.01, 0.06]
GIPA	−0.01	0.00	−1.10	0.27	[−0.02, 0.01]
Constant	0.57***	0.08	6.74	0.00	[0.40, 0.73]

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TABLE 6 (*Continued*) Difference of environmental quality in participation synergy degree regions.

	Coef	Std. Err	z	P > |z|	[Confi. Int.]
sigma2_e	0.02***	0.00	11.62	0.00	[0.01, 0.02]
*R*_square	0.14				
Model 12 SDM Dependent Variable = *EQ2*					
REGION_DUMMY	−0.040*	0.02	−1.72	0.08	[−0.08, 0.00]
EPR	2.68	1.75	1.54	0.12	[−0.74, 6.12]
GF	0.04***	0.01	3.44	0.00	[0.01, 0.07]
GIPA	−0.01	0.00	−1.10	0.27	[−0.03, 0.00]
Constant	0.62***	0.09	6.74	0.00	[0.44, 0.81]
sigma2_e	0.02***	0.00	11.62	0.00	[0.02, 0.03]
*R*_square	0.14				

Note: 1. The symbols *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
2. The setting of *REGION_DUMMY* variable is to separate high synergy degree regions and low synergy degree regions, *REGION_DUMMY* = 1 when the observation object is located at the regions with high synergy degree, *REGION_DUMMY* = 0 when the observation object is located at the regions with low synergy degree.
3. Models 7 and 8 are conducted using the OLS method; Models 9 and 10 are conducted using the GLS method; Models 11 and 12 are conducted using the SDM method; Models 7, 9, and 11 are conducted using the *EQ1* as the dependent variable; Models 8, 10, and 12 are conducted using the *EQ2* as the dependent variable.

FIGURE 8
Comparison of environmental quality in different intensity gap regions.

impact of differing fiscal arrangements on the enforcement of government-dominant regulations, such as environmental penalties or emissions standards.

5.3.3 Public awareness (*PA*)

Public awareness and education levels are critical factors that influence the effectiveness of public-dominant environmental regulations, such as community-driven initiatives or public participation in environmental decision-making (Anokye et al., 2024). In regions with higher levels of education and environmental awareness, the public may be more likely to comply with regulations and engage in environmentally friendly behaviors (Lye et al., 2024). To capture this influence, we use an education index that reflects the average education level of residents in each province. This variable helps control for the impact of public awareness on the success of public-dominant policies, as more educated populations may be more responsive to such initiatives.

TABLE 7 Robustness tests.

	Coef	Std. Err	z	P > |z|	[Confi. Int.]
Model 13 dependent Variable = *EQ1*					
HSP_Synergy	−0.21***	0.06	−3.30	0.00	[−0.34, −0.08]
IS	0.05***	0.01	4.31	0.00	[0.02, 0.07]
LGFC	0.05***	0.01	4.27	0.00	[0.02, 0.07]
PA	−0.00***	0.00	−0.95	0.34	[−0.02, 0.01]
Constant	0.69***	0.06	10.45	0.00	[0.56, 0.82]
Wald chi2	21.91***				
*R*_square	0.14				
Model 14 dependent Variable = *EQ2*					
HSP_Synergy	−0.23***	0.07	−3.33	0.00	[−0.38, −0.09]
IS	0.04***	0.01	3.43	0.00	[0.01, 0.07]
LGFC	0.06***	0.01	4.27	0.00	[0.03, 0.08]
PA	−0.00	0.01	−0.95	0.34	[−0.03, 0.01]
Constant	0.76***	0.07	10.45	0.00	[0.62, 0.90]
Wald chi2	21.91***				
*R*_square	0.14				

Note: 1. The symbols *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
2. Model 13 is conducted using the *EQ1* as the dependent variable; Model 14 is conducted using the *EQ2* as the dependent variable.

The results of the robustness tests are presented in Table 7 below. The robustness tests confirm that the primary conclusions of this study remain stable and are not significantly influenced by variations in regional industrial structures, local government fiscal capacity, or public awareness. The inclusion of these control variables helps to account for potential confounding factors that could affect the effectiveness of environmental regulations across different regions. The results indicate that, despite regional disparities in industrial composition and economic priorities, as well as differences in fiscal capacity and public awareness, the observed competitive effects between government-market regulations and the higher environmental benefits associated with government-public participation remain consistent and statistically significant. These findings suggest that the core relationships identified in the study are robust and not unduly affected by external factors related to regional economic development, local government governance capacity, or public engagement. Thus, the study's conclusions are not sensitive to the inclusion of these additional control variables, providing further support for the reliability and generalizability of the results. This reinforces the study's contributions to understanding the interaction effects of different environmental regulations and underscores the robustness of the findings in informing policy decisions related to environmental governance.

5.4 Discussion

Overall, contrary to conventional understanding, this study provides empirical evidence that highlights that, using the environmental administrative, environmental tax, and public environmental concern as proxy variables, the detrimental impact of heterogeneous subjects' participation synergy on environmental quality, and the observed interaction pattern among heterogeneous subjects dominant environmental regulations leans towards competition rather than cooperation. For one aspect, each incremental unit of synergy intensity is associated with a decline of approximately 22%–25% in environmental quality, and this decline caused by the participation synergy is robust in the heterogeneity of dependent variables and econometrics methodology. For another aspect, there are significant differences in environmental quality in regions with different participation synergy degrees, based on real situations in China, environmental quality is higher by 36‰–42‰ in regions with low synergy degrees than in regions with high synergy degrees.

The competition effects observed in this study can be explained by the dynamic interplay among heterogeneous subjects dominant environmental regulations. Using the environmental administrative, environmental tax, and public environmental concern as proxy variables, rather than working collaboratively, these regulations tend to compete with each other, leading to a negative impact on environmental quality. This competition arises due to various factors such as conflicting interests, limited resources, or different approaches to environmental governance. Firstly, heterogeneous subjects may have different goals and priorities when it comes to environmental regulation. For example, market-dominant environmental regulations primarily aim to encourage and support environmentally sound actions by using economic incentives (Ren et al., 2018). Conversely, government-dominant environmental regulations utilize compulsory legislation and enforcement mechanisms to achieve environmental objectives (Cui et al., 2022). The disparity in policy objectives contributes to the rivalry among stakeholders who may prefer one strategy over the other.

Secondly, each type of environmental regulation may have limited resources allocated to them, such as funding, personnel, and enforcement capabilities. When multiple regulations compete for these limited resources, it can create a situation where one regulation gains an advantage over the others, potentially leading to an imbalance in environmental protection efforts (Cheng et al., 2017; Li et al., 2022).

