Research Topics

The nexus between innovation and environmental sustainability

Edited by
Shaojian Wang, Jose Balsa-Barreiro, Yingcheng Li and Jianjun Tu

Published in
Frontiers in Environmental Science

ISSN 1664-8714
ISBN 978-2-8325-2132-8
DOI 10.3389/978-2-8325-2132-8

About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

The nexus between innovation and environmental sustainability

Topic editors
Shaojian Wang — Sun Yat-sen University, China
Jose Balsa-Barreiro — Massachusetts Institute of Technology, United States
Yingcheng Li — Southeast University, China
Jianjun Tu — Southwest University, China

Citation
Wang, S., Balsa-Barreiro, J., Li, Y., Tu, J., eds. (2023). *The nexus between innovation and environmental sustainability*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-8325-2132-8

Table of contents

frontiers | Frontiers in Environmental Science

TYPE Editorial
PUBLISHED 11 April 2023
DOI 10.3389/fenvs.2023.1194703

Check for updates

OPEN ACCESS

EDITED AND REVIEWED BY
Faik Bilgili,
Erciyes University, Türkiye

*CORRESPONDENCE
José Balsa-Barreiro,
jobalbar@media.mit.edu

SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 27 March 2023
ACCEPTED 31 March 2023
PUBLISHED 11 April 2023

CITATION
Balsa-Barreiro J, Wang S, Tu J, Li Y and Menendez M (2023), Editorial: The nexus between innovation and environmental sustainability. *Front. Environ. Sci.* 11:1194703.
doi: 10.3389/fenvs.2023.1194703

Editorial: The nexus between innovation and environmental sustainability

José Balsa-Barreiro[1,2]*, Shaojian Wang[3], Jianjun Tu[4], Yingcheng Li[5] and Monica Menendez[2]

[1]MIT Media Lab, Massachusetts Institute of Technology, Cambridge, MA, United States, [2]CITIES, Division of Engineering, New York University Abu Dhabi, Abu Dhabi, United Arab Emirates, [3]Guangdong Provincial Key Laboratory of Urbanization and Geo-simulation, School of Geography and Planning, Sun Yat-Sen University, Guangzhou, China, [4]College of Economics and Management, Southwest University, Chongqing, China, [5]School of Architecture, Southeast University, Nanjing, China

KEYWORDS

environmental sustainability, globalization, policy analysis, spatial planning, technological innovation, complexity

Editorial on the Research Topic
The nexus between innovation and environmental sustainability

Osborn (1948) notably discussed environmental destruction by humankind, and since then, we have only faced growing concerns about resource over-consumption and environmental degradation. In the last few decades, it has become more evident that natural environments are increasingly stressed, potentially harming human communities even in the short to medium term (Steffen et al., 2015). At a global scale, humanity consumes natural resources 1.8 times faster than the rate at which those resources are generated. The consumption rate differs enormously between countries, ranging from 9 in Qatar to 0.3 in Yemen. The two most powerful global economies also show substantial differences: 5.1 (United States) and 2.4 (China) (Global Footprint Network, 2018). Such differences can be explained by factors related to production models and economic maturity, as well as collective lifestyles and behavioral patterns, which must be understood in the right context (Balsa-Barreiro et al., 2022a; Balsa-Barreiro et al., 2022b). Despite technological breakthroughs in recent decades, many scholars emphasize that global economic growth has not been decoupled from environmental impacts and resource needs (Parrique et al., 2019; Hickel and Kallis, 2020). As a result, many countries in the early stages of *economic maturity*, such as China and other Southeast Asian countries, are still willing to pay high environmental costs for economic growth (Balsa-Barreiro et al., 2019). The trend for the coming years will depend on the implementation of successful eco-innovative approaches, the shift to more mature economies in certain regions, and potentially other factors, such as the emergence of a new geopolitical scenario related to an eventual *deglobalization* (Balsa-Barreiro et al., 2020) and the emergence of major changes in the labor market (Rossi and Balsa-Barreiro, 2020).

In order to maximize benefits while reducing environmental costs, societies will have to cope with crucial transformations based on eco-innovative approaches. Environmental sustainability requires innovative methods to promote industrial upgrading, clean energy, green financing, and social responsibility toward the environment (Madaleno et al 2022). Many of these transformations will be technologically driven, but must still incorporate multiple dimensions. Fukasaku (2020) refers to the key role of innovation policies, whereas Wiedmann et al. (2020) refer to lifestyle changes complementing technological shifts. Along this direction, we are observing how the most advanced countries are recently moving from linear economies to circular ones (Almeida and Cardoso, 2022; Nygaard, 2022) in order to shift away from the infinite-growth paradigm to alternative economic models that are compatible with ecological integrity.

The goal of this Research Topic is to analyze the link between innovation and environmental sustainability by evaluating factors such as knowledge (Dong et al.), finance policies (Gao et al.), trading (Andriamahery et al.), green financing (Zhang et al.), and environmental regulations (Sun; Chen et al.). These studies are conducted at different scales, from individuals (An et al.), to small datasets related to companies (Dong et al.; Zhang et al.), to wide regions in China (Dong et al.; Gao et al.; Sun et al.; Yin et al.) and Africa (Andriamahery et al.et al.; Chukwudi et al.). Zhang et al. (evaluating 49 countries) and Chen et al. (discussing OECD and Non-OECD economies) conducted the largest studies. In short, this Research Topic features 10 articles with contributions from 32 authors. Some highlights are summarized below:

Dong et al. evaluated 36 unicorn enterprises in China to study the relationship between knowledge and open innovation. Zhang et al. evaluated 176 innovative enterprises and demonstrated how the talent ecosystem and collaborative innovation positively affect innovation performance.

In China, Gao et al. evaluated the impact of science and technology finance policy on urban green development at the city level. They found that this impact varies by region and depends on the level of urban innovation, being more evident in the highly innovative cities located in the Midwestern region. Yin et al. analyzed how the innovation environment affected the transformation of resource-based cities in the Gansu Province during the last decade. Sun et al. estimated the impact of environmental regulations on innovation and productivity related to green agricultural technology across 30 provinces and cities. Results showed that as the level of regional economic development gradually increases, environmental regulation can have a significant impact on both innovation and productivity.

In Africa, Andriamahery et al. analyzed the relationship between trade and environmental quality in Sub-Saharan Africa. They estimated a set of trade variables such as income *per capita* growth, energy intensity, foreign direct investment, human capital, and CO_2 emissions. The results showed that trading has a consistently negative impact on the environment by increasing N_2O, ACH_4, and CO_2 emissions across the whole region, but also across the different income groups. Chukwudi et al. analyzed the asymmetric impact of technological innovation on CO_2 emissions in South Africa for the last six decades. They found that technological innovation helps reduce CO_2 emissions, whereas trade openness is environmentally harmful over the long term, despite the fact that it can be beneficial in the short term.

Zhang et al. discussed how technological innovation and green finance can contribute to clean energy transition, carbon emission reduction, and climate change mitigation in 49 countries with green bonds. Chen et al. examined the combinatory impact of environmental policies and technological innovation on the ecological footprint both for OECD and Non-OECD economies. An et al. demonstrated the positive impact of Internet payment technology on environmental sustainability by evaluating 623 individuals in China.

The articles published on this Research Topic contribute to a better understanding of the "*Nexus between innovation and environmental sustainability*". Now that this Research Topic is completed, we will endeavor in next special issues to open new approaches by facilitating trans-disciplinary discussion on this and/or closely related Research Topic aimed to improve human welfare by respecting ecological integrity for future generations.

Author contributions

JB-B drafted the manuscript and the rest of authors reviewed it. All authors contributed to the editorial article and approved the submitted version.

Acknowledgments

JB-B and MM acknowledge the support of the NYUAD Center for Interacting Urban Networks (CITIES), funded by Tamkeen under the NYUAD Research Institute Award CG001.

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.

References

Almeida, S., and Cardoso, A. (2022). Drivers and barriers in the transition from a linear economy to a circular economy. *J. Clean. Prod.* 341, 130865. doi:10.1016/j.jclepro.2022.130865

Balsa-Barreiro, J., Li, Y., Morales, A., and Pentland, A. (2019). Globalization and the shifting centers of gravity of world's human dynamics: Implications for sustainability. *J. Clean. Prod.* 239, 117923. doi:10.1016/j.jclepro.2019.117923

Balsa-Barreiro, J., Menendez, M., and Morales, A. (2022a). Scale, context, and heterogeneity: The complexity of the social space. *Sci. Rep.* 12, 9037. doi:10.1038/s41598-022-12871-5

Balsa-Barreiro, J., Menendez, M., and Morales, A. (2022b). Fitting the complexity of the social space into the right dimension. *Nat. Portfolio*

Behav. Soc. Sci. Available online at https://socialsciences.nature.com/posts/fitting-the-complexity-of-the-social-space-into-the-right-dimension (Access March 14th, 2023).

Balsa-Barreiro, J., Vie, A., Morales, A., and Cebrian, M. (2020). Deglobalization in a hyper-connected world. *Nat. Palgrave Commun.* 6 (28), 28. doi:10.1057/s41599-020-0403-x

Fukasaku, Y. (2020). "Innovation for environmental sustainability: A background," in *Innovation and the environment* (Paris, France: OECD Proceedings).

Global Footprint Network (2018). *Global footprint Network*. https://www.overshootday.org/how-many-earths-or-countries-do-we-need (Access March 14th, 2023).

Hickel, J., and Kallis, G. (2020). *Is green growth possible? New Polit. Econ.* 25 (4), 469–486. doi:10.1080/13563467.2019.1598964

Madaleno, M., Dogan, E., and Taskin, D. (2022). A step forward on sustainability: The nexus of environmental responsibility, green technology, clean energy and green finance. *Energy Econ.* 109, 105945. doi:10.1016/j.eneco.2022.105945

Nygaard, A. (2022). From linear to circular economy: A transaction cost approach to the ecological transformation of the firm. *Circular Econ. Sustain.* 2, 1127–1142. doi:10.1007/s43615-022-00158-w

Osborn, F. (1948). *Our plundered planet*. Boston, MA, USA: Little, Brown and Co.

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Kuokkanen, A., et al. (2019). *Decoupling Debunked: Evidence and arguments against green growth as a sole strategy for sustainability*. Brussels, Belgium: European Environmental Bureau (EEB).

Rossi, E., and Balsa-Barreiro, J. (2020). The future of work in the post-COVID-19 world. *Econ. Political Wkly.* 55 (44), 23–26.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., and Ludwig, C. (2015). The trajectory of the anthropocene: The great acceleration. *Anthropocene Rev.* 2 (1), 81–98. doi:10.1177/2053019614564785

Wiedmann, T., Lenzen, M., Keyßer, L., and Steinberger, J. (2020). Scientists' warning on affluence. *Nat. Commun.* 11, 3107. doi:10.1038/s41467-020-16941-y

frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 17 May 2022
doi: 10.3389/fenvs.2022.879681

Green Finance, Innovation and the Energy-Environment-Climate Nexus

Kai Quan Zhang[1,2], *Hsing Hung Chen*[3], *Li Zhi Tang*[1] *and Sen Qiao*[4]*

[1]School of Economics, Xiamen University, Xiamen, China, [2]School of Economics and Management, Longyan University, Longyan, China, [3]School of Business, Macau University of Science and Technology, Taipa, Macau SAR, China, [4]School of Business, Zhengzhou University, Zhengzhou, China

After the Paris Climate Conference (COP21), carbon neutrality and environmental sustainability have become the consensus of many countries. Technological innovation and green finance are the essential factors that can help to realize clean energy transition, carbon emission reduction and climate change mitigation. To investigate the pathways for sustainable development, this study includes innovation and green finance into simultaneous equations models within energy-environment-climate nexus. We examine the dynamic relationships for a sample of 49 countries with green bonds issued for the period 2007–2019. The results confirm that there are bidirectional relationships among renewable energy consumption, environmental pollution and climate change. Innovation can significantly promote renewable energy consumption, reduce CO_2 emissions and mitigate climate change. Green finance can effectively alleviate environmental pollution and climate change. Accelerating the development of green finance is the primary motivation for sustainable development. Green finance moderates the relationship between innovation and energy-environment-climate nexus. The positive impact of innovation on renewable energy consumption is enhanced by higher level of green finance. When the development of green finance is high, innovation has a greater negative influence on CO2 emissions, and the impact of innovation on climate change is weakened.

Keywords: green finance, innovation, renewable energy consumption, environmental pollution, climate change

OPEN ACCESS

Edited by:
Yingcheng Li,
Southeast University, China

Reviewed by:
Daniel Balsalobre-Lorente,
University of Castilla-La Mancha, Spain
Ehsan Rasoulinezhad,
University of Tehran, Iran

****Correspondence:***
Sen Qiao
qiaosenboy@163.com

Specialty section:
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

Received: *20 February 2022*
Accepted: *20 April 2022*
Published: *17 May 2022*

Citation:
Zhang KQ, Chen HH, Tang LZ and Qiao S (2022) Green Finance, Innovation and the Energy-Environment-Climate Nexus. Front. Environ. Sci. 10:879681. doi: 10.3389/fenvs.2022.879681

INTRODUCTION

The role of energy consumption is highly correlative with both environmental protection and climate change. The high emission level of CO_2 has become a serious global issue (Bekun et al., 2019). The BP statistics indicated that the global fossil energy-related CO_2 emission increased from 11.190 billion tonnes in 1965 to 34.356 billion tonnes in 2019, with a threefold increase. The Intergovernmental Panel on Climate Change (IPCC) predicted that energy-related carbon dioxide emissions will rise to 40–110% by 2030. Many countries are actively seeking the solutions to guarantee energy sustainability and reduce greenhouse gas emissions, with the increasingly serious problems of environmental pollution and climate change. Renewable energy has become a key element in the "fast zero" and "net zero" schemes, which can promote energy structure transition, protect ecological environment and mitigate climate change crisis. Assessing the impact of energy consumption on carbon emissions and climate change requires take into consideration not only fossil energy but also renewable energy (Brini, 2021; Usman and Balsalobre-Lorente, 2022). Thus, the new perspective on renewable energy does allow for building a rational theoretical base for the energy-environment-climate nexus.

Technological innovation acts as a catalyst for improving energy efficiency and reducing energy intensity. High value products can be obtained by advanced technology innovation with low energy consumption (Sohag, 2015). Energy innovation is an internal driving force for low-carbon economy, which lead to optimize energy consumption structure and accelerate the application of renewable energy. Government agencies have turned their attention to encourage substantial investment in technological innovation to reach solutions for environmental disruption and global warming, and achieve sustainable development (Ahmad et al., 2021). Technological innovation can promote energy conservation and emission reduction. Both low-carbon utilization of traditional fossil energy and large-scale utilization of renewable energy at low cost are highly dependent on technological innovation. Additionally, tackling global warming and other environmental threats requires a well-coordinated innovation program to curb high carbon dioxide emissions. Investments in technological innovation as an effective strategy is essential to sustainable improvements in energy security (Erdoğan et al., 2020; Zheng et al., 2021), carbon emission mitigation (Uluak et al., 2020; Jahanger et al., 2022), and climate change problems reduction (Lin and Zhu, 2019; Wang et al., 2020). Thus, technological innovation is a critical factor that can influence the energy-environment-climate nexus, deciding whether to achieve the goals of the Paris Conference Climate Change (COP21).

Green finance aims to reduce greenhouse gas emissions and protect environment by providing investment, financing and financial service for environmentally-friendly projects (Dogan and Seker, 2016; Dafermos and Nikolaidi, 2021; Sun, 2021). For example, the Equator Principles were designed to deal with environmental and social issues related to financing, and the climate finance provides financial assistance for green projects to mitigate and adapt to climate change. On the one hand, green finance can transfer financial resources from high-pollution and high-energy-consuming industries to green industries through structural effects, and reduce greenhouse gas emissions. It also can optimize the allocation of financial resources and promote the optimization and upgrade of green industrial structure (Gu et al., 2021). Various types of central banks have issued financial regulation tools to guide capital flows, such as climate-related financial disclosures (Campiglio et al., 2018). On the other hand, many countries have actively set out to change the extensive mode of economic growth, and realize high-quality economic development through emission reduction and ecological conservation (Ren et al., 2020). Green finance can relieve financing constraints on green activities, encourage enterprises to re-allocate various resources, and achieve the purpose of sustainable development (Yu et al., 2021).

In summary, the important position of innovation and green finance on sustainable development has moved from the margins to the mainstream. Innovation often faces financing constraints due to technological uncertainty and long R&D cycles. Green financial development may provide sufficient funds for activities of green technology innovation, which leads to improve energy efficiency, decrease carbon emission and reduce extreme weather risks. Technological innovation with rational financial support can stimulate the environmentally-friendly industrial scale, which result in environmental sustainability. The interaction of innovation and green finance has served as a potential solution to problems of energy structure transformation, environmental pollution reduction and climate change mitigation. This study integrates innovation and green finance into the framework of energy-environment-climate nexus. Simultaneous equations model is used to explain bidirectional causality between variables and the way in which they are endogenously determined within the same framework, which systematically examines the driving factors of the sustainable development.

This study contributes the previous studies in the following respects. First, this study introduces energy-environment-climate nexus in simultaneous equations model. Systematic and simultaneous discusses the bidirectional causality between energy consumption, environmental pollution and climate change. Providing a more comprehensive narrative of energy-environment-climate relative to previous studies. Second, this study has included innovation and green finance as explanatory variables into models within the energy-environment-climate dimensions. Evaluating the moderating effects of innovation index and green bonds on the analytical framework of energy-environment-climate nexus, which sets up a new perspective for the improvement of the theories and methodologies. Third, this study focuses on renewable energy consumption in the nexus, which can better explain the effects of renewable energy on carbon emission reduction and climate change mitigation from the perspective of energy structure transition. Fourth, this study applied simultaneous equations and system GMM models for examining the relationship among innovation, green finance and energy-environment-climate nexus. A dynamic three-equations set-up can relieve omitted variables bias and endogeneity problem, and the equation estimations are more efficient.

The framework of this study is revealed as follows. Section shows the *Introduction*. Section presents the *Literature review*. Section provides the *Data and methodology*. Section presents the *Results and discussions*. Section shows the *Conclusions and policy implications*.

LITERATURE REVIEW

Energy-Environment-Climate Dimension

There is a complex relationship among energy consumption, environmental pollution and climate change. Global warming is mainly caused by greenhouse gas emissions, which is due to widespread consumption and dependence on fossil energy to promote economic development (Chiu, 2017; Salari et al., 2021). Global communities are collaborating to find renewable energy as alternative energy sources for achieving environmental and economic sustainability (Pavlović et al., 2021). Usman and Balsalobre-Lorente (2022) revealed that investment in clean energy may reduce ecological footprint and mitigate climate-related extreme events for the top ten newly industrialized countries from 1990 to 2019. Dong et al. (2017) investigated the relationship between the renewable and natural gas energy sources and carbon dioxide emissions use via the augmented mean group estimator. They found that 1% increase in the level of renewable energy and natural gas consumption will reduce carbon dioxide emissions by 0.2601 and 0.1641% in BRICS countries. Bölük and Mert (2014) showed that clean energy emits about half as much carbon as fossil energy using the sample of 16 European Union countries in the period 1990–2008. In addition, Nyambuu and Semmler (2020) proved that renewable energy can effectively deal with climate change problems with a dynamic growth model. Rahman and Velayutham (2020) predicted the greenhouse gas emissions and investment costs caused by meeting electricity demand under different energy consumption condition. The results showed that clean energy is a vital way to mitigate global warming, and the cost of renewable energy is lower than that of non-renewable energy. Brini (2021) applied the autoregressive distributed lag model and granger causality tests to investigate the relationship between renewable energy generation and climate change for African countries from 1980 to 2014. The results revealed that renewable energy can effectively ameliorate greenhouse gas emissions in the long term, and increase in the proportion of clean energy consumption in total energy will help mitigate climate change.

Climate change seem to play an important role in energy consumption and carbon dioxide emissions. On the one hand, climate change can increase energy consumption. Liu et al. (2021) proved that climate change may have a punishing effect on environmental quality, global warming will accelerate the deterioration of air quality. The current global climate change shows a trend of increasing temperature year by year, which makes urban areas require a lot of energy, especially electricity to be consumed for cooling buildings (Javanroodi et al., 2018). On the other hand, climate change will threaten the safety of electricity generation (Sharifi and Yamagata, 2016). Extreme temperatures will destroy electricity generation equipment and decrease confidence in clean energy. Insufficient investment in clean energy will inhibit the development of renewable power generation, especially solar power generation (Chen et al., 2021). Zhao and Huang, (2020) expected that climate change has a negative impact on the potential of photovoltaic energy, and it may experience a slight decline of up to 6% in most regions of China.

Innovation and Energy-Environment-Climate Dimension

Technological innovation is the key factor of global energy pattern and low-carbon economic development. Innovation contributes to reducing energy consumption and optimizing energy structure. On the one hand, technological innovation helps to reduce emissions by improving energy efficiency (Sohag, 2015; Pradhan and Ghosh, 2022). Technological innovation can raise the efficiency of traditional fossil energy, achieve the target of energy conservation and emission reduction by decarbonization in the production process. It also can improve green total factor productivity, hoist technological capability of renewable energy, and accelerate development of clean energy industry. Jahanger et al. (2022) applied that technology innovation can mitigate carbon footprint and environmental pollution by providing energy efficiency in 73 developing countries during the period from 1990 to 2016. On the other hand, Innovation can promote energy consumption to shift from pollution-intensive fossil fuels consumption to renewable energy consumption, which contributes to the reduction of carbon emissions (Anwar et al., 2020). In fact, technological innovation can improve the supply capacity of renewable energy as well as optimize the energy mix (Chen and Lei, 2018). Tang and Tan (2013) applied that the main reason for reduction in fossil energy consumption is renewable energy innovation. Cheng et al. (2019) indicated that energy innovation stimulates renewable energy consumption in countries with low oil reserves. Geng and Ji (2016) found that technology innovation has a long-run equilibrium relationship with renewable energy consumption in United States, Germany, and other six developed countries from 1980 to 2010. Zheng et al. (2021) found that innovation also promotes renewable energy power generation in China. They applied that a 1% increase in the level of renewable energy innovation will lead to an increase of 0.411% in the province's renewable energy power generation. However, the contribution of energy innovation to economic growth will inevitably increase energy demand, which may totally or partially offset reduction in energy consumption (Ganda, 2019).

The innovation-environment link has revealed that many countries have focused on investing in research and development to achieve environmental sustainability and low-carbon development (Cantner and Dettmann., 2019). Technological innovation may be a cost-effective way to build low-carbon society (Bayer et al., 2013). Danish and Ulucak (2021) applied the dynamic auto-regressive distributive lag simulation method to prove that technology innovation is conducive to a significant reduction in carbon dioxide emissions in the United States in the short-run and long-run. Sæther (2021) underlined that decarbonization of the power sector is key to the global energy consumption transition from fossil fuels to renewables. They applied that technological innovation policies can enhance the efficiency of carbon emission reduction in wind power generation using the sample of 34 OECD countries and 5 BRICS countries in the period 2001–2018. Su and Moaniba (2017) explored that whether technology innovation can cope with environmental pollution. They implied that innovation responds positively to the deteriorating environment, and increasing greenhouse gas emissions from liquid and gas fuel will compel technology innovation with data from 70 countries.

Technology innovation is often regarded as a most effective approach to mitigate climate change. In order to deal with the problems of global warming and other threats to the environment, a series of technological innovation programs are made to control high greenhouse gas emissions. Promoting technological innovation will help achieve the climate change goals set by the Paris Agreement at COP21 (Wang et al., 2020). Investments in R&D as an effective strategy to reduce carbon emissions due to improve innovation capability and promote sustainable development. Lin and Zhu (2019) discussed the driving factors of renewable energy technology innovation. The intensive greenhouse gas emissions force governments to promote the level of renewable energy technological innovation, signifying that innovation processes respond positively to climate change.

Green Finance and Energy-Environment-Climate Dimension

The G20 defines green finance as investment and financing of environmentally sustainable development. Green finance stimulates a shift in energy consumption from fossil fuel resources to renewable resources by encouraging investment in clean energy projects. A more direct approach would be to impose quantitative limits on loans for carbon-intensive activities, reduce the proportion of bank credit to the fossil fuel sectors. Dafermos and Nikolaidi (2021) found that green differentiated capital influences the transmission channels of credit supply and loan spreads within a dynamic framework. Green funds can slow the pace of global warming by supporting environmentally friendly projects, and reduce financing restriction of enterprises. Muganyi et al. (2021) employed the semi-parametric difference-in-differences method to explain that green finance has significantly reduced industrial waste gas emissions in 290 Chinese cities during the period from 2011 to 2018. They emphasized that governments should accelerate the innovation of green financial products and services, and improve the green credit capacity of financial institutions. In addition, green finance and clean energy consumption will help reduce carbon intensity. Ren et al. (2020) implied that clean energy consumption is mainly affected by carbon intensity, which development lacks independent driving ability and mainly depends on green financial support in the long term. Reboredo (2018) found that the positive environmental externalities generated by green bonds trading contribute to the execution and proliferation of renewable energy solutions across countries. Li et al. (2022) further analyzed the relationship between green bonds and renewable energy index during the period from 2011 to 2019. The results showed that OECD countries raise 31 percent of green bond financing into the construction of the renewable energy index, the per unit energy efficiency of renewable energy will increase by 9.4 percent.

As green bonds and climate bonds are aligned with the sustainable development goals, more and more countries are beginning to recognize the potential of green finance in addressing environmental pollution and climate change. Climate finance aims to provide financial support for climate change mitigation and adaptation activities, which provide financial assistance to mitigate risks of environmental pollution and extreme weather change. Zerbib (2019) adopted a matching method to estimate the relationship between environmental preferences and green bonds, and found that the growing demand for environmental quality is the main driver of demand for green bonds. Flammer (2020) analyzed that the market mechanism of green bond financing in environmental sustainability. The results emphasized that the significance of green bonds in shaping environmentally responsible enterprises and pointed to the use of green bond as a financing policy tool to complete environmental protection targets.

Innovation, Green Finance and Energy-Environment-Climate Dimension

Many countries are trying to promote the development of green innovation and green finance to realize long-term climate targets (Li and Liao., 2018). Green innovation often forms financing constraints due to technological uncertainty and long R&D cycles (Andersen, 2017). The promotion effect of green finance on investments and loans for environmental sustainability, which has become a global consensus on environmental protection action (Acheampong et al., 2020). Green financial development can promote green technologies, improve energy efficiency, and thereby reduce carbon dioxide emissions per unit of output (Pan et al., 2019). Hu et al. (2021) proved that green technology innovation of enterprises needs to invest a lot of capital, which cannot be achieved by relying solely on traditional financing channels. Green finance can provide enterprises with comprehensive financial support on preferential terms, which can meet the needs of clean technology transformation and advanced production relations, effectively reduce carbon emissions. In fact, green financing seems to guarantee the effectiveness of environmental protection actions by a massive investment in technical human capital and technological innovation. Adequate and sustained funds can promote low-carbon technology innovation, and ultimately reduce environmental degradation and climate risks (Tamazian et al., 2009). Bird et al. (2011) analyzed that carbon finance can also promote the expansion of renewable energy scale through energy substitution effect, and the indirect effect of scale can further trigger the innovation of renewable energy technology by stimulating investment. Yu et al. (2021) proved that green finance policy alleviates financing constraints of green innovation. When companies face higher financing constraints, green innovation capacity will be impaired. Governments should design a comprehensive evaluation mechanism for green performance to ensure that funds flow to green innovation.

However, financial development can promote business activities by reducing the costs of credit for enterprise technological progress. The expansion of business activities and infrastructure projects will lead to an increase in energy consumption and greenhouse gas emissions (Sadorsky, 2011). Increased carbon dioxide emissions may result from the promotion effect of financial development on technology innovation. Productive technology can obtain financial support through green finance development, so as to further expand the production scale of enterprises. Energy-efficiency technological innovations lead to an increase in total actual energy consumption, a phenomenon known as the rebound effect of technology. Aluko and Obalade (2020) proved that financial development has an adverse impact on environmental quality through technology innovation, using the sample of 35 sub-Saharan African countries for the period 1985–2014.

TABLE 1 | Countries description.

Regions	Countries
Africa	Egypt, Morocco, South Africa
Asia	China, Indonesia, India, Japan, Malaysia, Philippines, Saudi Arabia, South Korea, Singapore, Thailand, Turkey, Vietnam
Europe	Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Lithuania, Netherlands, Norway, Poland, Portugal, Russian Federation, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom
North America	Canada, Costa Rica, Mexico, United States
Oceania	Australia, New Zealand
South America	Argentina, Brazil, Chile, Colombia, Peru, Uruguay

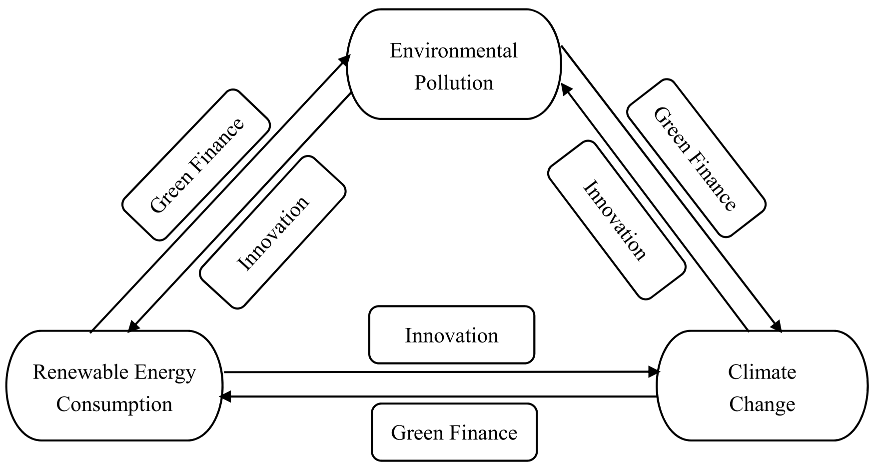

FIGURE 1 | Theoretical framework.

DATA AND METHODOLOGY

Data

The green bond market has grown dramatically in recent years, increased flows of capital flows into low-carbon economic activities. The global cumulative issuance of green bonds reached USD754bn by 2019, since its inception in 2007. The volume of green bonds issued was primarily driven by the European market, with 45 percent of global market. It is followed by the Asia-Pacific market (25 percent) and North American market (23 percent). United States leading with USD171.5bn, followed by China (USD107.3bn) and France (USD86.7bn).

The total number of countries with green bonds issued to 62 in 2019. The main countries from six continents, including Africa, Asia, Europe, North America, Oceania, and South America. In consideration of the typicality and availability of data, this study excluded the sample of countries with small volume of green bond issuance and incomplete data. We employed annual and unbalanced panel data of 49 countries over the period 2007–2019. The countries are described in **Table 1**.

This study included technology innovation and green finance as core variables into the simultaneous equations model of energy-environment-climate nexus. The theoretical framework is showed in **Figure 1**. The main variables include innovation, green finance, energy consumption, environmental pollution, climate change and other control variables. The innovation is measured by global innovation index, green finance is calculated as yearly green bond volume, energy consumption is calculated as a percentage of renewable energy to total energy consumption, environmental pollution is based on CO2 emissions, and climate change is measured by the variations of average temperatures. All variables come from the database of World Bank, World Intellectual Property Organization, Penn World Table and Climate Bonds Initiative. The variables are showed in detail in **Table 2**.

Methodology

Simultaneous Equations Model

The energy-environment-climate nexus is devoted to discuss the causal relationship among energy consumption, environmental pollution and climate change. The simultaneous equations model can not only allow the three independent variables are simultaneous determination, but also the reverse causality between the variables is permitted. Simultaneous estimation is more systematic and efficient than single-equation estimation (Tiba and Frikha, 2018). In addition, the method is straightforward to include new variables in simultaneous equations models, which can avert the omitted variables bias

TABLE 2 | Variables description.

	Variable	Symbol	Description
Dependent variables	Renewable energy consumption	RE	Renewable energy consumption/Total energy consumption (%)
	Environmental pollution	ENVIR	CO_2 emissions per capita (metric tons per capita)
	Climate change	CLIMA	Climate change is measured by the variations of average temperatures based on the year 2000 (°C) The average temperatures are evaluated by mean temperatures during the summer months (June, July and August) for countries with the capitals in the Northern Hemisphere; mean temperatures during the months (January, February and December) for countries with the capitals in the Northern Hemisphere
Independent variables	Innovation	INO	Ln (Global innovation index)
	Green finance	GF	Yearly green bond volume by currency (in USD, billion)
Control variables	Economic development	GDP	Ln (Real GDP per capita) (in USD)
	Climate Policy	CP	Joining of the Paris Agreement, if member state is 1, non-member state is 0
	Industrialization	Indus	Industry value added/GDP (%)
	Capital	CS	Ln (Capital stock at constant national prices) (in USD)
	Urbanization	Urban	Urban population/Total population (%)

(Arminen and Menegaki, 2019). Thus, this study employs the simultaneous equations model to analyze energy-environment-climate nexus, the traditional equations can be estimated based on previous literature as follows.

$$Energy_{i,t} = \alpha_0 + \alpha_1 ENVIR_{i,t} + \alpha_2 CLIMA_{i,t} + \alpha_3 GDP_{i,t} + \alpha_4 Indus_{i,t} + +\varepsilon_{it} \quad (1)$$

$$ENVIR_{i,t} = \beta_0 + \beta_1 Energy_{i,t} + \beta_2 CLIMA_{i,t} + \beta_3 GDP_{i,t} + \beta_4 GDP^2_{i,t} + \beta_5 Urban_{i,t} + \varepsilon_{it} \quad (2)$$

$$CLIMA_{i,t} = \gamma_0 + \gamma_1 Energy_{i,t} + \gamma_2 ENVIR_{i,t} + \gamma_3 GDP_{i,t} + +\varepsilon_{it} \quad (3)$$

Where $Energy_{i,t}$ is total energy consumption; $ENVIR_{i,t}$ is environmental pollution; $CLIMA_{i,t}$ is climate change; $GDP_{i,t}$ is economic development; $Indus_{i,t}$ is industrialization; $Urban_{i,t}$ is urbanization; ε_{it} is the error term; $t = 1, 2, \ldots,$ T time periods; and $i = 1, 2, 3 \ldots,$ N countries.

Based on the above equations, the model is improved as follows. First, this study has established a three-dimensional simultaneous equation framework for discussing the relationship among energy-environment-climate by including innovation and green finance as major variables. We also introduce the interaction term of innovation and green finance to further explore the moderating effect. Exploring the key role of global innovation index and green bonds in energy-environment-climate nexus. Second, accurately assessing the influence of energy consumption on climate change need to consider more than just the aggregate energy consumption, and the energy consumption structure should be taken into the framework. We used the renewable energy consumption instead of total energy consumption in the traditional model, which is helpful to explain the green transition of energy structure. Third, the models include new control variables (e.g., economic development, industrialization, urbanization, climate policy and capital stock) in simultaneous equations models to avoid the omitted variables bias and control for country-specific effects. Thus, the three main simultaneous equations can be estimated as follows.

Energy consumption equation

$$RE_{i,t} = \alpha_0 + \alpha_1 ENVIR_{i,t} + \alpha_2 CLIMA_{i,t} + \alpha_3 INO_{i,t} + \alpha_4 GF_{i,t} + \alpha_5 INO_{i,t} * GF_{i,t} + \alpha_6 GDP_{i,t} + \alpha_7 Indus_{i,t} + \alpha_8 Urban_{i,t} + \alpha_9 CP_{i,t} + \alpha_{10} CS_{i,t} + \varepsilon_{it} \quad (4)$$

Environmental pollution equation

$$ENVIR_{i,t} = \beta_0 + \beta_1 RE_{i,t} + \beta_2 CLIMA_{i,t} + \beta_3 INO_{i,t} + \beta_4 GF_{i,t} + \beta_5 INO_{i,t} * GF_{i,t} + \beta_6 GDP_{i,t} + \beta_7 GDP^2_{i,t} + \beta_8 Indus_{i,t} + \beta_9 Urban_{i,t} + \beta_{10} CP_{i,t} + \beta_{11} CS_{i,t} + \varepsilon_{it} \quad (5)$$

Climate change equation

$$CLIMA_{i,t} = \gamma_0 + \gamma_1 RE_{i,t} + \gamma_2 ENVIR_{i,t} + \gamma_3 INO_{i,t} + \gamma_4 GF_{i,t} + \gamma_5 INO_{i,t} * GF_{i,t} + \gamma_6 GDP_{i,t} + \gamma_7 Urban_{i,t} + \gamma_8 CP_{i,t} + \gamma_9 CS_{i,t} + \varepsilon_{it} \quad (6)$$

Where $RE_{i,t}$ is renewable energy consumption; $ENVIR_{i,t}$ is environmental pollution; $CLIMA_{i,t}$ is climate change; $INO_{i,t}$ is innovation; $GF_{i,t}$ is green finance; $INO_{i,t}*GF_{i,t}$ is interaction term of innovation and green finance; $GDP_{i,t}$ is economic development; $Indus_{i,t}$ is industrialization; $Urban_{i,t}$ is urbanization; $CP_{i,t}$ is climate policy; $CS_{i,t}$ is capital; ε_{it} is the error term; $t = 1, 2, \ldots,$ T time periods; and $i = 1, 2, 3 \ldots,$ N countries.

Estimation Methods

Endogenous problems are inevitable due to the complex relationship among energy consumption, environmental pollution and climate change. Endogeneity means that one or more explanatory variables are related to the random error term in the model. There are three main reasons for endogeneity problem, first, the omission of associated variables caused by the lack of comprehensive consideration. Second, the error generated in the process of selecting and measuring variables weakens the explanatory

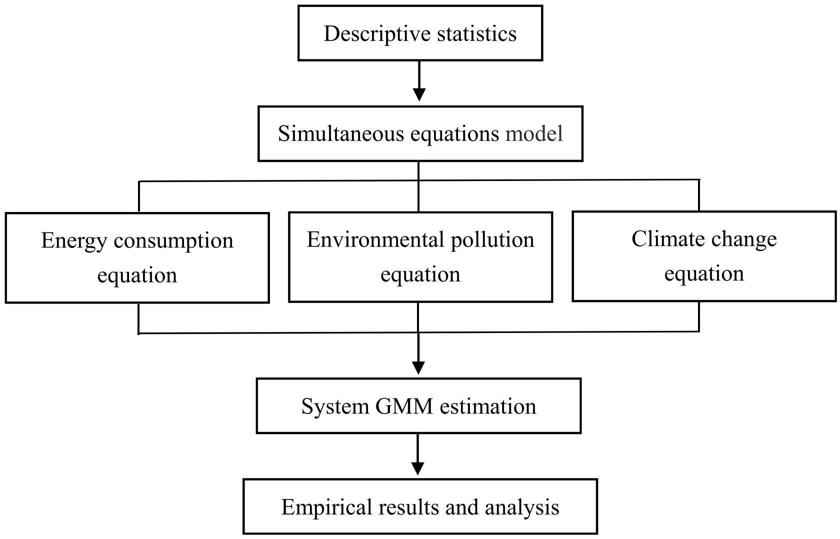

FIGURE 2 | Methodological framework.

degree. Third, the explanatory variable and the explained variable are mutually causal.

To estimate and measure energy-environment-climate phenomenon over time to address endogeneity issues more precisely. In this paper, the generalized method of moments estimation (GMM) is used for endogeneity correction (Arellano and Bond, 1991; Arellano and Bover, 1995). The dynamic panel model includes Difference GMM and System GMM. When there is a weak correlation between instrumental variable and the first difference of disturbance term, it is easy to form a weak instrumental variable, and the difference GMM estimator will produce a large error. Therefore, Blundell and Bond (1998) proposed the system GMM to solve the problem that the instrumental variable might be weakly correlated with the disturbance term in the first-order difference moment estimation. The system GMM estimator combines the difference equation and the level equation into the system of first-differenced equations to improve estimation efficiency. An explanatory variable may include the lagged dependent variable as its instrumental variable.