Thirdly, heterogeneous subjects may adopt different approaches and strategies in their environmental regulation efforts. These differences can result in clashes and competition as each subject tries to assert its preferred method or solution (Ji et al., 2022; Li et al., 2023). For instance, the government may favor command-and-control regulations, while market-based mechanisms may advocate for market incentives and pricing mechanisms.

6 The asymmetric strategy of heterogeneous subjects dominant environmental regulations

Based on the findings presented in Section 5, it is confirmed that competition effects exist among heterogeneous subjects dominant environmental regulations. These findings have important policy implications, suggesting that extreme levels of average environmental regulation participation by heterogeneous subjects should be avoided, and a more focused strategy should be adopted instead. However, while the above analysis focuses on the three types of heterogeneous subjects dominant environmental regulations, the political implications of these findings still remain somewhat unclear. To provide a more comprehensive understanding, a detailed analysis is conducted on the interaction between each pair of heterogeneous subjects dominant environmental regulations, through which an appropriate "asymmetric strategy" is thereby proposed. This analysis considers both perspectives of synergy index and introducing sequence. Based on determining competitive effects, the method of GLS with variance weight adjustment was used to study the asymmetric effects of different synergy indices on environmental quality.

6.1 Synergy index dimension: the asymmetric effects of different synergy index on environmental quality

First of all, the primary objective of this section is to investigate the most effective cooperation strategy by considering the synergy index dimension. To accomplish this, this study employs the coupling coordination method, resulting in the derivation of three additional variables (*GM_Synergy*, *GP_Synergy*, *MP_Synergy*). By comparing the changes in regression coefficients, the study aims to identify the environmental effects mode that yields the most favorable environmental outcomes. The research findings, presented in Table 8 and visually depicted in Figure 9, provide insights into the optimal cooperation strategy among the different environmental regulations.

The regression results reveal an asymmetric characteristic in the competition effects of heterogeneous subjects dominant environmental regulations on environmental quality. The environmental effects observed in the interaction between government- and public-dominant environmental regulations (i.e., variables of environmental administrative penalty and public environmental concern) are approximately 41% higher compared to the effects observed in the interaction between government- and market-dominant environmental regulations (i.e., variables of environmental administrative penalty and environmental tax) and are approximately 57% higher compared to the effects observed in the interaction between market- and public-dominant environmental regulations (i.e., variables of environmental tax and public environmental concern). Specifically, when government- and market-dominant environmental regulations interact, the combined effects do not yield significant environmental improvements. However, when government- and public-dominant environmental regulations interact, a positive impact on environmental quality is observed. Most notably, when market- and public-dominant environmental regulations interact, a conflicting or trade-off phenomenon emerges, suggesting that the simultaneous implementation of these regulations may have adverse effects on environmental quality.

In particular, in Models 14 and 20, the regression results indicate that the constraint of the *GM_Synergy* index (synergy index between variables of environmental administrative penalty and environmental tax) on environmental quality is statistically insignificant. However, in Models 15 and 21, each unit increase in the *GP_Synergy* index (synergy index between variables of environmental administrative penalty and public environmental concern) is associated with a significant 41% and 45.3% increase in environmental quality, respectively, at the significance level of 1%. Conversely, in Models 17 and 23, each unit increase in the *MP_Synergy* index (synergy index between variables of environmental tax and public environmental concern) leads to a significant 14.8% and 16.2% decrease in environmental quality, respectively, at a significance level of 1%.

6.2 Introducing sequence dimension: the asymmetric effects of different introducing sequences on environmental quality

Furthermore, this section aims to propose an appropriate policy strategy based on the introducing sequence dimension, which considers the order in which the three types of heterogeneous subjects dominant environmental regulations are implemented. To simulate different introducing sequence, the three variables representing the heterogeneous subjects dominant environmental regulations are added to regression models in a specific order. By contrasting the alterations in regression coefficients, the optimal environmental effects mode can be identified. The research findings are presented in Table 9 and visually represented in Figure 10, providing insights into the policy strategies for achieving desired environmental outcomes.

The findings of this study suggest that an "asymmetric strategy" is the most effective environmental management mode for

TABLE 8 Asymmetric effects of different synergy indexs on environmental quality.

	Dependent variable = *EQ1*						Dependent variable = *EQ2*					
	Mod 13	Mod. 14	Mod 15	Mod 16	Mod 17	Mod 18	Mod 19	Mod 20	Mod 21	Mod 22	Mod 23	Mod 24
GM_Synergy	−0.085 (−1.64)	−0.134 (−1.46)					−0.094 (−1.64)	−0.147 (−1.46)				
GP_Synergy			0.450*** (4.33)	0.410*** (3.64)					0.495*** (4.33)	0.453*** (3.63)		
MP_Synergy					−0.148** (−2.01)	−0.161** (−2.19)					−0.162** (−2.01)	−0.177** (−2.19)
EPR		2.64 (1.63)		1.86 (1.19)		1.98 (1.24)		2.90 (1.63)		1.88 (1.28)		2.18 (1.24)
GF		0.03*** (3.16)		0.01 (1.34)		0.03*** (3.14)		0.04*** (3.16)		0.01 (1.42)		0.03*** (3.14)
GIPA		−0.01 (−1.11)		−0.01*** (−1.46)		−0.01 (−1.42)		−0.01 (−1.11)		−0.01*** (−1.32)		−0.01 (−1.42)
Sigma2_e	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)
Log-likelihood	130.21	136.79	136.80	139.43	129.73	135.34	104.48	111.05	111.07	113.70	104.00	109.61
R_square	0.15	0.12	0.21	0.30	0.10	0.15	0.15	0.12	0.21	0.31	0.10	0.15

Note: 1. The symbols *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
2. *GM_Synergy* index denotes the synergy degree between government- and market-dominant environmental regulations; *GP_Synergy* index denotes the synergy degree between government- and public-dominant environmental regulations; *MP_Synergy* index denotes the synergy degree between market- and public-dominant environmental regulations.
3. Models 13 to 18 are conducted using *EQ1* as the dependent variable, and Models 19 to 24 are conducted using *EQ1* as the dependent variable for robustness.

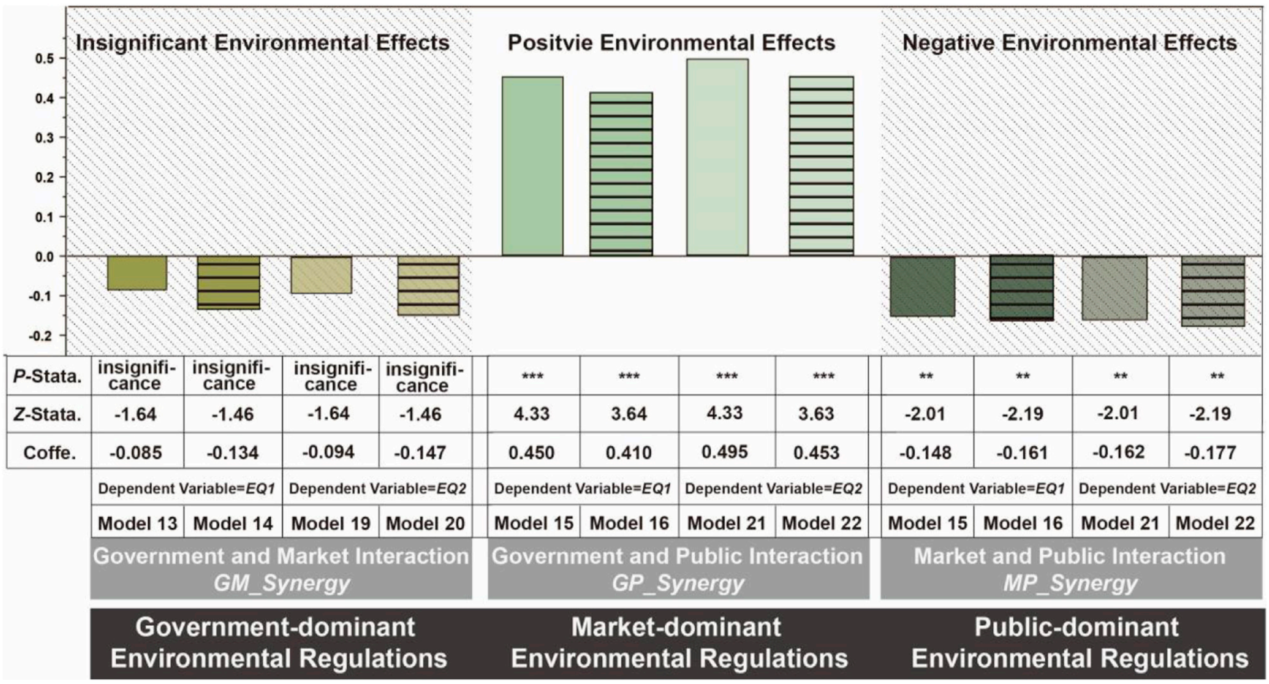

FIGURE 9
Asymmetric effects phenomenon in different synergy indexes.

TABLE 9 Asymmetric effects of different introducing sequences on environmental quality.

Panel A: Dependent variable = *EQ1*									
	Model 13	Model 14	Model 15	Model 16	Model 17	Model 18	Model 19	Model 20	Model 21
Government_DER	0.049*** (3.57)			0.041 (1.50)	0.050*** (3.65)		0.045 (1.49)	0.055*** (3.99)	
Market_DER		0.042*** (4.34)		0.30 (1.04)		0.032*** (3.66)	0.033 (1.67)		0.027*** (3.02)
Public_DER			0.017* (1.88)		0.017* (1.71)	0.020** (2.53)		0.034*** (3.10)	0.023*** (2.66)
Government_DER × *Market_DER*							−0.018 (−1.07)		
Government_DER × *Public_DER*								0.082** (2.24)	
Market_DER × *Public_DER*									−0.018*** (−2.63)
EPR	−1.13 (−0.29)	−0.38 (−0.10)	2.17 (1.36)	2.55* (1.66)	−1.32 (−0.34)	2.35 (1.51)	2.55* (1.67)	−1.26 (−0.30)	2.11** (1.37)
GF	0.02 (1.22)	0.06*** (2.97)	0.03*** (2.94)	0.00 (0.23)	0.02 (1.09)	0.03 (2.94)	0.00 (0.03)	0.02 (0.87)	0.03*** (3.01)
GIPA	−0.01 (−1.03)	−0.02 (−1.08)	−0.01 (−1.41)	−0.10 (−0.63)	0.18*** (3.20)	−0.01 (−0.83)	−0.00 (−0.68)	−0.01 (−1.01)	−0.00 (−1.07)
Sigma2_e	0.01*** (11.62)	0.01*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.36*** (11.99)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)
Log-likelihood	150.67	153.54	134.72	145.26	152.12	141.25	145.83	154.63	144.67
R_square	0.10	0.05	0.22	0.15	0.12	0.13	0.15	0.11	0.16
Panel A: Dependent Variable = *EQ2*									
	Model 22	Model 23	Model 24	Model 25	Model 26	Model 27	Model 28	Model 29	Model 30
Government_DER	0.054*** (3.57)			0.046* (1.84)	0.055*** (3.65)		0.049 (1.09)	0.060*** (4.900)	
Market_DER		0.046*** (4.34)		0.33 (1.50)		0.036*** (3.66)	0.036 (1.67)		0.030*** (3.02)
Public_DER			0.018* (1.88)		0.019* (1.71)	0.024** (2.53)		0.038*** (2.74)	0.025*** (2.66)
Government_DER × *Market_DER*							0.020 (1.07)		
Government_DER × *Public_DER*								0.090** (2.25)	
Market_DER × *Public_DER*									−0.02 (−2.63)
EPR	−1.24 (−0.29)	−0.41 (−0.10)	2.39 (1.36)	2.80* (1.66)	−1.46 (−0.34)	2.59 (1.51)	2.81* (1.67)	−1.74 (−0.41)	2.32** (1.37)
GF	0.03 (1.22)	0.07*** (2.97)	0.03*** (2.94)	0.00 (0.23)	0.02 (1.09)	0.03*** (2.94)	0.00 (0.03)	031 (1.19)	0.03*** (3.01)
GIPA	−0.02 (−1.03)	−0.02 (−1.08)	−0.01 (−1.41)	−0.10 (−0.63)	−0.01 (−1.01)	−0.00 (−0.83)	−0.00 (−0.68)	−0.01 (−1.00)	−0.01 (−1.07)
Sigma2_e	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.36*** (11.99)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)	0.02*** (11.62)

(Continued on following page)

TABLE 9 (*Continued*) Asymmetric effects of different introducing sequences on environmental quality.