In order to ensure the effectiveness of the system GMM, the following two tests should be passed. First, Arellano-Bond test is used to test the autocorrelation, the results should not reject the null hypothesis that there is no second-order autocorrelation of the model, that is, the p-value of second-order serial correlations is greater than 0.05, indicating that the estimators were consistent. Second, Sargan test is used to examine validity of the instruments, the p-value of Sargan test of models is greater than 0.05, indicating that there is no over-recognition problem of model instrumental variables, and the regression results maintain a certain accuracy. The methodological framework is showed in **Figure 2**.

TABLE 3 | Descriptive statistics.

Variable	Mean	Std. Dev.	Min	Max
ENVIR	6.6416	4.2328	0.4810	18.9708
RE	20.9078	17.3612	0.0059	88.8318
CLIMA	0.6725	1.2903	−3.31	6.7
INO	1.4769	1.0408	0.0165	4.9512
GF	13.0283	26.3432	0.001	108
GDP	11.5804	2.2023	6.8093	17.8846
Indus	27.8473	7.9934	13.6822	70.2203
Urban	70.9202	16.1919	24.374	98.156
CP	0.9558	0.2056	0	1
CS	15.0807	1.3662	11.2618	18.2188

RESULTS AND ANALYSIS

Descriptive Statistics

This study employs annual and unbalanced panel data of 49 countries over the period 2007–2019. The energy-environment-climate nexus simultaneous equations model includes five core variables (renewable energy consumption, environmental pollution, climate change, innovation and green finance), and control variables (GDP, industrialization, urbanization, climate policy and capital stock). **Table 3** provides descriptive statistics on each of variables.

In order to deal with the problems associated with the existence of unobtainable heterogeneity, a system GMM estimator with two-step robust standard error was employed in this study. All the models (energy consumption model, environmental pollution model and climate change model) passed the AR (2) test (p value >0.05) and Sargan test (p value >0.05), it shows that the statistical model does not have the problem of autocorrelation in second-order serial correlations and

TABLE 4 | Energy consumption model.

RE Model	(1)	(2)	(3)	(4)	(5)
$RE_{(t-1)}$	0.9162*** (0.0080)	0.8737*** (0.0065)	0.7794*** (0.0133)	0.7554*** (0.0308)	0.7692*** (0.0366)
ENVIR	−0.0479* (0.0248)	−0.0990*** (0.0262)	−0.5260*** (0.0559)	−0.6514*** (0.0446)	−0.6167*** (0.0306)
CLIMA	−0.0209 (0.0139)	−0.0207 (0.0130)	−0.0668*** (0.0072)	−0.0443*** (0.0156)	−0.0262* (0.0149)
INO	—	0.5492*** (0.0539)	—	0.7950*** (0.0650)	0.8140*** (0.0582)
GF	—	—	−0.0069* (0.0038)	−0.0114*** (0.0038)	−0.0883*** (0.0153)
INO*GF	—	—	—	—	0.0406*** (0.0056)
Control variables	Yes	Yes	Yes	Yes	Yes
AR (1)[a]	−3.3916	−3.3024	−2.5447	−2.466	−2.3652
p-value	0.0007	0.0010	0.0109	0.0137	0.0180
AR (2)[a]	−1.3837	−1.3586	−1.6175	−1.5626	−1.629
p-value	0.1771	0.1783	0.1058	0.1181	0.1033
Sargan test[b]	38.6263	35.2121	19.6358	25.4764	22.1789
p-value	0.2684	0.4106	0.9683	0.8222	0.9235

Note: Standard errors are showed in brackets. All models include control variables.
[a]*The Arellano-Bond test for zero autocorrelation, null hypothesis (H0): the disturbance terms have no autocorrelation (Arellano and Bover, 1995).*
[b]*The Sargan test for overidentifying restrictions, null hypothesis (H0): all putative instrumental variables are valid.*
***: $p < 0.01$.
**: $p < 0.05$.
*: $p < 0.1$.

over-identifying restrictions in instrumental variables. Thus, the regression results are accurate and reasonable.

Energy Consumption Function

For the energy consumption model given in **Table 4**. ENVIR has a significantly negative influence on RE, which is supported by Pavlović et al. (2021) and Ahmed et al. (2021). Areas with high carbon dioxide emissions are more dependent on fossil fuel consumption, which hinders the transformation of energy structure and inhibits the consumption of clean energy. Environmental degradation has not effectively formed a coercive mechanism for the governments to regulate greenhouse gas emissions.

CLIMA has a statistically significant and negative impact on RE. The evidence is consistent with work by Chen et al. (2021) and Zhao and Huang., 2020. Extreme temperatures will hinder the use of clean energy such as solar and wind, damage equipment and reduce the efficiency of power generation in the short term. Climate change also can arouse public concern, forcing governments and enterprises to transform energy structure and improve the utilization rate of clean energy. In fact, the influence of the former is more obvious at this stage.

INO has statistically significant and positive impact on RE, which is supported by Anwar et al. (2020) and Zheng et al. (2021). Technological innovation satisfies the target of energy conservation and improves clean energy consumption. Technological innovation can effectively alleviate the contradiction between supply and demand in energy market, and enterprises will embark on more efficient renewable energy innovation actions with a higher energy demand.

GF has statistically significant and negative impact on RE, which is not supported by Ren et al. (2020) and Li et al. (2022). Green bonds have failed to create incentives for renewable energy consumption. With an increasing green bonds investment in the buildings and transport sectors year by year, it has a crowding out effect on the clean energy sector, and inhibits the investments of renewable energy projects. In addition, greenwashing behavior may also make green bonds no different from ordinary financing methods, failing to effectively form special funds for green projects.

The interaction term INO*GF is positively correlated with RE. The positive effect of innovation on renewable consumption will increase as green finance is enhanced. The evidence is similar to finding by Bird et al. (2011) and Hu et al. (2021). Green finance may increase investment in clean technologies innovation, which lead to a shift in the energy structure from fossil-fuel resources to renewable resources. Sufficient funds will reduce uncertainty and financing constraints of green innovation, and encourage governments and enterprises to promote innovations and patents to promote high-quality development of renewable energy sectors.

Environmental Pollution Function

For the environmental pollution model given in **Table 5**. RE has a negative influence on ENVIR, which is supported by Rahman and Velayutham, (2020) and Usman and Balsalobre-Lorente, (2022). Excessive use of fossil energy is the primary cause of greenhouse gas emissions. Carbon dioxide emissions can be significantly reduced by using renewable energy sources, such as solar, nuclear and wind energy. When more renewable energy is used in power generation, carbon dioxide emissions are significantly reduced. And ultimately achieve the goals of environmental quality improvement.

CLIMA has a significantly positive impact on ENVIR. The evidence is consistent with work by Javanroodi et al. (2018) and Liu et al. (2021). Extreme weather events may frequently destroy electricity generation equipment, the investment of clean energy power generation will be curbed, especially solar and wind power sectors. Extreme temperatures can also make urban areas require a lot of energy, especially electricity to be consumed for cooling buildings. Thus, climate change will increase the probability of environmental pollution.

TABLE 5 | Environmental pollution model.

ENVIR Model	(1)	(2)	(3)	(4)	(5)
$ENVIR_{(t-1)}$	0.6470*** (0.0119)	0.6739*** (0.0147)	0.3900*** (0.0470)	0.3351*** (0.0356)	0.3388*** (0.0452)
RE	−0.1042*** (0.0068)	−0.0878*** (0.0075)	−0.1056*** (0.0085)	−0.1009*** (0.0095)	−0.1026*** (0.0095)
CLIMA	0.1441*** (0.0076)	0.1521*** (0.0076)	0.0768*** (0.0150)	0.0644*** (0.0092)	0.0641*** (0.0114)
INO	—	−0.3116*** (0.0704)	—	−0.6632*** (0.0542)	−0.6442*** (0.0759)
GF	—	—	−0.0328*** (0.0027)	−0.0316*** (0.0013)	−0.0424*** (0.0038)
INO*GF	—	—	—	—	0.0059** (0.0023)
Control variables	Yes	Yes	Yes	Yes	Yes
AR (1)[a]	−2.9521	−2.9655	−1.3897	−0.8444	−0.9384
p-value	0.0032	0.0030	0.1646	0.3984	0.3480
AR (2)[a]	0.9259	0.8313	−1.5965	−1.4730	−1.4422
p-value	0.3545	0.4058	0.1104	0.1382	0.1322
Sargan test[b]	41.8280	39.3825	25.3515	24.5007	24.1990
p-value	0.1674	0.2416	0.8269	0.8573	0.8674

Note: Standard errors are showed in brackets. All models include control variables.
[a]*The Arellano-Bond test for zero autocorrelation, null hypothesis (H0): the disturbance terms have no autocorrelation (Arellano and Bover, 1995).*
[b]*The Sargan test for overidentifying restrictions, null hypothesis (H0): all putative instrumental variables are valid.*
***: $p < 0.01$.
**: $p < 0.05$.
*: $p < 0.1$.

TABLE 6 | Climate change model.

CLIMA Model	(1)	(2)	(3)	(4)	(5)
$CLIMA_{(t-1)}$	0.0951*** (0.0223)	0.0838*** (0.0233)	0.0471 (0.0291)	0.0952*** (0.0269)	0.0814*** (0.0193)
ENVIR	0.2742*** (0.0404)	0.3011*** (0.0431)	0.3944*** (0.0387)	0.3474*** (0.0765)	0.3398*** (0.0756)
RE	−0.0637*** (0.0094)	−0.0636*** (0.0093)	−0.0666*** (0.0234)	−0.0976*** (0.0241)	−0.0740** (0.0287)
INO	—	−0.1926* (0.1168)	—	−0.3906** (0.1534)	−0.2820** (0.1312)
GF	—	—	−0.0103*** (0.0025)	−0.0074** (0.0034)	−0.0281*** (0.0268)
INO*GF	—	—	—	—	−0.0211* (0.0119)
Control variables	Yes	Yes	Yes	Yes	Yes
AR (1)[a]	−3.3154	−3.3017	−1.7323	−1.7705	−1.8403
p-value	0.0009	0.0010	0.0832	0.0766	0.0657
AR (2)[a]	−1.2953	−1.3677	−0.4452	−0.7242	−0.8595
p-value	0.1952	0.1714	0.6562	0.4689	0.3900
Sargan test[b]	37.9629	37.7709	23.9615	22.7399	21.9403
p-value	0.2935	0.3010	0.8749	0.9098	0.9289

Note: Standard errors are showed in brackets. All models include control variables.
[a]*The Arellano-Bond test for zero autocorrelation, null hypothesis (H0): the disturbance terms have no autocorrelation (Arellano and Bover, 1995).*
[b]*The Sargan test for overidentifying restrictions, null hypothesis (H0): all putative instrumental variables are valid.*
***: $p < 0.01$.
**: $p < 0.05$.
*: $p < 0.1$.

INO has a statistically significant and negative influence on ENVIR, which is supported by Sæther, (2021) and Jahanger et al. (2022). Green technology innovation facilitates the transition of the energy matrix from fossil energy consumption to the renewable energy sector due to its environmentally friendly character. Urgent investment in green technology innovation can meet energy demand at low carbon emissions level. Innovation may improve energy efficiency, reducing greenhouse gas emissions per unit of energy consumption.

GF has a significantly negative impact on ENVIR, which is supported by Flammer (2020) and Muganyi et al. (2021). Green financial development can encourage companies to improve energy efficiency by constantly upgrading equipment, and achieve targets of energy conservation and emission reduction. Green finance guides capital flow to low-carbon industries and restrains the flow to high-carbon sectors, and lead to carbon emissions reduction.

The interaction term INO*GF is positively correlated with ENVIR at the 5% significance level. The negative effect of technology innovation on CO_2 emissions is enhanced by higher levels of green finance, which is supported by Pan et al. (2019) and Acheampong et al. (2020). Financial development can encourage a higher level of R&D, decarbonization technology innovation is more favored by green finance due to carbon emissions reduction. Green bonds mode is suitable for low-carbon technology innovation, which has the characteristics of long cycle and large capital demand. Green financial policies can improve green innovation by effectively dissolving the impact of corporate financing constraints to achieve carbon emissions reduction. Thus, development of green finance can help improve environmental quality by supporting technological innovation.

Climate Change Function

For the climate change model given in **Table 6**. RE has a statistically significant and negative effect on CLIMA, which is supported by Nyambuu and Semmler (2020) and Brini (2021). Renewable energy is the main way to alleviate global warming as a virtually carbon-free energy resource. Governments take serious action on climate change mitigation by increasing clean energy consumption in the energy sector and optimizing the energy structure, and reduce unacceptable climate risks and extreme weather events.

ENVIR has a positive influence on CLIMA. The evidence is similar to finding by Chiu, (2017) and Salari et al. (2021). Carbon dioxide emissions are the main reason for global warming, an increasing greenhouse gas emissions will cause extreme climate problems. Reducing greenhouse gas emissions worldwide by decarbonizing of energy sector, which can ensure global temperatures change at reasonable levels.

INO has a significantly negative impact on CLIMA. Technological innovation is an effective way to mitigate climate change, which is supported by Lin and Zhu (2019) and Wang et al. (2020). The improvement of green technology innovation may reduce greenhouse gas emissions and mitigate global warming risks by increasing energy efficiency and upgrading low-carbon equipment. Offsetting carbon emissions through technologies of carbon capture and storage, which will achieve "net zero" emissions of greenhouse gases.

GF is negatively related to CLIMA, which is supported by Dafermos and Nikolaidi (2021). Green bonds are issued to alleviate financing constraints for the solutions of environmental and climate problems. Green bonds improve climate change adaptation through targeted funding, including improving infrastructure resilience to climate change impacts, and building climate observation and warning systems.

The interaction term INO*GF is negatively correlated with CLIMA at the 5% significance level. The negative effect of technological innovation on climate change will decrease as green finance is enhanced. The evidence is consistent with work by Sadorsky (2011) and Aluko and Obalade (2020). Although green financial development may relieve financing constraints and provide adequate and sustainable financing for innovation, the development of green finance will inevitably drive economic expansion, and expanded production scale may weaken the emission reduction effects of innovation.

CONCLUSIONS AND POLICY IMPLICATIONS

Conclusion

This study introduced innovation and green finance as explanatory variables into simultaneous equations models within the energy-environment-climate dimensions. We found that the promotion effect of technological innovation on renewable energy consumption. Innovation significantly reduces CO_2 emissions and climate change by improving renewable energy efficiency. The governance effect of green finance on environmental pollution and climate change indicates that green financial development will provide important impetus for sustainable development. Green bonds mitigate renewable energy consumption, the funds mainly flow to the field of energy conservation, green buildings and transport, which has a crowding out effect on renewable energy.

In the interaction term aspect, the positive effect of innovation on renewable energy consumption is enhanced by higher level of green finance. The negative relationship between innovation and CO_2 emissions are strengthen when level of green finance is high. The negative impact of innovation on climate change is weakened as green finance is enhanced. The green financial development will support adequate and sustained funding for innovation to promote renewable energy structure transformation and ameliorate environmental pollution.

In the energy-environment-climate nexus, there is bidirectional causality between renewable energy consumption and carbon dioxide emissions. The development of clean energy will support the low-carbon sustainable development. Deteriorating environment will in turn inhibit the development of renewable energy. There is a bidirectional causality between CO_2 emissions and climate change. Carbon dioxide emissions will lead to global warming and frequent climate extremes. Global warming in turn appears to increase carbon dioxide emissions and diffusion. There is a bidirectional relationship between climate change and renewable energy consumption. Extreme weather will inhibit the development of renewable energy sources by reducing the efficiency of energy generation and increasing maintenance costs. Renewable energy consumption will in turn cut down greenhouse gas emissions, and mitigate climate change.

This research has limitations that can serve as directions for further studies. First, we employed green bonds as a proxy for green finance, which could not reflect the whole picture of green finance. The further research can build a multi-dimensional finance index, including green investment, green credit, green securities and green insurance, and explore the financing mechanism of heterogeneous green finance. Secord, the sample involved the countries with green bonds issued as a whole. The further studies can subdivide countries into regions and characteristics, and offer country-specific policy implications.

Policy Implications

The policy implications are as follows.

First, governments should encourage clean energy development and make a more scientific and rational energy structure. Government agencies should attempt to shift from fossil fuels to clean and renewable energy so that CO_2 would be reduced at the global level. Countries should actively adjust energy systems to achieve the goal of carbon neutrality. The European Union set up a "20-20-20" goal, which is to raise the renewable energy consumption ratio to 20%, increase the energy efficiency by 20%, and decrease carbon emissions by 20% before

2020. China promised a "30-60" target, that is to realize emission peak before 2030 and achieve carbon neutrality by 2060. Governments should focus on developing green industries, such as energy conservation and environmental protection industry, cleaner production industry, ecological environment industry, clean energy industry and green building industry. It is necessary to remove the entry barriers for renewable energy sources, and ensure renewable energy products can access to generate electricity market competitively.

Second, governments should develop environment-related technologies as a priority item. They should strengthen international partnerships to improve global environmental standards, increase policy support for environmental-friendly innovation and decarbonization technologies. For example, China has proposed to establish a green development alliance of the "Belt and Road" countries, which is committed to promoting green investment, sharing technical knowledge and resolving environmental problems. In addition, countries should build inter-regional platforms for innovation cooperation to promote the technology upgrading, and shorten the time for new technologies commercialization.

Third, a comprehensive green financing system should be established. Governments should set up a whole industrial chain and large-scale green finance to ensure the development of low-carbon economy. They should emphasize the important status of the securities market in green financing, and raise funds via IPOs and secondary placements for eligible green enterprises. It is necessary to encourage the development of green bond index and green stock index, and gradually establish a compulsory environmental information disclosure mechanism for bond issuers and listed companies. Governments should stimulate the vitality of carbon assets by asset securitization, which can promote the allocative efficiency of carbon assets. In addition, it is necessary to promote the innovation of green financial products and tools to provide financial support for sustainable development. Flexible and diversified financial services should be applied in clean energy sectors.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

KZ: Conceptualization; Data curation; Methodology; Analysis; Project administration. HC: Investigation; Project administration; Resources; Software. LT: Investigation; Data curation; Resources. SQ: Formal analysis; Project administration; Review and editing.

FUNDING

This work was supported by Youth Project of Humanities and Social Sciences of Ministry of Education in China (grant number: 19YJC790103), Social Science Foundation of Fujian Province (grant number: FJ2021C023), Social Science Foundation of Fujian Province (grant number: FJ2021B028), Youth talent innovation team support program of Zhengzhou University (grant number: 32320293).

REFERENCES

Acheampong, A. O., Amponsah, M., and Boateng, E. (2020). Does Financial Development Mitigate Carbon Emissions? Evidence from Heterogeneous Financial Economies. *Energy Econ.* 88, 104768. doi:10.1016/j.eneco.2020.104768

Ahmad, M., Khan, Z., and Rahman, Z. U. (2021). Can innovation shocks determine CO2 emissions (CO2e) in the OECD economies? A new perspective. *Econ. Innovation New Technol.* 30 (1), 89–109. doi:10.1080/10438599.2019.1684643

Ahmed, Z., Ahmad, M., and Rjoub, H. (2021). Economic Growth, Renewable Energy Consumption, and Ecological Footprint: Exploring the Role of Environmental Regulations and Democracy in Sustainable Development. *Sustain. Dev.* doi:10.1002/sd.2251

Aluko, O. A., and Obalade, A. A. (2020). Financial Development and Environmental Quality in Sub-saharan Africa: Is There a Technology Effect? *Sci. Total Environ.* 747, 141515. doi:10.1016/j.scitotenv.2020.141515

Andersen, D. C. (2017). Do credit Constraints Favor Dirty Production? Theory and Plant-Level Evidence. *J. Environ. Econ. Manag.* 84, 189–208. doi:10.1016/j.jeem.2017.04.002

Anwar, K., Faqir, M., and Yang, C. G. (2020). The Impression of Technological Innovations and Natural Resources in Energy-Growth-Environment Nexus: A New Look into BRICS Economies. *Sci. Total Environ.* 727, 138265. doi:10.1016/j.scitotenv.2020.138265

Arellano, M., and Bond, S. (1991). Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations. *Rev. Econ. Stud.* 58 (2), 277–297. doi:10.2307/2297968

Arellano, M., and Bover, O. (1995). Another Look at the Instrumental Variable Estimation of Error-Components Models. *J. Econ.* 68 (1), 29–51. doi:10.1016/0304-4076(94)01642-d

Arminen, H., and Menegaki, A. N. (2019). Corruption, Climate and the Energy-Environment-Growth Nexus. *Energy Econ.* 80, 621–634. doi:10.1016/j.eneco.2019.02.009

Bayer, P., Dolan, L., and Urpelainen, J. (2013). Global Patterns of Renewable Energy Innovation, 1990–2009. *Energy Sustain. Dev.* 17 (3), 288–295. doi:10.1016/j.esd.2013.02.003

Bekun, F. V., Alola, A. A., and Sarkodie, S. A. (2019). Toward a Sustainable Environment: Nexus between CO2 Emissions, Resource Rent, Renewable and Nonrenewable Energy in 16-EU Countries. *Sci. Total Environ.* 657, 1023–1029. doi:10.1016/j.scitotenv.2018.12.104

Bird, L., Chapman, C., and Logan, J. (2011). Evaluating Renewable Portfolio Standards and Carbon Cap Scenarios in the U.S Electric Sector. *Energy Policy* 39 (5), 2573–2585. doi:10.1016/j.enpol.2011.02.025

Blundell, R., and Bond, S. (1998). Initial Conditions and Moment Restrictions in Dynamic Panel Data Models. *Econ. Pap.* 87, 115–143. doi:10.1016/s0304-4076(98)00009-8

Bölük, G., and Mert, M. (2014). Fossil & Renewable Energy Consumption, GHGs (Greenhouse Gases) and Economic Growth: Evidence from a Panel of EU (European Union) Countries. *Energy* 74, 439–446. doi:10.1016/j.energy.2014.07.008

Brini, R. (2021). Renewable and Non-renewable Electricity Consumption, Economic Growth and Climate Change: Evidence from a Panel of Selected African Countries. *Energy* 223, 120064. doi:10.1016/j.energy.2021.120064

Campiglio, E., Dafermos, Y., Monnin, P., Ryan-Collins, J., Schotten, G., and Tanaka, M. (2018). Climate Change Challenges for Central Banks and Financial Regulators. *Nat. Clim. Change* 8 (6), 462–468. doi:10.1038/s41558-018-0175-0

Cantner, U., and Dettmann, E. (2019). The Impact of Innovation and Innovation Subsidies on Economic Development in German Regions. *Reg. Stud.* 53 (9), 1284–1295. doi:10.1080/00343404.2019.1639656

Chen, W., and Lei, Y. (2018). The Impacts of Renewable Energy and Technological Innovation on Environment-Energy-Growth Nexus: New Evidence from a Panel Quantile Regression. *Renew. Energy* 123, 1–14. doi:10.1016/j.renene.2018.02.026

Chen, X., Fu, Q., and Chang, C. P. (2021). What Are the Shocks of Climate Change on Clean Energy Investment: A Diversified Exploration. *Energy Econ.* 95, 105136. doi:10.1016/j.eneco.2021.105136

Cheng, C., Ren, X., and Wang, Z. (2019). Heterogeneous Impacts of Renewable Energy and Environmental Patents on CO2 Emission - Evidence from the BRIICS. *Sci. Total Environ.* 668, 1328–1338. doi:10.1016/j.scitotenv.2019.02.063

Chiu, Y. B. (2017). Carbon Dioxide, Income and Energy: Evidence from a Non-linear Model. *Energy Econ.* 61, 279–288. doi:10.1016/j.eneco.2016.11.022

Dafermos, Y., and Nikolaidi, M. (2021). How Can Green Differentiated Capital Requirements Affect Climate Risks? A Dynamic Macro-Financial Analysis. *J. Financial Stab.* 54, 100871. doi:10.1016/j.jfs.2021.100871

Danish, and Ulucak, R. (2021). Renewable Energy, Technological Innovation and the Environment: A Novel Dynamic Auto-Regressive Distributive Lag Simulation. *Renew. Sustain. Energy Rev.* 150, 111433. doi:10.1016/j.rser.2021.111433

Dogan, E., and Seker, F. (2016). The Influence of Real Output, Renewable and Non-renewable Energy, Trade and Financial Development on Carbon Emissions in the Top Renewable Energy Countries. *Renew. Sustain. Energy Rev.* 60, 1074–1085. doi:10.1016/j.rser.2016.02.006

Dong, K. Y., Sun, R. J., and Hochman, G. (2017). Do natural Gas and Renewable Energy Consumption Lead to Less CO2 Emission? Empirical Evidence from a Panel of BRICS Countries. *Energy* 141, 1466–1478. doi:10.1016/j.energy.2017.11.092

Erdoğan, S., Çakar, N. D., and Ulucak, R. (2020). The Role of Natural Resources Abundance and Dependence in Achieving Environmental Sustainability: Evidence from Resource-based Economies. *Sustain. Dev.* 29 (1), 143–154. doi:10.1002/sd.2137

Flammer, C. (2020). Green Bonds: Effectiveness and Implications for Public Policy. *Environ. Energy Policy Econ.* 1 (1), 95–128. doi:10.1086/706794

Ganda, F. (2019). The Impact of Innovation and Technology Investments on Carbon Emissions in Selected Organisation for Economic Cooperation and Development Countries. *J. Clean. Prod.* 217, 469–483. doi:10.1016/j.jclepro.2019.01.235

Geng, J. B., and Ji, Q. (2016). Technological Innovation and Renewable Energy Development: Evidence Based on Patent Counts. *Int. J. Glob. Environ. Issues* 15 (3), 217. doi:10.1504/ijgenvi.2016.076945

Gu, B., Chen, F., and Zhang, K. (2021). The Policy Effect of Green Finance in Promoting Industrial Transformation and Upgrading Efficiency in China: Analysis from the Perspective of Government Regulation and Public Environmental Demands. *Environ. Sci. Pollut. Res.* 28 (34), 47474–47491. doi:10.1007/s11356-021-13944-0

Hu, G., Wang, X., and Wang, Y. (2021). Can the Green Credit Policy Stimulate Green Innovation in Heavily Polluting Enterprises? Evidence from a Quasi-Natural Experiment in China. *Energy Econ.* 98 (3), 105134. doi:10.1016/j.eneco.2021.105134

Jahanger, A., Usman, M., and Murshed, M. (2022). The Linkages between Natural Resources, Human Capital, Globalization, Economic Growth, Financial Development, and Ecological Footprint: The Moderating Role of Technological Innovations. *Resour. Policy* 76, 102569. doi:10.1016/j.resourpol.2022.102569

Javanroodi, K., Mahdavinejad, M., and Nik, V. M. (2018). Impacts of Urban Morphology on Reducing Cooling Load and Increasing Ventilation Potential in Hot-Arid Climate. *Appl. Energy* 231, 714–746. doi:10.1016/j.apenergy.2018.09.116

Li, N., Pei, X. D., and Huang, Y. Z. (2022). Impact of Financial Inclusion and Green Bond Financing for Renewable Energy Mix: Implications for Financial Development in OECD Economies. *Environ. Sci. Pollut. Res.* 29, 25544–25555. doi:10.1007/s11356-021-17561-9

Li, Z., and Liao, G. (2018). Green Loan and Subsidy for Promoting Clean Production Innovation. *J. Clean. Prod.* 187, 421–431. doi:10.1016/j.jclepro.2018.03.066

Lin, B. Q., and Zhu, J. P. (2019). Determinants of Renewable Energy Technological Innovation in China under CO2 Emissions Constraint. *J. Environ. Manag.* 247, 662–671. doi:10.1016/j.jenvman.2019.06.121

Liu, S., Xing, J., and Westervelt, D. M. (2021). Role of Emission Controls in Reducing the 2050 Climate Change Penalty for PM2.5 in China. *Sci. Total Environ.* 765, 144338. doi:10.1016/j.scitotenv.2020.144338

Muganyi, T., Yan, L. N., and Sun, H. P. (2021). Green Finance, Fintech and Environmental Protection: Evidence from China. *Environ. Sci. Ecotechnology* 7, 100107. doi:10.1016/j.ese.2021.100107

Nyambuu, U., and Semmler, W. (2020). Climate Change and the Transition to a Low Carbon Economy - Carbon Targets and the Carbon Budget. *Econ. Model.* 84 (1), 367–376. doi:10.1016/j.econmod.2019.04.026

Pan, X., Uddin, M. K., and Han, C. (2019). Dynamics of Financial Development, Trade Openness, Technological Innovation and Energy Intensity: Evidence from Bangladesh. *Energy* 171, 456–464. doi:10.1016/j.energy.2018.12.200

Pavlović, B., Ivezić, D., and Živković, M. (2021). A Multi-Criteria Approach for Assessing the Potential of Renewable Energy Sources for Electricity Generation: Case Serbia. *Ener. Rep.* 7, 8624–8632. doi:10.1016/j.egyr.2021.02.072

Pradhan, B. K., and Ghosh, J. (2022). A Computable General Equilibrium (CGE) Assessment of Technological Progress and Carbon Pricing in India's Green Energy Transition via Furthering its Renewable Capacity. *Energy Econ.* 106, 105788. doi:10.1016/j.eneco.2021.105788

Rahman, M. M., and Velayutham, E. (2020). Renewable and Non-renewable Energy Consumption-Economic Growth Nexus: New Evidence from South Asia. *Renew. Energy* 147, 399–408. doi:10.1016/j.renene.2019.09.007

Reboredo, J. C. (2018). Green Bond and Financial Markets: Co-movement, Diversification and Price Spillover Effects. *Energy Econ.* 74, 38–50. doi:10.1016/j.eneco.2018.05.030

Ren, X. D., Shao, Q. L., and Zhong, R. Y. (2020). Nexus between Green Finance, Non-fossil Energy Use, and Carbon Intensity: Empirical Evidence from China Based on a Vector Error Correction Model. *J. Clean. Prod.* 277, 122844. doi:10.1016/j.jclepro.2020.122844

Sadorsky, P. (2011). Financial Development and Energy Consumption in Central and Eastern European Frontier Economies. *Energy Policy* 39 (2), 999–1006. doi:10.1016/j.enpol.2010.11.034

Salari, M., Javid, R. J., and Noghanibehambari, H. (2021). The Nexus between CO2 Emissions, Energy Consumption, and Economic Growth in the. *U.S. Econ. Analysis Policy* 69, 182–194. doi:10.1016/j.eap.2020.12.007

Sæther, S. R. (2021). Climate Policy Choices: An Empirical Study of the Effects on the OECD and BRICS Power Sector Emission Intensity - ScienceDirect. *Econ. Analysis Policy* 71, 499–515. doi:10.1016/j.eap.2021.06.011

Sharifi, A., and Yamagata, Y. (2016). Principles and Criteria for Assessing Urban Energy Resilience: A Literature Review. *Renew. Sustain. Energy Rev.* 60, 1654–1677. doi:10.1016/j.rser.2016.03.028

Sohag, K. (2015). Dynamics of Energy Use, Technological Innovation, Economic Growth and Trade Openness in Malaysia. *Energy* 90, 1497–1507. doi:10.1016/j.energy.2015.06.101

Su, H. N., and Moaniba, I. M. (2017). Does Innovation Respond to Climate Change? Empirical Evidence from Patents and Greenhouse Gas Emissions. *Technol. Forecast. Soc. Change* 122, 49–62. doi:10.1016/j.techfore.2017.04.017

Sun, C. H. (2021). The Correlation between Green Finance and Carbon Emissions Based on Improved Neural Network. *Neural Comput. Appl.* doi:10.1007/s00521-021-06514-5

Tamazian, A., Chousa, J. P., and Vadlamannati, K. C. (2009). Does Higher Economic and Financial Development Lead to Environmental Degradation: Evidence from BRIC Countries. *Energy Policy* 37 (1), 246–253. doi:10.1016/j.enpol.2008.08.025

Tang, C. F., and Tan, E. C. (2013). Exploring the Nexus of Electricity Consumption, Economic Growth, Energy Prices and Technology Innovation in Malaysia. *Appl. Energy* 104 (4), 297–305. doi:10.1016/j.apenergy.2012.10.061

Tiba, S., and Frikha, M. (2018). Income, Trade Openness and Energy Interactions: Evidence from Simultaneous Equation Modeling. *Energy* 147, 799–811. doi:10.1016/j.energy.2018.01.013

Uluak, R., Koçak, E., Erdogan, S., and Kassouri, Y. (2020). Investigating the Non-linear Effects of Globalization on Material Consumption in the EU Countries:

Evidence from PSTR Estimation. *Resour. Policy* 67, 101667. doi:10.1016/j.resourpol.2020.101667

Usman, M., and Balsalobre-Lorente, D. (2022). Environmental Concern in the Era of Industrialization: Can Financial Development, Renewable Energy and Natural Resources Alleviate Some Load? *Energy Policy* 162, 112780. doi:10.1016/j.enpol.2022.112780

Wang, R., Mirza, N., and Vasbieva, D. G. (2020). The Nexus of Carbon Emissions, Financial Development, Renewable Energy Consumption, and Technological Innovation: What Should Be the Priorities in Light of COP 21 Agreements? *J. Environ. Manag.* 271 (6-10), 111027. doi:10.1016/j.jenvman.2020.111027

Yu, C. H., Wu, X. Q., and Zhang, D. (2021). Demand for Green Finance: Resolving Financing Constraints on Green Innovation in China. *Energy Policy* 153 (1), 112255. doi:10.1016/j.enpol.2021.112255

Zerbib, O. D. (2019). The Effect of Pro-environmental Preferences on Bond Prices: Evidence from Green Bonds. *J. Bank. Finance* 98, 39–60. doi:10.1016/j.jbankfin.2018.10.012

Zhao, X. H., and Huang, G. H. (2020). Impacts of Climate Change on Photovoltaic Energy Potential: A Case Study of China. *Appl. Ener.* 280, 115888. doi:10.1016/j.apenergy.2020.115888

Zheng, S. H., Yang, J., and Yu, S. W. (2021). How Renewable Energy Technological Innovation Promotes Renewable Power Generation: Evidence from China's Provincial Panel Data. *Renew. Energy* 177 (4), 1394–1407. doi:10.1016/j.renene.2021.06.023

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.

ORIGINAL RESEARCH
published: 30 May 2022
doi: 10.3389/fenvs.2022.881293

The Role of Payment Technology Innovation in Environmental Sustainability: Mediation Effect From Consumers' Awareness to Practice

Jiaji An, He Di, Meifang Yao and Shuaiqi Jin*

School of Business and Management, Jilin University, Changchun, China

Based on the traditional internal factor model, high environmental awareness should bring higher engagement in environmental practices. In reality, however, many studies have found no significant correlation between the two. To explain this, frontier research is focusing on what external factors influence environmental sustainability. As a typical example of such external factors, this article focuses on the innovation of Internet payment technology. Based on a survey of 623 individuals living across mainland China, we conduct path analysis, stepwise regression analysis, and a mediation test on Internet payment technology, environmental awareness, environmental protection practices, and demographics such as age, income, and sex. We find that Internet payment technology plays a significant mediator role between environmental awareness and environmental behaviors, and that demographics also affect sustainability. Internet payment technology can expand the range of ways in which consumers participate in environmental protection and encourage them to put more green practices through emotional and physical incentives. We thus demonstrate the positive impact of technological innovation on environmental sustainability and unfold the underlying mechanism. Besides providing a reference for other researchers, our study also proposes some applications relevant to the scientific community.

Keywords: payment technology innovation, environmental sustainability, consumers' awareness, consumers' practice, mediation effect

OPEN ACCESS

Edited by:
Yingcheng Li,
Southeast University, China

Reviewed by:
Luminita Ionescu,
Spiru Haret University, Romania
Grigorios L. Kyriakopoulos,
National Technical University of Athens, Greece
Jose Balsa,
Media Lab, Massachusetts Institute of Technology, Cambridge, United States

****Correspondence:***
He Di
dihe@jlu.edu.cn

Specialty section:
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

Received: *22 February 2022*
Accepted: *05 May 2022*
Published: *30 May 2022*

Citation:
An J, Di H, Yao M and Jin S (2022) The Role of Payment Technology Innovation in Environmental Sustainability: Mediation Effect From Consumers' Awareness to Practice. Front. Environ. Sci. 10:881293. doi: 10.3389/fenvs.2022.881293

1 INTRODUCTION

Planned behaviors based on psychological factors and their improved models are the traditional research foundations for individual participation in environmental protection behaviors. The theoretical model posits that personal environmental awareness or perception positively affects the degree of participation in environment-friendly practices. Yet according to a survey conducted by the Ministry of Ecology and Environment of the People's Republic of China, 2018, there is a phenomenon of "high awareness, low practice" in waste classification, green consumption, and participation. In environmental behavior research, the inconsistent or weak influence of environmental attitudes on environmental behaviors has been partially verified and gradually attracted more research attention (Brand, 1997). Blake (1999) proposes that external factors mediate between environmental attitudes and environmental behaviors, such as personality and feasibility. This is inconsistent with the traditional theoretical model of internal factor research, so the original analysis alone cannot explain the complicated relationship between environmental awareness and environmental behavior. To solve this problem, some scholars began to pay attention to the influence and mechanism of individual demographics and external situational factors, that is, new technology, such as the Internet and other media (Garz, 2014; Ellison et al., 2015; Peng et al., 2019). Similarly, many studies contend that technological innovation can directly affect sustainability (Murty and Kumar, 2003; Yin et al., 2014; Gkika et al., 2020; Iqbal et al., 2022). To build on these earlier works, this article innovatively focuses on the digital technology of Internet payments, exploring its role in sustainability. With the rapid development of Internet technology in recent years, especially the increasing green and low-carbon life scenes based on network payment technology, many new platforms have emerged for public participation in environmental protection. These platforms have brought new opportunities and possibilities for the public to implement green and low-carbon behaviors (Liu and Hao, 2017; Li and Liu, 2018). Internet payments can reduce the printing of paper receipts, while online shopping and online utility payments can greatly reduce the need to drive to make purchases, thereby reducing CO_2 emissions. Therefore, Internet payment technology has a natural spillover effect in the field of environmental protection, and should be investigated as an external situational factors (Yang et al., 2018). This research is motivated by the unresolved questions of whether and how Internet payment technology spillover significantly impacts on individual environmental perception and green practices.

Our focus on China is motivated by the following considerations. Based on population dynamics, Balsa-Barreiro et al. (2019) analyzed the shifting locations of centers of gravity of four basic global indicators during 1960–2016: gross domestic product (GDP), CO_2 emissions, total population, and urban population. They found that the centers of gravity of GDP and CO_2 emissions have shifted eastward: the weight of CO_2 emissions to GDP is ×2 in China and ×1.6 in the Asian region, compared to ×0.5 in Japan, ×0.6 in the United States, and ×0.3 in the European Union. This demonstrates that the economic growth model of some countries in Southeast Asia consumes high levels of resources. This has been particularly true of China: according to 2018 data from the United Nations Environment Programme, China is the country with the largest CO_2 emissions, accounting for over one-quarter of the global total. Therefore, studying China's environmental issues is especially valuable for global sustainability.

This study uses data from China to empirically analyze the impact of Internet payment technology on personal environmental awareness and green practices, aiming to open the black box of the internal mechanism of action to yield theoretical and practical implications.