Panel A: Dependent Variable = *EQ2*									
	Model 22	Model 23	Model 24	Model 25	Model 26	Model 27	Model 28	Model 29	Model 30
Log-likelihood	124.93	127.81	108.99	119.52	126.39	115.52	120.10	128.90	118.93
R_square	0.10	0.05	0.22	0.15	0.12	0.13	0.15	0.11	0.16

Note: 1. The symbols *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
2. Models in Panel A are performed using the variable *EQ1* as the dependent variable, and Models in Panel B are performed using the variable *EQ2* as the dependent variable.
3. Models 13 to 15 and 22 to 24 are performed by adding the variables of heterogeneous subjects dominant environmental regulations sequentially, Models 16 to 18 and 25 to 27 are performed by adding each pair of the variables of heterogeneous subjects dominant environmental regulations sequentially, Models 19 to 21 and 28 to 30 are performed by adding the variables of interaction items sequentially.

maximizing environmental effects. Introducing the participation of both the environmental administrative penalty and public environmental concern in environmental management is recommended, as it leads to higher environmental benefits compared to the participation of the government and the market or the market and the public. In fact, the involvement of the environmental administrative penalty and environmental tax in environmental management is found to be less effective and may even be considered a waste of resources, woresly, the environmental tax and public environmental concern generates a negative impact on the environment. Introducing both environmental administrative penalty and public environmental concern in environmental management leads to 6‰–17‰ higher environmental benefits compared to introducing environmental administrative penalty and environmental tax, and 21‰–23‰ higher benefits compared to environmental tax and public environmental concern combined participation.

Specifically, for the participation of the government and the market in environmental regulation, there are no significant environmental effect changes after the two subjects participate in environmental regulation. In Figure 10A and Models 16, 19, 25, and 28, after the government and the market both participate in environmental regulation, the statistical significance of the variables of *Government_DER* and *Market_DER* degrades to the insignificance compared to the original results in Models 13, 14, 22, and 23. In addition, when paying attention to the interaction effects, in Models 19 and 28, the statistical value of the interaction item remains insignificant, which emphasizes again that the interaction between the government and market participation barely affects environmental quality improvement.

Conversely, for the participation of the government and the public in environmental regulation, the environmental effect level of the government (the public) increases by around 6‰ (17‰) after the public (the government) participates, the statistical significance of which are all at the 1% level. In Figure 10B and Models 17, 20, 26, and 29, after the government and the market both participate in environmental regulation, the statistical value of the variables of *Government_DER* and *Public_DER* increases by around 6‰–17‰ compared to the original results in Models 13, 15, 22, and 24. In addition, when paying attention to the interaction effects, in Models 20 and 29, each increasing unit of interaction item between the government and public participation would lead to around 55‰–60‰ environmental quality improvement, the statistical significance of which are all at the 1% level.

Worsley, for the participation of the market and the public in environmental regulation, the environmental effect level of the market (the public) increases by around 15‰ (6‰) after the public (the market) participates, the statistical significance of which are all at the 1% level. In Figure 10C and Models 18, 21, 27, and 30, after the market and the public both participate in environmental regulation, the statistical value of the variables of *Market_DER* and *Public_DER* increases by around 6‰–15‰ compared to the original results in Models 14, 15, 23, and 24. In addition, when paying attention to the interaction effects, in Models 21 and 30, each increasing unit of interaction item between the market and public participation would lead to around 27‰–30‰ environmental quality declining, the statistical significance of which are all at the 1% level.

6.3 Discussions

In summary, based on policy strategy analysis, it can be proven that the "asymmetric strategy" is the most appropriate environmental management model for maximizing environmental effects. Introducing the participation of both the environmental administrative penalty and public environmental concern in environmental management is recommended, as it leads to higher environmental benefits. Conversely, the involvement of the environmental administrative penalty and environmental tax in environmental management is found to be less effective and may even be considered a waste of resources, woresly, the environmental tax and public environmental concern generates a negative impact on the environment. The observed asymmetric phenomenon signifies that the interactions among the three types of heterogeneous subjects do not result in uniform environmental effects. Instead, the outcomes differ based on the specific combinations of subjects involved in environmental regulation.

From the perspective of the synergy index analysis, the environmental effects observed in the interaction between government- and public-dominant environmental regulations (i.e., variables of environmental administrative penalty and public environmental concern) are approximately 41% higher than the effects observed in the interaction between government- and market-dominant environmental regulations (i.e., variables of environmental administrative penalty and environmental tax), and are approximately 57% higher than the effects observed in the interaction between market- and public-dominant environmental regulations (i.e., variables of environmental tax and public environmental concern).