2 LITERATURE REVIEW AND HYPOTHESES

2.1 Theories on Psychological Influencing Factors

2.1.1 Theory of Planned Behavior

In 1975, Fishbein and Ajzen proposed the theory of reasoned action (TRA), which posits how attitudes form based on cognitive information and consciously affect individual behavior. The basic assumption is that people are rational and will synthesize various kinds of information to consider the meaning and consequences of their actions before acting in a certain way (Fishbein and Ajzen, 1975). Ajzen's later research (2011) found that human behavior is affected by external environment. On this basis, he expanded the TRA by adding the new concept of perceived behavioral control (PBC), thus developing a new behavioral theory model: the theory of planned behavior (TPB). This posits that human behavior results from deliberate thoughts, and that behavior is produced and changed through a complex psychological process. The TPB has been endorsed by several scholars. Hopkins and Potcovaru (2021) found that consumer attitudes, values, needs, and expectations were affected by external factors such as COVID-19. Also focusing on effects of the pandemic, Priem (2021) found that COVID-19-related lockdowns limited the financial behavior of individual investors. Regarding environmental behavior, the main determinant according to the TPB is willingness to engage in environmental behavior, while three other factors are also influential: environmental attitude, subjective norms, and PBC (Ajzen, 2011). Since the TPB was first applied in environmental research, increasing numbers of scholars have begun to study the willingness of individuals to pay the price for improving environmental conditions, engaging in environment-conscious behaviors, and execution practices. Scholars contend that the TPB fully affirms the role of environmental attitudes but somewhat weakens the influence of external behavior constraints. For example, in Kaiser and Gustcher's (2003) survey of 895 Swiss residents, PBC did not have an obvious effect on environmental behavior.

2.1.2 Norm Activation Model

Due to the limited explanatory power of the TPB on environmental awareness and behavior differences, Schwartz (1977) proposed the norm activation model. It assumes that social norms must first become individual norms before they can influence an individual's pro-social behavior. The activation of individual norms depends on two factors: the individual's awareness of the consequences of the action (AC) and ascription of responsibility for these consequences (AR). Therefore, according to this model, only when AC and AR are high will individual norms be activated, leading the individual to take environmental actions (Schwartz, 1977). As the norm activation theory does not fully consider differences in environmental behaviors caused by individual heterogeneity, it is often used to research mandated forms of environmental protection behavior in areas such as recycling, energy conservation, and yard-waste landfill. Therefore, there are certain limitations to the application of this model (Black et al., 1985).

2.1.3 Value-Belief-Norm Theory

Stern (2000) combined norm activation theory with value theory to propose the value-belief-norm (VBN) theory. It emphasizes the causal chain of value→belief→personal norms: values on environmental behaviors lead to beliefs that then activate behavioral norms. The individual's sense of responsibility for

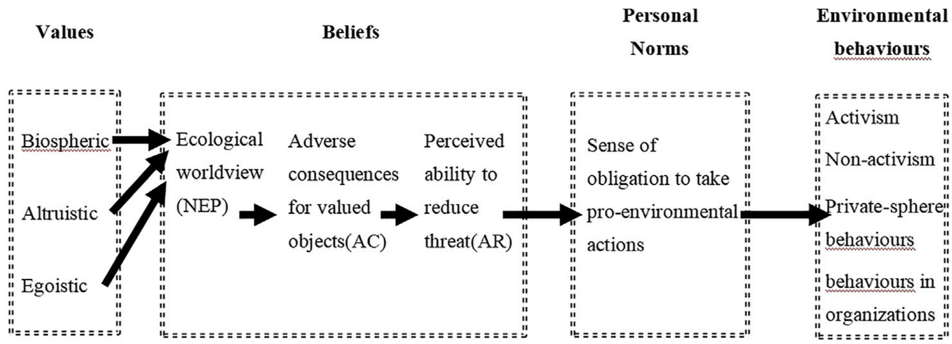

FIGURE 1 | A schematic representation of variables in the VBN theory of environmentalism.

taking environmental actions, and finally the environmental actions. Relevant values include biospheric values, altruistic values, and egoistic values, of which the latter will negatively affect environmental behavior. The theoretical model is depicted in **Figure 1**.

The VBN theory incorporates values into the analysis model, explores the types of values and their effects, and broadens the influencing factors of environmental behavior research. However, there has been insufficient discussion of external factors and individual heterogeneity (Bamberg and Moser, 2007).

Based on the three branches of theory considered above, environmental awareness is an important internal factor that positively affects environmental behavior. Birtus and Lăzăroiu (2021) studied the neurobehavioral economics of the COVID-19 pandemic from the perspective of consumer cognition, perception, sentiment, choice, and decision-making; they found a significant positive relationship between consumer cognition and decision-making. Similarly, Rydell and Kucera (2021) examined the relationship between cognitive attitudes, behavioral choices, and purchasing habits during the COVID-19 pandemic; they also found that cognitive attitudes directly affected behavioral choices. Accordingly, we propose the following hypothesis:

H_1. Environmental awareness and sustainability are positively related.

2.2 External Situational Factors: The A-B-C Model of Behavior

As mentioned earlier, the problem of "high awareness, low practice" for environmental protection is contrary to traditional psychological theory. Therefore, while the classical theoretical model analyzes the individual's internal psychology, environmental behavior research increasingly considers external factors, concentrating especially on the inconsistent or weak influence of environmental attitudes on environmental behaviors. Scholars have focused on other factors that mediate this relationship, such as norms, values, and external situational factors (Peng, 2013). Guagnano et al. (1995) proposed an A-B-C model for predicting waste recycling behavior. The model integrates internal (psychological) processes with external conditions, and considers environmental behaviors (B) to be the result of the individual's general and specific environmental attitude (A) and of external conditions (C). Specifically, when external conditions are favorable and environmental attitudes positive, environmental behaviors will occur; when external conditions are unfavorable and individuals hold negative environmental attitudes, environmental behaviors will not occur; when external conditions are relatively neutral, environmental attitudes have a strong effect on environmental behavior. The A-B-C model proposes that environmental behaviors result from the combined influence of environmental attitudes and external conditions, and points out that the effect of environmental attitudes on environmental behaviors depends on the specific external conditions. This theory opened a new direction of environmental behavior research, thus attracting scholars to start investigating external factors (Steg et al., 2005; Scherbaum et al., 2008). Therefore, this study adopts the A-B-C model.

2.2.1 Influence of Demographic Features

Many studies have shown that demographics such as gender, age, social status, education level, and residence attributes can impact on environmental behaviors. Wang and Zhong (2016) found that individual gender and age factors significantly impacted on residents' private environmental behavior in China. Mi et al. (2019) studied the driving force of environmental knowledge among people with different education levels; they found that people with higher education levels had greater willingness to engage in low-carbon purchasing behavior. Gong and Lei (2007) used factor analysis and multiple linear regression to study the impact of gender on the environmental behaviors of residents in different fields; they found that women were more inclined than men to adopt environmentally friendly behaviors. Empirical research by Li (2006) showed that gender and education level have important influences on individual environmental behaviors. In Al Mamun et al. (2018) study of green consumption behaviors, low-income households were found to engage significantly less than did high-income households. Nakamura (2020) contends that sustainability behavior is not always uniform across residents of a specific region. In sum, these demographics need to be considered.

2.2.2 Influences of External Situational Variables

Situational variables are external factors that impact on an individual's implementation of environmental behaviors. For instance, environmental pollution, environmental governance behaviors, social norms, behavioral costs, and mass media are all considered to have significant impacts (Yuan, 2016; Štreimikienė et al., 2021). De Young (1990) found that Michigan residents' garbage collection behaviors were significantly influenced by whether community public facilities such as recycling bins had been set up, whether these facilities were convenient to use, and whether engaging in these behaviors was time-consuming. Based on a questionnaire survey, Men and Xiong (2018) found that government input indirectly affects the public's ecological behaviors by influencing the public's environmental knowledge and environmental awareness. Kyriakopoulos et al. (2020) investigated the environmental behaviors of business and accounting students at the University of West Attica, Greece. They found that environmental education had a significant positive effect on environmental behavior, while also increasing the significance of the effect of ecological sensitivity on environmental behavior. Other studies contend that in addition to school education, family environmental awareness positively affects students' green behaviors (Ntanos et al., 2018). Wang and Han (2016) found that the interweaving of economic development and environmental pollution impacted on public environmental protection behavior. On this basis, scholars began to pay attention to the impact of the Internet on environmental attitudes and behaviors.

2.3 Internet and Environmental Behaviors

As research into Internet payment technology and environmental protection is relatively new, there are few existing theoretical discussions. Research on the Internet and environmental behaviors is mostly based on information dissemination attributes, the popularization of environmental protection information, the supervision of environmental behavior, the fear of vicious environmental protection news, and the spread of positive environmental protection information (Krätzig and Warren-Kretzschmar, 2014). Hong (2013) and Stockemer (2018) found that for residents who frequently use the Internet to browse information, the increased transparency of government information induced greater participation in decision-making on environmental protection and in environmental supervision, forming a positive environmental attitude. Through increasing participation in environmental protection decision-making, Internet use has promoted the democratization process and strengthened the cooperative relationship between the government and netizens. In addition, the Internet provides an important channel for the government to promote the idea of "environmental protection and benefiting the people." Environmental protection improves physical health, in turn improving one's income-earning ability, which may induce a positive attitude toward the environment (Wang and Ye, 2016). Analyzing China's comprehensive social survey data, Peng et al. (2019) found that regular use of the Internet to browse information promoted residents' environmental protection attitudes and environmental literacy; moreover, residents' environmental literacy was improved more by regular Internet use than by formal (academic) education.

Drawing on information transfer theory to explain why internal environmental literacy lags behind external environmental literacy, Ellison et al. (2015) and Okazaki and Taylor (2013) pointed out that information flow is impeded by blockages and the inability to enjoy equal access to information. The emergence of online media has broken the pattern of unevenly distributed information, helping to build an advanced, better-structured system of environmental knowledge and deepen environmental knowledge reserves, thereby reducing the external gap in and improving the overall level of environmental literacy. Fischer and Reuber (2011) contend that network information interaction is inclusive: netizens at different levels can chat about hot topics on environmental protection, exchanging knowledge and views, thereby enhancing one another's environmental literacy.

Most studies in this field explore whether information dissemination on the Internet is related to environmental protection, green and sustainable development, and the majority find positive correlations. However, Internet payment technology represents a step beyond information media: as a tool to replace or supplement traditional payment methods, it has potential technological spillover effects on environmental awareness and practice. Therefore, this article extensively investigates the impact of Internet payment technology. As a sub-concept in the Internet category, Internet payment technology can be expected to positively affect environmental behaviors. Based on the conclusions of the cutting-edge research (Barbu et al., 2021; Ionescu, 2021; Bin, 2022), we propose the following hypothesis:

H_2. Use of Internet payment technology and sustainability are positively related.

2.4 Mediation Effect of Internet Payment Technology

Internet payment technology is rapidly becoming a global hotspot and the focus of in-depth scholarly research. Kshetri (2017) pointed out it has already achieved all-round impact on residents' lives in the emerging economies of China and India. China has become a major country in the application of Internet payment technology. According to data from iResearch Consulting (2020), the transaction amount of Internet payments in China was USD 31.7 trillion in 2019, ranking first in the world. According to the 43rd "Statistical Report on the Development of China's Internet," as of December 2018, China had 827 million Internet users and the penetration rate of Internet payment technology had reached 59.6% (Cyberspace Administration of China, 2019).

With the rapid development of Internet payment technology, it has become an important platform for residents to participate in environmental protection (Policy Research Center for Environment and Economy, 2019a). Internet payment technology promotes public green consumption in four main ways. First, it guides consumers to buy green products. Internet payment technology significantly reduces the cost for consumers to obtain green information on products (Chen and Wu, 2020; He et al., 2021), and comparative advantages of green products by a wide range of consumer groups (Lv, 2018). Internet payment technology also improves the competitiveness of green products in the market, guiding consumers to purchase these products through the transmission and sequencing of information. Second, it can give the public ways and incentives to implement green behaviors in different consumption scenarios (He, 2018; Li, 2018; Luo et al., 2019). For example, some online payment platforms enable users to accumulate “green energy” that they can ultimately exchange for the planting of a real sapling in the desert (Ren et al., 2019; Wu et al., 2019; Xia, 2019). Third, as Internet payment technology relies on the sharing economy of payment platforms and the rise of idle goods trading platforms, it facilitates the reuse of consumer goods and optimizes resource allocation (Huang, 2018). Fourth, Internet payment technology increases the online proportion of consumption and payment and reduces related travel, thereby lowering carbon emissions (Wang et al., 2018).

Green consumption behaviors based on Internet payment platforms are continuing to increase. In terms of green product consumption, over 65 million people bought green commodities on the Alibaba platform in 2015 (“Alibaba Green Consumption Big Data Report”), which indicates the substantial scale of the online green consumer population. The overall purchase of energy-saving home appliances increased by 25% year-on-year from 2013 to 2015 (Chinese Internet Data Information Network, 2016). In 2018 (vs. 2017), sales volume on the Taobao platform increased by over 100% for eco-friendly shopping bags, by 51% for environment-friendly home improvement building materials, and by over 50% for energy-saving and environment-friendly LED lights. As of the end of August 2019, the carbon emissions saved by use of Internet payments amounted to nearly 7.93 million tons, equivalent to saving 11.6 billion kWh of electricity—approximately equal to the annual electricity consumption of all residents in a super city. Paying through the Internet also saved 373 billion plastic bags, which would cover an area of nearly 160,000 km^2 (larger than Greece). It would take at least 100 years for these plastic bags to completely degrade (Policy Research Center for Environment and Economy, 2019b).

In summary, Internet payment technology provides more opportunities for environment-conscious people to participate in environmental practices through diversified platforms and channels, at a lower cost and in a convenient and friendly way. Therefore, there is a logical basis for Internet payment technology positively affecting environmental behaviors, especially as a mediating mechanism. May et al. (2021) examined the relationship between corporate social responsibility, employee green behaviors, and environmental sustainability. They found that organizational trust and identity may play an intermediary role. This enlightened us that external factors may mediate the relationship between perception and behavior. We thus propose the following hypothesis:

H_3. Use of Internet payment technology mediates the effect of environmental awareness on sustainability.

The above theoretical analysis and literature review revealed that while most research still uses the traditional internal factor model, attention is increasing on the mediator role of external situational factors. Studies focusing on the role of the Internet are primarily at the stage of qualitative analysis, and thus lack quantitative empirical evidence. To address this gap, this study adopts the A-B-C model and investigates Internet payment technology as an innovative external situational variable, aiming to discover whether it mediates between environmental awareness and sustainability.

Based on the above analysis, **Figure 2** depicts the research framework.

3 METHODS

3.1 Questionnaire Design and Data Processing

This article uses the classic five-point Likert scale, adding self-designed questions to Peng et al.’s (2019) questionnaire on the relationship between the Internet and the environment. In order to filter out invalid responses, we also designed logically related questions that do not enter the model. We distributed our online questionnaire to residents of 31 provinces in mainland China. Through the largest online questionnaire distribution platform in China, a total of 1,083 questionnaires were distributed in May 2020, which were taken back in August 2020. After excluding invalid responses and those with missing information, 623 were retained for analysis of the study variables. Sustainability is the explained variable; environmental awareness is the explanatory variable; Internet payment technology is the intermediary variable; and demographics are the control variables. Data were processed using SPSS 25.0. The confidence interval is set to 95%.

3.1.1 Dependent Variable

The concept of sustainability includes green, environmental practice, recycling ,etc. In designing the questionnaire, we focused on the attributes of environmental practices, referring to the degree of residents’ actual participation in environmental protection activities. Such activities include the use of old objects, low-carbon transportation, tree planting, garbage recycling, and other public welfare projects targeting environmental protection (Liu and Hao, 2017). Sustainability was quantified through seven questions each covering a distinct aspect: reducing paper shopping receipts, reducing dependence on plastic packaging, not using disposable tableware, low-carbon travel, item reuse, tree planting, and other environmental protection projects. Each question was answered on a 5-point scale; the higher the score, the higher is the degree of environmental sustainability. Summing up the scores of each question produced the overall score for sustainability (SS).

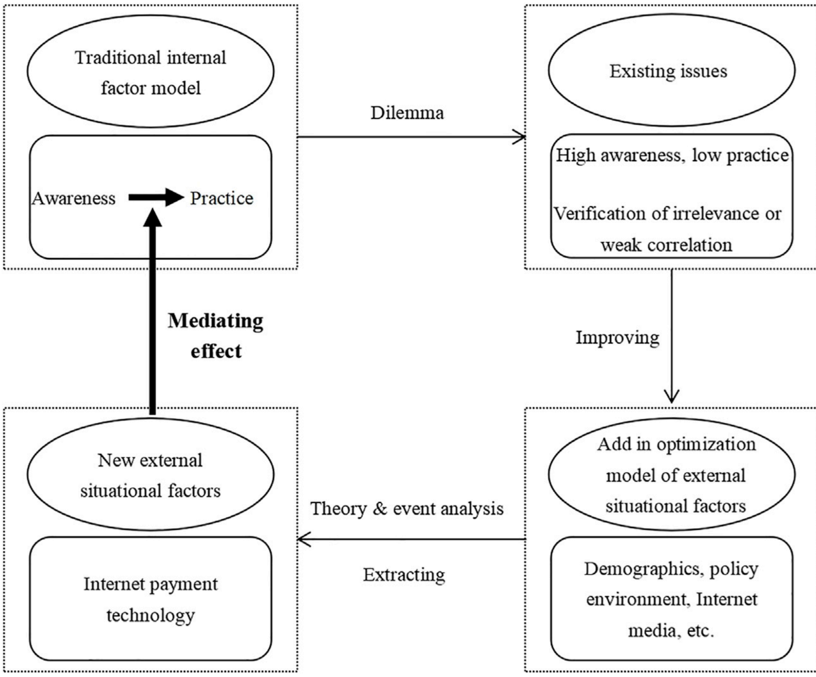

FIGURE 2 | Research logic framework.

3.1.2 Independent Variable

Environmental awareness refers to residents' views on, attitudes toward, and knowledge of environmental protection (Stern and Dietz, 1994). This research quantifies environmental awareness through 15 questions covering seven aspects: consumers' willingness to purchase green products, extra costs for green added value, awareness of environmental knowledge, environmental protection norms of people around them, ease of participating in environmental protection, environmental value recognition, and basic conditions of environmental protection. Each question was answered on a 5-point scale; the higher the score, the higher is environmental awareness. Summing up the scores for each question produced the overall score for environmental awareness (EA).

3.1.3 Mediator

Scholars often measure Internet payments by the total transaction amount (Weeks, 2018; Yao et al., 2018). Although this indicator is somewhat representative, it does not capture the per capita transaction amount of Internet payments, the number of such transactions per capita, and the transaction penetration rate, all of which reflect the application degree of Internet payment technology (Dorn, 2018). To include more comprehensive information and take into account the reliability of the data, we quantified the use of Internet payment technology (IPT) using the Internet Payment Development Index developed by the Institute of Internet Finance, Peking University (China Center for Economic Research, 2018). This index has been adopted by the National Development Institute, and so has recognized authority. It provides a value for each region in each year. To ensure the consistency and validity of the data from 2016 to 2019, we average the cross-year data and match the region data with the residence location of each respondent.

3.1.4 Control Variables

Based on previous findings on which demographics influence environmental perceptions and practices (Wang and Zhong, 2016; Li, 2006; Gong and Lei, 2007), this study includes five control variables: sex (SE), age (AG), education level (EL), monthly household income (HI), and urban-county-rural distribution (UCR). They are classified and scored based on the scale results.

The definitions and descriptions of all study variables are presented in **Table 1**.

3.2 Reliability and Validity Tests of the Questionnaire

To ensure the consistency and rationality of the questionnaire items (Brener et al., 2002; Ratko et al., 2020), the scales measuring the dependent variable, independent variable, and mediator (22 items in total) were subject to the following tests of reliability and validity.

3.2.1 Reliability

Reliability is achieved when repeatedly measuring the same object using the same method produces consistent results (Long and Johnson, 2000). We used the Cronbach's α coefficient to test the

TABLE 1 | Variable definitions.

Category	Variable	Definition
Dependent variable	SS	Sustainability, calculated using responses to seven questions on a 5-point Likert scale. The higher the total score (out of 35), the higher is environmental sustainability
Independent variable	EA	Environmental awareness, calculated using responses to 14 questions on a 5-point Likert scale. The higher the total score (out of 70), the higher is environmental awareness
Mediator	IPT	Internet payment technology, measured using the Internet Payment Development Index developed by the Institute of Internet Finance, Peking University. There is a separate index value for each of the 31 provinces in mainland China
Control Variables	SE	Sex, measured as 1 point for male (336/623 respondents) and 2 points for female (287/623)
	AG	Age, measured by young to old according to five-point-scale, on which a higher score means older. (≤19, 89 respondents; 20–29, 153; 30–39, 141; 40–49, 138; ≥50, 102)
	EL	Education level, measured from low to high on a 5-point scale, on which a higher score denotes a higher education level. (≤High school, 31 respondents; diploma, 48; undergraduate, 373; master degree, 137; PhD, 34)
	HI	Monthly household income, measured monthly on a 5-point scale, on which a higher score denotes a higher income. (<¥ 5,000, 111 respondents; ¥ 5,000–¥ 10,000, 303; ¥ 10,001–¥ 20,000, 82; ¥ 20,001– ¥ 30,000, 77; >¥ 30,000, 50)
	UCR	The urban-county-rural distribution of respondents, with 1 point for urban residents, 2 points for county residents, and 3 points for rural residents. (Urban, 435 respondents; County, 129; Rural, 59)

TABLE 2 | First validity test.

Component	Factor loading					Communality
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	
Green consumption tendency	−0.226	0.045	−0.029	−0.260	0.490	**0.361**
Reduce unnecessary travel	0.005	−0.103	0.830	−0.020	0.060	0.703
Willingness to bear the premium of green products	0.085	0.182	0.041	0.758	0.084	0.624
Environmental knowledge reserve	0.108	0.492	0.123	0.340	−0.135	0.403
Choice of disposable tableware	−0.070	−0.154	0.054	0.033	0.856	0.765
Choice of low-carbon travel mode	0.041	0.576	−0.181	0.032	0.289	0.450
Recycle old objects	0.017	0.707	−0.027	−0.037	−0.111	0.515
Willingness to pay for green value added	−0.174	0.075	0.082	−0.650	0.244	0.525
Reduce usage of plastic packaging and paper receipts	−0.011	0.069	0.857	0.011	−0.041	0.742
Number of times participated in environmental protection practices	0.203	0.728	0.051	0.018	−0.085	0.581
Environmental awareness of people around you	0.718	−0.047	0.117	0.020	0.000	0.532
Environmental orientation of people around you	0.734	0.014	0.139	0.051	−0.152	0.585
Personal understanding of the importance of environmental protection	0.761	0.050	0.026	0.062	−0.066	0.591
Activation of personal environmental norms	0.798	0.005	−0.005	0.204	−0.140	0.699
Difficulty of engaging in environmental projects	0.771	0.090	−0.073	0.104	−0.084	0.625
Confidence in implementing environmental protection	0.838	0.098	0.001	0.143	−0.141	0.753
External opportunities to implement environmental protection	0.783	0.154	−0.018	0.094	−0.025	0.646
Willingness to incur additional costs for purchasing environment-friendly products	0.735	−0.026	−0.057	0.339	−0.021	0.659
Plan to implement environmental behavior	0.854	0.089	−0.000	0.136	−0.086	0.763
Degree of effort involved in environmental protection projects	0.848	0.028	0.037	0.133	−0.067	0.744
Role of the Internet in spreading environmental knowledge	0.726	0.221	−0.116	−0.196	0.014	0.628
Effectiveness of incentives for sustainable behavior	0.737	0.236	−0.188	−0.182	0.028	0.668
Eigenvalue (Unrotated)	7.835	1.755	1.583	1.375	1.014	—
% of Variance (Unrotated)	35.614%	7.977%	7.195%	6.251%	4.610%	—
Cumulative % of Variance (Unrotated)	35.614%	43.591%	50.786%	57.037%	61.648%	—
Eigenvalue (Rotated)	7.388	1.845	1.579	1.498	1.253	—
% of Variance (Rotated)	33.582%	8.384%	7.179%	6.807%	5.696%	—
Cumulative % of Variance (Rotated)	33.582%	41.966%	49.145%	55.952%	61.648%	—
Kaiser-Meyer-Olkin	0.913					—
Bartlett's Test of Sphericity						—
	6,770.304					
df	231					—
p-value	0.000					—

Bold indicates <0.4 which means it didn't pass the empirical test.

TABLE 3 | Final validity test.

Component	Factor loading					Communality
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	
Reduce unnecessary travel	0.004	−0.111	0.828	−0.022	0.066	0.702
Willingness to bear the premium of green products	0.092	0.172	0.039	0.761	0.188	0.654
Environmental knowledge reserve	0.116	0.476	0.127	0.382	−0.104	0.413
Choice of disposable tableware	−0.111	−0.124	0.044	−0.035	0.887	0.817
Choice of low-carbon travel mode	0.021	0.582	−0.177	−0.004	0.194	0.408
Recycle old objects	0.016	0.699	−0.017	−0.022	−0.192	0.527
Willingness to pay for green value added	−0.194	0.110	0.085	−0.663	0.294	0.583
Reduce usage of plastic packaging and paper receipts	−0.008	0.058	0.858	0.021	−0.022	0.741
Number of times participated in environmental protection practices	0.202	0.730	0.061	0.045	−0.054	0.582
Environmental awareness of people around you	0.716	−0.055	0.115	−0.002	−0.070	0.534
Environmental orientation of people around you	0.741	0.009	0.139	0.030	−0.176	0.601
Personal understanding of the importance of environmental protection	0.764	0.051	0.026	0.044	−0.062	0.593
Activation of personal environmental norms	0.807	0.000	−0.007	0.191	−0.121	0.702
Difficulty of engaging in environmental projects	0.774	0.091	−0.074	0.102	−0.052	0.626
Confidence in implementing environmental protection	0.845	0.096	0.001	0.141	−0.107	0.754
External opportunities to implement environmental protection	0.783	0.154	−0.018	0.095	−0.002	0.646
Willingness to incur additional costs for purchasing environment-friendly products	0.740	−0.030	−0.060	0.334	0.028	0.663
Plan to implement environmental behavior	0.859	0.094	−0.001	0.133	−0.008	0.764
Degree of effort involved in environmental protection projects	0.853	0.033	0.035	0.127	0.011	0.745
Role of the Internet in spreading environmental knowledge	0.721	0.246	−0.114	−0.192	0.133	0.648
Effectiveness of incentives for sustainable behavior	0.731	0.256	−0.185	−0.174	0.113	0.677
Eigenvalue (Unrotated)	7.746	1.751	1.563	1.321	1.003	—
% of Variance (Unrotated)	36.885%	8.338%	7.441%	6.289%	4.777%	—
Cumulative % of Variance (Unrotated)	36.885%	45.223%	52.664%	58.953%	63.730%	—
Eigenvalue (Rotated)	7.402	1.844	1.575	1.461	1.101	—
% of Variance (Rotated)	35.247%	8.780%	7.502%	6.956%	5.245%	—
Cumulative % of Variance (Rotated)	35.247%	44.027%	51.529%	58.485%	63.730%	—
Kaiser-Meyer-Olkin	0.913					—
Bartlett's Test of Sphericity						—
	6,674.733					
df	210					—
p-value	0.000					—

reliability of the questionnaire (Bland and Altman, 1997). The calculation formula is:

$$\alpha = (k/(k-1))*\left(1-\left(\sum Si^2\right)/\left(ST^2\right)\right) \quad (1)$$

where k is the total number of questions in the scale; Si^2 is the variance of the ith question; and ST^2 is the variance of the total score of all questions (Jackson et al., 2020). The Cronbach's α of the whole questionnaire is 0.832, which is greater than the threshold of 0.8, confirming that reliability is sufficiently high (Eisinga et al., 2013; Lisawadi et al., 2019).

3.2.2 Validity

Validity measures whether the design of the questions is scientific (Mayer-Davis et al., 2019). We used factor analysis to test whether the relationship between each factor and its corresponding questions is good. First, we measured the communality of each factor to screen for invalid questions. The results are shown in **Table 2**.

The communality of "green consumption tendency" (used to evaluate environmental awareness) is smaller than 0.4, which shows that the information of this question cannot be effectively expressed (Mayer-Davis et al., 2019). Therefore, we removed this item and ran the validity analysis again. The results are shown in **Table 3**.

All questions now had communality values above 0.4, indicating that the information of research subject can be effectively extracted. The Kaiser-Meyer-Olkin (KMO) value is 0.913, which exceeds the threshold of 0.6 required to indicate valid data. In addition, the rotated cumulative percentage of variance is 63.730%, which exceeds the 50% threshold required to indicate that the information amount of the research subject can be effectively extracted (Chung et al., 2004). In summary, the test results reported in **Table 3** confirm that the questionnaire measures have good validity. After excluding the question with low communality, seven questions are used to evaluate sustainability and 14 to evaluate environmental awareness.

3.3 Mediation Effect

Although measurement software can directly analyze a mediation effect, it does not intuitively reflect the identification process of each stage of the effect. To test the mediation effect, we adopted from the field of psychology the causal step method, following the three steps shown in **Figures 3**, **4**. This method has been used by many psychologists (Coman et al., 2017; Fairchild et al.,

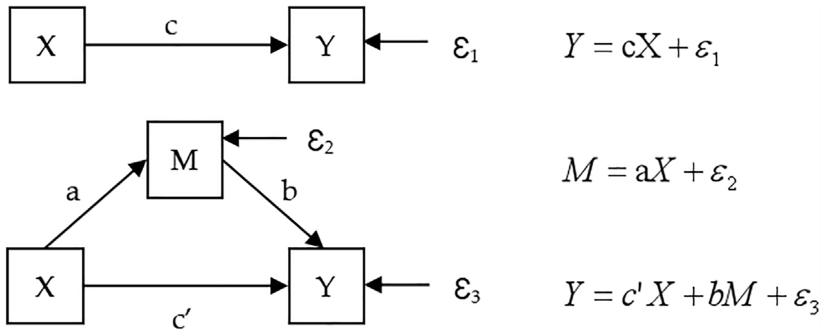

FIGURE 3 | Model of mediating effect.

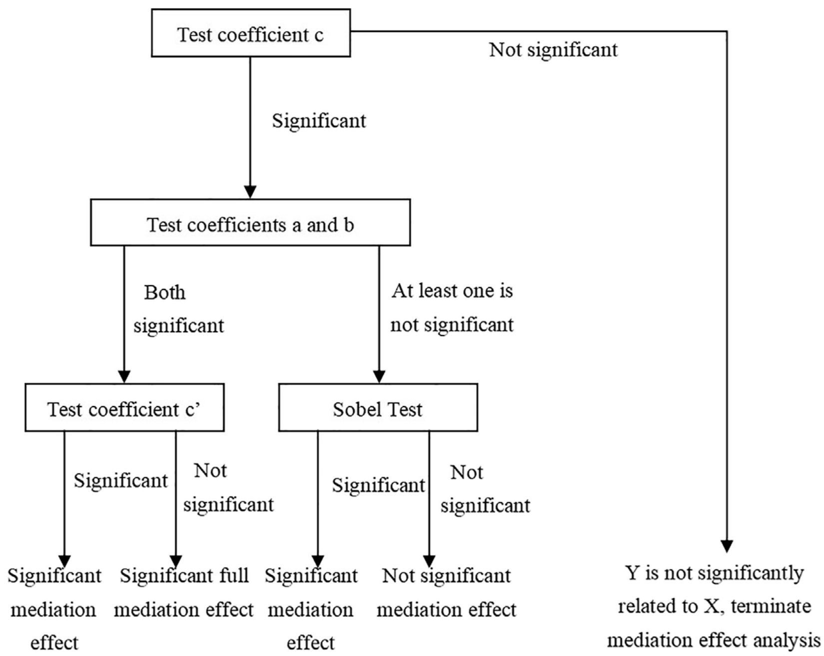

FIGURE 4 | Mediating effect test process.

2019; Liu et al., 2021). Compared with measurement software, it can better reflect the intermediate process and internal mechanism of the mediation effect, highlighting causal links (Intasao and Hao, 2018; Zhao et al., 2020). The explanatory variable is EA (X), the mediating variable is IPT (M), and the explanatory variable is SS (Y).

We first explored the influence of the independent variable on the dependent variable ($Y = cX + \varepsilon_1$). If coefficient c is not statistically significant, the mediation effect analysis is immediately terminated and we conclude that the variable does not play a mediator role. If c is significant, we proceed to the second step of analyzing the correlation between independent variable and the mediating variable ($M = aX + \varepsilon_2$). If coefficient a is significant, we proceed to the third step. If a is not significant, we also perform the Sobel test after calculating coefficient b in that third step. The third step of the analysis is to test the multivariate correlation between the independent variable, mediator, and dependent variable ($Y = c'X + bM + \varepsilon_3$), determining the significance of coefficients b and c'. Combining the results of the second and third steps, if both a and b are significant, then a significant coefficient c' confirms a significant partial mediation effect, whereas a non-significant coefficient of c' confirms a significant full mediation effect.

Based on the above analysis of the classic mediation effect model, the correlation between the independent variable and the mediator also needs to be considered. Peng et al. (2019) found that residents who often use the Internet to browse information have a higher level of environmental literacy. Accordingly, we propose the following hypothesis:

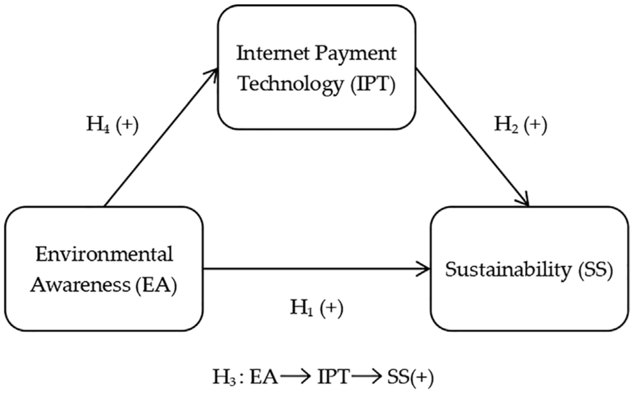

FIGURE 5 | Research model and hypotheses.

H_4. Environmental awareness and use of Internet payment technology are positively related.

The research model and hypotheses are depicted in **Figure 5**.

4 RESULTS

4.1 Descriptive Analysis

Table 4 presents the descriptive statistics of all the study variables. The standard deviations of EA, SS, and IPT are large, suggesting a high degree of heterogeneity in respondents' perception and behavior, and there is a clear gap between environmental protection attitudes and behaviors among different people which can be inferred from the value of the standard deviation. This high degree of heterogeneity in the sample somewhat increases the credibility of the experiment (Beck, 1992; Liu and Hao, 2017; Stockemer, 2018). Because the range of values is far greater for IPT than for the other variables, we use the logarithm of IPT in our analyses (ln (IPT)).

The descriptive statistics also manifest the phenomenon of "high awareness, low practice" in the field of sustainable development. Specifically, the mean scores of EA and SS were 48.717 points and 17.241 points, respectively 70% and 49% of the maximum possible scores.

4.2 Path Analysis: Demographics

This section uses path analysis to test the correlations between demographic variables (i.e., the five control variables) and EA and SS, respectively.

4.2.1 Demographics and Environmental Awareness

Table 5 reports the regression coefficients between demographic variables and EA. Gender, age, and income are each positively correlated with EA, consistent with prior findings (Zelezny et al., 2000; Hunter et al., 2004). Conversely, there is no significant correlation between either education level or urban-county-rural areas and EA. Based on these findings, we infer that women, older individuals, and households with a higher monthly income tend to have higher environmental awareness.

TABLE 4 | Descriptive statistics.

Variable	N	Min.	Max.	Mean	SD	Median
SE	623	1.000	2.000	1.543	0.499	2.000
AG	623	1.000	5.000	2.952	1.057	3.000
EL	623	1.000	5.000	3.294	0.773	3.000
HI	623	1.000	5.000	2.835	1.232	3.000
UCR	623	1.000	3.000	1.220	0.554	1.000
SS	623	7.000	27.000	17.241	2.950	17.000
EA	623	14.000	66.000	48.717	8.211	49.000
IPT	623	85.100	318.500	121.791	32.608	117.400

4.2.2 Demographics and SS

Table 6 reports the regression coefficients between demographic variables and SS. Only monthly household income is significantly correlated with SS, showing a positive relationship. This indicates that higher family income is associated with higher actual participation in environmental protection (Olli et al., 2001). This may be because more income equates to higher disposable funds, which can be invested in green consumption or environmental protection projects.

4.3 Stepwise Regression

We used SPSS 25.0 to perform a stepwise regression testing the mediation effect. Following the logic of regression analysis explained in **Section 3**, the mediation effect is tested in four steps:

Step 1. Verify the correlation between EA and SS.

Step 2. Verify the correlation between EA and ln(IPT).

Step 3. Verify the correlation between EA, ln(IPT), and SS.

Step 4. If appropriate, carry out a Sobel test.

The results are reported in **Table 7**. First, in Model 2 we find a significant positive correlation between EA and SS ($B = 0.128$, $p < 0.05$), indicating that people with higher environmental awareness engage more in environmental practices. This supports H_1. It should be noted that this result does not conflict with the "high awareness, low practice" phenomenon in a given individual: the positive correlation is for the overall sample.

Second, in Model 1 we find no significant correlation between EA and ln (IPT) ($p = 0.079$), indicating that residents' environmental awareness is not significantly related to their use of Internet payment technology. Thus, H_4 is not supported and a Sobel test must be conducted to observe whether the mediation effect is significant.

Third, Model 3 shows significant positive correlations between EA and SS ($B = 0.125$, $p < 0.05$) and between ln (IPT) and SS ($B = 1.841$, $p < 0.05$) in the overall mediation effect model, thus further verifying H_1 and supporting H_2. Moreover, adding ln (IPT) in Model 3 increases the value of R^2 to 0.457, compared to 0.443 in Model 2, indicating a higher goodness of fit.

Fourth, we use the Sobel test to verify the mediation effect, reporting the results in **Table 8**. The confidence interval of the Sobel test is 4.49%, from which we can conclude that the partial

TABLE 5 | Path analysis: demographic variables and environmental awareness.

X	→	*Y*	Unstandardized coefficients	SE	*Z*	*p*	Standardized coefficients
SE	→	EA	1.793	0.671	2.671	0.008	0.109
AG	→	EA	0.947	0.337	2.812	0.005	0.122
EL	→	EA	−0.440	0.440	−1.001	0.317	−0.041
HI	→	EA	0.649	0.286	2.265	0.023	0.097
UCR	→	EA	0.714	0.639	1.118	0.263	0.048

TABLE 6 | Path analysis: demographic variables and sustainability.

X	→	*Y*	Unstandardized coefficients	Std. Error	*Z*	*p*	Standardized coefficients
SE	→	SS	−0.361	0.242	−1.489	0.137	−0.061
AG	→	SS	−0.193	0.122	−1.591	0.112	−0.069
EL	→	SS	0.128	0.159	0.807	0.420	0.034
HI	→	SS	0.243	0.103	2.350	0.019	0.101
UCR	→	SS	0.384	0.231	1.664	0.096	0.072

TABLE 7 | Stepwise regression.

	Model 1				Model 2				Model 3			
	ln (IPT)				SS				SS			
	B	Std. Error	*t*	*p*	*B*	Std. Error	*t*	*p*	*B*	Std. Error	*t*	*p*
Constant	4.630**	0.072	64.018	0	11.441**	1.04	11.006	0	2.918	2.854	1.022	0.307
SE	−0.01	0.016	−0.616	0.538	−0.590*	0.229	−2.572	0.01	−0.572*	0.228	−2.511	0.012
AG	−0.01	0.008	−1.299	0.195	−0.314**	0.115	−2.731	0.006	−0.295*	0.114	−2.58	0.01
EL	0.025*	0.01	2.392	0.017	0.184	0.149	1.233	0.218	0.138	0.149	0.929	0.353
HI	−0.030**	0.007	−4.357	0	0.16	0.098	1.64	0.102	0.215*	0.098	2.181	0.03
UCR	0.094**	0.015	6.229	0	0.292	0.217	1.347	0.179	0.119	0.222	0.537	0.592
EA	0.002	0.001	1.758	0.079	0.128**	0.014	9.383	0	0.125**	0.014	9.203	0
ln (IPT)									1.841**	0.575	3.202	0.001
R^2	0.432				0.443				0.457			

Note: *p < 0.1; **p < 0.05.

TABLE 8 | Sobel test.

Sobel's SE = $\sqrt{[(a \cdot SEb)^2 + (b \cdot Sea)^2]}$ =	0.002
Z = Indirect Effect + Sobel's SE =	1.696
Portion of (*X*→*Y*) due to *M* = (c − c′)/c =	4.49%

mediation effect is significant. To ensure the stability of the experimental results, we use the bootstrap procedure with 1,000 samples. As reported in **Table 9**, the results show that the 95% confidence interval does not include both a positive number and a negative number (95% CI: 0.000–0.007), thus indicating that ln (IPT) has a mediation effect between EA and SS. EA first affects ln (IPT), then SS through ln (IPT). The results provided support for $H_{3.}$

For the control variables, we see in Model 3 (**Table 7**) that there are significant negative correlations between SE and SS ($B = -0.572$, $p < 0.05$) and between AG and SS ($B = -0.295$, $p < 0.05$), whereas HI and SS are significantly positively correlated ($B = 0.215$, $p < 0.05$). By contrast, neither EL nor UCR are significantly correlated with SS.

5 DISCUSSION

Based on the A-B-C model, this study investigated the mechanism between environmental awareness and sustainability by considering the potential mediator role of Internet payment technology. We proposed and tested several hypotheses based on theoretical analysis and prior studies. Stepwise regression yielded the following main findings.

First, environmental awareness can significantly promote sustainability. This is consistent with traditional theories of environmental behavior research, such as the TPB, norm activation theory, and value-belief-norm theory. Focused on psychological influencing factors, these theories posit that individuals need high awareness of the results of environmental actions for individual norms to be activated,

TABLE 9 | Bootstrap sampling test.

Path	Effect	Boot Std. Error	Boot LLCI	Boot ULCI	z	p
EA →In (IPT) →SS	0.003	0.002	0	0.007	1.796	0.073

Note: LLCI: lower limit confidence interval; ULCI: lower limit confidence interval.

leading them to adopt environmental behaviors (Kim and Chung, 2011; Lao and Wu, 2013; Ntanos et al., 2018; Kyriakopoulos et al., 2020). This study's findings provide empirical proof. Specifically, it can be discussed and explained from three aspects. First, sustainable practices benefit the community, society, and future generations. For individuals, it has a typical spillover effect and outstanding externalities. Based on the economic man assumption, sustainability is inconsistent with personal short-term profit-seeking. Therefore, the value norm of environmental awareness is the most important internal factor for environmental protection behaviors (Fretwell and Greig, 2019). Second, people with higher environmental awareness are more inclined to pay attention to positive environmental information, advocate environmental values, and disseminate environmental knowledge. They also tend to implement more environmental practices to set an example for others (Sadorsky, 2012; Mohiuddin et al., 2018). Third, people with higher environmental awareness often pay more attention to and are more anxious about negative information on sustainability (Cho et al., 2007). Therefore, they are more likely to be motivated by crisis and, thus, more actively implement environmental behaviors.

The second main finding is that environmental awareness does not significantly affect the use of Internet payment technology. Although Internet payment technology can function as an external factor promoting sustainability, it primarily functions as a payment tool (Kim, 2018). Therefore, this findings is consistent with practice in real life. We explored residents' motivations for using Internet payment technology. Only 16% of people reported using Internet payment technology from the perspective of sustainable development; the vast majority of respondents indicated other reasons, such as convenience and simplicity.

Third, Internet payment technology was significantly positively related to sustainability. This reflects the role it plays in guiding consumers to buy green products, significantly reducing the cost of obtaining green information about products, and enabling the social functions, green responsibilities, and comparative advantages of green products to be accepted by a wide range of consumer groups. Internet payment technology can also give the public ways and incentives to implement green behaviors in different consumption scenarios. According to Lao (2019) statistics, China's 500 million plus users of Internet payment technology have collectively achieved a reduction in carbon emissions of 7.92 million tons, as well as the planting of 122 million trees, whose planting area is 1.5 times the size of Singapore.

Fourth, Internet payment technology plays a mediator role between environmental awareness and sustainability. The empirical results have a certain practical basis. Internet payment technology provides richer scenes and platforms for green consumption and green public welfare, which gives residents more convenient opportunities to engage more extensively in sustainable development, thus enabling environmental awareness to more fully affect environmental protection practices. We summarize in **Table 10** the ways in which Internet payment technology can facilitate or promote sustainability actions. Internet payment technology gives residents greater and broader opportunities to engage directly in environmental protection, via platforms enabling diversified green consumption and sustainable practices. This technology also shortens the distance between individuals and sustainability, and broadens the channels for participating in environmental behaviors (Romm, 2002).

TABLE 10 | Opportunities for sustainability supported by Internet payment platforms.

Category	Behavior
Green travel	Walking Shared bike Bus Metro
Reduced travel	Online train ticket purchasing Online movie ticket purchasing Green government services Utility bill payment Doctor appointment Green office work
Reduced paper and plastic usage	International tax refund Offline payment Electronic receipt Green take-away food Paperless reading Plastic reduction Take-away coffee
Highly economical energy consumption	Electronic Toll Collection payment
Recycling	Package recycling Green packaging Used goods recycling

Fifth, we found that some demographics significantly affect sustainability. Regarding gender, our path analysis found that females have higher environmental awareness (consistent with Liang et al., 2018) but males are more likely to engage in environmental practices (consistent with Hong, 2005). In terms of age, older individuals were found less likely to engage in sustainability, confirming that young people are still the main protagonists in sustainable development. As regards income, higher monthly household income was associated with a greater likelihood of participating in sustainability. Combining the results of the path and regression analyses, we infer that young males with high income levels are most likely to engage in environmental practices.

6 CONCLUSION

6.1 Contributions

This article focus on a new research perspective, integrating Internet payment technology as a new external situational factor in an A-B-C-model. Our study makes the following theoretical and practical contributions.

First, to enhance research on the external contextual factors influencing sustainability, through the mediation effect analysis, we compare goodness of fit in models with and without the external situational factor of Internet payment technology. It verifies the importance of this external factor, thereby expanding theoretical models focused on internal (psychological) factors.

Second, this study verifies the role of technological innovation in breaking the traditional environmental protection and green development model. Specifically, it provides empirical data supporting the mediator role of Internet payment technology in the field of sustainability.

Third, by analyzing demographic variables, we profile which populations have higher environmental awareness and engage more in sustainability. Women who are older and have higher monthly household income tend to have higher environmental awareness, whereas younger males with high income levels are more likely to participate in sustainable development. These results not only verify the conclusions of previous studies (Li, 2006; Gong and Lei, 2007) but also provide a basis to further refine understanding of how demographics impact on sustainability.

Fourth, this study empirically proves the mediator role played by Internet payment technology between environmental awareness and environmental behaviors, thereby clarifying the internal mechanism of action. Our serial mediation model of environmental awareness–Internet payment technology–sustainability can be used as a reference in subsequent research.

Sustainability is an important issue for all mankind. According to Balsa-Barreiro et al. (2019), CO_2 emissions are highly correlated with GDP. Compared with Western countries, developing countries have lower resource utilization efficiency. China is the largest developing country and the second largest economy. Accordingly, raising China's level of environmental sustainability will benefit the world. Moreover, relevant experience provides a valuable reference for other developing countries. From the perspective of population dynamics, the marginal utility of carbon-reduction effects will be much higher in the East than in the West. This study provides some inspiration for global environmental governance and green development. First, our data show that Internet payment technology can increase residents' participation in environmental protection. Our study thereby presents new ideas for sustainable development in other countries and encourages the innovative application of Internet payment technology. Second, this article reveals which demographics are associated with higher environmental awareness and higher sustainability. This should help governments and enterprises to more accurately identify target groups, more effectively promote green products and green public welfare projects.

6.2 Limitations and Future Research Directions

This study has certain limitations. First, we did not examine the endogenous variables of sustainable development, such as the internal factors proposed by the value-belief-norm theory (personal values, beliefs, world views, and responsibility). Instead, we grouped internal factors to measure the overall level of an individual's environmental awareness. Future research should consider more internal factors within the research model. Second, the scores assigned to each question are averaged without weighting to generate the values of each variable. In future research, factor analysis or a Pareto test can be used to assign weights to scale questions, thereby obtaining more accurate experimental results. Third, we did not discuss the correlations between some control variables and the independent variable, and did not consider possible endogenous effects. Future research should explore the endogeneity among variables to further refine the model.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Ethical review and approval was not required for this study in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JA and HD were responsible for writing the initial draft of the manuscript, developing the main propositions and conducting the study. HD and SJ were responsible for modifying and improving the manuscript. MY was responsible for reviewing and editing the manuscript. All authors have read and approved the submitted version.

FUNDING

This research was funded by the National Natural Science Foundation of China (No. 72091313).

REFERENCES

Ajzen, I. (2011). The Theory of Planned Behaviour: Reactions and Reflections. *Psychol. Health* 26 (9), 1113–1127. doi:10.1080/08870446.2011.613995

Al Mamun, A., Mohamad, M. R., Yaacob, M. R. B., and Mohiuddin, M. (2018). Intention and Behavior towards Green Consumption Among Low-Income Households. *J. Environ. Manag.* 227, 73–86. doi:10.1016/j.jenvman.2018.08.061

Balsa-Barreiro, J., Li, Y., Morales, A., and Pentland, A. S. (2019). Globalization and the Shifting Centers of Gravity of World's Human Dynamics: Implications for Sustainability. *J. Clean. Prod.* 239, 117923. doi:10.1016/j.jclepro.2019.117923

Bamberg, S., and Möser, G. (2007). Twenty Years after Hines, Hungerford, and Tomera: a New Meta-Analysis of Psycho-Social Determinants of Pro-environmental Behaviour. *J. Environ. Psychol.* 27 (1), 14–25. doi:10.1016/j.jenvp.2006.12.002

Barbu, C. M., Florea, D. L., Dabija, D.-C., and Barbu, M. C. R. (2021). Customer Experience in Fintech. *Jtaer* 16 (5), 1415–1433. doi:10.3390/jtaer16050080

Beck, U. (1992). *Risk Society: Towards a New Modernity*. London, UK: Sage Publications.

Bin, L. (2022). Goods Tariff vs Digital Services Tax: Transatlantic Financial Market Reactions. *Econ. Manag. Financ. Mark.* 17 (1), 9–30. doi:10.22381/emfm17120221

Birtus, M., and Lăzăroiu, G. (2021). The Neurobehavioral Economics of the COVID-19 Pandemic: Consumer Cognition, Perception, Sentiment, Choice, and Decision-Making. *Anal. Metaphys.* 20, 89–101. doi:10.22381/am2020216

Black, J. S., Stern, P. C., and Elworth, J. T. (1985). Personal and Contextual Influences on Househould Energy Adaptations. *J. Appl. Psychol.* 70 (1), 3–21. doi:10.1037/0021-9010.70.1.3

Blake, J. (1999). Overcoming the 'value-action Gap' in Environmental Policy: Tensions between National Policy and Local Experience. *Local Environ.* 4 (3), 257–278. doi:10.1080/13549839908725599

Bland, J. M., and Altman, D. G. (1997). Statistics Notes: Cronbach's Alpha. *Bmj* 314 (7), 572. doi:10.1136/bmj.314.7080.572

Brand, K. W. (1997). "Environmental Consciousness and Behaviour: the Greening of Lifestyles," in *The International Handbook of Environmental Sociology*. Editors M. Redclift and G. Woodgate (Cheltenham: Edward Elgar)), 204.

Brener, N., Kann, L., McManus, T., Kinchen, S., Sundberg, E., and Ross, J. (2002). Reliability of the 1999 Youth Risk Behavior Survey Questionnaire. *J. Adolesc. Health* 31 (4), 336–342. doi:10.1016/S1054-139X(02)00339-7

Chen, A. C.-H., and Wu, H.-H. (2020). How Should Green Messages Be Framed: Single or Double? *Sustainability* 12, 4257. doi:10.3390/su12104257

China Center for Economic Research (2018). Peking University Internet Finance Development Index Report (Phase 1). Available at: https://www.ccer.pku.edu.cn/yjcg/yjbg/243148.htm (accessed May 24, 2020).

Chinese Internet Data Information Network (2016). Ali Research Institute: 2016 China Green Consumer Report. Available at: http://www.199it.com/archives/503487.html (Accessed May 25, 2020).

Cho, Y., Lee, J., and Kim, T.-Y. (2007). The Impact of ICT Investment and Energy Price on Industrial Electricity Demand: Dynamic Growth Model Approach. *Energy Policy* 35 (9), 4730–4738. doi:10.1016/j.enpol.2007.03.030

Coman, E. N., Thoemmes, F., and Fifield, J. (2017). Commentary: Causal Effects in Mediation Modeling: an Introduction with Applications to Latent Variables. *Front. Psychol.* 8, 151. doi:10.3389/fpsyg.2017.00151

Cyberspace Administration of China (2019). Statistical Report on Internet Development in China. Available at: http://www.cac.gov.cn/2019-02/28/c_1124175677.htm (accessed May 25, 2020).

De Young, R. (1990). Recycling as Appropriate Behavior: a Review of Survey Data from Selected Recycling Education Programs in Michigan. *Resour. Conservation Recycl.* 3 (4), 253–266. doi:10.1016/0921-3449(90)90022-V

Dorn, S. (2018). Assessing the Promise and Risks of Income-Based Third-Party Payment Programs. *Commonw. Fund. Issue Briefs* 5 (1), 1–13.

Eisinga, R., Grotenhuis, M. t., and Pelzer, B. (2013). The Reliability of a Two-Item Scale: Pearson, Cronbach, or Spearman-Brown? *Int. J. Public Health* 58 (4), 637–642. doi:10.1007/s00038-012-0416-3

Ellison, N. B., Gibbs, J. L., and Weber, M. S. (2015). The Use of Enterprise Social Network Sites for Knowledge Sharing in Distributed Organizations. *Am. Behav. Sci.* 59 (1), 103–123. doi:10.1177/0002764214540510

Fairchild, A. J., Cai, C., McDaniel, H., Shi, D., Gottschall, A., and Masyn, K. E. (2019). Evaluating a Method to Estimate Mediation Effects with Discrete-Time Survival Outcomes. *Front. Psychol.* 10, 740. doi:10.3389/fpsyg.2019.00740

Fischer, E., and Reuber, A. R. (2011). Social Interaction via New Social Media: (How) Can Interactions on Twitter Affect Effectual Thinking and Behavior? *J. Bus. Ventur.* 26 (1), 1–18. doi:10.1016/j.jbusvent.2010.09.002

Fretwell, K., and Greig, A. (2019). Towards a Better Understanding of the Relationship between Individual's Self-Reported Connection to Nature, Personal Well-Being and Environmental Awareness. *Sustainability* 11 (5), 1386. doi:10.3390/su11051386

Garz, M. (2014). Good News and Bad News: Evidence of Media Bias in Unemployment Reports. *Public Choice* 161 (3–4), 499–515. doi:10.1007/s11127-014-0182-2

Gim Chung, R. H., Kim, B. S. K., and Abreu, J. M. (2004). Asian American Multidimensional Acculturation Scale: Development, Factor Analysis, Reliability, and Validity. *Cult. Divers. Ethn. Minority Psychol.* 10 (1), 66–80. doi:10.1037/1099-9809.10.1.66

Gkika, E. C., Anagnostopoulos, T., Ntanos, S., and Kyriakopoulos, G. L. (2020). User Preferences on Cloud Computing and Open Innovation: a Case Study for University Employees in Greece. *JOItmC* 6 (2), 41. doi:10.3390/joitmc6020041

Gong, W. J., and Lei, J. (2007). An Analysis of Gender Difference in the Environmental Concern and Environmentally Friendly Behaviors of Chinese Urban Residents: Based on the Research of GSS in 2003. *Humanit. Soc. Sci. J. Hainan Univ.* 3, 340. doi:10.15886/j.cnki.hnus.2007.03.018

Guagnano, G. A., Stern, P. C., and Dietz, T. (1995). Influences on Attitude-Behavior Relationships. *Environ. Behav.* 27 (5), 699–718. doi:10.1177/0013916595275005

He, H., Zhang, S., and Zhu, L. (2021). Green Product Quality Supervision Strategy in Online Shopping with Consumer Evaluation and Complaint. *Front. Environ. Sci.* 9, 1–16. doi:10.3389/fenvs.2021.702151

He, M. Y. (2018). An Analysis of the Communication Strategy of Environmental Public Welfare in the "Internet +" Era: Take "Ant Forest" as an Example. *Radio Tv. J.* 7, 204–205. doi:10.19395/j.cnki.1674-246x.2018.07.115

Hill, R. J., Fishbein, M., and Ajzen, I. (1977). Belief, Attitude, Intention and Behavior: An Introduction to Theory and Research. *Contemp. Sociol.* 6 (2), 244–334. doi:10.2307/2065853

Hong, D. Y. (2005). Environmental Awareness of Chinese Urban Residents. *Jiangsu Soc. Sci.* 1, 127.

Hong, H. (2013). Government Websites and Social Media's Influence on Government-Public Relationships. *Public Relat. Rev.* 39 (4), 346–356. doi:10.1016/j.pubrev.2013.07.007

Hopkins, E., and Potcovaru, A.-M. (2021). Consumer Attitudes, Values, Needs, and Expectations Due to COVID-19. *Anal. Metaphys.* 20, 202–215. doi:10.22381/am20202114

Huang, X. (2018). On the Development of Sharing Economy under the Background of Internet. *Co-op. Eco. Technol.* 16, 46–47. doi:10.13665/j.cnki.hzjjykj.2018.16.015

Hunter, L. M., Hatch, A., and Johnson, A. (2004). Cross-National Gender Variation in Environmental Behaviors*. *Soc. Sci. Q* 85 (3), 677–694. doi:10.1111/j.0038-4941.2004.00239.x

Intasao, N., and Hao, N. (2018). Beliefs about Creativity Influence Creative Performance: the Mediation Effects of Flexibility and Positive Affect. *Front. Psychol.* 9, 1810. doi:10.3389/fpsyg.2018.01810

Ionescu, L. (2021). Corporate Environmental Performance, Climate Change Mitigation, and Green Innovation Behavior in Sustainable Finance. *Econ. Manag. Financ. Mark.* 16 (3), 94–106. doi:10.22381/emfm16320216

Iqbal, K., Hassan, S. T., Wang, Y., Shah, M. H., Syed, M., and Khurshaid, K. (2022). To Achieve Carbon Neutrality Targets in Pakistan: New Insights of Information and Communication Technology and Economic Globalization. *Front. Environ. Sci.* 9, 1–10. doi:10.3389/fenvs.2021.805360

iResearch Consulting (2020). 2019Q4 China Third-Party Payment Industry Data Release. Available at: https://www.iresearch.com.cn/Detail/report?id=3543&isfree=0 (accessed May 25, 2020).

Jackson, I. L., Okonta, J. M., and Ukwe, C. V. (2020). Development and Psychometric Evaluation of the Patient's HIV Knowledge Questionnaire (PHKQ). *Int. J. Clin. Pharm.* 42 (2), 695–702. doi:10.1007/s11096-020-00963-z

Kaiser, F. G., and Gutscher, H. (2003). The Proposition of a General Version of the Theory of Planned Behavior: Predicting Ecological Behavior1. *J. Appl. Soc. Pyschol* 33 (3), 586–603. doi:10.1111/j.1559-1816.2003.tb01914.x

Kim, J. (2018). Platform Adoption Factors in the Internet Industry. *Sustainability* 10, 3185. doi:10.3390/su10093185

Krätzig, S., and Warren-Kretzschmar, B. (2014). Using Interactive Web Tools in Environmental Planning to Improve Communication about Sustainable Development. *Sustainability* 6, 236–250. doi:10.3390/su6010236

Kshetri, N. (2017). The Evolution of the Internet of Things Industry and Market in China: an Interplay of Institutions, Demands and Supply. *Telecommun. Policy* 41 (1), 49–67. doi:10.1016/j.telpol.2016.11.002

Kyriakopoulos, G., Ntanos, S., and Asonitou, S. (2020). Investigating the Environmental Behavior of Business and Accounting University Students. *Ijshe* 21 (4), 819–839. doi:10.1108/IJSHE-11-2019-0338

Lao, K. F., and Wu, J. (2013). Research on Influencing Mechanism of Consumer Green Consumption Behavior Referring to TPB. *Fin. Econ.* 2, 91.

Lao, M. (2019). The Third Anniversary of Ant Forest's Launch, 500 Million Users Accumulated Carbon Emission Reduction of 7.92 Million Tons. Available at: http://www.techweb.com.cn/internet/2019-08-27/2751495.shtml (Accessed May 25, 2020).

Li, M. D. (2018). Exploring the Communication Model of "Internet + Public Welfare" from the Perspective of Scene Theory: Taking "Ant Forest" as an Example. *News World* 6, 69–73. doi:10.19497/j.cnki.1005-5932.2018.06.022

Li, W. J. (2006). *An Analysis of Multi-Factors Affecting Individual Environment Behavior: A Survey in Wuyishan City*. Master's thesis. Xiamen: Xiamen University.

Li, X. C., and Liu, H. (2018). Research on Influencing Factors Model of Urban Residents' Low-Carbon Travel Behavior Decision. *Urban Manag. Sci. Technol.* 20 (4), 51.

Liang, S.-W., Fang, W.-T., Yeh, S.-C., Liu, S.-Y., Tsai, H.-M., Chou, J.-Y., et al. (2018). A Nationwide Survey Evaluating the Environmental Literacy of Undergraduate Students in Taiwan. *Sustainability* 10 (6), 1730. doi:10.3390/su10061730

Lisawadi, S., Ahmed, S. E., Reangsephet, O., and Shah, M. K. A. (2019). Simultaneous Estimation of Cronbach's Alpha Coefficients. *Commun. Statistics - Theory Methods* 48 (13), 3236–3257. doi:10.1080/03610926.2018.1473882

Liu, C., and Hao, Y. (2017). Research on Green Economy Platform of Agricultural Products Based on "Internet +. *Manag. Obs.* 15, 34.

Liu, M., Li, J., Xiong, T., Liu, T., and Chen, M. (2021). Intermediary Management and Employee Corporate Culture Identification Mediation and Mediation Effect Verification. *Front. Psychol.* 12, 545816. doi:10.3389/fpsyg.2021.545816

Long, T., and Johnson, M. (2000). Rigour, Reliability and Validity in Qualitative Research. *Clin. Eff. Nurs.* 4 (1), 30–37. doi:10.1054/cein.2000.0106

Luo, Y. D., Wei, Y. X., and Ding, H. (2019). An Analysis of the Co-creation Behavior of Online Public Welfare Value: Taking "Ant Forest" as an Example. *Mark. Wkly.* 4, 24.

Lv, Y. C. (2018). *The Study on Green Consumption and its Realization Approaches Based on Sharing Economy*. Doctoral thesis. Wuhan: Zhongnan University of Economics and Law.

May, A. Y. C., Hao, G. S., and Carter, S. (2021). Intertwining Corporate Social Responsibility, Employee Green Behavior, and Environmental Sustainability: The Mediation Effect of Organizational Trust and Organizational Identity. *Econ. Manag. Financ. Mark.* 16 (2), 32–61. doi:10.22381/emfm16220212

Mayer-Davis, E. J., Vitolins, M. Z., Carmichael, S. L., Hemphill, S., Tsaroucha, G., Rushing, J., et al. (1999). Validity and Reproducibility of a Food Frequency Interview in a Multi-Cultural Epidemiologic Study. *Ann. Epidemiol.* 9 (5), 314–324. doi:10.1016/s1047-2797(98)00070-2

Men, D., and Xiong, R. C. (2018). Analysis of the Mechanism for Public Environmental Protection Behaviors: Based on the Impact of the Government Input Effect. *Sch. View* 15 (17), 94. doi:10.16619/j.cnki.rmltxsqy.2018.17.013

Mi, L. Y., Cong, J. Q., and Ding, C. Q. (2019). Why Urban Residents' Deeds Do Not Match Their Attitude? A Dual Mediation Model of Knowledge-Behavior in Low-Carbon Consumption. *Resour. Sci.* 41 (5), 908.

Ministry of Ecology and Environment of the People's Republic of China (2018). The Ministry of Ecology and Environment and Other Five Departments Jointly Issued the "Code of Conduct for Citizens' Ecological Environment (Trial). Available at: http://www.mee.gov.cn/gkml/sthjbgw/qt/201806/t20180605_442476.htm (accessed May 25, 2020).

Mohiuddin, M., Al Mamun, A., Syed, F., Mehedi Masud, M., and Su, Z. (2018). Environmental Knowledge, Awareness, and Business School Students' Intentions to Purchase Green Vehicles in Emerging Countries. *Sustainability* 10, 1534. doi:10.3390/su10051534

Murty, M. N., and Kumar, S. (2003). Win-win Opportunities and Environmental Regulation: Testing of Porter Hypothesis for Indian Manufacturing Industries. *J. Environ. Manag.* 67 (2), 139–144. doi:10.1016/s0301-4797(02)00203-7

Nakamura, A. (2020). Environmental Disparities in an Urban Area, Rural-Urban Migration, and Urban Unemployment. *Asia-Pac. J. Reg. Sci.* 4 (2), 463–477. doi:10.1007/s41685-019-00128-5

Ntanos, S., Kyriakopoulos, G., Arabatzis, G., Palios, V., and Chalikias, M. (2018). Environmental Behavior of Secondary Education Students: a Case Study at Central Greece. *Sustainability* 10 (5), 1663. doi:10.3390/su10051663

Okazaki, S., and Taylor, C. R. (2013). Social Media and International Advertising: Theoretical Challenges and Future Directions. *Int. Mark. Rev.* 30 (1), 56–71. doi:10.1108/02651331311298573

Olli, E., Grendstad, G., and Wollebaek, D. (2001). Correlates of Environmental Behaviors: Bringing Back Social Context. *Environ. Behav.* 33 (2), 181–208. doi:10.1177/0013916501332002

Peng, D. Y., Li, Y. C., and Li, C. Q. (2019). Research on the Impact of Internet Use on Environmental Attitudes and Environmental Literacy. *Fin. Sci.* 8, 97.

Peng, Y. C. (2013). A Review of Foreign Environmental Behavior Influencing Factors Research. *China Popul. Res. Environ.* 8, 142.

Policy Research Center for Environment and Economy (2019a). Chinese Low-Carbon Life Report Released: in the Past Three Years, the Internet Is Setting off a Low-Carbon Life Boom. Ministry of Ecology and Environment of the People's Republic of China. Available at: http://www.prcee.org/zyhd/201908/t20190828_730376.html (accessed May 25, 2020).

Policy Research Center for Environment and Economy (2019b). The Political Research Center Released the "Research Report on Public Low-Carbon Lifestyle under the Background of Internet Platform." Ministry of Ecology and Environment of the People's Republic of China. Available at: http://www.prcee.org/yjcg/yjbg/201909/t20190909_733041.html (accessed May 25, 2020).

Priem, R. (2021). An Exploratory Study on the Impact of the COVID-19 Confinement on the Financial Behavior of Individual Investors. *Econ. Manag. Financ. Mark.* 16 (3), 9–40. doi:10.22381/emfm16320211

Radakovic, R., Gray, D., Dudley, K., Mioshi, E., Dick, D., Melchiorre, G., et al. (2020). Reliability and Validity of the Brief Dimensional Apathy Scale. *Arch. Clin. Neuropsychol.* 35 (5), 539–544. doi:10.1093/arclin/acaa002

Ren, B. J., Gao, S. H., and Zhu, Y. H. (2019). Research on Online Charity Behavior of College Students: Taking "Ant Forest" as an Example. *Labour secur. World.* 18, 78.

Romm, J. (2002). The Internet and the New Energy Economy. *Resour. Conservation Recycl.* 36 (3), 197–210. doi:10.1016/s0921-3449(02)00084-8

Rydell, L., and Kucera, J. (2021). Cognitive Attitudes, Behavioral Choices, and Purchasing Habits during the COVID-19 Pandemic. *J. Self-Gov. Manag. Econ.* 9 (4), 35–47. doi:10.22381/jsme9420213

Sadorsky, P. (2012). Information Communication Technology and Electricity Consumption in Emerging Economies. *Energy Policy* 48, 130–136. doi:10.1016/j.enpol.2012.04.064

Scherbaum, C. A., Popovich, P. M., and Finlinson, S. (2008). Exploring Individual-Level Factors Related to Employee Energy-Conservation Behaviors at Work. *J. Appl. Soc. Pyschol* 38 (3), 818–835. doi:10.1111/j.1559-1816.2007.00328.x

Schwartz, S. H. (1977). Normative Influences on Altruism. *Adv. Exp. Soc. Psychol.* 10, 221–279. doi:10.1016/s0065-2601(08)60358-5

Souza, A. L., Andrade, J. C., Alvarez, G., and Santos, N. (2013). Carbon Finance in the World and in Brazil: a Study on Financing, Investment Funds and Indices of Environmental Sustainability to Promote a Low Carbon Economy. *GeAS* 2 (2), 177–207. doi:10.5585/geas.v2i2.71

Steg, L., Dreijerink, L., and Abrahamse, W. (2005). Factors Influencing the Acceptability of Energy Policies: a Test of VBN Theory. *J. Environ. Psychol.* 25 (4), 415–425. doi:10.1016/j.jenvp.2005.08.003

Stern, P. C., and Dietz, T. (1994). The Value Basis of Environmental Concern. *J. Soc. Issues* 50 (3), 65–84. doi:10.1111/j.1540-4560.1994.tb02420.x

Stern, P. C. (2000). New Environmental Theories: Toward a Coherent Theory of Environmentally Significant Behavior. *J. Soc. Isssues* 56 (3), 407–424. doi:10.1111/0022-4537.00175

Stockemer, D. (2018). The Internet: an Important Tool to Strengthening Electoral Integrity. *Gov. Inf. Q.* 35 (1), 43–49. doi:10.1016/j.giq.2017.11.009

Štreimikienė, D., Mikalauskienė, A., Sturienė, U., and Kyriakopoulos, G. L. (2021). The Impact of Social Media on Sales Promotion in Entertainment Companies. *E+M* 24 (2), 189–206. doi:10.15240/tul/001/2021-2-012

Wang, Q., and Ye, J. Y. (2016). Health Status, Income and Overtime Labor of Migrant Workers. *Chin. Rural. Econ.* 2, 2.

Wang, X. X., and Zhong, Y. (2016). An Empirical Study of Influencing Factors for Environmental Behavior of China Urban Residents Based on a Nationwide Public Opinion Survey in 2013. *J. Shanghai Jiaot. Uni. Phil. Soc. Sci.* 107 (01), 71. doi:10.13806/j.cnki.issn1008-7095.2016.01.007

Wang, Y. J., and Han, D. L. (2016). Economic Development, Environmental Pollution and Public Pro-environmental Behavior: a Multi-Level Analysis of the 2013 Chinese General Social Survey. *J. Renmin Uni. China* 2, 79.

Wang, Y. Y., Wang, Y., and Pan, Y. (2018). The Status Quo of Internet Carbon Finance: Taking Ant Forest as an Example. *Shanxi Agri. Econ.* 9, 111–112. doi:10.16675/j.cnki.cn14-1065/f.2018.09.076

Weeks, J. (2018). Paradigm Change in Integrative Care: Third-Party Payment and the Cost-Benefit . . . Plus MorePlus More. *Integr. Med. (Encinitas)* 17 (4), 24.

Wu, J. Y., Mao, Q. Q., and Dong, B. C. (2019). Research on the Sustainable Development of Personal Carbon Accounts in the Era of Big Data: Taking Ant Financial as an Example. *Times Fin.* 14, 103.

Xia, W. (2019). *A Research of Public Welfare Communication Effect Based on Internet Thinking: Take "Ant Forest" as an Example*. Master's thesis. Shanghai: Shanghai International Studies University.

Yang, J. X., Liu, Y. F., and Liu, M. M. (2018). The Challenges and Countermeasures for City-Level Low-Carbon Transportation Development in the Intemet Era. *Environ. Prot.* 46 (11), 43. doi:10.14026/j.cnki.0253-9705.2018.11.010

Yao, M., Di, H., Zheng, X., and Xu, X. (2018). Impact of Payment Technology Innovations on the Traditional Financial Industry: a Focus on China. *Technol. Forecast. Soc. Change* 135, 199–207. doi:10.1016/j.techfore.2017.12.023

Yeon Kim, H., and Chung, J. E. (2011). Consumer Purchase Intention for Organic Personal Care Products. *J. Consum. Mark.* 28 (1), 40–47. doi:10.1108/07363761111101930

Yin, H., Wang, H. J., Liu, S. J., and Kang, Q. (2014). Research and Application of Key Technology in Digital Environment Protection System. *China Popul. Resour. Environ.* 24 (171), 442.

Yuan, Y. Y. (2016). An Empirical Analysis on Residents' Environmental Behavior and Influence Factors in China: Based on CGSS2013 Data. *J. Arid. Land Resour. Environ.* 212 (04), 42. doi:10.13448/j.cnki.jalre.2016.110

Zelezny, L. C., Chua, P.-P., and Aldrich, C. (2000). New Ways of Thinking about Environmentalism: Elaborating on Gender Differences in Environmentalism. *J. Soc. Isssues* 56, 443–457. doi:10.1111/0022-4537.00177

Zhao, J., Wei, G., Chen, K.-H., and Yien, J.-M. (2020). Psychological Capital and University Students' Entrepreneurial Intention in China: Mediation Effect of Entrepreneurial Capitals. *Front. Psychol.* 10, 2984. doi:10.3389/fpsyg.2019.02984

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

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 26 July 2022
doi: 10.3389/fenvs.2022.918422

Effect of Science and Technology Finance Policy on Urban Green Development in China

Chen Gao[1]*, *Pingting Song*[2], *Ya Wen*[3] *and Deyong Yang*[3]

[1]China Economics and Management Academy, Central University of Finance and Economics, Beijing, China, [2]Accounting School, Harbin University of Commerce, Harbin, China, [3]School of Economics, Beijing Technology and Business University, Beijing, China

Green sustainable development is a major challenge faced by countries worldwide. Against the strategic background of innovation-driven development, studying the impact of science and technology finance policy (STFP) on urban green development is of great practical significance. Based on urban panel data from 2003 to 2019, this study systematically examines whether and how STFP affects urban green development in China using the difference-in-differences (DID) method. The empirical results show that STFP has significantly stimulated the urban green development level, and the effect of policy implementation has increased first and then decreased over time. The findings remain robust when using propensity score matching DID to avoid selection bias and other factors that may interfere with the estimation results. Additionally, technological innovation and green innovation are essential channels for STFP to improve urban green development. The impact of STFP is found to vary by region and by the level of urban innovation. Specifically, the policy effect is more pronounced in midwestern and high-innovation cities but less obvious in eastern and low-innovation cities. In conclusion, this study provides city-level empirical evidence from China for an in-depth understanding of the green economy effect of STFP. It also provides theoretical guidance and policy references for accelerating the green transition in the context of sustainable development.

Keywords: science and technology finance policy, green development, technological innovation, green innovation, China, DID method

OPEN ACCESS

Edited by:
Jose Balsa,
Massachusetts Institute of Technology, United States

Reviewed by:
Elchin Suleymanov,
Baku Engineering University, Azerbaijan
Cüneyt Dumrul,
Erciyes University, Turkey

***Correspondence:**
Chen Gao
gaoc9206@163.com

Specialty section:
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

Received: *12 April 2022*
Accepted: *23 June 2022*
Published: *26 July 2022*

Citation:
Gao C, Song P, Wen Y and Yang D (2022) Effect of Science and Technology Finance Policy on Urban Green Development in China. Front. Environ. Sci. 10:918422. doi: 10.3389/fenvs.2022.918422

1 INTRODUCTION

In recent years, China's economy has maintained rapid growth, rising to become the second largest globally. China has also contributed to the history of world development. However, as the economy transitions from high-speed growth to high-quality development, China must overcome important hurdles of pollution control and ecological restoration (Zhang, 2007; Sheng and Tang, 2016; Shao et al., 2018). In the traditional industrial era, production activities were driven by the input of factors that produced large amounts of pollutant emissions. This is not conducive to long-term economic development (Reid et al., 2007). Balsa-Barreiro et al. (2019) analyzed the global shift of centers of gravity related to gross domestic product (GDP), carbon dioxide (CO_2) emissions, total population, and urban population during 1960–2016. They pointed out that China now shows evidence of a certain economic maturity, indicating more efficiency in the consumption of resources and energy. China is in a more advanced stage of industrialization than India, with a slight decoupling trend between economic growth and emissions. Yet, many regions and industries in China continue to pursue economic development through a model of high investment and high pollution, resulting in increasingly prominent environmental problems (Yue et al., 2018; Wang and Feng, 2021). China's Environmental Performance Index score and ranking have remained relatively low over recent years (Pan et al., 2021). In January 2022, China's urban air quality report showed an average of 59.5% of days with excellent air quality in 168 cities, a 5.3 percentage point decrease year on year. However, environmental quality varies greatly between Chinese cities.

The novel green development model represents a shift from the traditional development model. It incorporates environmental protection into the goal of sustainable development while remaining constrained by environmental and resource-carrying capacity constraints (Dai et al., 2016; Bagheri et al., 2018). The 14th Five-Year Plan points out that harnessing the urban and rural living environment and maintaining the stability of the ecosystem is vital to promoting high-quality economic development and improving people's quality of life. As an important part of the new development concept, green development needs the participation and support of enterprises and the public. To this end, the government needs to elevate the concept to the national strategic level (Li et al., 2020). In 2011, the Ministry of Science and Technology and four other ministries established pilot cities to "promote the combination of technology and finance"—the country's first policy measure to foster technological innovation at financial level. In general, the government is committed to increasing research and development (R&D) investment to pursue technological progress, aiming to improve production efficiency and energy efficiency (Liu and Lin, 2019). Continuous financial development makes high-tech industries and advanced technologies more attractive to domestic and foreign markets, thus helping to transform the current economic development model into green development (Qian et al., 2021). Previous studies have mainly examined the unilateral impact of technological innovation or financial development on environmental protection, with only a few scholars combining the two. Therefore, researching how science and technology finance policy (STFP) impacts urban green development has essential reference value and practical significance for China's efforts toward establishing a new development pattern and promoting high-quality development.

Studies have shown that combining technology and finance can promote regional economic growth. However, few studies report the impact of STFP implementation on green development, and the effect mechanism has not been thoroughly examined. We address this gap in the literature as follows. First, we construct 18 secondary index evaluation systems based on ecology, economy, and society, then use the entropy weight method to measure the indicators of urban green development. Second, we utilize the difference-in-differences (DID) method to evaluate the effect of STFP implementation. In addition, we apply propensity score matching (PSM)–DID to eliminate selection bias. Third, we use dynamic tests to study the time-varying impact of STFP on urban green development. Fourth, we introduce technological innovation and green innovation as two variables for mechanism analysis, thus deepening our understanding of the relationship between STFP and green development. Finally, because economic development and innovation levels vary significantly across regions, we divide the sample into eastern and midwestern cities and into high-innovation and low-innovation cities to investigate the heterogeneity of the influence of STFP on urban green development.

The study makes four main contributions. First, by analyzing the impact of STFP on urban green development, we enrich theory on the green economy, expand the literature on evaluating STFP's economic impact, and provide valuable insights for the widespread promotion of STFP. Second, we address the lack of empirical evidence on the impact of STFP on urban green development. Third, in terms of evaluation methods, our study considers the implementation of STFP as an exogenous impact on each city and uses the DID method to effectively analyze how STFP affects the green economy. Compared with previous research, our approach avoids interference from other relevant policies on the measurement results, producing more accurate findings. Fourth, our results show that continuing to deepen STFP can not only improve technological innovation but also help promote green innovation.