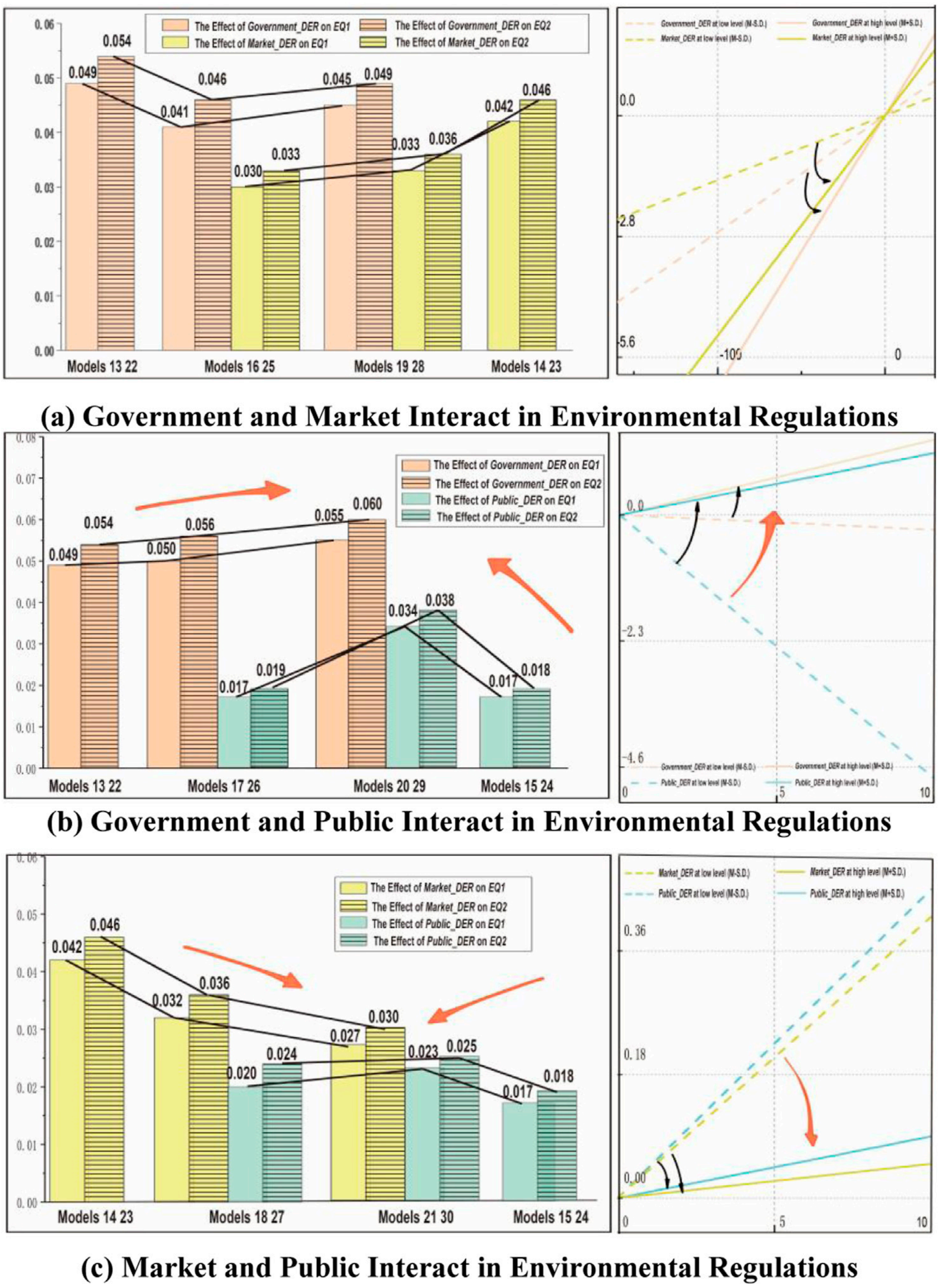

FIGURE 10
Asymmetric effects phenomenon in different introducing sequences. **(A)** Government and market interact in environmental regulations. **(B)** Government and public interact in environmental regulations. **(C)** Market and public interact in environmental regulations.

Similarly, from the perspective of the introducing sequence analysis, the environmental effects when the government- and public-dominant environmental regulations (i.e., variables of environmental administrative penalty and public environmental concern) interact are higher by around 6‰–17‰ compared to the effects when the government- and market-dominant environmental regulations interact (i.e., variables of environmental administrative penalty and environmental tax), and are higher by around 21‰–23‰ compared to the effects when the market- and public-dominant environmental regulations interact (i.e., variables of environmental tax and public environmental concern).

7 Conclusion, practical implications, and future research orientations

7.1 Conclusion

Due to the increasingly serious environmental issues, diverse sectors of society have become actively involved in environmental governance, leading to the emergence of three types of environmental regulations dominated by the government, the market, and the public. Consequently, extensive research has been conducted within the academic community to explore the environmental effects of these three types of regulations. Nevertheless, a notable limitation identified in most of these research is the deliberate division of the several environmental regulations, analyzing them independently without taking into account their concurrent implementation. As a result, the true dynamics of the interactions between these heterogeneous subjects' dominant environmental regulations are not fully captured.

Therefore, a crucial pursuit within academia is to comprehensively investigate the collective effects of these heterogeneous subjects dominant environmental regulations on environmental quality improvement. It is imperative to understand whether these different environmental regulations exhibit cooperative or competitive effects on the environment and how they can be effectively synergized to maximize their overall environmental impact. Answering these fundamental questions is extremely important for developing effective and efficient environmental governance strategies that can tackle the urgent environmental challenges faced by our society.

Motivated by this, this study seeks to investigate the overall impacts of three heterogeneous subjects dominant environmental regulations on environmental quality. Additionally, it tries to provide an appropriate optimum political strategy to maximize the effects on the environment. Based on the panel data from 2010 to 2021 in 30 observing provinces, this study employs a multi-step approach. Firstly, using the environmental administrative, environmental tax, and public environmental concern as proxy variables, the variable of heterogeneous subjects participation synergy index (*HSP-Synergy*) is constructed to measure the development synergy degree among various environmental regulations, the construction of which makes it possible that incorporate heterogeneous subjects dominant environmental regulations into one united single observing system. Secondly, this study investigates the impact of heterogeneous subjects participation synergy index (*HSP-Synergy*) on environmental quality, thereby determining whether the interaction among heterogeneous subjects dominant environmental regulations is characterized by competition or cooperation. Lastly, this study explores different combination models of each pair of environmental regulations, with the aim of proposing the optimal cooperation strategy for heterogeneous subjects dominated environmental regulations that maximize environmental effects.

Three main conclusions could be obtained as follows. Firstly, using the environmental administrative, environmental tax, and public environmental concern as proxy variables, the heterogeneous subjects participation synergy index (*HSP-Synergy*) is introduced as a metric to assess the development synergy among different environmental regulations. The results reveal significant variations in the degree of participation synergy among heterogeneous subjects across different provinces, which can significantly impact environmental quality. And based on the characteristics and intensity of heterogeneous subjects participation synergy, the provinces and regions in China can be categorized into three distinct stages, coordinated, transiting, and maladjustment and decline stage.

Secondly, using the environmental administrative, environmental tax, and public environmental concern as proxy variables, the competition effects are confirmed in the affecting process of heterogeneous subjects dominant environmental regulations on environmental quality, and the observed interaction pattern among heterogeneous subjects dominant environmental regulations leans towards competition rather than cooperation. Instead of working collaboratively towards shared environmental goals, these regulations exhibit a tendency to compete with each other, resulting in adverse consequences for environmental quality.

Empirical analysis and regression modeling reveal that the participation synergy among heterogeneous subjects has a detrimental rather than beneficial effect on environmental quality, the increase in synergy would statistically and significantly cause the decline in environmental improvement. For one aspect, each incremental unit of synergy intensity is associated with a decline of approximately 22%–25% in environmental quality, and this decline caused by the participation synergy is robust in the heterogeneity of dependent variables and econometrics methodology. For another aspect, there are significant differences in environmental quality in regions with different participation synergy degrees, based on real situations in China, environmental quality is higher by 36‰–42‰ in regions with low synergy degrees than in regions with high synergy degrees.

Thirdly, the "asymmetric strategy" is proved as the most appropriate environmental management model for maximizing environmental effects. Introducing the participation of both the environmental administrative penalty and public environmental concern in environmental management is recommended, as it leads to higher environmental benefits. Conversely, the involvement of the environmental administrative penalty and environmental tax in environmental management is found to be less effective and may even be considered a waste of resources, woresly, the environmental tax and public environmental concern generates a negative impact on the environment. The observed asymmetric phenomenon signifies that the interactions among the three types of heterogeneous subjects do not result in uniform environmental effects. Instead, the outcomes differ based on the specific combinations of subjects involved in environmental regulation.