The remainder of this study is organized as follows: **Section 2** describes the literature review and research hypothesis. **Section 3** describes the methodology, which mainly introduces variables and model settings. **Section 4** reports the results of the empirical analysis. **Section 5** describes the discussion. **Section 6** includes the conclusion and policy recommendations of this study.

2 LITERATURE REVIEW AND RESEARCH HYPOTHESIS

2.1 Literature Review

With the rapid development of big data, artificial intelligence, and cloud computing, the combination of technology and finance stems from the profit-seeking nature of financial capital and the high returns of technological innovation. The effective combination can promote joint technological and financial development (Perez, 2007). Now endorsed by many scholars, Schumpeter (1912) pointed out that entrepreneurs' innovation can lead to the accumulation of financial capital. Through continuous innovation, enterprises can establish a competitive advantage in the market. Continued investments in tangible and intangible assets foster innovation (Porter, 1992). In addition, Bernier and Plouffe (2019) point out that financial innovation combines two essential drivers of economic growth. Technological innovation can boost financial competitiveness; in turn, financial deepening will nurture enterprises' innovation vitality, thereby promoting sustainable economic development (Samila and Sorenson, 2011).

However, most studies fail to mention the concept of "science and technology finance," and relevant literature mainly explores the relationship between scientific and technological innovation and financial development. Zhao et al. (2009) advanced relevant research by providing a relatively comprehensive definition of science and technology finance. Fang (2015) suggests that technology finance is a new economic paradigm that promotes the effective integration of innovative elements such as technology, capital innovation, and entrepreneurship. Its function is to help enterprises achieve high added value and improve market competitiveness. The literature has also empirically examined the effects of science and technology finance on the economy (Shen et al., 2022), innovation (Sheng et al., 2021), R&D (Brown et al., 2017), and industrial agglomeration (Zhang and Zhang, 2018). However, there has been little empirical research on whether and how it affects green development.

The concept of green development was proposed at the Fifth Plenary Session of the 18th Central Committee of the Communist Party of China and has since received growing research attention (Wang et al., 2018). Green development is an economic and social development strategy that aims for efficiency, sustainability, and harmony. It advocates that all countries should prioritize the future while stimulating economic growth, and join together to create a beautiful picture of "clear waters and green mountains as valuable as mountains of gold and silver." Studies of green development have mainly focused on two aspects. First, scholars have used various methods—most commonly, data envelopment analysis—to calculate a green development efficiency index (Zhu et al., 2020; Li C. et al., 2021). Second, many studies have investigated the influencing factors of green development, including political, economic, technological, and natural factors. Political factors mainly include government support (Guo and Liu, 2022) and environmental regulations (Zou and Zhang, 2022); economic factors mainly include financial development (Yuan et al., 2019), level of openness (Huang and Liu, 2021), and industrial structure (Xie and Li, 2021); the main technological factor is innovation (Xu et al., 2021a); and natural factors primarily include resource structure (Fong et al., 2022) and energy consumption (Moutinho et al., 2017).

The ecological environment directly affects and is a critical subsystem supporting regional green development. It contributes to the harmonious coexistence of man and nature (Sun et al., 2018). Since China entered the World Trade Organization in 2001, its carbon dioxide emissions have shown a strong upward trend. Severe environmental problems have directly threatened China's sustainable economic development and public health (Shahbaz et al., 2020). Many studies have shown that technological innovation and financial development impact the regional ecological environment (Abid et al., 2021; Kihombo et al., 2021).

Many scholars have used IPAT or STIRPAT methods to analyze the impact of technological innovation on the ecological environment (Dietz and Rosa, 1994; York et al., 2003). Technological innovation promotes energy efficiency through technology spillover effects. Nathaniel et al. (2021) contend that technological innovation could directly improve environmental quality by developing technologies related to environmental protection. However, some scholars argue that technological innovation has a negative or no impact on energy efficiency (Hübler and Keller, 2010; Adom and Amuakwa-Mensah, 2016). Relatedly, Usman and Hammar (2021) contend that technological innovation is not conducive to improving environmental quality. Specifically, they point out that technological innovation expands a region's ecological footprint, making the ecological environment more vulnerable.

Financial development can improve environmental quality by encouraging investment in green technologies. For example, the development and use of energy-efficient appliances and electric vehicles can improve energy efficiency and thus help reduce carbon emissions (Shobande and Ogbeifun, 2022). Financial development also attracts foreign direct investment, which can promote the exchange of green technology, thereby positively affecting environmental quality (Ahmad et al., 2021). However, some scholars have shown that financial development is not conducive to improving environmental quality. Using data from 59 countries along the Belt and Road routes, Baloch et al. (2019) found that financial development worsened environmental quality by increasing the ecological footprint. In Yasin et al.'s (2020) study of 110 developed countries and developing countries, financial development was found to reduce the ecological footprint of developing countries but not improve their environmental quality. Tahir et al. (2021) revealed that financial development significantly promoted carbon emissions and reduced environmental quality in South Asian economies.

Market failure may cause environmental degradation and ecological damage in a market economy system, necessitating regulatory and public policy intervention by the government (Zhang et al., 2019). The Chinese government set up a pilot policy of "combining technology and finance" in 41 cities in 2011. Most research on STFP uses the DID method to examine its impact on the innovation level (Zheng S. M. et al., 2020), industrial structure development (Hu and Liu, 2021), and regional economic development (Xu et al., 2021b). The policy, in particular, has been found to ease corporate financing constraints by increasing financial investment in science and technology, driving regional financial development, and promoting the further improvement of innovation levels in pilot regions. The advancement of regional capabilities in scientific and technological innovation has accelerated the transformation of new and old kinetic energy and the optimization and upgrading of the industrial structure, thereby raising their potential economic return. However, the STFP implementation effect is highly variable. Ma and Li (2019) contend that STFP plays a positive role in promoting technological innovation in both high-level cities and low-level cities but with more obvious effects in the latter. According to Hu and Liu (2021), the impact of STFP on the transformation and upgrading of industrial structure is positive in the eastern region, negative in the central region, and non-existent in the western region. Xu et al. (2021a) found that the pilot policy has the greatest positive impact on economic development in the eastern region, followed by the central region, but has no such impact in the western region. Many other researchers have analyzed the impact of digital finance on green innovation (Cao et al., 2021; Liu J. et al., 2022). It is widely accepted that digital finance positively impacts green innovation, although the extent of this effect varies across regions and industries. Analyzing provincial panel data, Wang and Gu (2021) found that technology finance can propel the high-quality development of China's economy. They also stated that future research should start with the impact of science and technology finance on the ecological environment. Thus, our research can fill the gap in the current research.

2.2 Research Hypothesis

As the two most active factors in economic and social development, technology and finance have together transformed the development mode from factor driven to innovation driven. Science and technology are the primary forces of production, and technological progress requires financial support. Continuously improving the combination of technology and finance is critical for promoting independent innovation and increasing total factor productivity. The primary goal of STFP is to leverage public funds to guide market financial investment, encourage enterprises' technological innovation, optimize the industrial structure, and achieve high-quality economic development. Therefore, STFP can achieve regional green development through financing and innovation effects.

On the one hand, the government plays a guiding and driving role, using the market mechanism to encourage financial institutions to actively participate in technological innovation. The government thereby helps high-tech enterprises overcome financing barriers and provides financial support for the realization of regional green development. On the other hand, pilot cities are more likely than other cities to gather innovative talents, technologies, products, and markets, all of which can provide technical support for green development. Accordingly, we hypothesize:

Hypothesis 1 (H1). STFP promotes urban green development.

Technological innovation promotes the transformation of production modes to promote ecosystem restoration, which is crucial for resolving resource and environmental problems (Destek and Manga, 2021). It can also indirectly stimulate the development of a regional green economy by promoting the transformation of old and new kinetic energy and optimizing the industrial structure. In situations where local government competition aggravates deterioration of the urban ecological environment, financial marketization can promote the green development of the industry by improving urban innovation capabilities. Capital inflow enables the reallocation of financial resources from high-polluting, high-emission industries to clean-energy-based industries. After obtaining technology funds, some enterprises can develop technological innovation and upgrades, thereby improving their production efficiency and reducing pollution output. Green development differs from the traditional economic development of the past, with a fundamental change in the mode of production, as the driving force of development. Innovation not only distorts the market but also causes transformation. By adjusting the industrial structure, the level of green economic development can be driven up.

Hypothesis 2 (H2). STFP improves urban green development by promoting technological innovation.

Compared with ordinary projects, green technology innovation projects are characterized by a long R&D cycle and income uncertainty, resulting in more serious financial constraints (Zhang and Chiu, 2020). With the increasing prominence of environmental problems, the government and financial institutions will force and encourage enterprises to assume responsibility for sustainable development. The implementation of STFP has continuously improved investment and financing system of green intellectual property. Promoting the realization of science and technology innovation achievements will stimulate enterprises' green innovation vitality. Correspondingly, enterprises that pursue green innovation can obtain more resources and benefits, such as a higher social reputation, good relationship with the government, and greater market share (Burns et al., 2016). Green technology innovation can effectively improve the use efficiency and market scope of eco-environmental elements to reflect the intrinsic value. Moreover, green innovation can continuously enhance the competitiveness of the green industry, cultivating new advantages that help it strongly support green development.

Hypothesis 3 (H3): STFP improves urban green development by promoting green innovation.

3 METHODOLOGY

3.1 Spatial Distribution

This study examines the impact of STFP on urban green development using the DID method and a quasi-natural experiment of STFP combined with panel data from 256 cities in China. To assess the effect of the pilot policy, this study uses the Stata16 external command "Spmap" to draw the spatial distribution comparison diagram of green development before and after implementing the STFP, as shown in **Figure 1**. The pilot cities for STFP are mainly distributed in the eastern and central regions. Through comparison, it is found that the green development level prior to the implementation of the STFP is relatively low. Most pilot cities had green development levels ranging from 0.0783 to 0.1474, with only a few cities falling between 0.1474 and 0.2165. After the policy's implementation, the green development level of almost all pilot cities has increased to 0.1474. Moreover, the green development level of pilot cities in the eastern region is generally higher than that of pilot cities in the midwestern region, indicating that economic development is an essential reference point for the government when establishing pilot cities. It is necessary to investigate the impact of STFP on urban green development from the perspective of heterogeneity in this study.

3.2 Model Setting

The DID method is commonly used to study the effects of policy evaluations related to technological innovation. It effectively avoids the bias of estimation results caused by trends and random factors (Acemoglu and Johnson, 2007). The Ministry of Science and Technology issued the STFP in 2011, and the pilot policy covers 16 regions in China, including 41 cities. The sample duration selected in this study is from 2003 to 2019. The policy immediately affected the cities that participated in the pilot work in 2016. Therefore, this study uses the data from the first batch of pilot cities as the experimental group for investigation, and the data from the second batch of pilot cities to test the robustness of the benchmark results. Although Ningbo was included in the

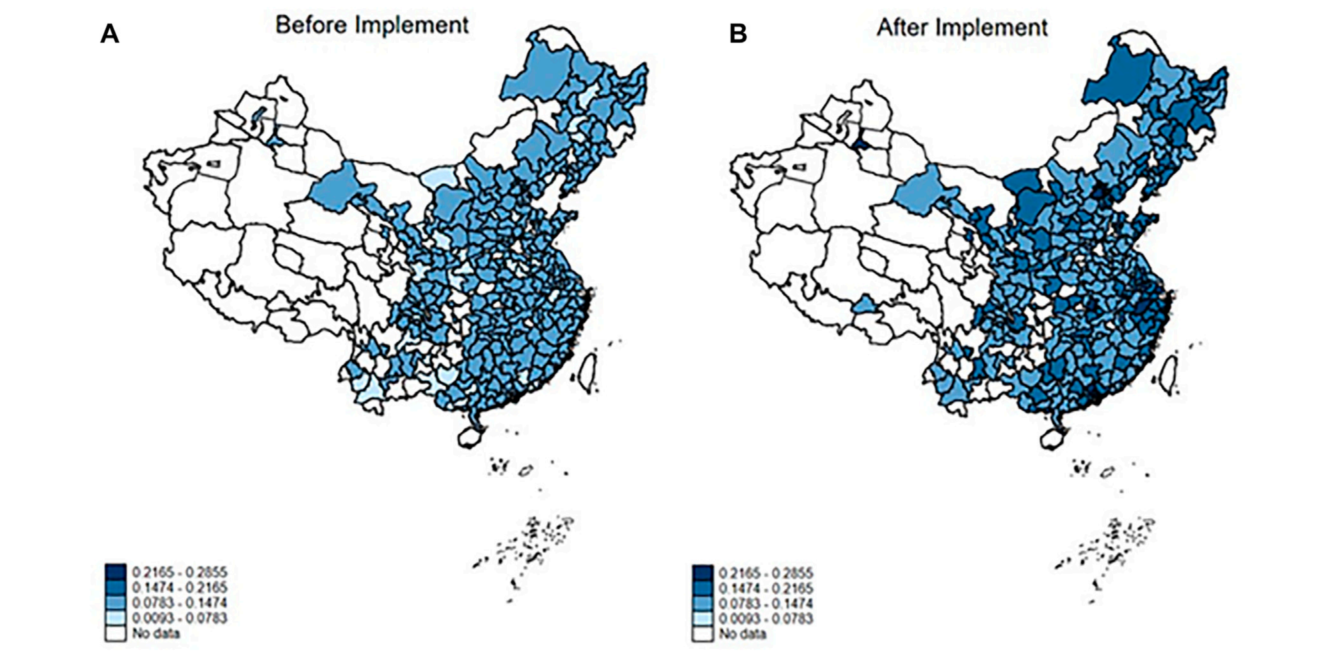

FIGURE 1 | Spatial distribution of green development before and after the implementation of STFP. **(A)** Green development level before the implementation of STFP; **(B)** Green development level after the implementation of STFP.

second batch of pilot cities, the Ningbo High-Tech Zone policy pilot began in 2012. Considering that the high-tech urban zone is the focus of urban innovation, this study includes Ningbo in the first batch of research pilot cities. Based on this, this study selects 215 other cities as the control group in addition to the 41 pilot cities, providing a good quasi-natural experiment for analyzing the implementation effect of STFP. This study uses the DID method to test the impact of STFP on urban green development. The model is constructed as follows:

$$\text{green}_{\text{it}} = \alpha_0 + \alpha_1 treat_{it} \times post_{it} + \sum \alpha_x control_{it} + D_i + D_t + \varepsilon_{it}, \tag{1}$$

where i and t are the city and year, respectively; $green_{it}$ is the explained variable, that is, green development; $treat_{it}$ indicates whether city i is a dummy variable for the pilot of STFP, the experimental group city $treat_{it} = 1$, and the control group city $treat_{it} = 0$; $post_{it}$ represents the dummy variable of policy implementation time, before implementation $post_{it} = 0$, after implementation $post_{it} = 1$; $control_{it}$ is a collection of control variables, including financial development level (fin_{it}), financial investment in science and technology (exp_{it}), openness ($open_{it}$), population density (pop_{it}), informatization level (inm_{it}), and government size (gov_{it}); D_i and D_t represent urban fixed effect and time fixed effect, respectively; and ε_{it} is a random disturbance term. The coefficient of the multiplication term ($treat_{it} \times post_{it}$) is the focus of attention. When α_1 is significantly greater than 0, it indicates that the STFP has effectively impelled urban green development; otherwise, it means that the effect of the pilot policy is not obvious.

3.3 Variable Description

3.3.1 Dependent Variable: Indicators for Urban Green Development

Starting with the definition of green development and based on the United Nations Sustainable Development Goals and the "society-economy-nature" composite ecosystem theory (Commission on Sustainable Development, 2000), this study constructs three first-level indicators, including ecological development (*ecology*), economic development (*economy*), and social development (*society*) to assess urban green development. Referring to the research methodology of Hu et al. (2021), this study constructs a total of 18 secondary index evaluation systems (see **Table 1**). The entropy method is used to calculate the comprehensive index system of green development.

3.3.2 Explanatory Variable: Science and Technology Finance Policy

This study uses cross terms ($treat \times post$) to measure science and technology financial policy, where *treat* is the urban dummy variable. If a city is approved as a policy pilot after 2011, *treat* is taken as 1; otherwise, it is assumed to be 0. *post* is a time dummy variable. Before 2011, *post*= 0; after 2011, *post*= 1.

3.3.3 Other Variables: Control Variable and Mediator Variable

In order to prevent endogenous problems caused by missing important variables, this study selects the following control variables based on the relevant literature on the influencing factors of green economy development (Zheng Y. et al., 2020;

TABLE 1 | Evaluation system of green development.

Comprehensive indicators	Level 1 indicator	Level 2 indicator
Green development	Ecological development	Industrial wastewater emission intensity
		Industrial sulfur dioxide emission intensity
		Green coverage ratio
		Ratio of industrial solid wastes utilized
		Urban domestic sewage treatment rate
		Domestic waste disposal rate
	Economic development	GDP growth rate
		Fiscal revenue growth
		Average salary of on-the-job employees
		Proportion of tertiary industry
		GDP per unit of urban construction land
		GDP per unit of industrial electricity consumption
	Social development	Internet penetration rate
		Natural population growth rate
		Urban registered unemployed per 10,000 people
		Number of college students per 10,000 people
		Number of beds in medical and health institutions per 10,000 people
		Number of social security employees per 10,000 people

Liu B. et al., 2021; Wang and Yi, 2021): 1) Financial development (fin), as measured by the ratio of regional GDP to the balance of financial deposits and loans. A high level of financial development allows for more green investment and green credit, which injects vitality into local green development. 2) Financial investment in science and technology (exp), as measured by the proportion of regional GDP spent on science and technology finance. Increasing financial investment in science and technology can provide more intellectual capital for the local area, assisting in the improvement of green technology efficiency. 3) Openness ($open$), as measured by the proportion of the actual use of foreign capital in the regional GDP. Local enterprises can fully learn and introduce foreign advanced technology by opening to the outside world, thereby improving the ability of green technology innovation to achieve green economic development. 4) Population density (pop), which is measured by the ratio of the population to the total urban area. Excessive population density will adversely affect the ecological environment to a certain extent, restricting the realization of green development in the local area. 5) Informatization (inm), as represented by the rate of urban Internet penetration. Informatization can effectively stimulate the efficient utilization of energy and resources, providing a good foundation for the coordinated development of the economy and ecology. 6) Government size (gov), which is measured by the proportion of the government's public financial expenditure in the regional GDP, is conducive to the construction of green economy demonstration zones, thereby promoting the integration of environmental protection and economic development. 7) Technological innovation ($tino$), as measured by the number of patent applications, including the number of granted invention patents, utility model patents disclosed, and appearance patents disclosed. 8) Green innovation ($gino$), as measured by the proportion of green patent applications in the total number of patent applications. Among these, 1) to 6) are the control variables, and 7) and 8) are mediator variables. For the sake of intuition, **Table 2** shows the main variables and their descriptions. And descriptive statistics of the main variables are shown in **Table 3**. All the above variable data come from the China Urban Statistical Yearbook, China Economic Net Statistical Database, and EPS Statistical Database. The missing data of some variable years are filled by the interpolation method.

3.4 Parallel Trend Test

The DID method's premise is to ensure that the regression results are unbiased. The condition is that the treatment and control groups must maintain parallel time trends before implementing the policy. If the pre-event time trends are inconsistent between the treatment group and the control group, other exogenous shocks are considered to have caused the explained variable to change. **Figure 2** shows the time trend of the green development level of pilot cities and non-pilot cities for STFP and judges whether the two curves have an ex ante parallel trend based on the practice of Yu and Zhang (2017). It can be seen that the green development level of the treatment and control groups has always maintained the same trend from 2003 to 2011, with no difference. From 2011 to 2019, the two sets of curves show obvious differences. The growth rate of the green economy in pilot cities is significantly higher than that in non-pilot cities, especially in 2014. The treatment group grew further apart from the control group. Therefore, this study adopts the DID model to examine the implementation effect of the STFP, which satisfies the parallel trend assumption.

4 EMPIRICAL RESULTS

4.1 Benchmark Regression Test Results

In order to analyze the impact of STFP on urban green development, the DID method is used for estimation in this study, and the regression results are shown in **Table 4**. Column (1) shows the estimated results after adding control variables and without controlling time and region fixed effects. Column (2) reports the estimated results after adding control variables while

TABLE 2 | Description of variables.

Theme	Variable name	Notation	Computing method
Dependent variables	Green development	*green*	calculated by the entropy method
	Ecological development	*ecology*	calculated by the entropy method
	Economic development	*economy*	calculated by the entropy method
	Social development	*society*	calculated by the entropy method
Explanatory variable	Science and technology finance policy	*treat × post*	Urban dummy variable × Time dummy variable
Control variables	Financial development	*fin*	Ratio of the balance of financial deposits and loans in GDP
	Financial investment in science and technology	*exp*	Proportion of government spending on science and technology finance in GDP
	Openness	*open*	Proportion of the actual use of foreign capital in GDP
	Population density	*pop*	Ratio of the population to the total urban area
	Informatization	*inm*	Urban Internet penetration rate
	Government size	*gov*	Proportion of the government's public financial expenditure in GDP
Mediator variables	Technological innovation	*tino*	Total number of patent applications
	Green innovation	*gino*	Proportion of the number of green patent applications in the total number of patent applications

TABLE 3 | Descriptive statistics of variables.

Variable	N	Average	Standard deviation	Minimum	Maximum
green	4,269	0.0410	0.0160	0.00600	0.140
treat × post	4,269	0.0730	0.260	0	1
fin	4,269	2.387	2.134	0.508	38.24
exp	4,269	0.0310	0.0360	0	0.792
open	4,269	0.00300	0.00400	−0.0250	0.115
pop	4,269	441.5	354.6	4.700	2,869
inm	4,269	1,438	1,639	14.44	19,000
gov	4,269	0.194	0.218	0.0150	6.041
tino	4,269	6.547	1.823	1.609	12.22
gino	4,269	0.0960	0.0830	0	1.101

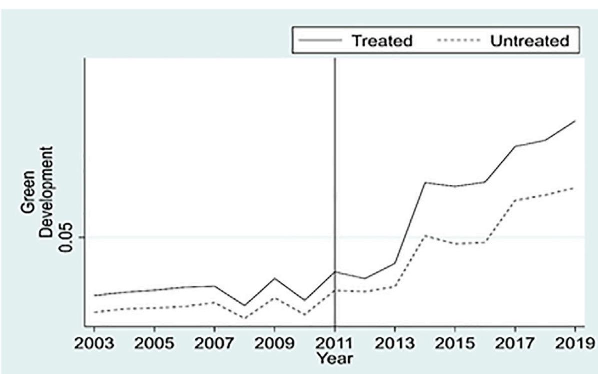

FIGURE 2 | Parallel trend test of double difference method.

controlling time and region fixed effects. From the results in the first two columns, it is found that the coefficients of the *treat* × *post* are all significantly positive, which preliminarily shows that the implementation of the STFP has a significant role in promoting the improvement of urban green development.

At the same time, we use DID method to further study the impact of STFP on the three sub-variables of urban green development. These findings are reported in columns (3) to (5) of **Table 4**. The results show that the STFP has strongly impeded urban economic and social development. The findings imply that the implementation of the pilot policy can drive local government funds to enter the technology industry, thereby effectively solving the financing constraints of technology companies. Once a region helps companies solve financing constraints, it will attract more high-tech companies to settle in. The entry of new enterprises increases the entrepreneurial and employment opportunities of residents and promotes the development of the local economy. However, an unexpected result is that the STFP had a non-significant inhibitory effect on urban ecological development. One possible explanation is that while the pilot policy has driven the city's overall development, enterprises will produce a large amount of waste in rapid economic development, resulting in ecosystem destruction. Will this negative effect ameliorate over time? This study will examine the dynamic effects of pilot policies on ecological development in the following sections.

4.2 Dynamic Effect Test Results

In order to reflect the impact of STFP on the changes in the green development of pilot cities since 2011, this study uses a dynamic effect test. **Table 5** shows the dynamic regression results for the

TABLE 4 | Benchmark regression test results.

Variable	Green (1)	Green (2)	Ecology (3)	Economy (4)	Society (5)
treat × post	0.0064***	0.0051***	−0.0043	0.0003***	0.0270***
	(9.85)	(9.79)	(−1.39)	(5.30)	(10.89)
fin	0.0012***	−0.0000	0.0000	−0.0000*	0.0001
	(11.88)	(−0.09)	(0.11)	(−1.67)	(0.40)
exp	−0.0579***	0.0121	0.1785***	0.0037***	−0.0458
	(−6.35)	(1.57)	(3.95)	(4.31)	(−1.26)
open	−0.0515	−0.0513*	0.5836***	−0.0045	−0.6749***
	(−1.26)	(−1.68)	(3.24)	(−1.31)	(−4.66)
pop	−0.0000***	0.0000**	−0.0000	0.0000*	0.0000***
	(−4.05)	(2.26)	(−1.63)	(1.84)	(2.80)
inm	0.0000***	0.0000***	−0.0000***	0.0000***	0.0000***
	(61.05)	(25.94)	(−3.16)	(3.49)	(30.70)
gov	0.0098***	−0.0048***	−0.0304***	−0.0005***	−0.0092
	(5.91)	(−3.88)	(−4.16)	(−3.92)	(−1.57)
_cons	0.0284***	0.0301***	0.1735***	0.0014***	0.1061***
	(86.37)	(19.89)	(19.46)	(8.29)	(14.79)
Time effect	No	Yes	Yes	Yes	Yes
City effect	No	Yes	Yes	Yes	Yes
N	4,269	4,269	4,269	4,269	4,269
Adjusted R^2	0.615	0.874	0.490	0.854	0.901

*Note: ***, **, and * mean that the variables are significant at the levels of 1%, 5%, and 10%, respectively;* t-*statistic in parentheses.*

TABLE 5 | The dynamic effect test of STFP on green development.

Variable	Green (1)	Ecology (2)	Economy (3)	Society (4)
treat × $post_{2011}$	0.0051***	−0.0043	0.0003***	0.0270***
	(0.001)	(0.003)	(0.000)	(0.002)
treat × $post_{2012}$	0.0061***	−0.0032	0.0003***	0.0302***
	(0.001)	(0.003)	(0.000)	(0.003)
treat × $post_{2013}$	0.0079***	0.0000	0.0005***	0.0373***
	(0.001)	(0.003)	(0.000)	(0.003)
treat × $post_{2014}$	0.0094***	−0.0014	0.0004***	0.0439***
	(0.001)	(0.003)	(0.000)	(0.003)
treat × $post_{2015}$	0.0086***	0.0028	0.0004***	0.0385***
	(0.001)	(0.004)	(0.000)	(0.003)
treat × $post_{2016}$	0.0073***	0.0031	0.0004***	0.0318***
	(0.001)	(0.004)	(0.000)	(0.003)
treat × $post_{2017}$	0.0057***	−0.0022	0.0004***	0.0264***
	(0.001)	(0.005)	(0.000)	(0.004)
treat × $post_{2018}$	0.0063***	0.0048	0.0003***	0.0266***
	(0.001)	(0.006)	(0.000)	(0.004)
treat × $post_{2019}$	0.0070***	0.0041	0.0002	0.0321***
	(0.001)	(0.007)	(0.000)	(0.005)
Controls	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes
City effect	Yes	Yes	Yes	Yes
N	4,269	4,269	4,269	4,269

*Note: ***, **, and * mean that the variables are significant at the levels of 1%, 5%, and 10%, respectively;* t-*statistic in parentheses.*

impact of STFP on green development and its three sub-variables. It can be found that urban green development, economic development, and social development have been continuously improved for some time after the implementation of the STFP. Until 2013, economic development had reached its peak, while green development and social development had reached their peak in 2014. Subsequently, the effect of the pilot policy showed a downward trend, but the coefficient remained significantly positive. It means that the implementation effect of STFP on urban green development, economic development, and social development has increased first and then decreased over time. From the regression results of ecological development, it can be seen that although the implementation of the STFP initially has an inhibitory effect on urban ecological development, its inhibitory effect gradually decreases over time. It reflects that the negative impact of STFP on the ecological environment has been weakening. However, by 2015, the inhibitory effect had become a facilitative effect.

4.3 Robustness Test Results

4.3.1 PSM-DID Results

This study aims to examine the impact of STFP on urban green development. The pilot and non-pilot cities could be analyzed separately to compare changes in green development from before to after the pilot policy's implementation, and thereby infer the policy effect. However, given the non-random nature of STFP, this simple direct comparison would lead to selective errors. The PSM method can solve this problem (Rosenbaum and Rubin, 1983). Specifically, the probability of each city being included in the pilot is estimated based on city characteristics, then cities in the treatment group, and matched with cities in the control group that have the most similar probability of pilot inclusion. After the samples are matched, the DID method is used to estimate the impact of STFP on urban green development.

However, the parallel trend assumption must be satisfied before using PSM. The kernel density distribution is used to test the matching effect of the propensity score (Liu X. et al., 2022), as shown in **Figure 3**. Before matching, the treatment and control groups' propensity scores were quite different; after matching, the

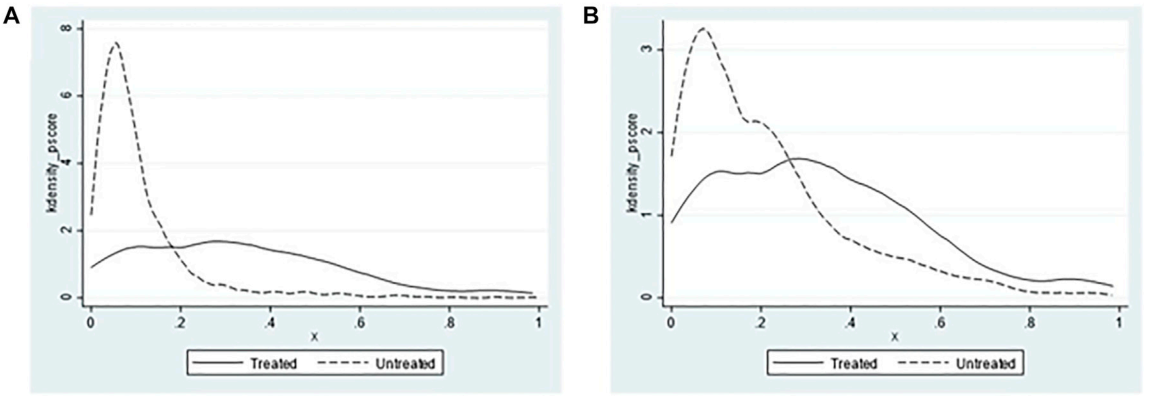

FIGURE 3 | Nuclear density distribution. **(A)** Prior to matching, the treatment and control group's propensity scores are quite different; **(B)** After matching, the distribution probability density function values of the two groups are very close.

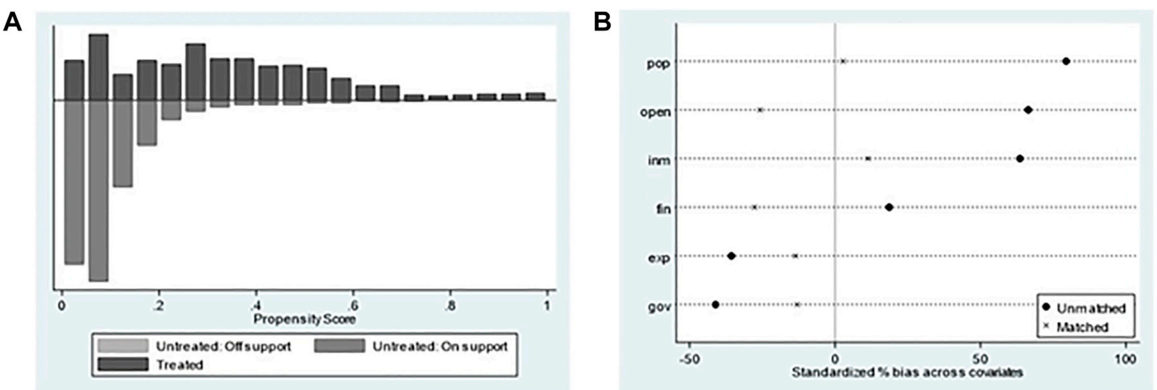

FIGURE 4 | Common support hypothesis testing. **(A)** Common value range of propensity score matching; **(B)** The standardization of control variables before and after matching.

TABLE 6 | Robustness test results.

Variable	PSM-DID method	Eliminate extreme values	Exclude other policy effects	Introduce the second batch of pilot cities
	(1)	(2)	(3)	(4)
treat × post	0.0035***	0.0040***	0.0050***	0.0028***
	(4.26)	(8.40)	(9.53)	(8.25)
$(\text{treat} \times \text{post})_1$	-	-	0.0009*	-
	-	-	(1.77)	-
Controls	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes
City effect	Yes	Yes	Yes	Yes
N	1,416	4,269	4,269	4,269
Adjusted R^2	0.869	0.891	0.874	0.873

*Note: ***, **, and * mean that the variables are significant at the levels of 1%, 5%, and 10%, respectively;* t*-statistic in parentheses; $(\text{treat} \times \text{post})_1$ represents the multiplication term of the smart city dummy variable and the time dummy variable.*

two groups had very close probability density function values, indicating that matched samples can somewhat reduce the selection bias. In addition, a common support hypothesis test was conducted to determine whether the mean value of covariates in the two sample groups significantly differed after matching compared to before matching, as shown in **Figure 4**. We found that most of the samples after matching were in the common support area, with no apparent difference. This shows that the quality of the matched samples is relatively good and that the PSM-DID method is appropriate for robustness testing. The PSM-DID regression results are reported in column (1) of **Table 6**. They show that the implementation of STFP significantly propelled urban green development, which is consistent with the benchmark regression estimation results, indicating their robustness.

4.3.2 Other Robustness Test Results

In addition to using the PSM-DID method to solve the possible impact of the selection bias on regression results, we also apply the following three methods to test the robustness:

First, we eliminate the extreme values of this study. To eliminate any extreme outliers for each variable, which may distort results on the STFP implementation effect, we performed 1% abbreviated processing for all samples. The regression results after eliminating extreme values are reported in column (2) of **Table 6**. The regression coefficient of STFP was significantly positive, indicating that STFP is conducive to urban green development. This is consistent with the benchmark regression results, indicating that they are robust.

Second, we exclude any other policy effects. When estimating the impact of STFP on urban green development, the concurrent influence of other policies may cause the actual effect of STFP to be overestimated or underestimated. To avoid such interference, we identified other policy events that followed the implementation of STFP. Smart city construction began in 2013, marking a new era in urban development strategy, supported by emerging information technology. Therefore, we incorporate the smart city construction policy of 2013 into the benchmark regression model as another quasi-natural experiment. As reported in column (3) of **Table 6**, the results show that smart city construction has played a significant role in promoting urban green development. Although the coefficient of STFP remained significantly positive, its coefficient value decreased compared with the benchmark regression results. This demonstrates that the benchmark results overestimate the role of STFP on urban green development but are nonetheless relatively robust.

Third, we introduce the second batch of pilot cities in 2016. After introducing the second batch of pilot cities for STFP, if the sign of the policy coefficient remains significantly positive, it is confirmed that the role of STFP on urban green development is effective. Because the two batches of cities are selected as pilot projects at different times, this study used the staggered DID method to re-estimate the benchmark model. The results are shown in column (4) of **Table 6**. The significance and coefficient of policy variables are consistent with the benchmark regression results after introducing the second batch of pilot studies, demonstrating that the results of this study are robust.

4.4 Mediating Effect Test Results

Using the intermediary-effect model proposed by Baron and Kenny (1986), we constructed the following recursive model to verify whether technological innovation and green innovation are the mechanisms by which STFP affects urban green development. Based on **Eq. 1**, the following equations are constructed:

TABLE 7 | Mechanism test results based on technological innovation and green innovation.

	Technological Innovation		Green Innovation	
	Tino	Green	Gino	Green
Variable	(1)	(2)	(3)	(4)
treat × post	0.1113***	0.0052***	0.0072*	0.0051***
	(2.94)	(9.99)	(1.81)	(9.70)
tino	-	–0.0009***	-	-
	-	(–4.15)	-	-
gino	-	-	-	0.0069***
	-	-	-	(3.35)
Controls	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes
City effect	Yes	Yes	Yes	Yes
N	4,269	4,269	4,269	4,269
Adjusted R^2	0.947	0.875	0.714	0.875

*Note: ***, **, and * mean that the variables are significant at the levels of 1%, 5%, and 10%, respectively; t-statistic in parentheses.*

$$M_{it} = \beta_0 + \beta_1 treat_{it} \times post_{it} + \sum \beta_x control_{it} + D_i + D_t + \varepsilon_{it}, \tag{2}$$

$$\mathrm{green}_{it} = \gamma_0 + \gamma_1 treat_{it} \times post_{it} + \gamma_2 \mathrm{M}_{it} + \sum \gamma_x control_{it} + \mathrm{D}_i + \mathrm{D}_t + \varepsilon_{it}, \tag{3}$$

where M is the mechanism variable, including two mechanisms of technological innovation (*tino*) and green innovation (*gino*). The establishment of the mechanism effect needs to satisfy three preconditions at the same time: (1) The coefficient α_1 is significant, which means that the explanatory variable ($treat \times post$) has a direct effect on the explained variable (*green*). (2) The coefficient β_1 is significant, indicating that the explanatory variable ($treat \times post$) affects the mechanism variable (M). (3) The coefficient γ_2 is significant, indicating that the variable (M) plays a mediating effect when the explanatory variable ($treat \times post$) affects the explained variable (*green*). If the coefficient γ_1 is significant, there is a partial mediating effect. If the coefficient γ_1 is not significant, there is a complete mediating effect.

Columns (1) and (3) of **Table 7** show the estimation results of **Eq. 2**, that is, the impact of the implementation of STFP on technological innovation and green innovation, respectively. It can be seen that the estimated coefficients of STFP are significantly positive, indicating that STFP can significantly boost urban independent innovation ability and accelerate green-innovation-level improvement. Columns (2) and (4) of **Table 7** report the estimation results of **Eq. 3**, which tests whether technological innovation and green innovation are the channels through which STFP affects urban green development. According to the results in column (2), the estimated coefficient of technological innovation is negative, which indicates that technological innovation as a mediator masks the effect of an independent variable on a dependent variable. It is a generalized

TABLE 8 | Heterogeneity analysis test results.

	Eastern	Midwestern	High innovation	Low innovation
	(1)	(2)	(3)	(4)
treat × post	0.0047***	0.0054***	0.0048***	0.0023*
	(6.32)	(6.84)	(7.09)	(1.79)
Controls	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes
City effect	Yes	Yes	Yes	Yes
N	1921	2,348	2,142	2,127
Adjusted R2	0.870	0.881	0.877	0.873

*Note: ***, **, and * mean that the variables are significant at the levels of 1%, 5%, and 10%, respectively; t-statistic in parentheses.*

mediation effect (Wen and Ye, 2014). The result in column (4) shows that the estimated coefficients of green innovation are significantly positive, which preliminarily indicates that green innovation is an important channel for STFP to promote urban green development.

4.5 Heterogeneity Analysis

4.5.1 Regional Heterogeneity

The above results show that STFP can significantly promote urban green development but is subject to regional variation, depending on the development situation. According to their regions, we divide the sample into eastern and midwestern cities. As reported in columns (1) and (2) of **Table 8**, the regression results show that the implementation of STFP has a significantly positive influence on green development in both eastern and midwestern cities. However, comparing the coefficient of the explanatory variable reveals that the effect is greater in midwestern cities.

4.5.2 Innovative-Level Heterogeneity

According to the 2017 China Urban and Industrial Innovation Report, China's innovation index accounts for 16–26% of the economy. The eastern region is home to 13 of the top 20 cities in the innovation index. The report also identified a considerable imbalance in the regional distribution of the urban innovation index, with prominent agglomeration in the eastern region. It can thus be inferred that, against the background of different innovation levels, the impact of STFP implementation on urban green development is heterogeneous. Following the methodology of Ma and Li (2019), we divided the sample cities into two groups (high innovation and low innovation) according to the mean value of innovation level from 2003 to 2019. As reported in columns (3) and (4) of **Table 8**, the results show that the implementation of STFP played a significant role in promoting green development in both high-innovation and low-innovation cities. However, the policy effect is greater in high-innovation cities.

5 DISCUSSION

The benchmark regression results indicate that science and technology finance policy (STFP) can significantly promote urban green development. The government's policy support for high-quality economic development is still in the continuous improvement stage, and STFP is an important influencing factor. This is consistent with the findings of King and Levine (1993), Yan and Wu (2020), and Wang and Gu (2021). Compared with developed countries, China's financial market is still maturing, raising the urgent need for a policy-based financial system with complete structure and functions to support technological innovation (Zheng S. M. et al., 2020). In this regard, the government's guiding role is crucial, and STFP can ease the financing constraints of technology-based enterprises and thereby stimulate innovation vitality. In recent years, government policies have encouraged technological innovation and green development in China, while scientific research institutions and scholars have become increasingly interested in green and sustainable development. Continuous improvement of the policy environment is also significant in enhancing urban green development. Therefore, our findings support H1.

We also discovered that STFP is an important driver of urban economic development and social development. Contrary to traditional theories, however, STFP has no significant effect on ecological development. This could indicate that the pilot policy has not done enough to promote, or perhaps has not even considered, ecological protection. Importantly, the initial plan for implementing STFP aimed to provide high-quality financial services to support the development of technological innovation (Yuan et al., 2018). The government must attach importance to the upgrading of STFP from product systems to ecosystems, thereby promoting the achievement of carbon peak and, ultimately, carbon neutrality nationwide. In addition, the dynamic effect test used in this study suggests that the impact of STFP will change over time. When the government formulates a policy, it should account for time variability in the policy effect to maximize its effectiveness.

In the intermediary-effect model, we investigated the situation of technological innovation and green innovation as mediating variables simultaneously. STFP exhibits a positive correlation with urban technological innovation, confirming the finding of Ma and Li (2019). Several scholars have demonstrated that technological innovation promotes economic development (Pradhan et al., 2016; Kogan et al., 2017). However, our results indicate that technological innovation inhibits urban green development. Hence, technological innovation appears to mask the relationship between STFP and green development. When the masking effect exists, the research perspective should change from how the independent variable affects the dependent variable to how the independent variable does not affect the dependent variable. Specifically, technological innovation constrains the impact of STFP on urban green development. One explanation is that the implementation of STFP encourages the agglomeration of resources, talents, and enterprises to engage in innovative activities, leading to a negative effect on urban green development through elevated energy demand, resource shortages, and pollutant discharges. Another explanation is that under the sound policy guarantee and government investment, STFP can indeed attract market capital injection and activate technological progress. However, due to China's lack of supporting policies, the capital flows into high-polluting industries. Hence, technological progress can produce energy rebounds (Hu et al., 2019).

STFP and green innovation have a significant positive correlation, indicating that the implementation of STFP will lead to improvement in the green innovation level, which is consistent with the findings of Gu and Chai (2021). We also draw a similar conclusion to Ahmed et al. (2022) that green innovation contributes to green economic growth. In this regard, STFP can guide market funds to flow into fundamental innovation fields with high risk and low return and promote economic structural adjustment to enhance energy utilization, thereby promoting urban green development (Liu Y. et al., 2021). In addition, the implementation of STFP provides greater opportunities for innovative enterprises and talents. Enterprises adopt green production mode and incubate green technology products, which is significant in promoting urban green development further. STFP can also promote technological innovation to improve energy efficiency and shift the energy consumption structure, thereby pushing urban development in a resource-saving direction. Exploring the mechanism through which STFP influences urban green development provides a rational basis for assessing the effect of STFP implementation.

In the regional heterogeneity test, STFP was found to promote green development more effectively in midwestern cities than in eastern cities. This is consistent with the results of Zhang et al. (2021). Possible explanations are as follows. Compared to midwestern cities, eastern cities have a higher level of economic development and better infrastructure. The government of eastern cities can formulate other relevant policies to promote green development, making the precise role of STFP unclear. Conversely, compared with the eastern region, the midwestern region has much greater room to improve through scientific and technological achievements and the construction of a financial service system. Therefore, the marginal utility of the pilot policy is greater in midwestern cities. With regards to urban green development, the implementation of STFP has provided timely help in midwestern cities but merely put the "icing on the cake" in eastern cities.

In the innovation-level heterogeneity test, the policy was found to have a greater positive effect in high-innovation cities, which have better technological innovation industries than low-innovation cities. The implementation of STFP can greatly alleviate financing constraints on green science and technology industries, while further driving other supporting industries for environmental protection. Despite significant policy support for developing a green economy in low-innovation cities, they still lack advanced technology and a sound financial system (Ma and Li, 2019).

6 CONCLUSION AND RECOMMENDATIONS

We use DID model to deeply explore the impact of STFP on urban green development. This study considers STFP implementation as a quasi-natural experiment and analyzes panel data of 256 cities in China from 2003 to 2019. The conclusions are as follows. First, there is a significant positive correlation between STFP and urban green development, indicating that STFP has supported the acceleration of green city construction. The results are robust to using PSM-DID to avoid selection bias and overcome the potential interference of other determinants of green development. Second, regarding the three sub-variables of urban green development, we find that STFP significantly promoted economic and social development—consistent with the green development results—but appears to inhibit ecological development. However, the latter relationship is not statistically significant and gradually diminishes over time. Third, technological innovation and green innovation are the paths through which STFP facilitated urban green development. STFP promotes urban green development by improving green innovation, whereas technological innovation exerts a "masking effect" on the effects of STFP in pilot cities. Forth, heterogeneity analysis shows that STFP can significantly promote green development in any area, thereby confirming the stability of our main results. However, the effect of this policy shows regional heterogeneity and innovation heterogeneity. Specifically, STFP has had a stronger positive impact on green development in midwestern and high-innovation cities than in eastern and low-innovation cities.

Based on our research conclusions, we propose the following policy recommendations. First, local governments should pay attention to the positive externality of STFP on urban green development. Meanwhile, local governments should vigorously support investment in science and technology finance based on regional characteristics, aiming to ease the financing constraints of technological innovation enterprises (Hu et al., 2021). In addition, it is considered to include cities with a good innovation environment and rich financial resources in the scope of the policy pilot. When formulating policies to promote the green development of cities, policymakers should guide various social capitals toward actively supporting the green economy. Attention must be paid to coordination and linkages between cities so as to meet the requirements of harmonious regional development.

Second, considering that STFP has a time-varying influence on urban green development, local governments should formulate technological finance policies from a developmental and forward-looking perspective. In all stages of the policy implementation process, local governments should play a prominent guiding role by scientifically evaluating and flexibly using the policy's advantages to maximize its contribution to urban sustainable green development (Li G. et al., 2021). In addition, the promulgation of policies should not be too hasty. Recognizing the time lag from implementation to maximizing utility, policymakers should avoid promulgating too many policies of the same nature in a short time.

Third, local governments should pay more attention to investing more in technology research and green innovation. By improving the level of talent training and enhancing the technological innovation service system, local governments can direct the flow of funds to core high-tech industries and push forward high-quality economic development. On the one hand, local governments should improve traditional industries' quality, capacity, and efficiency through emerging technologies such as financial big data, blockchain, cloud computing, and artificial intelligence. The advantages brought by financial technology innovation can better serve urban green development. On the other hand, given the importance of green innovation to sustainable economic development, the government should encourage enterprises to shift the focus of innovation activities from traditional technology to green technology.

Finally, given the regional imbalances in economic development and innovation, differentiated policies should be formulated for combining technology and finance. The empirical results show that STFP plays a more prominent role in the green development of midwestern cities and high-innovation cities, which is partly explained by marginal utility. As each city has unique resource endowments and industrial characteristics, undifferentiated technological and financial policies waste resources and exacerbate the problem of unbalanced development.

Some study limitations must be considered when interpreting our findings. First, we could not comprehensively investigate the policy effect in cities in remote areas for which data of sufficient authenticity and integrity were unavailable. Second, cities included in the second batch of pilot projects beginning in 2016 were excluded from the main effect test, as they have only been affected by the policy for a short time. Therefore, the effectiveness of STFP in these cities was not evaluated, raising the need for further investigation. Future research could examine the impact of STFP on green development from a micro perspective, for example, by considering county-level or enterprise-level data. Moreover, it is important to explore multiple channels for the impact of STFP on green development.

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

CG: conceptualization, writing—original draft, and formal analysis; PS: data curation, methodology, and software; YW: visualization and investigation; and DY: writing—review and editing and supervision.

FUNDING

This study was funded by the Projects of National Social Science Fund of China (20FJLB010).

REFERENCES

Abid, A., Mehmood, U., Tariq, S., and Haq, Z. U. (2021). The Effect of Technological Innovation, FDI, and Financial Development on CO2 Emission: Evidence from the G8 Countries. *Environ. Sci. Pollut. Res.* 29 (8), 11654–11662. doi:10.1007/s11356-021-15993-x

Acemoglu, D., and Johnson, S. (2007). Disease and Development: The Effect of Life Expectancy on Economic Growth. *J. Political Econ.* 115, 925–985. doi:10.1086/529000

Adom, P. K., and Amuakwa-Mensah, F. (2016). What Drives the Energy Saving Role of FDI and Industrialization in East Africa? *Renew. Sustain. Energy Rev.* 65, 925–942. doi:10.1016/j.rser.2016.07.039

Ahmad, M., Khan, Z., Rahman, Z. U., Khattak, S. I., and Khan, Z. U. (2021). Can Innovation Shocks Determine CO2 Emissions (CO2e) in the OECD Economies? A New Perspective. *Econ. Innovation New Technol.* 30 (1), 89–109. doi:10.1080/10438599.2019.1684643

Ahmed, F., Kousar, S., Pervaiz, A., Trinidad-Segovia, J. E., del Pilar Casado-Belmonte, M., and Ahmed, W. (2022). del Pilar Casado-Belmonte, M., and Ahmed, WRole of Green Innovation, Trade and Energy to Promote Green Economic Growth: A Case of South Asian Nations. *Environ. Sci. Pollut. Res.* 29 (5), 6871–6885. doi:10.1007/s11356-021-15881-4

Bagheri, M., Guevara, Z., Alikarami, M., Kennedy, C. A., and Doluweera, G. (2018). Green Growth Planning: A Multi-Factor Energy Input-Output Analysis of the Canadian Economy. *Energy Econ.* 74, 708–720. doi:10.1016/j.eneco.2018.07.015

Baloch, M. A., Zhang, J., Iqbal, K., and Iqbal, Z. (2019). The Effect of Financial Development on Ecological Footprint in BRI Countries: Evidence from Panel Data Estimation. *Environ. Sci. Pollut. Res.* 26 (6), 6199–6208. doi:10.1007/s11356-018-3992-9

Balsa-Barreiro, J., Li, Y., Morales, A., and Pentland, A. S. (2019). Globalization and the Shifting Centers of Gravity of World's Human Dynamics: Implications for Sustainability. *J. Clean. Prod.* 239, 117923. doi:10.1016/j.jclepro.2019.117923

Baron, R. M., and Kenny, D. A. (1986). The Moderator-Mediator Variable Distinction in Social Psychological Research: Conceptual, Strategic, and Statistical Considerations. *J. Personality Soc. Psychol.* 51, 1173–1182. doi:10.1037/0022-3514.51.6.1173

Bernier, M., and Plouffe, M. (2019). Financial Innovation, Economic Growth, and the Consequences of Macroprudential Policies. *Res. Econ.* 73, 162–173. doi:10.1016/j.rie.2019.04.003

Brown, J. R., Martinsson, G., and Petersen, B. C. (2017). What Promotes R&D? Comparative Evidence from Around the World. *Res. Policy* 46, 447–462. doi:10.1016/j.respol.2016.11.010

Burns, B. L., Barney, J. B., Angus, R. W., and Herrick, H. N. (2016). Enrolling Stakeholders under Conditions of Risk and Uncertainty. *Strategic Entrepreneursh. J.* 10 (1), 97–106. doi:10.1002/sej.1209

Cao, S., Nie, L., Sun, H., Sun, W., and Taghizadeh-Hesary, F. (2021). Digital Finance, Green Technological Innovation and Energy-Environmental Performance: Evidence from China's Regional Economies. *J. Clean. Prod.* 327, 129458. doi:10.1016/j.jclepro.2021.129458

Commission on Sustainable Development (2001). *Report on the Ninth Session*. New York: United Nations Economic and Social Council.

Dai, H., Xie, X., Xie, Y., Liu, J., and Masui, T. (2016). Green Growth: The Economic Impacts of Large-Scale Renewable Energy Development in China. *Appl. Energy* 162, 435–449. doi:10.1016/j.apenergy.2015.10.049

Destek, M. A., and Manga, M. (2021). Technological Innovation, Financialization, and Ecological Footprint: Evidence from BEM Economies. *Environ. Sci. Pollut. Res.* 28, 21991–22001. doi:10.1007/s11356-020-11845-2

Dietz, T., and Rosa, E. A. (1994). Rethinking the Environmental Impacts of Population, Affluence and Technology. *Hum. Ecol. Rev.* 1 (2), 277–300.

Fang, H. T. (2015). Essence of Sci-Tech Finance. *Forum Sci. Technol. China* 5, 5–10. doi:10.13580/j.cnki.fstc.2015.05.002

Fong, W., Sun, Y., and Chen, Y. (2022). Examining the Relationship between Energy Consumption and Unfavorable CO2 Emissions on Sustainable Development by Going through Various Violated Factors and Stochastic

Disturbance-Based on a Three-Stage SBM-DEA Model. *Energies* 15, 569. doi:10.3390/en15020569

Gu, J. H., and Chai, H. Q. (2021). Has the Science and Technology Finance Promoted Green Innovation: Evidence from the Pilot Policy of Combining Science and Technology with Finance. *Sci. Technol. Progr. Policy* 11, 1–8.

Guo, Y., and Liu, Y. (2022). Sustainable Poverty Alleviation and Green Development in China's Underdeveloped Areas. *J. Geogr. Sci.* 32, 23–43. doi:10.1007/s11442-021-1932-y

Hu, D. L., Shen, H., and Liu, Z. M. (2019). Study on the Spatial-Temporal Evolution and Formation Mechanism of Energy Eebound Effect in Chinese Cities. *Chin. Soft Sci.* 11, 96–108. doi:10.3390/rs11242933

Hu, H., and Liu, C. (2021). Whether Science and Technology Finance Policy Promote the Transformation and Upgrading of Industrial Structure? *Stud. Inter. Fin.* 5, 24–33. doi:10.16475/j.cnki.1006-1029.2021.05.003

Hu, S., Zeng, G., Cao, X., Yuan, H., and Chen, B. (2021). Does Technological Innovation Promote Green Development? A Case Study of the Yangtze River Economic Belt in China. *Int. J. Environ. Res. Public Health* 18, 6111. doi:10.3390/ijerph18116111

Huang, Q., and Liu, M. (2021). Trade Openness and Green Total Factor Productivity: Testing the Role of Environment Regulation Based on Dynamic Panel Threshold Model. *Environ. Dev. Sustain* 24, 9304–9329. doi:10.1007/s10668-021-01825-y

Hübler, M., and Keller, A. (2010). Energy Savings via FDI? Empirical Evidence from Developing Countries. *Envir. Dev. Econ.* 15 (1), 59–80. doi:10.1017/S1355770X09990088

Kihombo, S., Ahmed, Z., Chen, S., Adebayo, T. S., and Kirikkaleli, D. (2021). Linking Financial Development, Economic Growth, and Ecological Footprint: What Is the Role of Technological Innovation? *Environ. Sci. Pollut. Res.* 28 (43), 61235–61245. doi:10.1007/s11356-021-14993-110.1007/s11356-021-14993-1

King, R. G., and Levine, R. (1993). Finance, Entrepreneurship and Growth. *J. Monetary Econ.* 32 (3), 513–542. doi:10.1016/0304-3932(93)90028-E

Kogan, L., Papanikolaou, D., Seru, A., and Stoffman, N. (2017). Technological Innovation, Resource Allocation, and Growth*. *Q. J. Econ.* 132 (2), 665–712. doi:10.1093/qje/qjw040

Li, C., Wan, J., Xu, Z., and Lin, T. (2021). Impacts of Green Innovation, Institutional Constraints and Their Interactions on High-Quality Economic Development across China. *Sustainability* 13 (9), 5277. doi:10.3390/su13095277

Li, Y., Chen, Y., and Li, Q. (2020). Assessment Analysis of Green Development Level Based on S-type Cloud Model of Beijing-Tianjin-Hebei, China. *Renew. Sustain. Energy Rev.* 133, 110245. doi:10.1016/j.rser.2020.110245

Li, G., Zhou, Y., Liu, F., and Wang, T. (2021). Regional Differences of Manufacturing Green Development Efficiency Considering Undesirable Outputs in the Yangtze River Economic Belt Based on Super-SBM and WSR System Methodology. *Front. Environ. Sci.* 8, 631911. doi:10.3389/fenvs.2020.631911

Liu, B., Zuo, Q., and Diao, Y. (2021). The Value and Pathways of Green Technology Innovation for Ecological Conservation and High-Quality Development of the Yellow River Basin. *Resour. Sci.* 43 (02), 423–432. doi:10.18402/resci.2021.02.19

Liu, J., Jiang, Y., Gan, S., He, L., and Zhang, Q. (2022). Can Digital Finance Promote Corporate Green Innovation? *Environ. Sci. Pollut. Res.* 29, 35828–35840. doi:10.1007/s11356-022-18667-4

Liu, K., and Lin, B. (2019). Research on Influencing Factors of Environmental Pollution in China: A Spatial Econometric Analysis. *J. Clean. Prod.* 206, 356–364. doi:10.1016/j.jclepro.2018.09.194

Liu, X., Li, Y., Chen, X., and Liu, J. (2022). Evaluation of Low Carbon City Pilot Policy Effect on Carbon Abatement in China: An Empirical Evidence Based on Time-Varying DID Model. *Cities* 123, 103582. doi:10.1016/j.cities.2022.103582

Liu, Y., Liu, M., Wang, G., Zhao, L., and An, P. (2021). Effect of Environmental Regulation on High-Quality Economic Development in China-An Empirical Analysis Based on Dynamic Spatial Durbin Model. *Environ. Sci. Pollut. Res.* 28, 54661–54678. doi:10.1007/s11356-021-13780-2

Ma, L. Y., and Li, X. M. (2019). Does Science and Technology Finance Policies Promote Regional Innovation? Quasi-Natural Experiment Based on the Pilot Policy of Combining Science and Technology with Finance. *Chin. Soft Sci.* 33, 30–42.

Moutinho, V., Madaleno, M., and Robaina, M. (2017). The Economic and Environmental Efficiency Assessment in EU Cross-Country: Evidence from DEA and Quantile Regression Approach. *Ecol. Indic.* 78, 85–97. doi:10.1016/j.ecolind.2017.02.042

Nathaniel, S. P., Murshed, M., and Bassim, M. (2021). The Nexus between Economic Growth, Energy Use, International Trade and Ecological Footprints: The Role of Environmental Regulations in N11 Countries. *Energy Ecol. Environ.* 6 (6), 496–512. doi:10.1007/s40974-020-00205-y

Pan, X., Cheng, W., Gao, Y., Balezentis, T., and Shen, Z. (2021). Is Environmental Regulation Effective in Promoting the Quantity and Quality of Green Innovation? *Environ. Sci. Pollut. Res.* 28, 6232–6241. doi:10.1007/s11356-020-10984-w

Perez, C. (2007). *Technological Revolution and Financial Capital*. Beijing: The University Press.

Porter, M. E. (1992). Capital Disadvantage: America's Failing Capital Investment System. *Harv Bus. Rev.* 70 (5), 65–82. doi:10.1108/eb022838

Pradhan, R. P., Arvin, M. B., Hall, J. H., and Nair, M. (2016). Innovation, Financial Development and Economic Growth in Eurozone Countries. *Appl. Econ. Lett.* 23 (16), 1141–1144. doi:10.1080/13504851.2016.1139668

Qian, Y., Liu, J., and Forrest, J. Y.-L. (2021). Impact of Financial Agglomeration on Regional Green Economic Growth: Evidence from China. *J. Environ. Plan. Manag.* 65, 1611–1636. doi:10.1080/09640568.2021.1941811

Reid, H., Simms, A., and Johnson, V. (2007). "Up in Smoke? Asia and the Pacific," in *Fifth Report of the Working Group on Climate Change and Development* (London: New Economics Foundation).

Rosenbaum, P. R., and Rubin, D. B. (1983). The Central Role of the Propensity Score in Observational Studies for Causal Effects. *Biometrika* 70, 41–55. doi:10.1093/biomet/70.1.41

Samila, S., and Sorenson, O. (2011). Venture Capital, Entrepreneurship, and Economic Growth. *Rev. Econ. Statistics* 93, 338–349. doi:10.1162/rest_a_00066

Schumpeter, J. A. (1912). *The Theory of Economy Development*. Cambridge M A: Harvard University Press.

Shahbaz, M., Shafiullah, M., Khalid, U., and Song, M. (2020). A Nonparametric Analysis of Energy Environmental Kuznets Curve in Chinese Provinces. *Energy Econ.* 89, 104814. doi:10.1016/j.eneco.2020.104814

Shao, S., Tian, Z., and Fan, M. (2018). Do the Rich Have Stronger Willingness to Pay for Environmental Protection? New Evidence from a Survey in China. *World Dev.* 105, 83–94. doi:10.1016/j.worlddev.2017.12.033

Shen, L., He, G., and Yan, H. (2022). Research on the Impact of Technological Finance on Financial Stability: Based on the Perspective of High-Quality Economic Growth. *Complexity* 2022, 15. doi:10.1155/2022/2552520

Sheng, N., and Tang, U. W. (2016). The First Official City Ranking by Air Quality in China - A Review and Analysis. *Cities* 51, 139–149. doi:10.1016/j.cities.2015.08.012

Sheng, X., Lu, B., and Yue, Q. (2021). Impact of Sci-Tech Finance on the Innovation Efficiency of China's Marine Industry. *Mar. Policy* 133, 104708. doi:10.1016/j.marpol.2021.104708

Shobande, O. A., and Ogbeifun, L. (2022). The Criticality of Financial Development and Energy Consumption for Environmental Sustainability in OECD Countries: Evidence from Dynamic Panel Analysis. *Int. J. Sustain. Dev. World Ecol.* 29 (2), 153–163. doi:10.1080/13504509.2021.1934179

Sun, C., Tong, Y., and Zou, W. (2018). The Evolution and a Temporal-Spatial Difference Analysis of Green Development in China. *Sustain. Cities Soc.* 41, 52–61. doi:10.1016/j.scs.2018.05.006

Tahir, T., Luni, T., Majeed, M. T., and Zafar, A. (2021). The Impact of Financial Development and Globalization on Environmental Quality: Evidence from South Asian Economies. *Environ. Sci. Pollut. Res.* 28 (7), 8088–8101. doi:10.1007/s11356-020-11198-w

Usman, M., and Hammar, N. (2021). Dynamic Relationship between Technological Innovations, Financial Development, Renewable Energy, and Ecological Footprint: Fresh Insights Based on the STIRPAT Model for Asia Pacific Economic Cooperation Countries. *Environ. Sci. Pollut. Res.* 28 (12), 15519–15536. doi:10.1007/s11356-020-11640-z

Wang, M.-X., Zhao, H.-H., Cui, J.-X., Fan, D., Lv, B., Wang, G., et al. (2018). Evaluating Green Development Level of Nine Cities within the Pearl River Delta, China. *J. Clean. Prod.* 174, 315–323. doi:10.1016/j.jclepro.2017.10.328

Wang, M., and Feng, C. (2021). The Win-Win Ability of Environmental Protection and Economic Development during China's Transition. *Technol. Forecast. Soc. Change* 166, 120617. doi:10.1016/j.techfore.2021.120617

Wang, Q., and Yi, H. (2021). New Energy Demonstration Program and China's Urban Green Economic Growth: Do Regional Characteristics Make a Difference? *Energy Policy* 151, 112161. doi:10.1016/j.enpol.2021.112161

Wang, S., and Gu, S. (2021). Research on the Impact of S&T Finance on the High-Quality Development of Chinese Economy—Theoretical Analysis and Empirical Test. *Economist* 2, 81–91. doi:10.16158/j.cnki.51-1312/f.2021.02.009

Wen, Z., and Ye, B. (2014). Analyses of Mediating Effects: The Development of Methods and Models. *Adv. Psychol. Sci.* 22 (5), 731. doi:10.3724/SP.J.1042.2014.00731

Xie, W., and Li, X. (2021). Can Industrial Agglomeration Facilitate Green Development? Evidence from China. *Front. Environ. Sci.* 9, 745465. doi:10.3389/fenvs.2021.745465

Xu, Y., Dong, B., and Chen, Z. (2021a). Can Foreign Trade and Technological Innovation Affect Green Development: Evidence from Countries along the Belt and Road. *Econ. Change Restruct.* 55, 1063–1090. doi:10.1007/s10644-021-09337-5

Xu, Y., Li, T., and Lu, L. (2021b). Research on the Effect of the Pilot Policy of Combining Technology and Finance on Regional Economic Growth: Based on the Perspective of Technological Innovation and Industrial Structure Rationalization. *J. Chongqing Univ.* 27, 1–15. doi:10.11835/j.issn.1008-5831.jg.2021.03.004

Yan, Y., and Wu, Z. (2020). Regional Innovation Distribution and its Dynamic Evolution: Policy Impact and Spillover Effect-Based on the Perspective of Innovation Motivation. *PLoS One* 15 (7), e0235828. doi:10.1371/journal.pone.0235828

Yasin, I., Ahmad, N., and Chaudhary, M. A. (2020). Catechizing the Environmental-Impression of Urbanization, Financial Development, and Political Institutions: A Circumstance of Ecological Footprints in 110 Developed and Less-Developed Countries. *Soc. Indic. Res.* 147 (2), 621–649. doi:10.1007/s11205-019-02163-3

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 (3), 351–365. doi:10.1016/S0921-8009(03)00188-5

Yu, Y. Z., and Zhang, S. H. (2017). Urban Housing Prices, Purchase Restriction Policy and Technological Innovation. *Chin. Ind. Econ.* 6, 98–116. doi:10.19581/j.cnki.ciejournal.2017.06.020

Yuan, H., Zhang, T., Feng, Y., Liu, Y., and Ye, X. (2019). Does Financial Agglomeration Promote the Green Development in China? A Spatial Spillover Perspective. *J. Clean. Prod.* 237, 117808. doi:10.1016/j.jclepro.2019.117808

Yuan, Z. M., Li, T., and Jia, Y. H. (2018). Research on Technological Finance Policy Implementation: Factors and Model Building—Questionnaire and Case Study. *Res. Econ. Manag.* 39 (4), 55–66. doi:10.13502/j.cnki.issn1000-7636.2018.04.005

Yue, S., Lu, R., Chen, H., and Yuan, J. (2018). Does Financial Development Promote the Win-Win Balance between Environmental Protection and Economic Growth? *Environ. Sci. Pollut. Res.* 25, 36438–36448. doi:10.1007/s11356-018-3549-y

Zhang, D., Mohsin, M., Rasheed, A. K., Chang, Y., and Taghizadeh-Hesary, F. (2021). Public Spending and Green Economic Growth in BRI Region: Mediating Role of Green Finance. *Energy Policy* 153, 112256. doi:10.1016/j.enpol.2021.112256

Zhang, G., Deng, N., Mou, H., Zhang, Z. G., and Chen, X. (2019). The Impact of the Policy and Behavior of Public Participation on Environmental Governance Performance: Empirical Analysis Based on Provincial Panel Data in China. *Energy Policy* 129, 1347–1354. doi:10.1016/j.enpol.2019.03.030

Zhang, W., and Chiu, Y.-B. (2020). Do Country Risks Influence Carbon Dioxide Emissions? A Non-Linear Perspective. *Energy* 206, 118048. doi:10.1016/j.energy.2020.118048

Zhang, Y. H., and Zhang, T. (2018). Research on Impact of Sci-Tech Finance on the Co-Agglomeration of Producer Service and Manufacturing Industry. *Chin. Soft Sci.* 3, 47–55.

Zhang, Z.-X. (2007). China Is Moving Away the Pattern of "Develop First and Then Treat the Pollution". *Energy Policy* 35, 3547–3549. doi:10.1016/j.enpol.2007.02.002

Zhao, C. W., Chen, C. F., and Tang, Y. K. (2009). *Sci-Tech Finance*. Beijing: Science Press.

Zheng, S. M., Wu, Y. J., and Zhou, K. (2020). Research on Policy Effect the Integration of Technology and Finance: Based on DID Model. *Chin. Soft Sci.* 1, 49–58.

Zheng, Y., Chen, S., Chen, S., and Wang, N. (2020). Does Financial Agglomeration Enhance Regional Green Economy Development? Evidence from China. *Green Financ.* 2, 173–196. doi:10.3934/GF.2020010

Zhu, B., Zhang, M., Huang, L., Wang, P., Su, B., and Wei, Y.-M. (2020). Exploring the Effect of Carbon Trading Mechanism on China's Green Development Efficiency: A Novel Integrated Approach. *Energy Econ.* 85, 104601. doi:10.1016/j.eneco.2019.104601

Zou, H., and Zhang, Y. (2022). Does Environmental Regulatory System Drive the Green Development of China's Pollution-Intensive Industries? *J. Clean. Prod.* 330, 129832. doi:10.1016/j.jclepro.2021.129832

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

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 17 August 2022
DOI 10.3389/fenvs.2022.982368

OPEN ACCESS

EDITED BY
Jose Balsa-Barreiro,
Massachusetts Institute of Technology,
United States

REVIEWED BY
Kamlesh Maurya,
IMS Unison University, India
Antonio Sanchez-Bayon,
Rey Juan Carlos University, Spain

*CORRESPONDENCE
Wen Zhang,
youzhaoshai8521@163.com

SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 30 June 2022
ACCEPTED 22 July 2022
PUBLISHED 17 August 2022

CITATION
Zhang W and Liu C (2022), Research on the influence of talent ecosystem on firm innovation performance: Based on the mediating role of collaborative innovation.
Front. Environ. Sci. 10:982368.
doi: 10.3389/fenvs.2022.982368

Research on the influence of talent ecosystem on firm innovation performance: Based on the mediating role of collaborative innovation

Wen Zhang* and Chao Liu

Business School, Xi'an University of Finance and Economics, Xi'an, China

This paper extends previous studies on the organizational innovation by analyzing the impact of talent ecosystem on firm innovation performance in innovative enterprises. In addition, the mediating effect of collaborative innovation on the relationship between talent ecosystem and firm innovation performance is analyzed. Grounded in the Resource -Based View (RBV) theory, this paper develops an integrative research model which analyzes those relations using structural equation modeling on a dataset of 176 innovative enterprises. Results suggest that talent competence, organizational environment and regional environment of talent ecosystem have a significant positive impact on collaborative innovation, and organizational environment has a stronger effect on collaborative innovation; talent ecosystem can influence innovation performance to different degrees through the mediating role of collaborative innovation (technology synergy and capability synergy); technology synergy in collaborative innovation positively affects innovation performance, while Technology synergy in collaborative innovation positively affects innovation performance, while capability synergy has no significant effect on innovation performance. The findings of the study provide new ideas for enterprises to improve talent ecosystem and enhance innovation performance.

KEYWORDS

talent ecosystem, innovation performance, collaborative innovation, resource-based view, China

Introduction

From the current world economic development trend, firm innovation to be a driver of firm GVC participation across countries (Reddy et al., 2021), and this change inevitably puts forward new change requirements for HRM work, research on strategic HRM has increasingly emphasized HR systems as an interrelated set of practices to which employees are exposed to achieve some overarching organizational goal. And the idea of changing new thinking is gradually becoming an important direction for the upgrading and transformation of human resources management (Rondi et al., 2022). In recent years, the interdisciplinary integration research is increasing day by day. The talent ecosystem introduces the idea of ecology into the research field of management, and constantly urges new management ideas in the in-depth exploration of the interaction mode between various elements and the environment, the competition and cooperation mode between talents and organizations, which has attracted the attention of scholars. As an important subject of innovation, how to use and improve their own talent ecosystem, and how to optimize the collaborative innovation behavior of enterprises from the interaction of individual talent, organizational environment and regional environment in the talent ecosystem, so as to improve the innovation performance, are all realistic problems faced by enterprises. In reality, many enterprises, especially large and medium-sized enterprises, objectively have a talent ecosystem, and the way for enterprises to build and improve their talent ecosystem is mainly to develop and adjust their human resource strategies. In terms of theoretical research, talent ecosystem is a composite ecosystem applied to the field of social science, which can apply ecological ideas to study the organization, environment and mechanism related to talent in social system, and provide new ways and thinking for the management of the relationship between talent, organization and environment.

Park and Burgess (1921) first introduced the concept of human ecology in Introduction to the Science of Sociology, pointing out that social science research can study human ecology according to the model of community evolution and turnover in the natural world. Since then, the intersection of ecology and social sciences has increased and become a hot spot for scholars. Deolalika and Hasan (1999) proposed the issues related to human resource ecosystem based on the strategic level of enterprises by analyzing the environmental changes of human resource development before and after the Asian financial crisis.Talent ecosystem can be defined as attracting, motivating and retaining talented workers depending on talent markets with various platforms or developing existing talents' skills and capabilities according to newly emerging skill needs of companies (Karaboga et al., 2020). The enterprise talent ecosystem has the function of value output, and can continuously complete the information-energy flow and material circulation based on human resources. Previous studies have more or less explored the interaction between system talent factors, organizational factors and environmental factors and organizational innovation, for example, Altinoz (2018) pointed out that "talent management has also developed in parallel with the information age and has caused people to become the most valuable capital in creating competitive advantage." Michaelis et al. (2018)'s research provides empirical evidence for a clearer picture of innovation culture, as well as how innovation culture relates to new product performance. Hueske et al. (2015)'s research uses stakeholder theory to identify external innovation barriers and takes the external environment as a single level of analysis.

It can be seen that talent ecosystem is an important way to enhance the innovation performance of enterprises, and enterprises with good talent ecosystem are more likely to obtain information, reduce innovation cost and enhance innovation performance than those without good talent ecosystem. In the era of knowledge economy, collaborative innovation has gradually become the main way for enterprises to carry out innovation activities. Relying on an individual or an enterprise to carry out innovation alone can no longer meet the requirements of the whole process of innovation activities. Therefore, collaborative innovation can reduce the dependence of an enterprise on an individual and reduce the negative impact of an individual in case of defects (Gloor, 2006) and gradually becomes the main form of enterprise innovation. Collaborative innovation is an innovation activity in which different elements are organically coupled and complement each other, and this process often leads to value growth, which makes collaborative innovation involving multiple individuals and elements a key area of research. Pan and Li (2016) consider the cost functions of product and process innovation are dependent on the knowledge accumulations of product and process innovation. To maximize the value of process and product innovation, supply chain members should conduct collaborative innovation (Lee and Schmidt, 2017). Wang and Hu (2020) argued that innovation can be achieved across enterprise and industry boundaries by sharing knowledge, technology and ideas among innovation agents. Under the collaborative innovation paradigm, collaborative behavior becomes a necessity for innovation activities, and the boundaries of enterprises are no longer closed, and technological and capability collaboration is no longer limited to the internal organization. By conducting internal and external collaboration, firms can reduce uncertainty in the process of technology innovation realization and improve innovation performance. In fact, through resource and information sharing in the talent ecosystem, enterprises promote the realization of collaborative innovation behavior. At the same time, because collaborative innovation in the talent ecosystem is systematic and talent-oriented, it can ensure that the utility of core resources for innovation increases, and when the utility of all elements in the talent ecosystem increases, the innovation performance of enterprises can also be improved. The role of collaborative innovation in the relationship between talent ecosystem as a strategic resource and innovation performance is one of the focuses of this paper.

However, there are few studies on the interaction between talent ecosystem, innovation behavior and innovation performance at enterprise level, and the following research gaps exist: firstly, there is no systematic research on the structural dimensions of talent ecosystem at enterprise level; secondly, there are few studies on the influence mechanism of different dimensions of talent ecosystem on innovation performance, and the corresponding theoretical analysis framework has not been established yet, which provides obvious theoretical guidance for the improvement of enterprise innovation performance. Finally, innovation performance, as a direct result of innovation behavior, is the product of the interaction and reconstruction of various groups and elements in the talent ecosystem, and the influence of talent ecosystem on innovation performance may be influenced by collaborative innovation behavior. This paper examines the literature on the elements of talent ecosystem and concludes that although there are differences in the understanding of the elements, the existing studies generally consider talent elements as the core structural elements of talent ecosystem and the ecological environment associated with talent, including organizational environment elements and social environment elements, as the basis of talent ecosystem construction. Thus, this paper divides the talent ecosystem into three dimensions: talent competence, organizational environment, and regional environment. Drawing on scholars' elaboration on the concept of collaborative innovation and considering the internal perspective of enterprise talent ecosystem, this paper attributes collaborative innovation behavior to the synergy between enterprises in both technology and capability. On this basis, we attempt to empirically study the relationship between enterprise talent ecosystem and innovation performance and verify the mediating effect of collaborative innovation in this process, so as to provide a new path for enterprises to gain sustainable competitive advantage and promote innovation performance.

In summary, the main contributions of this paper are as follows: 1) Using the ecosystem as the research perspective, we use empirical analysis to discover the path, intensity and effect of the talent ecosystem and the innovation performance of enterprises, which not only expands the research perspective of modern enterprise human resource management, but also enriches the research scope of ecological theory. 2) Using collaborative innovation as a mediator, we construct the path of "talent ecosystem—collaborative innovation—innovation performance," and sort out the inner mechanism of talent ecosystem affecting innovation performance. 2) Using collaborative innovation as the mediator, we build the path of "talent ecosystem—collaborative innovation—enterprise innovation performance," and sort out the inner mechanism of talent ecosystem affecting enterprise innovation performance, which effectively remedies the lack of research on the relationship between talent ecosystem, collaborative innovation and innovation performance. 3) From the micro-enterprise perspective, we have systematically explained the path of enterprise innovation performance, which is a new interpretation of the path of enterprise innovation performance by using empirical methods to verify the mechanism of the role of talent ecosystem and enterprise innovation performance, which undoubtedly deepens the theoretical study of organizational innovation.

Theoretical background and hypotheses

The Resource-based view (RBV) has become a standard to explain why firms in the same industry vary systematically in performance over time (Hoopes et al., 2003). This suggests that the effects of individual, firm-specific resources on performance can be significant (Mahoney and Pandian 1992). The RBV generally tends to define resources broadly and includes assets, infrastructure, skills, and so on. In this regard, it is based on two underlying assertions: resource heterogeneity and resource immobility. Resources possessed by competing firms are heterogeneously distributed and may be a source of competitive advantage when they are valuable, rare, difficult to imitate, and not substitutable by other resources (Barney 1991). Based on resource-based theory, Hult argue that an organization's strategic resources or capabilities first influence the organization's strategic behavior, and strategic behavior further influences organizational performance, strategic behavior is a mediating variable for the influence of an organization's strategic resources or capabilities on its strategic performance (Ketchen et al., 2007).

Collaborative innovation is derived and developed from collaborative theory. In 1969, Haken first proposed the concept of "Synergetics." He pointed out that Synergetics is an effective method to deal with complex systems, which can solve the phenomena or problems composed of many complex systems encountered in social practice (Hermann, 1977). Palford pointed out in their research that collaborative innovation activities are three dynamic ability processes of perception, acquisition and reconfiguration, and its mechanism is that perception enables enterprises to identify innovation opportunities faster. Then collect information to obtain the required innovation knowledge, and finally complete the innovation through resource reconfiguration. And these three parts are interrelated and continuous, which helps enterprises cope with the changing business environment and gain competitive advantage (Alford and Duan, 2018). Supported by the collaborative innovation theory, it helps to put forward solutions suitable for the enterprise's own talent ecosystem itself.