This asymmetric characteristic is statistically and significantly confirmed by empirical research. From the synergy index, the environmental effects are approximately 41% higher in the government- and public-dominant interaction (i.e., variables of environmental administrative penalty and public environmental concern) compared to the government- and market-dominant interaction (i.e., variables of environmental administrative penalty and environmental tax), and approximately 57% higher compared to the market- and public-dominant interaction (i.e., variables of environmental tax and public environmental concern). Similarly, in terms of the introducing sequence, the environmental effects are higher by around 6‰–17‰ in the government- and public-dominant interaction (i.e., variables of environmental administrative penalty and public environmental concern) compared to the government- and market-dominant interaction (i.e., variables of environmental administrative penalty and environmental tax), and higher by around 21‰–23‰ compared to the market- and public-dominant interaction (i.e., variables of environmental tax and public environmental concern).

7.2 Practical implications

The “Asymmetric Strategies” policy framework proposed in this article aims to optimize and manage the interactions among various environmental regulations. Although further elaboration on policy patterns is still needed to assist local environmental policymakers in applying the “Asymmetric Strategies” approach in real-world contexts, the strategy can be implemented through three main avenues. First, for local environmental policymakers, it is crucial to assess and determine the current interaction dynamics between multiple environmental instruments. By employing the “Intensity Gap” calculation method and the “Dominant Environmental Instruments” identification method introduced in this study, policymakers can identify the prevailing cooperation patterns among various tools. These patterns include “Regulation-based Dominant,” “Market-based Dominant,” and “Intensity Balanced.” Accurately identifying the existing policy cooperation pattern is vital for shaping future policy decisions and improving their effectiveness.

Next, in regions where no dominant instruments have emerged, resulting in an “Intensity Balanced” pattern, it is advisable for local policymakers to prioritize regulatory frameworks as the primary strategy while positioning market-based solutions as secondary. The findings of this article suggest that attention should be given to the range of environmental tools available. Given that market-oriented economies still require regulatory oversight, the design of environmental regulations and legal structures should be a focal point.

Lastly, in regions where dominant instruments have already been established—namely, the “Regulation-based Dominant” and “Market-based Dominant” patterns—it is recommended that policymakers maintain their focus on the most effective environmental tools and ensure the continued dominance of these tools in their respective areas.

7.3 Limitations and future orientations

Based on the competitive effects of heterogeneous subjects dominant environmental regulations on environmental quality uncovered in this study, there are still some limitations in this study that can drive future research opportunities. Firstly, negative environmental effects were uncovered in this research when the market and public environmental regulations interact, the findings of which are unique among current literature, worthing of deep research. Thus, negative environmental effects among the market and public environmental regulations serve as a worthy future research direction when theories accumulate enough. Secondly, it is worth noting that only one province has achieved the coordination stage, therefore, future researchers could delve deeper into the potential reasons behind competitive effects by considering the practical backgrounds of environmental regulations in various provinces of China. Thirdly, considering it is mainly the interaction between each pair of environmental regulations discussed in this study, it is thereby worth studying the policy strategy of the three kinds of environmental regulations when the research literature and methods are matured.

Moreover, environmental regulations vary significantly across regions, which in turn affects environmental quality and warrants further investigation. From a market perspective, the industrial structure and economic priorities differ among Chinese provinces, potentially leading to variations in the intensity and focus of environmental regulations across these areas (Zhou and Zhang, 2024). From a governmental standpoint, local governments exhibit differing levels of commitment to environmental governance, influenced by factors such as fiscal relationships between them, which may also affect the effectiveness of local environmental policies (Wang F. et al., 2024; Wei et al., 2024). Additionally, from a public perspective, disparities in residents' education levels and environmental awareness can influence the success of these regulations (Wang Y. et al., 2024). Building on these perspectives, the future researchers can expand upon and deepen the findings of the study, thereby enhancing the overall scope and depth of the research.

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

HX: Conceptualization, Funding acquisition, Investigation, Methodology, Writing–original draft. XT: Funding acquisition, Supervision, Writing–review and editing, Data curation. TL: Investigation, Validation, Visualization, Writing–review and editing. MK: Formal Analysis, Resources, Software, 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.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

Anokye, K., Mohammed, A. S., Agyemang, P., Agya, B. A., Amuah, E. E. Y., and Sodoke, S. (2024). Understanding the perception and awareness of senior high school teachers on the environmental impacts of plastic waste: implications for sustainable waste education and management. *Soc. Sci. Humanit. Open* 10, 100999. doi:10.1016/j.ssaho.2024.100999

Cai, H., Wang, Z., Zhang, Z., and Xu, L. (2023). Does environmental regulation promote technology transfer? Evidence from a partially linear functional-coefficient panel model. *Econ. Model.* 124, 106297. doi:10.1016/j.econmod.2023.106297

Cheng, Z., Li, L., and Liu, J. (2017). The emissions reduction effect and technical progress effect of environmental regulation policy tools. *J. Clean. Prod.* 149, 191–205. doi:10.1016/j.jclepro.2017.02.105

Chess, C. (2000). Evaluating environmental public participation: methodological questions. *J. Environ. Plan. Manag.* 43, 769–784. doi:10.1080/09640560020001674

Cui, S., Wang, Y., Zhu, Z., Zhu, Z., and Yu, C. (2022). The impact of heterogeneous environmental regulation on the energy eco-efficiency of China's energy-mineral cities. *J. Clean. Prod.* 350, 131553. doi:10.1016/j.jclepro.2022.131553

Dong, F., Li, Y., Gao, Y., Zhu, J., Qin, C., and Zhang, X. (2022). Energy transition and carbon neutrality: exploring the non-linear impact of renewable energy development on carbon emission efficiency in developed countries. *Resour. Conserv. Recycl.* 177, 106002. doi:10.1016/j.resconrec.2021.106002

Gani, A. (2021). Fossil fuel energy and environmental performance in an extended STIRPAT model. *J. Clean. Prod.* 297, 126526. doi:10.1016/j.jclepro.2021.126526

Guerola-Navarro, V., Stratu-Strelet, D., Botella-Carrubi, D., and Gil-Gomez, H. (2023). Media or information literacy as variables for citizen participation in public decision-making? A bibliometric overview. *Sustain. Technol. Entrep.* 2, 100030. doi:10.1016/j.stae.2022.100030

Guo, X., Fu, L., and Sun, X. (2021). Can environmental regulations promote greenhouse gas abatement in OECD countries? Command-and-control vs. market-based policies. *Sustainability* 13, 6913. doi:10.3390/su13126913