This paper considers talent ecosystem as strategic resources, collaborative innovation as strategic behavior, and innovation performance as the expression of strategic performance. Thus, this paper, from a knowledge-based perspective, studies the relationship between talent ecosystem, collaborative innovation and innovation performance as well as the mediating effect of collaborative innovation on the relationship between talent ecosystem and innovation performance. The theoretical model involves three main

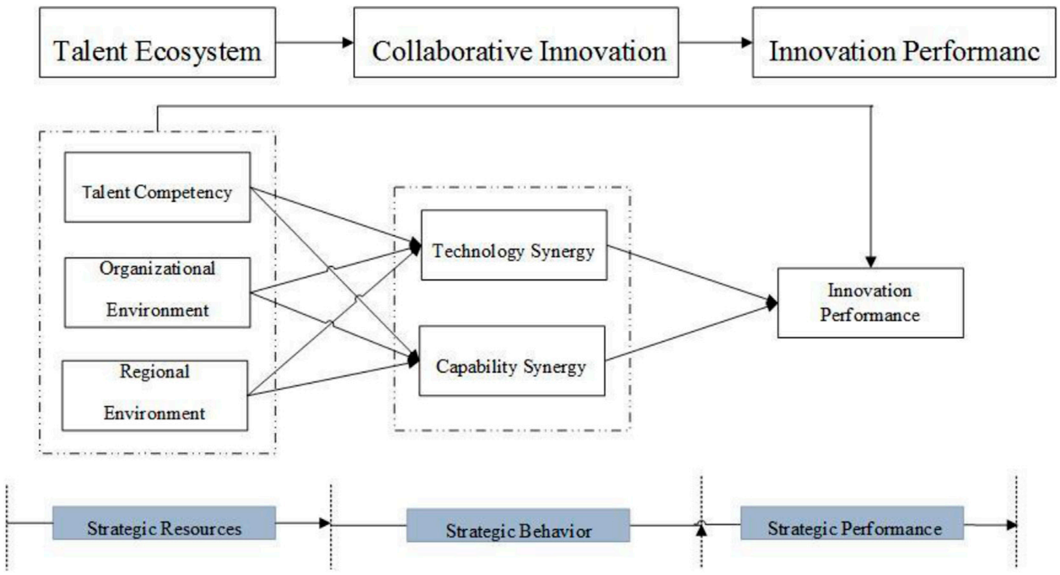

FIGURE 1
Conceptual model.

variables: First, talent ecosystem (including talent competency, organizational environment and regional environment). The second is collaborative innovation (including technology synergy and capability synergy). The third is innovation performance (including new product launch frequency, new product development cycle, new product market acceptance, new product quality, and new product market development power). The relationship between them is shown in Figure 1.

Talent ecosystem and collaborative innovation

The value output of the talent ecosystem is a complex process, which depends not only on the improvement of the competency characteristics of the talent population in the talent ecosystem, but also on the improvement of the organizational environment, such as the support of the corporate culture for innovation and the improvement of the management style, and as an important support of the system, the regional environmental factors such as the support of government departments are also closely related to it. In order to adapt to the complex and dynamic development environment, enterprises use the mobility of talent resources to continuously carry out material circulation, and form a relatively stable system of interdependence among talent individuals, talent and organization, talent and environment, so as to promote energy flow and information transmission. The talent competency of talent ecosystem is the combination of knowledge, skills, traits and other competency characteristics that are closely related to good innovation performance of organizational innovation talents in the process of conducting innovation activities. Technology synergy refers to a firm ability to effectively transform common technologies into capabilities by cooperation (Soto-Acosta and Meroño-Cerdan 2008).In terms of research on the relationship between talent competency and technology synergy, Clarysse et al. (2014) pointed out that knowledge heterogeneity and organizational knowledge capabilities positively affect the path relationship of knowledge synergy in collaborative innovation; Hoffman and HegartyW (1993) pointed out that the competency trait of innovation individual managers' innovativeness helps companies identify innovation opportunities, promote a corporate atmosphere that encourages innovation, improve the process of innovation activities, and achieve mutational innovation. Based on scholars' research, this paper argues that collaborative innovation is the main form of current innovation activities, and that companies realize the interaction of knowledge within the talent ecosystem based on talent competencies during the implementation of innovation behaviors, which in turn promotes the integration of technology sources and achieves technology synergy.

Competency synergy is mainly characterized by the consistency of vision, the degree of cooperation and trust, and the ability to coordinate and collaborate among innovation individuals. A high degree of capability synergy means a better willingness to collaborate and a higher degree of mutual trust, which not only promotes the collaboration process but also reduces the occurrence of undesirable behaviors (Juana et al., 2018). Generally speaking, partnership runs through the whole collaborative innovation process, and a harmonious collaborative relationship can effectively reduce communication costs, promote capability synergy, and improve the efficiency of collaborative innovation behavior (Gallear et al., 2012). The innovation of knowledge and technology depends on talents (Yang, 2018). Moreover, the ability to innovate, especially in dynamic environments, results from the collective ability of employees to share and combine knowledge (Nahapiet and Goshal, 1998). Collaborative innovation behavior relies on talent competence, and the level of competence of individual talents is often closely related to the consistency of goal vision, the degree of trust, and the degree of coordination and cooperation of collaborative subjects, which shows that talent competence can have an important impact on capability collaboration. Based on the above analysis, this paper proposes the following hypotheses.

Ha1: There is a positive relationship between talent competency and technology synergy.
Ha2: There is a positive relationship between talent competency and capability synergy.

The organizational environment in the talent ecosystem is the innovation culture and climate fostered by the organization to support innovative behavior. Organizational environment is referred to as a set of norms, procedures, beliefs and core values that guide and direct its members' thinking and behaviors toward each other as well as the organization's related stakeholders (Cadorin et al., 2017). The organizational environment largely determines the ability of firms to collaborate on innovation. Organizational factors are important drivers for the adoption and implementation of IT innovations (Aboelmaged 2014). In the discussion of the relationship between organizational environment and technology synergy, it has been pointed out that the technological innovation capability of enterprises is not only influenced by resource factors, but also by the environment of interaction between innovation subjects and other factors (Todtling 1992). An innovation-oriented organizational environment not only enables firms to search for complementary or alternative innovation resources in a timely manner, but also gives them a strong advantage in predicting the potential business value of technologies and technological innovation opportunities (Lam et al., 2021), which facilitates technology synergy. As argued by Kayworth,organizational culture is a key factor in facilitating an effective knowledge management process, including knowledge creation, transfer, and application of new and existing knowledge (Kayworth and Leidner, 2004), and it is easier to form technology synergy. In a study related to the relationship between organizational environment and capability synergy, it has been confirmed that organizational culture plays an important role in developing knowledge management. How firms interact with related stakeholders determines the efficiency of managing external information, which in turn, affects the firms' ability to implement open innovation (Zhu et al., 2019). Aenetz et al. (2011) pointed out that providing a comfortable and positive climate is beneficial for reducing individual stress and enabling innovative talents to engage in innovation activities more efficiently. Thus, this paper argues that the organizational environment plays an important role in capability synergy. Based on the above analysis of the relationship between organizational environment and technology synergy and capability synergy, the following hypotheses are proposed.

Ha3: There is a positive relationship between organizational environment and technology synergy.
Ha4: There is a positive relationship between organizational environment and capability synergy.

The regional environment mainly examines how well the resource, technological, policy, financial, and infrastructural environment of the firm's region supports innovation activities. In terms of research related to the relationship between regional environment and collaborative innovation, Thorgren suggested that government-related policies play an important role in stimulating collaborative innovation behavior of firms (Thorgren et al., 2009). By increasing the scope and frequency of knowledge collaboration among heterogeneous firms, governments can increase the dynamism of knowledge exchange and thus contribute to the growth of firms' innovation performance (Abdollahbeigi and Salehi, 2019). Sun and Cao found that industry innovation policy can mitigate market failures, guide innovation, reset resources, improve the competitive and innovation environments, help build innovation networks, and improve firm innovation capabilities (Sun and Cao 2018).The regional innovation environment can play a supportive role in clustering innovation factors and promoting technological synergy. However, innovation activities are difficult to be achieved by individual enterprises alone, and require the coordination of multiple actors to develop into a good synergy of capabilities. For example, Pulka studied that the government can play a policy-oriented role through political advantages to strengthen the willingness of various subjects to continuously participate in collaborative innovation and promote capability synergy, which helps to reduce the potential risks of collaboration and the probability of opportunistic behavior (Pulka et al., 2021). Building a positive social climate may be crucial to motivate employees to work together through electronic networks and increase e-business use for collaboration and knowledge sharing (Valkokari et al., 2012). Based on the above scholars' studies, this paper argues that regional environment plays an important role in capability synergy. On the basis of technology and capability synergy, regional environment can play a strong role in supporting collaborative innovation behavior. Based on the above analysis, this paper proposes the following hypotheses.

Ha5: There is a positive relationship between regional environment and technology synergy.
Ha6: There is a positive relationship between regional environment and capability synergy.

Talent ecosystem and innovation performance

Hearn and Pace (2006) first proposed the concept of Value-Creating Ecologies (VCEs), and in their study, they elaborated on the value symbiosis, arguing that the value creation of this symbiosis depends on the industrial ecosystem composed of talents, enterprises, related sectors, and other subjects ecosystem. Innovation performance is one of the important forms of their value performance, therefore, the concept of value creation ecology itself contains the inner logic that organizational ecosystems can influence organizational performance (Baležentis et al., 2021). In terms of research on the relationship between talent competency and innovation performance. A joint survey of Capgemini and Linkedin indicates that organization-wide digital talent gap has become a big challenge that affects both competitiveness and digital transformation progress negatively (Capgemini Research Institute and LinkedIn 2017). Vyakarnam and Handelberg (2005) state that higher innovation performance is generated thanks to the integration of knowledge, skills, and competencies of different individuals in innovation activities. Based on the above studies, this paper argues that talent competency directly affects innovation performance, and the stronger the talent competency, the better the innovation performance should be.

In terms of research on the relationship between different dimensions of organizational environment and innovation performance, Goodale et al. (2011) verified that top management support, organizational boundaries in organizational environment have a significant positive effect on innovation performance based on research data from 177 different industries in the U.S. Pasamar et al. (2015) argued that organizational culture encourages change is more beneficial to break the limits and also tends to be associated with higher levels of innovation associated with higher levels of innovation. Shen et al. (2022) investigated the impact of technological innovation on promoting ecosystem performance. Drawing on the views of related scholars, this paper argues that organizational environment can influence firms' innovation performance, and the stronger the role of organizational environment in supporting innovation, the better the innovation performance.

The supporting role of regional innovation environment is mainly reflected in the technological development of enterprises relying on various innovation policies and innovation infrastructure to promote the diffusion of new technologies, so as to realize the scale effect of economic growth. In the context of innovation management research, the external environment is often used as an important antecedent variable in the mechanism of action of firms' innovation activities. Firms in real-life situations are always able to receive various signals from the external environment and, as adaptive organizations, constantly respond to stimuli in an adaptive manner. Resource-based theory suggests that the outcome output of innovation activities is related to the acquisition, replenishment and integration of resources. Referring to the external environment, including both market and technological turbulence, Mina's research highlighted the negative role of technological turbulence in sustainable innovation (Nasiri et al., 2021). Drawing on the views of related scholars, this paper argues that the regional environment can have a significant impact on the innovation performance. The comprehensive analysis leads to the following three hypotheses.

Hb1: There is a positive relationship between talent competency and firm innovation performance.
Hb2: There is a positive relationship between organizational environment and firm innovation performance.
Hb3: There is a positive relationship between regional environment and firm innovation performance.

Collaborative innovation and innovation performance

Collaborative innovation activities can interact information resources and change the situation of one-way, even closed information channels among collaborative subjects (Wang and Hu 2020). Collaboration can provide enterprises with ways and opportunities to obtain high-quality resources. Only by cooperating with both or more parties to build a good collaborative relationship, can they reduce obstacles in promoting knowledge and information transmission, improve resource utilization efficiency, and then improve innovation performance.How can collaborative innovation behavior of enterprises affect innovation performance? First, the key to collaborative innovation lies in technological synergy. By participating in technically collaborative R&D, enterprises are more likely to collect and store a larger amount of heterogeneous technical knowledge, which can also provide greater support for technological innovation. Technological synergy is the extent to which firms collaborate at the technological level in carrying out innovation activities. The supporting effect of technological synergy on innovation performance is mainly manifested as follows: in the process of carrying out collaborative innovation activities, technological synergy can effectively expand enterprise technical information channel resources, and the wider the scope of cooperation, the more it can broaden the width of technology and knowledge base, and the more it can enrich the variety of enterprise knowledge sources, which in turn can promote the improvement of enterprise innovation performance (Benitez et al., 2020). Generally speaking, knowledge sources and knowledge stocks within enterprises are relatively stable, and at the same time, technical problems often show homogeneity, so for knowledge-intensive industries, especially high-tech enterprises, extensive cooperation is a proven way for enterprises to expand knowledge increment in the development process, and it is also an effective form for enterprises to acquire complementary knowledge, unique ideas and breakthrough technological innovations. It is beneficial to spawn original innovation activities and create collective value. The collision of knowledge and technologies from different firms increases the level of knowledge flow and subsequently enhances innovation performance (Carliss et al., 2011). Jesús Nieto and Santamaría (2007) found a significant positive relationship between the degree of collaboration among suppliers, customers and research organizations and the degree of product innovation based on research data from Spanish manufacturing firms. A large number of empirical studies have shown that the synergy between firms and external technology sources can enable firms to obtain support in the acquisition of complementary resources and achieve the accumulation of diverse knowledge within the firm, in addition, technology synergy has incomparable advantages in reducing corporate risks and sharing R&D costs, which can ultimately promote innovation performance.

Secondly, capability synergy characterizes the degree of trust, coordination and consistency of vision among collaborative subjects in the process of innovation activities. Whether knowledge can be efficiently shared and absorbed in the process of collaborative innovation is usually determined by the degree of capability synergy among innovation subjects. The supporting effect of capability synergy on innovation performance is mainly manifested by the fact that in the innovation process, collaborative subjects discover new opportunities by interacting with others, which leads to the improvement of innovation creation capability (Xu et al., 2018). In particular, when firms search for technologies across borders, their ability to adapt to the dynamic changing environment is also enhanced by achieving capability synergy through coordination and cooperation with different innovators (Wang et al., 2014). Firms are developing more and more collaborative behaviours (shared databases, repositories, discussion forums, workflow.) for the execution of the innovation process (Meroño-Cerdan et al.,. 2008a). As a consequence, Meroño-Cerdan et al. (2008b) found that most collaborative behaviours are positively related to innovation performance. Meanwhile, deep collaboration among innovation subjects often implies lower knowledge transfer costs, information asymmetry risks and higher trust and cooperation tacit understanding, which makes the transfer, integration and sharing of tacit knowledge more efficient (Serrano and Fischer, 2007). And the closer the collaboration between subjects and the higher the degree of capability synergy, the higher the degree of understanding of the innovation elements required for R&D and the innovation resources endowed by collaborating partners, the more targeted the enterprises can acquire, assimilate and transform technological knowledge in the synergy, and the more advantageous they can gain in reducing the innovation knowledge search cost and screening cost and promoting the innovation performance. Based on the above arguments, the following two hypotheses are proposed.

Hc1: There is a positive relationship between technology synergy and firm innovation performance.
Hc2: There is a positive relationship between capability synergy and firm innovation performance.

The intermediary role of collaborative innovation

The essence of collaborative innovation is the collaborative behavior of each innovation subject to reach innovation synergy and achieve value increase based on the interaction of elements. These interactions and diverse collaboration are mainly manifested in the synergy of each innovation subject in terms of technology and capability. In the process of talent ecosystem acting on innovation performance, the collaborative innovation behavior of enterprises can expand the scope of resource search, and enterprises can identify the needed technologies in the larger knowledge system, realize the complementary knowledge in the R&D process, and gradually improve the technical synergy of collaborative teams in the process of continuously realizing the synergy of technology sources, and at the same time continuously feed themselves to form a sustainable innovation capability, so the collaborative innovation in Therefore, collaborative innovation plays a mediating role in the relationship between talent ecosystem and innovation performance. The innovation effectiveness of enterprises depends on the implementation of innovation strategies, and innovation behavior not only determines the level of technological innovation, but also the market share of enterprises (Ritter and Gemünden, 2004). The essence of the intermediary role of the internal collaborative network is the interaction of resources in the collaborative network. Specifically, the integration of innovation factors requires the collaborative network as a medium for transferring flows, while collaborative sharing based on the collaborative network also plays an important role in the firm's ability to enhance innovation creation and commercialization (Stoji, 2021). As a result, the following hypothesis is proposed.

Hd: Collaborative innovation mediates the relationship between talent ecosystem and firm innovation performance.

Research methodology

Data collection and sample

The organizations selected for this study are innovative enterprises from China. As countries around the world continue to make efforts in innovation research and development, pilot innovative enterprises have developed into an important part of improving national innovation system. In the new era of innovation development, scholars at home and abroad have also continuously invested in the research and discussion of innovative enterprises in the academic research field. Innovative enterprises are enterprises that possess independent intellectual property rights and well-known brands and rely on technological innovation to gain competitive advantages. Taking innovative enterprises as the research object, based on the pilot list of innovative enterprises approved by the Chinese government, this paper preliminarily screened innovative enterprises in China, selected representative innovative enterprises as the research object, and collected data by mailing questionnaires. Data collection was conducted in two stages: a pilot study and a questionnaire were conducted. Nine SMEs were randomly selected from a database to pretest the questionnaires. Based on these responses and subsequent interviews with participants in the pilot study, minor modifications were made to the questionnaire for the next phase of data collection.

The population considered in this study was the set of all Chinese innovative enterprises. In order to avoid potential errors, each enterprise was filled out by at least two people. 176 enterprises were involved in this research. A total of 370 were identified and contacted for participation. The survey was administered in face-to-face interviews with to the CEO of the companies and the unit of analysis for this study was the company. In total, 352 valid questionnaires were obtained, yielding a response rate of 95.1 percent. The dataset was examined for potential bias in terms of non-response by comparing the characteristics of early and late participants in the sample. These comparisons did not reveal significant differences in terms of general characteristic and model variables, suggesting that non-response did not cause any survey bias.

Measures

Measurement items were introduced on the basis of a careful literature review. The survey questionnaire was originally designed in English as the key measures used in this study were operationalized using already established instruments published in that language. Scales were measured on a 5-point Likert scale with anchors from strongly disagree (1) to strongly agree (5). We used the back-translation method to ensure the validity of the translation (Brislin 1980). Existing scales were translated into Chinese and, where necessary, slight wording changes were made to adapt the questions to the context of the study. The research instrument was pretested with several different researchers and managers. Our primary objective was to detect inadequate wording and facilitate the ease of administering the instrument. The results from the pretest showed no particular bias, but some respondents had trouble understanding certain items.

Variables were operationalized as multi-item constructs. This paper contains six latent variables: talent competency, organizational environment, regional environment, technology synergy, capability synergy, and innovation performance. The talent competency construct mainly characterizes the degree of talent competency within the enterprise, mainly referring to the scale compiled by Wright (2005) and Spencer and Spencer (1993). The organizational environment concept is mainly characterized as the innovation culture, innovation atmosphere and innovation environment in the organization where the company conducts innovation activities, mainly referring to the scales developed by Castro et al. (2013) and Hurley and Hult (1998). The regional environment level indicators mainly examine the status of resources, technology, policy, finance and infrastructure environment in the region where the firm is located, mainly referring to the research results of Zahra (1993). The measurement of the concept of collaborative innovation mainly refers to the research results of Desouza and Awazu (2006) (Carson and Gilmore, 2000) and Abhari et al. (2017), and the concept includes two dimensions of technology synergy and capability synergy. Among them, the technology synergy dimension is measured by five measures and the capability synergy dimension is measured by three measures. Innovation performance is a multidimensional variable, and this paper draws on the innovation performance measurement indicators of Zhang and Li (2010), and it is measured by five indicators: Launch frequency of new products, development cycle of new products, market acceptance of new products, quality of new products and market development power of new products. The formulation and criteria for answering the questionnaire are defined in the Appendix.

Data analysis

In this paper, the reliability of the six latent variable scales was measured using Cronbach's alpha coefficient to determine the reliability of each scale. The measurement results showed (Table 1) that the alpha coefficient values of each latent variable were greater than 0.8, indicating a high degree of stability of each scale. Before the factor analysis, the KMO values were used to determine the bias correlation among the variables, and the Bartlett's sphericity test was used to determine the independence of the variables. The validity test results showed

TABLE 1 Test results of reliability and validity.

Variable	Cronbach's α	Factor loadings	KMO	Bartlett's sphericity test		Cumulative variance contribution rate%
				Chi-square value	*p* value	
Talent competence	0.935	>0.6	0.951	1986.190	0.000	69.005
Organizational environment	0.840	>0.5	0.855	669.963	0.000	62.173
Regional environment	0.906	>0.7	0.825	961.770	0.000	78.379
Technology synergy	0.864	>0.5	0.841	829.226	0.000	64.900
Capability synergy	0.843	>0.6	0.718	441.296	0.000	76.236
Innovation performance	0.927	>0.7	0.888	1340.076	0.000	77.462

(Source: own elaboration).

TABLE 2 Correlation analysis.

	M	SD	Talent competence	Organizational environment	Regional environment	Technology synergy	Capability synergy	Innovation performance
Talent competence	3.782	0.836	1					
Organizational environment	3.779	0.817	0.426**	1				
Regional environment	3.236	1.053	0.365**	0.318**	1			
Technology synergy	3.765	0.835	0.554**	0.579**	0.369**	1		
Capability synergy	3.742	0.980	0.548**	0.511**	0.364**	0.828**	1	
Innovation performance	3.381	1.015	0.543**	0.534**	0.453**	0.620**	0.583**	1

Note: ** indicates significance level $p < 0.01$ (Source: own elaboration).

that the KMO values of the six latent variables in the conceptual model were all greater than 0.7, and the significance levels of the approximate chi-square values of the Bartlett's sphericity test were all 0.000 (less than 0.001). Moreover, the cumulative variance contributions of the extracted factors of the six latent variables were higher than 60%, and the factor loadings of each construct were higher than 0.5, so the six latent variables met the requirements of structural validity. In addition, all the scales in this paper were derived from validated mature scales, and the measurement items had good content validity. The comprehensive test results indicated that the validity level of the measurement items was high, and each variable was suitable for factor analysis.

The correlation analysis of each research variable was performed, and the results are shown in Table 2, and there is a significant correlation between each variable. This conclusion initially proves the hypothesis proposed in this paper, and in order to ensure the reliability, the paper then applies the structural equation model for the subsequent analysis.

In this paper, validation factor analysis was conducted on each latent variable using AMOS software, and the results showed that the combined reliability (CR) of the six latent variables in the conceptual model were all greater than 0.8, and the question-item measures had good internal consistency. In addition, the average variance variances (AVE) of the six latent variables were all greater than 0.5, which reached the ideal value, indicating that the convergent validity was generally good. The goodness-of-fit indicators of the three constructs of talent ecosystem, collaborative innovation, and innovation performance all reach the standard values and have good structural validity, and the factor loadings of each latent variable question item exceed 0.5, and the model test results indicate that the explanatory relevance of the question items to the factors is significant. Combined with the above test results, the inherent quality of the pre-defined models for the three constructs of talent ecosystem, collaborative innovation, and innovation performance is ideal.

Instrument validation

According to the conceptual model, this paper uses AMOS24.0 to construct the initial structural equation model for calculation. Among them, three exogenous latent variables of talent competency, organizational environment and regional environment are subordinate dimensions of

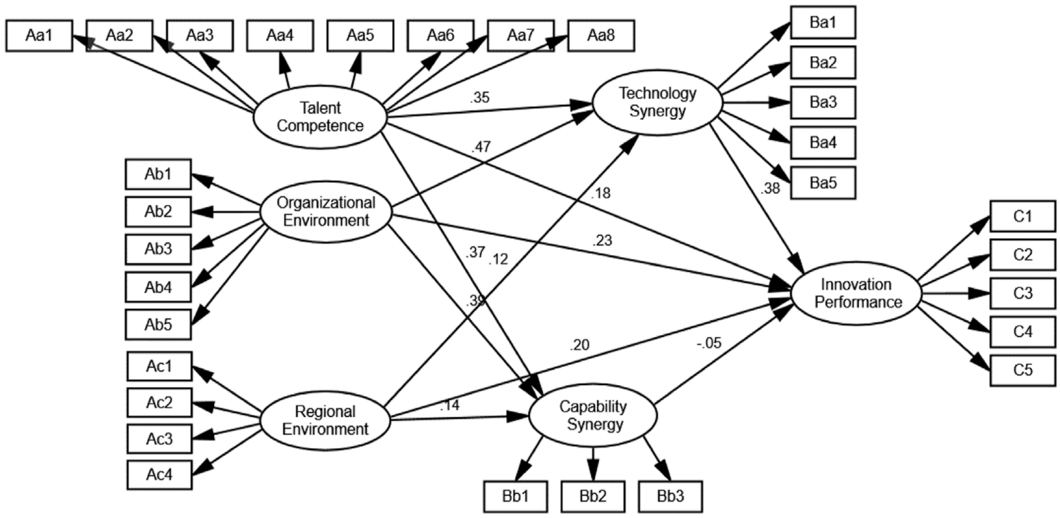

FIGURE 2
Final structural equation model.

TABLE 3 Comparison of simulation fitting results.

Indicator	χ^2/df	RMSEA	GFI	AGFI	NFI	CFI	RFI	TLI	PNFI	PCFI
Fitting criteria	<3且>1	<0.08	>0.8	>0.8	>0.9	>0.9	>0.9	>0.9	>0.5	>0.5
Before correction	2.506	0.065	0.852	0.824	0.877	0.922	0.863	0.913	0.788	0.828
After correction	1.798	0.048	0.886	0.862	0.913	0.959	0.902	0.954	0.808	0.849

(Source: own elaboration).

TABLE 4 Results of structural equation model path coefficients and hypothesis testing.

Hypothesis	Standardized path coefficients	C.R.	p	Result
Ha1Talent competency→Technology synergy	0.354	6.222	***	√
Ha2 Talent competency→Capability synergy	0.366	6.279	***	√
Ha3 Organizational environment→Technology synergy	0.465	7.344	***	√
Ha4 Organizational environment→Capability synergy	0.388	6.135	***	√
Ha5 Regional environment→Technology synergy	0.122	2.403	0.016	√
Ha6 Regional environment→Capability synergy	0.136	2.578	0.010	√
Hb1 Talent competency→Innovation performance	0.180	3.147	0.002	√
Hb2 Organizational environment→Innovation performance	0.231	3.500	***	√
Hb3 Regional environment→Innovation performance	0.196	4.078	***	√
Hc1 Technology synergy→Innovation performance	0.374	4.711	***	√
Hc2 Capability synergy→Innovation performance	−0.047	−0.881	0.378	×

Note: **indicates significance level p < 0.01 (Source: own elaboration).

talent ecosystem, characterizing the structural features of enterprise talent ecosystem. In addition, three endogenous latent variables of innovation performance, technology synergy and capability synergy are also set. The initial structural equation model was carried out 10 iterations using the great likelihood estimation, and finally converged

TABLE 5 Results of the test of the mediating effect of collaborative innovation.

	Estimate	S.E.	Bias-corrected bootstrap		Effect	Result
			Lower 95% CI	Upper 95% CI		
Talent competency→	0.123	0.039	0.056	0.214	Indirect effect	Partial mediation
Collaborative innovation→	0.191	0.063	0.065	0.307	Direct effect	
Innovation performance	0.314	0.057	0.204	0.431	Total effect	
Organizational environment→	0.240	0.062	0.134	0.385	Indirect effect	Partial mediation
Collaborative innovation→	0.355	0.124	0.138	0.625	Direct effect	
Innovation performance	0.595	0.106	0.419	0.838	Total effect	
Regional environment→	0.035	0.019	0.004	0.081	Indirect effect	Partial mediation
Collaborative innovation→	0.172	0.046	0.084	0.264	Direct effect	
Innovation performance	0.206	0.045	0.117	0.294	Total effect	

(Source: own elaboration).

to obtain the model fit index, followed by the correction of the initial model by increasing the correlation between error variables, and after the correction, the model fit indexes all reached the ideal values to obtain the final structural equation model (Figure 2).

After the model was revised, AMOS24.0 was run to analyze and calculate again, and the results are shown in Table 3. All the indicators are within the ideal range of the fitted indicators and are optimized compared with the initial model, and the overall fit is good. The hypothesis test results show (Table 4) that the path relationship of capability synergy on enterprise innovation performance is not significant, i.e., Hc2 does not pass the test ($p > 0.05$), and all other path hypotheses are supported, i.e., Ha1, Ha2, Ha3, Ha4, Ha5, Ha6, Hb1, Hb2, Hb3, and Hc1 pass the hypothesis test.

In this paper, we use the Bootstrap test in AMOS to reveal the mediating effect of collaborative innovation between talent ecosystem and innovation performance. We set the sampling number to 2000 and repeat sampling with put-back, and use Bias-corrected Bootstrap to estimate (95% confidence interval). The opposite is not significant. As shown in Table 5, the interval of indirect effect of collaborative innovation between talent ecosystem and innovation performance does not contain 0, thus the indirect effect is significant and the mediating effect exists. To determine whether the mediating effect of co-innovation is partially mediated or fully mediated, the direct and total effects should be further verified. The results of Bootstrap test in this study show that both the direct effect and the total effect interval do not contain 0 (95% confidence interval), so it is partial mediation, i.e., hypothesis Hd is supported. Collaborative innovation plays a partially mediating role in the effect of corporate talent ecosystem on corporate innovation performance.

Result

Based on the resource-based theory, this paper establishes the conceptual model of "talent ecosystem-collaborative innovation-firm innovation performance" and selects 352 samples for empirical testing.

(1) Talent competency, organizational environment and regional environment of talent ecosystem have positive effects on technological synergy and capability synergy in collaborative innovation, but the strength of the effects are not consistent. Specifically, organizational environment has a stronger effect on technology synergy and capability synergy, followed by talent competency. A good organizational innovation environment is very important for enterprises to implement collaborative innovation behaviors, and the benign operation of enterprise talent ecosystem largely benefits from a good internal environment of the organization. It can be seen that the creativity of enterprise talents is inseparable from their internal innovation environment. Enterprises should provide a good innovation atmosphere for talents in collaborative innovation, cultivate a corporate culture conducive to innovation, build a platform for communication, and strengthen individual cooperation; at the same time, they should respect the main role of talents in collaborative innovation behavior, continuously explore the value of talents from all aspects of their competency, adjust the structure of talents, and realize the great improvement of their competency and the effective guarantee of organizational environment, so as to promote the implementation of collaborative innovation behavior.
(2) Talent competency, organizational environment and regional environment indirectly contribute to the innovation performance of enterprises through collaborative innovation (both technology synergy and

capability synergy), collaborative innovation plays a part in mediating the relationship between talent ecosystem and innovation performance. In addition, among the three paths of talent ecosystem acting on innovation performance, organizational environment has the greatest influence on innovation performance through the intermediary of collaborative innovation. The empirical test results show that enterprises should focus on the improvement of organizational environment in the process of building and improving talent ecosystem. Enterprises should cultivate a good organizational environment with the spirit of innovation and continuously strengthen the supporting role of organizational environment in the process of implementing collaborative innovation strategy, and at the same time, they should make good use of the catalytic role of regional environment to realize the gathering and flow of talents, knowledge, information and other elements, interact more high-quality resources to realize collaborative innovation, and then provide support for the improvement of innovation performance.

(3) In the path relationship between collaborative innovation and innovation performance, technological synergy positively affects innovation performance, while capability synergy does not show a significant effect on enterprise innovation performance. The results of this hypothesis test indicate that technology synergy dominates in innovation performance improvement. Firms are able to use the exchange of energy in the talent ecosystem to acquire high-quality knowledge and resources, and then absorb and integrate them to achieve collaborative innovation at the technological level, and sustain their efforts in innovative products or services to create higher innovation performance. Hypothesis Hc2 does not pass the test, which means that capability synergy has no significant effect on the innovation performance. The capability synergy of collaborative innovation is a more complex synergistic activity, which is long-term and complex from the determination of synergistic goals to the deployment of resources, collaboration, benefit sharing, risk management, and the final achievement of innovation results, and the synergistic effect of $1 + 1 > 2$ can be achieved only after a certain period of collaboration between all elements and subjects in the enterprise talent ecosystem. This also indicates to a certain extent that capability synergy is a long-term process and there is a certain time lag in the improvement of innovation performance among the innovation subjects of talent ecosystem.

Conclusion

This paper develops an integrative research model which analyzes those relations using SEM on a dataset of innovative enterprises. Results suggest that talent competence, organizational environment and regional environment of talent ecosystem have a significant positive impact on collaborative innovation, and organizational environment has a stronger effect on collaborative innovation; talent ecosystem can influence innovation performance to different degrees through the mediating role of collaborative innovation (technology synergy and capability synergy); technology synergy in collaborative innovation positively affects innovation performance, while Technology synergy in collaborative innovation positively affects innovation performance, while capability synergy has no significant effect on innovation performance. The management enlightenment based on enterprise innovation are as follows: (1) Enterprises should improve the competence level of innovation talents, improve the knowledge structure, innovation ability and personal traits of innovation groups from the knowledge dimension, skill dimension and quality dimension of talents, seek to maximize the talent potential and talent value in the enterprise talent ecosystem, and continuously activate the source of value creation. (2) Enterprises should improve the organizational innovation environment, give full consideration to the long-term nature of collaborative innovation, focus innovation development on smooth communication channels while minimizing the state of conservative and stagnant behavior due to fear of criticism, and make continuous efforts in creating an innovation ecological atmosphere to promote the interaction of innovation elements; in addition, enterprises should establish a more flexible organizational structure to continuously break through the shackles that bind creativity. The shackles of creativity should be broken. (3) Enterprises should improve the level of adaptability of the external environment, continuously cultivate the sensitivity to seek innovation opportunities from the regional environment, and improve the ability to utilize and integrate regional innovation resources. At the same time, the government should constantly improve the regional innovation environment, provide systematic and effective policy support from the regional industrial development layout, financial support, cultural atmosphere, infrastructure and other aspects, promote the establishment of multi-party collaborative innovation mechanism, break the adverse situation of market segmentation and industrial monopoly, provide efficient support for the mutual penetration and integration of different regions and industries, and help the upgrading of enterprise innovation.

Based on the current research on the relationship between talent ecosystem, collaborative innovation and innovation performance and the shortcomings of this paper, the following perspectives are proposed for future research: First, due to various limitations, the sample representativeness of the questionnaire survey is limited, and subsequent research can try to extract objective data from the public information of some enterprises or local governments for empirical analysis. Secondly, the role of enterprise talent ecosystem and collaborative innovation in innovation performance is a long-term process, and the empirical value of the research findings may be further enhanced if the data are obtained by long-term tracking. Thirdly, this paper proposes the important mediating variable of collaborative innovation in the study of the relationship between talent ecosystem and innovation performance, but it is unknown whether there are other mediating or moderating variables that play a role in this process based on different research perspectives, and the related research boundary needs to be broadened.

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.

Ethics statement

Ethics review and approval/written informed consent was not required as per local legislation and institutional requirements.

Author contributions

WG, writing–original draft preparation, formal analysis; CL, writing–original draft preparation, methodology. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by Shaanxi Social Science Foundation Project (2019S031); Shaanxi Soft Science Program Research Project (2022KRM172); Shaanxi Education Department Key Base Project (18JZ027). Project of Scientific Research Program of Xi'an University of Finance and Economics (20FCJH004).

Conflict of interest

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abdollahbeigi, B., and Salehi, F. (2019). The effect of external environment characteristics on effective IT governance through organizational performance. *J. Technol. Manag. Technopreneursh. (JTMT)* 7 (1), 19–28.

Abhari, K., Davidson, E. J., and Xiao, B. (2017). Co-Innovation platform affordances: Developing a conceptual model and measurement instrument. *Ind. Management&Data Syst.* 117 (5), 873–895. doi:10.1108/imds-05-2016-0156

Aboelmaged, M. G. (2014). Predicting e-readiness at firm-level: An analysis of technological, organizational and environmental (TOE) effects on e-maintenance readiness in manufacturing firms. *Int. J. Inf. Manag.* 34 (5), 639–651. doi:10.1016/j.ijinfomgt.2014.05.002

Aenetz, B. B., Lucas, T., and Arnetz, J. E. (2011). Organizational climate, occupational stress, and employee mental health: Mediating effects of organizational efficiency. *J. Occup. Environ. Med.* 53 (1), 34–42. doi:10.1097/jom.0b013e3181ffo5b

Alford, P., and Duan, Y. (2018). Understanding collaborative innovation from a dynamic capabilities perspective. *Int. J. Contemp. Hosp. Manag.* 30 (06), 2396–2416. doi:10.1108/ijchm-08-2016-0426

Altınöz, M. (2018). Yetenek yönetiminin algılanması üzerine karşılaştırmalı bir araştırma. *Selçuk Üniversitesi Sos. Bilim. Enstitüsü Derg.* 39, 82–95.

Baležentis, T., Blancard, S., Shen, Z., and Štreimikienė, D. (2021). Analysis of environmental total factor productivity evolution in European agricultural sector. *Decis. Sci.* 52 (2), 483–511. doi:10.1111/deci.12421

Barney, J. B. (1991). Firm resources and sustained competitive advantage. *J. Manag.* 7, 99–120. doi:10.1177/014920639101700108

Benitez, G. B., Ayala, N. F., and Frank, A. G. (2020). Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation. *Int. J. Prod. Econ.* 228, 107735. doi:10.1016/j.ijpe.2020.107735

Brislin, R. W. (1980). "Translation and content analysis of oral and written material," in *Handbook of cross-cultural psychology*. Editors H. C. Triandis and J. W. Berry (Boston: Allyn & Bacon), 349–444.

Cadorin, E., Johansson, S. G., and Klofsten, M. (2017). Future developments for science parks: Attracting and developing talent. *Industry High. Educ.* 31, 156–167. doi:10.1177/0950422217700995

Capgemini Research Institute and LinkedIn (2017). The digital talent gap:are companies doing enough? Available at: https://www.capgemini.com/wp-content/uploads/2017/10/Digital-Talent-Gap-Report_Digital.pdf (accessed 08 28, 2019).

Carliss, B., Hippel, V., and Eric, A. (2011). Modeling a paradigm shift:from producer innovation to user and open collaborative innovation. *Organ. Sci.* 22 (6), 1399–1417. doi:10.1287/orsc.1100.0618

Carson, D., and Gilmore, A. (2000). SME marketing management competencies. *Int. Bus. Rev.* 9 (3), 363–382. doi:10.1016/s0969-5931(00)00006-8

Castro, M. D., Delgado-Verde, M., Navas-López, J. E., and Cruz-González, J. (2013). The moderating role of innovation culture in the relationship between knowledge assets and product innovation. *Technol. Forecast. Soc. Change* 80 (2), 351–363. doi:10.1016/j.techfore.2012.08.012

Clarysse, B., Wright, M., Bruneel, J., and Mahajan, A. (2014). Creating value in ecosystems: Crossing the chasm between knowledge and business ecosystems. *Res. Policy* 43 (7), 1164–1176. doi:10.1016/j.respol.2014.04.014

Deolalika, A., and Hasan, R. (1999). *Human resource development and the asian economic crisis facts,issues and policy*. Seattle, Washington: University of Washington, 44–50.

Desouza, C. K., and Awazu, Y. (2006). Knowledge management at SMEs: Five peculiarities. *J. Knowl. Manag.* 10 (1), 32–43. doi:10.1108/13673270610650085

Gallear, D., Ghobadian, A., and Chen, W. (2012). Corporate responsibility, supply chain partnership and performance: An empirical examination. *Int. J. Prod. Econ.* 140 (1), 83–91. doi:10.1016/j.ijpe.2012.01.016

Gloor, P. A. (2006). *Swarm creativity:competitive advantage through collaborative innovation networks*. New York: Oxford University Press, 407–408.