Hao, Y., Deng, Y., Lu, Z.-N., and Chen, H. (2018). Is environmental regulation effective in China? Evidence from city-level panel data. *J. Clean. Prod.* 188, 966–976. doi:10.1016/j.jclepro.2018.04.003

Holston, D., and Greene, M. (2023). The LSU AgCenter healthy communities initiative: community-participatory policy, systems, and environmental change. *J. Nutr. Educ. Behav.* 55, 381–386. doi:10.1016/j.jneb.2023.02.003

Huang, M., Ding, R., and Xin, C. (2021). Impact of technological innovation and industrial-structure upgrades on ecological efficiency in China in terms of spatial spillover and the threshold effect. *Integr. Environ. Assess. Manag.* 17, 852–865. doi:10.1002/ieam.4381

Ji, X., Wu, G., Lin, J., Zhang, J., and Su, P. (2022). Reconsider policy allocation strategies: a review of environmental policy instruments and application of the CGE model. *J. Environ. Manage.* 323, 116176. doi:10.1016/j.jenvman.2022.116176

Khan, M. A., Riaz, H., Ahmed, M., and Saeed, A. (2021). Does green finance really deliver what is expected? An empirical perspective. *Borsa Istanb. Rev.* 22, 586–593. doi:10.1016/j.bir.2021.07.006

Li, S., Zhu, X., and Zhang, T. (2023). Optimum combination of heterogeneous environmental policy instruments and market for green transformation: empirical evidence from China's metal sector. *Energy Econ.* 123, 106735. doi:10.1016/j.eneco.2023.106735

Li, W., Liu, J., and Li, D. (2012). Getting their voices heard: three cases of public participation in environmental protection in China. *J. Environ. Manage.* 98, 65–72. doi:10.1016/j.jenvman.2011.12.019

Li, X., Ozturk, I., Majeed, M. T., Hafeez, M., and Ullah, S. (2022). Considering the asymmetric effect of financial deepening on environmental quality in BRICS economies: policy options for the green economy. *J. Clean. Prod.* 331, 129909. doi:10.1016/j.jclepro.2021.129909

Liu, W., Jiao, F., Ren, L., Xu, X., Wang, J., and Wang, X. (2018). Coupling coordination relationship between urbanization and atmospheric environment security in Jinan City. *J. Clean. Prod.* 204, 1–11. doi:10.1016/j.jclepro.2018.08.244

Luo, Y., Nyarko Mensah, C., Lu, Z., and Wu, C. (2022). Environmental regulation and green total factor productivity in China: a perspective of Porter's and compliance hypothesis. *Ecol. Indic.* 145, 109744. doi:10.1016/J.ECOLIND.2022.109744

Lye, C.-T., Ng, T.-H., and Law, J.-W. (2024). The role of general and specific pro-environmental education in household waste management in Malaysia: evidence from quantile regression. *Environ. Challenges* 15, 100933. doi:10.1016/j.envc.2024.100933

Nenavath, S. (2022). Impact of fintech and green finance on environmental quality protection in India: by applying the semi-parametric difference-in-differences (SDID). *Renew. Energy* 193, 913–919. doi:10.1016/j.renene.2022.05.020

O'Rourke, D., and Macey, G. P. (2003). Community environmental policing: assessing new strategies of public participation in environmental regulation. *J. Policy Anal. Manag.* 22, 383–414. doi:10.1002/pam.10138

Pan, X., Ai, B., Li, C., Pan, X., and Yan, Y. (2019). Dynamic relationship among environmental regulation, technological innovation and energy efficiency based on large scale provincial panel data in China. *Technol. Forecast. Soc. Change* 144, 428–435. doi:10.1016/j.techfore.2017.12.012

Ren, S., Li, X., Yuan, B., Li, D., and Chen, X. (2018). The effects of three types of environmental regulation on eco-efficiency: a cross-region analysis in China. *J. Clean. Prod.* 173, 245–255. doi:10.1016/j.jclepro.2016.08.113

Slunge, D., and Alpizar, F. (2019). Market-based instruments for managing hazardous chemicals: a review of the literature and future research agenda. *Sustainability* 11, 4344. doi:10.3390/su11164344

Sun, J., Zhai, N., Miao, J., Mu, H., and Li, W. (2023). How do heterogeneous environmental regulations affect the sustainable development of marine green economy? Empirical evidence from China's coastal areas. *Ocean. Coast. Manag.* 232, 106448. doi:10.1016/j.ocecoaman.2022.106448

Tan, Z., Wu, Y., Gu, Y., Liu, T., Wang, W., and Liu, X. (2022). An overview on implementation of environmental tax and related economic instruments in typical countries. *J. Clean. Prod.* 330, 129688. doi:10.1016/j.jclepro.2021.129688

Tang, K., Hailu, A., Kragt, M. E., and Ma, C. (2016a). Marginal abatement costs of greenhouse gas emissions: broadacre farming in the Great Southern Region of Western Australia. *Aust. J. Agric. Resour. Econ.* 60, 459–475. doi:10.1111/1467-8489.12135

Tang, K., Hailu, A., Kragt, M. E., and Ma, C. (2018). The response of broadacre mixed crop-livestock farmers to agricultural greenhouse gas abatement incentives. *Agric. Syst.* 160, 11–20. doi:10.1016/j.agsy.2017.11.001

Tang, K., Kragt, M. E., Hailu, A., and Ma, C. (2016b). Carbon farming economics: what have we learned? *J. Environ. Manage.* 172, 49–57. doi:10.1016/j.jenvman.2016.02.008

Tang, K., Qiu, Y., and Zhou, D. (2020). Does command-and-control regulation promote green innovation performance? Evidence from China's industrial enterprises. *Sci. Total Environ.* 712, 136362. doi:10.1016/j.scitotenv.2019.136362

Tang, K., Yang, L., and Zhang, J. (2016c). Estimating the regional total factor efficiency and pollutants' marginal abatement costs in China: a parametric approach. *Appl. Energy* 184, 230–240. doi:10.1016/j.apenergy.2016.09.104

Tang, X., Zhou, X., and Kholaif, M. M. N. H. K. (2023). Does green finance achieve its goal of promoting coordinated development of economy–environment? Using the pollutant emission efficiency as a proxy. *Environ. Dev. Sustain.* 26, 9973–10002. doi:10.1007/s10668-023-03129-9

Todaro, N. M., Gusmerotti, N. M., Daddi, T., and Frey, M. (2023). Do environmental attitudes affect public acceptance of key enabling technologies? Assessing the influence of environmental awareness and trust on public perceptions about nanotechnology. *J. Clean. Prod.* 387, 135964. doi:10.1016/j.jclepro.2023.135964

Wang, A., Si, L., and Hu, S. (2023). Can the penalty mechanism of mandatory environmental regulations promote green innovation? Evidence from China's enterprise data. *Energy Econ.* 125, 106856. doi:10.1016/j.eneco.2023.106856

Wang, C., Wang, F., Zhang, X., Yang, Y., Su, Y., Ye, Y., et al. (2017). Examining the driving factors of energy related carbon emissions using the extended STIRPAT model based on IPAT identity in Xinjiang. *Renew. Sustain. Energy Rev.* 67, 51–61. doi:10.1016/j.rser.2016.09.006

Wang, F., Cheng, S., Chen, M., and Cheng, S. (2024). Does sub-provincial fiscal decentralization reform improve energy transition? Evidence from a county-level quasi-natural experiment in China. *J. Clean. Prod.* 481, 144156. doi:10.1016/j.jclepro.2024.144156

Wang, L., Liu, B., He, Y., Dong, Z., and Wang, S. (2023). Have public environmental appeals inspired green total factor productivity? Empirical evidence from Baidu Environmental Search Index. *Environ. Sci. Pollut. Res.* 30, 30237–30252. doi:10.1007/s11356-022-23993-8

Wang, X., and Wang, Q. (2021). Research on the impact of green finance on the upgrading of China's regional industrial structure from the perspective of sustainable development. *Resour. Policy* 74, 102436. doi:10.1016/j.resourpol.2021.102436

Wang, Y., Zhao, Z., Shi, M., Liu, J., and Tan, Z. (2024). Public environmental concern, government environmental regulation and urban carbon emission reduction—analyzing the regulating role of green finance and industrial agglomeration. *Sci. Total Environ.* 924, 171549. doi:10.1016/j.scitotenv.2024.171549

Wei, T., Chen, M., Wang, F., and Cheng, S. (2024). The impact of public demands on local environmental governance performance: evidence from civil environmental complaints placed on leaders at different government levels in China. *J. Environ. Manage.* 360, 121216. doi:10.1016/j.jenvman.2024.121216

Wu, H., Hao, Y., and Ren, S. (2020). How do environmental regulation and environmental decentralization affect green total factor energy efficiency: evidence from China. *Energy Econ.* 91, 104880. doi:10.1016/j.eneco.2020.104880

Wu, R., Wang, J., Wang, S., and Feng, K. (2021). The drivers of declining CO2 emissions trends in developed nations using an extended STIRPAT model: a historical and prospective analysis. *Renew. Sustain. Energy Rev.* 149, 111328. doi:10.1016/j.rser.2021.111328

Xie, Z., Wu, R., and Wang, S. (2021). How technological progress affects the carbon emission efficiency? Evidence from national panel quantile regression. *J. Clean. Prod.* 307, 127133. doi:10.1016/j.jclepro.2021.127133

Xing, L., Xue, M., and Hu, M. (2019). Dynamic simulation and assessment of the coupling coordination degree of the economy–resource–environment system: case of Wuhan City in China. *J. Environ. Manage.* 230, 474–487. doi:10.1016/j.jenvman.2018.09.065

Xu, C., Cheng, H., and Liao, Z. (2018). Towards sustainable growth in the textile industry: a case study of environmental policy in China. *Pol. J. Environ. Stud.* 27, 2325–2336. doi:10.15244/pjoes/79720

York, R., Rosa, E. A., and Dietz, T. (2003). STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. *Ecol. Econ.* 46, 351–365. doi:10.1016/s0921-8009(03)00188-5

Yu, W., and Jin, X. (2022). Does environmental information disclosure promote the awakening of public environmental awareness? Insights from Baidu keyword analysis. *J. Clean. Prod.* 375, 134072. doi:10.1016/j.jclepro.2022.134072

Yuan, H., Feng, Y., Lee, C.-C., and Cen, Y. (2020). How does manufacturing agglomeration affect green economic efficiency?. *Energy Econ.* 92, 104944. doi:10.1016/j.eneco.2020.104944

Zhang, C., Zhou, D., Wang, Q., Ding, H., and Zhao, S. (2022). Will fiscal decentralization stimulate renewable energy development? Evidence from China. *Energy Policy* 164, 112893. doi:10.1016/j.enpol.2022.112893

Zhang, M., and Zhao, Y. (2023). Does environmental regulation spur innovation? Quasi-natural experiment in China. *World Dev.* 168, 106261. doi:10.1016/j.worlddev.2023.106261

Zhang, N., and Jiang, X.-F. (2019). The effect of environmental policy on Chinese firm's green productivity and shadow price: a metafrontier input distance function approach. *Technol. Forecast. Soc. Change* 144, 129–136. doi:10.1016/j.techfore.2019.04.015

Zhang, Y., Wang, J., Xue, Y., and Yang, J. (2018). Impact of environmental regulations on green technological innovative behavior: an empirical study in China. *J. Clean. Prod.* 188, 763–773. doi:10.1016/j.jclepro.2018.04.013

Zhao, P., Zeng, L., Li, P., Lu, H., Hu, H., Li, C., et al. (2022). China's transportation sector carbon dioxide emissions efficiency and its influencing factors based on the EBM DEA model with undesirable outputs and spatial Durbin model. *Energy* 238, 121934. doi:10.1016/j.energy.2021.121934

Zhao, Q., Tian, G., Jing, X., and Hu, H. (2023). Impact of economic development and environmental regulations on greywater footprint loads in the Yellow River Basin in China. *Ecol. Indic.* 154, 110586. doi:10.1016/j.ecolind.2023.110586

Zhao, X., Shang, Y., Magazzino, C., Madaleno, M., and Mallek, S. (2023). Multi-step impacts of environmental regulations on green economic growth: evidence in the lens of natural resource dependence. *Resour. Policy* 85, 103919. doi:10.1016/j.resourpol.2023.103919

Zhou, X., and Tang, X. (2022). Spatiotemporal consistency effect of green finance on pollution emissions and its geographic attenuation process. *J. Environ. Manage.* 318, 115537. doi:10.1016/j.jenvman.2022.115537

Zhou, X., Tang, X., and Zhang, R. (2020). Impact of green finance on economic development and environmental quality: a study based on provincial panel data from China. *Environ. Sci. Pollut. Res.* 27, 19915–19932. doi:10.1007/s11356-020-08383-2

Zhou, X., and Zhang, Y. (2024). Administration or marketization: environmental regulation, marketization and agricultural green total factor productivity. *J. Environ. Manage.* 370, 122433. doi:10.1016/j.jenvman.2024.122433