Goodale, J. C., Kuratko, D. F., Hornsby, J. S., and Covin, J. G. (2011). Operations management and corporate entrepreneurship: The moderating effect of operations control on the antecedents of corporate entrepreneurial activity in relation to innovation performance. *J. Operations Manag.* 29 (1-2), 116–127. doi:10.1016/j.jom.2010.07.005

Hearn, G., and Pace, C. (2006). Value-creating ecologies: Understanding next generation business systems. *Foresight* 8 (01), 55–65. doi:10.1108/14636680610647147

Hermann, H. (1977). *Synergetics*. Berlin: Self-Organizing Systems, 417–434.

Hoffman, R. C., and HegartyW, H. (1993). Top management influence on innovations: Effects of executive characteristics and social culture. *J. Manag.* 19 (3), 549–574. doi:10.1177/014920639301900303

Hoopes, D. G., Madsen, T. L., and Walker, G. (2003). Guest editors' introduction to the special issue: Why is there a resource-based view? Toward a theory of competitive heterogeneity. *Strateg. Manag. J.* 24 (10), 889–902. doi:10.1002/smj.356

Hueske, A.-K., Endrikat, J., and Guenther, E. (2015). External environment, the innovating organization, and its individuals: A multilevel model for identifying innovation barriers accounting for social uncertainties. *J. Eng. Technol. Manag.* 3 (5), 45–70. doi:10.1016/j.jengtecman.2014.10.001

Hurley, R., and Hult, G. (1998). Innovation, market orientation, and organizational learning: An integration and empirical examination. *J. Mark.* 62 (3), 42–54. doi:10.2307/1251742

Jesús Nieto, M., and Santamaría, L. (2007). The importance of diverse collaborative networks for the novelty of product innovation. *Technovation* 27 (6-7), 367–377. doi:10.1016/j.technovation.2006.10.001

Juana, C. S., Filippos, E., and Salvador, S. (2018). Beliefs about others' intentions determine whether cooperation is the faster choice. *Sci. Rep.* 8 (1), 1–10.

Karaboga, T., Gurol, Y. D., Binici, C. M., and Sarp, P. (2020). Sustainable digital talent ecosystem in the new era:impacts on businesses, governments and universities. *Istanbul Bus. Res.* 49 (2), 360–379.

Kayworth, T., and Leidner, D. (2004). Organizational culture as a knowledge resource. *Handb. Knowl. Manag.* 1, 235–252.

KetchenJR, D. J., Tomas, G., Hult, M., and Slater, S. F. (2007). Toward greater understanding of market orientation and the resource-based view. *Strateg. Manag. J.* 9 (28), 961–964. doi:10.1002/smj.620

Lam, L., Nguyen, P., Le, N., and Tran, K. (2021). The relation among organizational culture, knowledge management, and innovation capability: Its implication for open innovation. *JOItmC.* 7 (1), 66. doi:10.3390/joitmc7010066

Lee, H. L., and Schmidt, G. (2017). Using value chains to enhance innovation. *Prod. Oper. Manag.* 26 (4), 617–632. doi:10.1111/poms.12665

Mahoney, J. T., and Pandian, J. R. (1992). The resource-based view within the conversation of strategic management. *Strateg. Manag. J.* 13 (5), 363–380. doi:10.1002/smj.4250130505

Meroño-Cerdan, A., Soto-Acosta, P., and Lopez-Nicolas, C. (2008a). Analyzing collaborative technologies' effect on performance through intranet use orientations. *J. Ent. Info. Manag.* 21 (1), 39–51. doi:10.1108/17410390810842246

Meroño-Cerdan, A., Soto-Acosta, P., and Lopez-Nicolas, C. (2008b). How do collaborative technologies affect innovation in SMEs?[J]. *Int. J. e-Collaboration* 4 (4), 33–50. doi:10.4018/jec.2008100103

Michaelis, T. L., Aladin, R., and Pollack, J. M. (2018). Innovation culture and the performance of new product launches: A global study. *J. Bus. Ventur. Insights* 9 (12), 116–127. doi:10.1016/j.jbvi.2018.04.001

Nahapiet, J., and Ghoshal, S. (1998). Social capital, intellectual capital, and the organizational advantage. *Acad. Manage. Rev.* 23 (2), 242–266. doi:10.5465/amr.1998.533225

Nasiri, M., Saunila, M., Rantala, T., and Ukko, J. (2021). Sustainable innovation among small businesses:The role of digital orientation, the external environment, and company characteristics. *Sustain. Dev.* 30 (2), 1–11. doi:10.1002/sd.2267

Pan, X., and Li, S. (2016). Dynamic optimal control of process–product innovation with learning by doing. *Eur. J. Oper. Res.* 248 (1), 136–145. doi:10.1016/j.ejor.2015.07.007

Park, R. E., and Burgess, E. W. (1921). *Introduction to the science of sociology*. Chicago Illinois: The University of Chicago Press, 707–708.

Pasamar, S., Lopez-Cabrales, A., and Valle-Cabrera, R., (2015). Ambidexterity and intellectual capital architectures for developing dynamic capabilities: Towards a research agenda. *Eur. J. Int. Manag.* 9 (1), 74–87. doi:10.1504/ejim.2015.066672

Pulka, B. M., Ramli, A., and Mohamad, A. (2021). Entrepreneurial competencies, entrepreneurial orientation, entrepreneurial network, government business support and SMEs performance. The moderating role of the external environment. *J. Small Bus. Enterp. Dev.* 28 (4), 586–618. doi:10.1108/jsbed-12-2018-0390

Reddy, K., Chundakkadan, R., and Sasidharan, S. (2021). Firm innovation and global value chain participation. *Small Bus. Econ.* 57 (2), 1995–2015. doi:10.1007/s11187-020-00391-3

Ritter, T., and Gemünden, H. G. (2004). The impact of a company's business strategy on its technological competence, network competence and innovation success. *J. Bus. Res.* 57 (5), 548–556. doi:10.1016/s0148-2963(02)00320-x

Rondi, E., Überbacher, R., von Schlenk-Barnsdorf, L., De Massis, A., and Hülsbeck, M. (2022). One for all, all for one: A mutual gains perspective on HRM and innovation management practices in family firms. *J. Fam. Bus. Strategy* 13 (2), 100394–100451. doi:10.1016/j.jfbs.2020.100394

Serrano, V., and Fischer, T. (2007). Collaborative innovation in ubiquitous systems. *J. Intell. Manuf.* 18 (5), 599–615. doi:10.1007/s10845-007-0064-2

Shen, Z., Wang, S., Boussemart, J. P., and Hao, Y. (2022). Digital transition and green growth in Chinese agriculture. *Technol. Forecast. Soc. Change* 181, 121742. doi:10.1016/j.techfore.2022.121742

Soto-Acosta, P., and Meroño-Cerdan, A. (2008). Analyzing e-business value creation from a resource-based perspective. *Int. J. Inf. Manag.* 28 (1), 49–60. doi:10.1016/j.ijinfomgt.2007.05.001

Spencer, L. M., and Spencer, S. M. (1993). *Competenceat work: Models for superior performance*. New York: John Wiley&Sons,Inc press.

Stoji, N. (2021). Collaborative innovation in emerging innovation systems: evidence from central and eastern europe. *J. Technol. Transf.* 46 (6), 531–562. doi:10.1007/s10961-020-09792-8

Sun, Y., and Cao, C. (2018). The evolving relations between government agencies of innovation policymaking in emerging economies: A policy network approach and its application to the Chinese case. *Res. Policy* 47, 592–605. doi:10.1016/j.respol.2018.01.003

Thorgren, S., Wincent, J., and Örtqvist, D. (2009). Designing interorganizational networks for innovation: An empirical examination of network configuration, formation and governance. *J. Eng. Technol. Manag.* 26 (3), 148–166. doi:10.1016/j.jengtecman.2009.06.006

Tödtling, F. (1992). Technological change at the regional level: The role of location, firm structure, and strategy. *Environ. Plan. A* 24 (11), 1565–1584. doi:10.1068/a241565

Valkokari, K., Paasi, J., and Rantala, T. (2012). Managing knowledge within networked innovation. *Knowl. Manag. Res. Pract.* 10 (1), 27–40. doi:10.1057/kmrp.2011.39

Vyakarnam, S., and Handelberg, J. (2005). Four themes of the impact of management teams on organizational performance: Implications for future research of entrepreneurial teams. *Int. Small Bus. J.* 23 (2), 236–256. doi:10.1177/0266242605052072

Wang, C., Rodan, S., Fruin, M., and Xu, X. (2014). Knowledge networks, collaboration networks, and exploratory innovation. *Acad. Manage. J.* 57 (2), 484–514. doi:10.5465/amj.2011.0917

Wang, C., and Hu, Q. (2020). Knowledge sharing in supply chain networks: effects of collaborative innovation activities and capability on innovation performance. *Technovation* 7 (06), 102010–102095. doi:10.1016/j.technovation.2017.12.002

Wright, K. Personal knowledge management: Supporting individual knowledge worker performance. *Knowl. Manag. Res. Pract.* 3, 156–165. doi:10.1057/palgrave.kmrp.8500061

Xu, J., Hou, Q., Niu, C., Wang, Y., and Xie, Y. (2018). Process optimization of the University-Industry-Research collaborative innovation from the perspective of knowledge management. *Cognitive Syst. Res.* 52, 995–1003. doi:10.1016/j.cogsys.2018.09.020

Yang, J. (2018). Research on the innovation method of continuing education model for professional technical personnel in manufacturing industry. *Educ. Sciences-Theory&Practice* 18 (5), 2325–2331.

Zahra, S. A. (1993). Environment, corporate entrepreneurship, and financial performance: A taxonomic approach. *J. Bus. Ventur.* 8 (4), 319–340. doi:10.1016/0883-9026(93)90003-n

Zhang, Y., and Li, H. (2010). Innovation search of new ventures in a technology cluster: The role of ties with service intermediaries. *Strateg. Manag. J.* 31 (1), 88–109. doi:10.1002/smj.806

Zhu, X., Xiao, Z., Dong, M. C., and Gu, J. (2019). The fit between firms' open innovation and business model for new product development speed: A contingent perspective. *Technovation* 86–87, 75–85. doi:10.1016/j.technovation.2019.05.005

frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 12 September 2022
DOI 10.3389/fenvs.2022.986429

Check for updates

OPEN ACCESS

EDITED BY
Jose Balsa-Barreiro,
Massachusetts Institute of Technology,
United States

REVIEWED BY
Mucahit Aydin,
Sakarya University, Turkey
Md Shabbir Alam,
University of Bahrain, Bahrain

*CORRESPONDENCE
Anselme Andriamahery,
tzedekandriamahery@hbpu.edu.cn
Md Qamruzzaman,
qamruzzaman@bus.uiu.ac.bd

SPECIALTY SECTION
This article was submitted to
Environmental Economics and
Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 05 July 2022
ACCEPTED 11 August 2022
PUBLISHED 12 September 2022

CITATION
Andriamahery A, Danarson JH and Qamruzzaman M (2022), Nexus between trade and environmental quality in sub-saharan Africa: Evidence from panel GMM.
Front. Environ. Sci. 10:986429.
doi: 10.3389/fenvs.2022.986429

Nexus between trade and environmental quality in sub-saharan Africa: Evidence from panel GMM

Anselme Andriamahery[1]*, Jules Harris Danarson[2] and Md Qamruzzaman[3]*

[1]School of Economics and Management, Hubei Polytechnic University, Huangshi, Hubei, China, [2]School of International Education, Guangxi University of Finance and Economics, Nanning, Guangxi, China, [3]School of Business and Economics, United International University, Dhaka, Bangladesh

Environmental sustainability is a burning fact worldwide, especially in developing nations. Equitable economic development, environmental protection, energy efficiency and security have been placed at the apex of economic discussant and policy formulation. This paper establishes the relationship between trade and environmental quality in Sub-Saharan Africa (SSA). Following the Environmental Kuznets Curve (EKC) theory, we investigate the existence of an inverted U-shape correlation between income per capita growth and nitrous oxide (N_2O), agricultural methane (ACH_4), and carbon dioxide (CO_2) emissions to ascertain the presence of EKC. We also analyze how trade variables, income per capita growth, energy intensity, foreign direct investment, human capital, and CO_2 emissions are related. The results show that trade significantly increases N_2O, ACH_4, and CO_2 emissions for the overall sample of SSA and its income groups [Upper-Middle-Income Countries (UMIC), Lower-Middle-Income Countries (LMIC), and Low-Income Countries (LIC)] using a panel GMM. This paper concludes that reducing emissions is feasible in the future as shown by the existence of the EKC, and trade has a consistently negative impact on the environment in SSA countries, regardless of wealth level. On the policy note, the study suggested that domestic trade liberalization and foreign ownership in the economy play a detrimental role, and thus industrialization has to ensure energy efficiency and energy security.

KEYWORDS
environmental quality, trade, energy intensity, foreign direct investment, environmental kuznets curve

1 Introduction

Sub-Saharan Africa's economic and social status is still precarious and open to internal and foreign shocks. Economic diversification and development are hampered because of the low level of investment (Bangwayo-Skeete, 2012). Many nations have just recently emerged from civil wars that severely hampered their development efforts, while new armed conflicts have started elsewhere in the continent (Chakraborty and Basu, 2002). Economic growth has slowed in the area during the last two decades because of these wars and other reasons, such as bad weather and a decline in terms of trade (Syed et al., 2022). Despite recent economic growth improvements, the subcontinent continues to struggle to reduce poverty, with little or no better housing amenities, insufficient formal education and/or low quality of education, poor health leading to short life expectancies, and so on. Trade is one of the methods or strategies that can be used to achieve growth. On the other hand, some scholars believe that trade aids economic growth (Dollar and Kraay, 2003; Ferdaous and Qamruzzaman, 2014; Mia et al., 2014; Qamruzzaman and Ferdaous, 2014; Hye and Lau, 2015; Musila and Yiheyis, 2015; Gnangnon, 2020). But the real question is how much will it cost? Even though SSA needs economic growth, we must not lose sight of the need for long-term growth. Accordingly, growth that considers environmental quality must be a top priority. This highlights the link between trade and the environment in Sub-Saharan Africa.

Researchers are primarily interested in investigating the environmental Kuznets curve (EKC) because they want to learn more about the relationship between income and pollution (see (Stern, 2004; Qamruzzaman, 2022a; Zhao and Qamruzzaman, 2022)). The EKC hypothesis can be traced back to Kuznets (Kuznets, 1955), who proposed that income disparity rises in the early years of economic expansion and falls as the economy grows. Grossman and Krueger (Grossman and Krueger, 1991) were the first to use the EKC hypothesis. They discovered a similar inverse U-shaped relationship between environmental deterioration and GDP per capita. The current research validates the existence of the EKC SSA region, but at various moments in time (in percentages). Because of the economic research on the relationship between CO_2 emissions and trade openness, there are major concerns among policymakers, economists, and the general public. Trade between countries has increased significantly since establishing the "General Agreement on Tariffs and Trade" (GATT), eliminating trade barriers and boosting trade liberalization. Similarly, the creation of the World Trade Organization (WTO) as a replacement for GATT has boosted global trade tremendously. The establishment of the "Commerce Facilitation Agreement" (TFA) (WTO, 2017) is the most recent approach to promoting global trade. It is expected to enhance global trade by one trillion dollars annually, with developing nations reaping the greatest benefits. However, the TFA's main concern is the long-term effects of negative externalities. Carbon emissions in global supply value chains are increasing quicker than some economic measures, such as real income or population growth (Peters et al., 2011). We know from economic theory that increased commerce leads to increased economic growth. Furthermore, increased economic expansion could harm the environment due to emissions into the atmosphere. As a result, affected countries will be expected to use environmentally friendly production processes to improve environmental quality.

Countries benefit economically from trade, using their comparative advantage to create and trade goods and services. The value of global merchandise exports surged more than 260 times from $59 billion in 1948 to $15.5 trillion in 2016, and a country's exports now account for 29 percent of its GDP (WTO, 2017). While globalization has advantages in terms of trade, it also has unintended effects on economies and the environment. Sub-Saharan African countries are vulnerable to climate change's effects, with substantial risks of weather-related natural disasters such as storms, flooding, and droughts. These African countries have inadequate capacity to regulate, mitigate and adapt to these negative impacts. The wide-ranging effects of such incapacity impact trade and economic growth. The dispute over whether the trade is good or detrimental to the environment has sparked a discussion among academics. Environmental and trade economists have yet to agree on whether the trade is beneficial or harmful to the environment. The relationship between the environment and international trade is extremely complicated, with numerous variables that can lead to a favorable or bad outcome. The theoretical literature on the impact of commerce on pollution levels yields conflicting results. When disparities in environmental policy models are used to cause commerce between countries, according to Helbling, Batini (Helbling et al., 2005), there could be an increase in emissions after liberalization. On the other hand, when Models that leverage differences in endowments to promote trade between countries are used, they imply that emissions drop after liberalization (Hamid et al., 2022a).

According to the findings of several academics, trade openness is linked to lower pollution levels Antweiler, Copeland (Antweiler et al., 2001), (Cole and Elliott, 2003; Frankel and Rose, 2005; Sun et al., 2021) used panel cointegration methods to investigate the relationship between trade openness and carbon dioxide emissions (CO_2). Their research revealed that trade openness could have both detrimental and good effects on environmental pollution emissions, but the consequences varied depending on the type of country. Boleti, Garas (Boleti et al., 2021) used annual data from 88 industrialized and developing nations from 2002 to 2012 to investigate the link between economic complexity and environmental performance. Their findings suggested that increasing economic complexity could lead to improved environmental performance and, as a result, that product sophistication did not increase environmental degradation. However, they discovered a positive association between economic complexity and air quality, which means increased exposure to PM2.5 and CO_2 emissions. Pei, Sturm (Pei et al., 2021) built a unique micro dataset for China for 2007, combining two rich firm-level datasets, and discovered that export status and export intensity were associated with decreased sulfur dioxide (SO_2) emissions. In both the total sample of Sub-Saharan Africa and its subgroups, trade considerably increases nitrous oxide (N_20), agricultural methane (ACH_4), and carbon dioxide (CO_2) emissions, according to the current study (UMIC, LMIC, and LIC). Even though trade degrades the environment in the total sample of Sub-Saharan Africa, the impact on the environment, in the long run, is relatively stronger in the LMIC than in the UMIC and LIC for all environmental variables, according to the current study (N_2O, ACH_4, and CO_2). In the short term, the estimates show that trade increases all emissions (N_2O, ACH_4, and CO_2) in the general sample of SSA, UMIC, and LMIC; however, trade increases CO_2 emissions while decreasing N_2O and ACH in the LIC. This may give policymakers sufficient knowledge of the types of trade and environmental rules that should be enacted in various countries. However, as evidenced by the presence of the EKC, this study implies that future reductions of such emissions are possible.

When it comes to studies on trade and environmental quality, there is no one-size-fits-all approach. To assess these correlations, researchers employed a variety of contaminants and methodologies. However, it is important to know that regional variables must be considered regarding global pollutants like CO_2, Nitrous Oxide (N_2O), and Agricultural Methane (Agricultural CH4). To uncover the empirical data on the impact of trade on environmental quality in SSA, it is critical to pose the following questions: (i) Has trade had a bad or good influence on the environment in Sub-Saharan Africa? (ii) Is commerce the primary source of GHG emissions in Sub-Saharan Africa? (iii) How does energy intensity affect emissions in Sub-Saharan Africa? (iv) Are we pursuing the correct type of trade that will result in long-term economic growth? Accordingly, the purpose of this study is to answer these crucial questions.

The current study uses the traditional KAYA identity to examine the impact of trade and energy consumption on CO_2, N_2O, and ACH_4 emissions as proxies for greenhouse gas emissions. The KAYA identity states that a total CO_2 emission can be expressed as the product of four factors: human population, per capita GDP, energy intensity (per unit of GDP), and carbon intensity measured as emissions per unit of energy consumed (Yamaji et al., 1993; Kaya and Yokobori, 1997). It is a more concrete version of the more general I=PAT Equation, which connects variables that affect the degree of human effect on climate change. In this case, the base KAYA or I=PAT model regresses CO_2 emissions on population, energy intensity, and per capita GDP (Apergis and Payne, 2010; Sharif Hossain, 2011; Arouri et al., 2012; Bölük and Mert, 2014; Farhani et al., 2014). Some researchers have recently proposed changing the KAYA or I=PAT paradigm (Iwata et al., 2010; Jayanthakumaran et al., 2012; López-Menéndez et al., 2014; Dogan and Deger, 2016). This study regresses GHG emissions (CO_2, N_2O, and ACH4) on trade, income per capita growth, energy intensity, foreign direct investment, and human capital, which modifies the KAYA model. The inclusion of trade (natural resource earnings) demonstrates that trade can explain some fluctuations in emissions (CO_2, N_2O, and ACH_4) while avoiding the problem of variable omission bias as well. An increase in commerce (as a proxy for natural resource earnings) may increase natural resource exports which may, in turn, enhance economic activity and necessitate additional energy supply. The inclusion of trade to explain the variations in GHG emissions is significant because global trade rises while GHG emissions fall, especially in advanced countries (Managi et al., 2009).

The current focus in the environment-resource-growth literature is on resource dependency or abundance, not only in economic growth but also in terms of greenhouse gas emissions and climate change. In brief, the current study adds to the existing body of knowledge in the environment-resource-growth literature in the following ways:

First, most recent studies have analyzed the effects of trade (natural resources) on greenhouse gas emissions using resource dependence or abundance (GHGs). Brunnschweiler (Brunnschweiler, 2010) questioned Sachs and Warner's 1995) findings by claiming that a commonly used measure of resources, the ratio of resource exports to GDP, is endogenous. As a result, dividing exports by the size of the economy implies that the ratio is not independent of a country's economic policies and institutions, which affect both GDP level and growth. In light of the preceding evidence, we chose the "Natural Resources Revenues" proxy to avoid issues with measuring trade openness, particularly in the SSA region, where exchange rates are frequently volatile and can alter the assessment of imports and exports GDP.

Second, previous empirical research on the consequences of commerce on the environment has been conducted. However, to our knowledge, the present literature solely focuses on the panel studies conducted at the regional level of Sub-Saharan Africa. Because these pollutants are global, our research looked at the effects of trade (using a proxy of natural resource revenues) on CO_2, Nitrous Oxide (N_2O), and Agricultural methane (agricultural CH_4) emissions for both Sub-Saharan Africa and its subgroups based on their income levels to examine both the short-term and long-run relationships, using the dynamic panel and vector error correction models. To the best of our knowledge, no study has looked into the relationship between trade and N_2O and agricultural CH_4 using a panel of Sub-Saharan African countries with different economic levels. Although a few country-specific studies have attempted to investigate the relationship between trade and emissions in general, none of these studies has looked at the impact of trade on specific emissions like N_2O and agricultural CH_4 using data from a panel of Sub-Saharan African countries. This analysis is more fascinating by including Sub-Saharan Africa and categorizing countries based on income levels. The division of SSA into income groups also reveals which countries pollute the most; it also reveals that each group of countries requires different policies and a variety of policy techniques to improve the environmental quality while clarifying which group of countries should prioritize mitigation policies and which group requires more support in terms of mitigation and adaptation policies (Hamid et al., 2022b).

Third, as other scholars have done, the Environmental Kuznets Curve's turning points are measured in percentages rather than dollars. This is made possible by including an income per capita growth variable in our model, measured in percentages rather than the traditional income per capita. As a result of this strategy, this study determines the various percentage threshold levels of EKC turning points at which the countries' economic growth should begin to reduce, resulting in improved environmental quality. As a result, this study adds to the body of knowledge in the areas of commerce (natural resource earnings) and greenhouse gas emissions in sub-Saharan African countries. To our knowledge, the previous research on this topic focused on monetary turning points rather than percentage turning points. Therefore, the current study brings a unique contribution to the literature in existence by identifying this percentage turning point, at which countries' growth should be focused on the improvement of the air quality. This study validates the occurrence of EKC in SSA and its subgroups band. Thus, the current study adds to the previous literature by demonstrating the presence of multiple EKC percentage turning points for a reduction in greenhouse gas emissions.

Furthermore, the present paper is a comprehensive study of the short-term and long-run effects of trade on CO_2, N_2O, and ACH_4 emissions, as well as the use of natural resource revenues as a proxy for trade rather than the traditional resource abundance/dependence variable, establishing the EKC turning points in percentages rather than the traditional monetary terms and covering the entire SSA and grouping countries into income levels.

The remainder of the paper is laid out as follows: the second section provides an overview of trade and the environment in Sub-Saharan Africa. The Literature Review is included in Section 3. The Methodology is covered in Section 4. Section 5 discusses the presentation and interpretation of the results, while Section 6 gives policy recommendations and conclusions.

1.1 Overview of trade and the environment in sub-saharan Africa

The recent economic expansion in Sub-Saharan Africa is thought to have resulted in "greater exploitation of renewable natural resources beyond their regenerative potential and by increasing GHG emissions." Natural resource-based industries, such as mining, agriculture, forestry, and fisheries, employ 80 percent of the workforce. Similarly, agriculture accounts for over 33% of Africa's GDP. The export and/or use of natural resources such as forestry products, topsoil, and fish stocks have been linked to the African region's recent growth, sometimes at alarming rates.

In SSA, population growth has been tremendous, posing severe environmental and socio-economic issues. This places a lot of pressure on governments to provide services like health and education and citizens' jobs. It will be difficult for governments to raise living standards and reduce unemployment without high economic growth rates. As a result of the rapid population expansion, local natural resources such as water, fuel, and food are under stress. Though demographic development provides an opportunity, it also poses severe obstacles for governments in SSA to provide for their citizens, particularly regarding the environment. In several SSA nations, the negative implications of the recent economic progress outstrip the local government's capacity to deal with such consequences. Waste collection and sanitation systems cannot handle the volumes of waste generated by such economic activities, resulting in significant degradation of the urban and aquatic environments. According to Skellern, Markey (Skellern et al., 2017), though the manufacturing industry boosts economic growth, some countries overlook its development's environmental implications or challenges. There are, for example, insufficient environmental restrictions, and/or they are frequently not applied to the expansion of the manufacturing and extractive industries in SSA, resulting in water, air, and land pollution as well as ecosystem damage. These are the negative effects of globalization, which are hard to deal with, hence the urgency of the present research (Murshed et al., 2022).

Globalization has increased international trade's scale and complexity to unprecedented levels. There has been a movement in the production of goods and services in recent years, first to China, then to other developing countries in the global south (Jiang (Jiang and Green, 2017; Jianguo and Qamruzzaman, 2017; Qamruzzaman, 2022b). Chinese industrial businesses have recently begun to move their operations to SSA countries. However, consequences such as greenhouse gas (GHG) emissions and water use have shifted to less developed countries, particularly SSA (Liu et al., 2017). From 1.26 in 1995 to 1.43 in 2008, the average frequency of carbon embodied in traded items crossing borders rose (Zhang and Cheng, 2009).

Pollution or degradation of the environment is one of the most important concerns that developing countries, particularly in SSA, must address. The majority of SSA countries' economies are growing at a cost. In Nigeria, for example, crude oil is the primary source of foreign cash as national revenue. The erosion and pollution of the environment have become the people's sorrow due to the ongoing drilling in oil-rich areas of the Niger Delta. Gas is continuously burned, degrading the quality of the atmosphere. Oil leaks have made it difficult for inhabitants in these locations to carry out their farming activities; also, the water in the streams is no longer fit for human use.

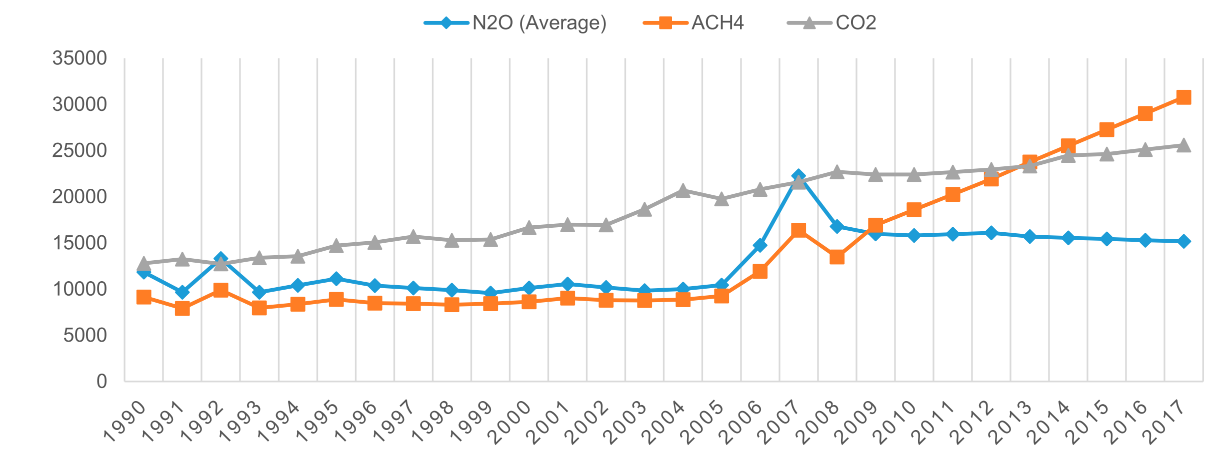

FIGURE 1
Nitrous Oxide (N_2O), Agricultural Methane (ACH_4) and Carbon Dioxide (CO_2) emissions in Sub-Saharan Africa (on average). Source. World Bank data and author calculations.

According to statistics provided between 1973 and 2008, Nigerian gas and crude oil output as a percentage of GDP fluctuated between 21.1 and 37.5 percent (Otekunrin et al., 2021).

According to Yingjun et al. (2021), as a civilization's population grows, people of that society place great demands on finite resources such as land and other natural resources to survive. Most SSA countries began as agricultural economies, but as their economies evolved, they transitioned from rural to industrialized status. These developed societies consume more resources, putting a greater strain on the environment. Economic growth is achieved but at the cost of the environment. Air pollution, natural resource depletion, climate change, noise pollution, deforestation, and other environment-related issues accompany economic progress in many of these SSA countries. The two major issues the African continent faces are the failure to provide safe drinking water to an ever-increasing population and a lack of sanitation.

Figure 1 shows pollution as nitrogen oxide emissions (thousand metric tons of CO_2 equivalent), agricultural methane emissions (thousand metric tons of CO_2 equivalent), and CO_2 emissions (kt). However, in Figure 2, the variable used as a proxy for trade is NRR (measured in billions of dollars). Figure 1 shows that, on average, nitrogen oxide and agricultural methane emissions remained stable until 2005. Between 2005 and 2007, both emissions considerably increased before declining in 2008. After 2008, nitrous oxide emissions continued to reduce but at a slower rate, while the agricultural methane emissions quickly grew until 2017. CO_2 emissions, on the other hand, continued to rise. Figure 2 shows that the earnings obtained by Sub-Saharan African countries followed a similar pattern of nitrogen oxide and agricultural methane emissions on average. Despite some fluctuation, natural resource revenues generally climbed from 1990 to 2008 before declining in 2009. After 2009, the NRR increased until 2011, then declined. The link between trade and pollution could explain the same pattern in the two graphs. It can be seen from the graphs that nitrous oxide and agricultural methane emissions decreased between 2007 and 2009. This could be linked to a drop in commerce around the same period due to a financial crisis when the natural resource exports were severely impacted, and so were the entire economies of Sub-Saharan African countries.

2 Literature review

As more people use more fossil fuels, greater quantities of carbon dioxide (CO_2) are emitted into the atmosphere. These releases have started to alter the composition of the atmosphere significantly. 280 parts per million were the concentration of carbon dioxide in the atmosphere during the start of the industrial revolution. Today, concentrations have reached 360 parts per million (Tucker, 1995). Understanding the link between emissions and economics is a critical part of putting up worldwide restrictions since growing CO_2 concentrations have been identified as a significant contributor to probable global warming. Recently, climate change and global warming have become more detrimental to human well-being. There is speculation that increased economic activity and environmental deterioration are major contributors to environmental degradation (Alvarado and Toledo, 2017). The industrial structure of emerging nations links economic activity and environmental deterioration more damaging in these regions. Environmental degradation is the accumulated effects of economic expansion with the application of conventional energy consumption (Banday and Aneja, 2020), trade expansion (Alola, 2019), financial development (Acheampong

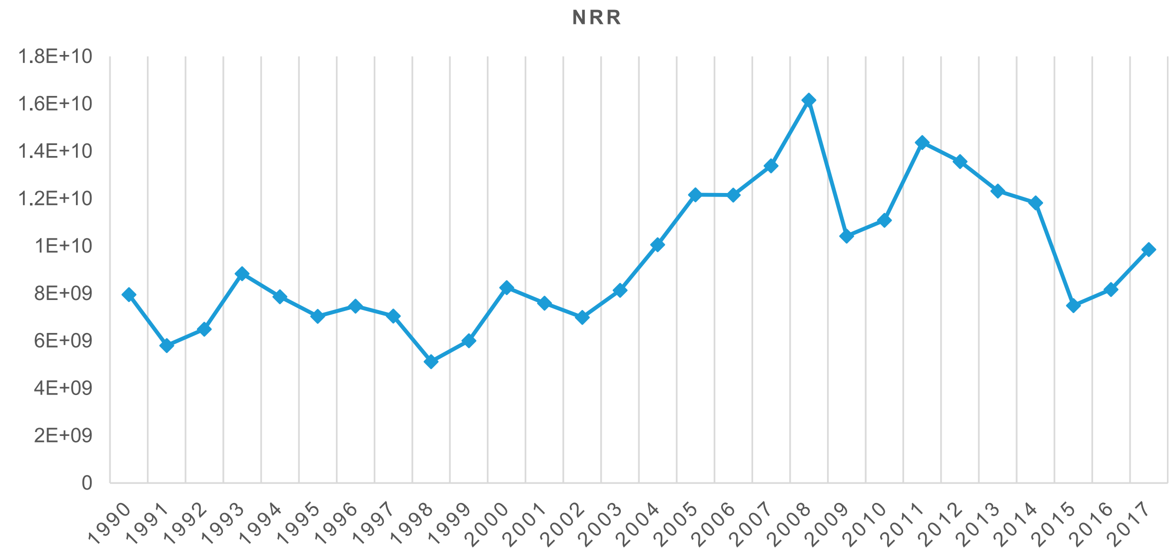

FIGURE 2
Natural Resources Revenues (NRR) in Sub-Saharan Africa (on average). Source. World Bank data and author calculations.

et al., 2020) and global economic and financial integration (Shahbaz et al., 2019). The elimination of national territory is a consequence of the current era of economic globalization, which must first be comprehended from an economic standpoint to be comprehended in its most comprehensive sense. The global economy is governed by unregulated market forces, most of which are multinational corporations located wherever the global market's greatest advantages. In contrast, the globalization process is not limited to the economic component; it also encompasses political, cultural, and environmental components (Eriksen et al., 2014).

Economic globalization not only realigns the global economy but also causes a worldwide redistribution of energy needs, population, and notably, the urban population, which is related to globalization's environmental and social components. The effects of globalization on human dynamics has investigated and established (Balsa-Barreiro et al., 2019). The environmental impact and economic development are both significantly altered by globalization. It has been prominently highlighted, which has prompted nations to cooperate more closely by eliminating cross-border obstacles and connecting global economies through FDI and trade openness (Vongpraseuth and Choi, 2015). Even if globalization benefits economies by fostering expansion, it negatively affects ecosystems (Khan and Ullah, 2019).

The causes of pollution are commonly thought to be the result of economic activity and growth, implying that a rise in output can lead to increased pollution levels in the atmosphere. However, the relationship between environmental deterioration and economic growth is a complex system that may react differently at different times and places. Some believe that economic expansion would eventually harm the environment, while others believe that after a certain point, economic progress can contribute to a cleaner environment (Dinda, 2004). The Environmental Kuznets Curve (EKC) arose from Simon Kuznets' research into the relationship between economic growth and income inequality. It was used to investigate the relationship between per capita income (PCI) and sulfur dioxide (SO_2) concentrations in the atmosphere in 47 cities across 31 countries (Elbadawi and Rocha, 1992). The relationship between PCI and sulfur dioxide content is positive up to a point, after which the trend reverses, forming an inverted U-shape curve.

The EKC's theoretical foundation is based on the repercussions of industrialization; it means a shift from agricultural commodity production in rural areas to industrial output in urban areas. Due to the intensification of industrial production activities, there will be an increase in pollution due to increased industrialization. However, when income levels rise, innovative technology to reduce emissions may become available. It is also thought that once economies develop to a certain point, these countries' economic activities will shift to the creation of services, slowing emissions and eventually reducing them. Furthermore, citizens will begin to campaign for a cleaner environment, which the political elite will take into account; this perhaps is leading to environmentally friendly policies and investments (Bashir et al., 2021). This scenario has been explained by three effects, scale, composition, and technology.

Copeland and Taylor (Copeland and Taylor, 2004) proposed the pollution haven hypothesis (PHH) to explain the impact of trade on the environment. According to the idea, if a country has strong environmental rules, companies in that country may be forced to migrate to a country with lenient environmental regulations and legislation. As a result, we can classify the PHH as a situation in which lax environmental rules provide a comparative advantage to countries and alter international trade patterns. Because of trade liberalization, and because many developed countries have a comparative advantage in producing pollution-intensive commodities, production of these goods could be shifted to developing countries, where environmental laws and regulations are believed to be less strict or poorly implemented. However, this could result in a reduction in one country's emissions while a rise in another, masking the impact of international commerce on emissions. The magnitude, composition, and technology effects completely explain the environmental implications of trade liberalization (Antweiler et al., 2001; Farhani et al., 2014). Because of worldwide trade, global production has been separated into "clean" or "green" and "dirty" productions (Jänicke et al., 1997). This phenomenon only causes local pollution to varying, whereas global pollution levels remain the same or even rise. The displacement hypothesis explains this. The "pollution haven theory" has various production regulations and costs, which can support the displacement hypothesis.

Several studies have developed models based on empirical and theoretical literature to investigate the environmental impact of trade liberalization. The impact of global trade on environmental sustainability plays a significant role in developing trade policies. Shahbaz, Nasreen (Shahbaz et al., 2017a), Shahzadi, Javed (Shahzadi et al., 2014) used the fully modified ordinary least squares (FMOLS) approach to evaluate 105 countries from 1980 to 2014, dividing them into high-(developed), middle-(developing), low-(underdeveloped) income, and global panels. The study's findings for all panels demonstrate an inverted U-shaped relationship between environmental quality and trade. Similarly, Shahbaz, Hye (Shahbaz et al., 2013) find a negative association between pollution and trade openness because free trade generates a lot of research and development (R&D) schemes through foreign direct investment (FDI), resulting in an improvement in environmental quality. Sohag, Begum (Sohag et al., 2015) used mean group (MG) approaches, such as cross-correlated and augmented methods, to investigate the impact of trade, population growth, real GDP growth, and energy consumption on CO_2 emissions in 82 developing countries from 1980 to 2012. The findings suggest that a 1% increase in trade (while keeping the control variables constant) reduces CO_2 emissions by 0.3 percent. Meanwhile, the findings for middle-income, low-income, and the panel for all nations were not definitive. To approximate the entire impact of trade on environmental quality, Managi, Hibiki (Managi et al., 2009) used the instrumental variables modus operandi. The estimates suggest that international trade increases emissions in developing economies while decreasing emissions in developed economies: this increase in emissions was attributed to the scale and some aspects of trade composition effects.

It is also reported that trade openness was investigated and shown to have a detrimental impact on emissions in South Africa. Because their integration into world trade is insufficient, South Africa, Kenya, and Togo have not gained benefits/profits from global trade. Their primary exports are natural resources, whereas their primary imports are manufactured items. Given the continuous swings in commodity prices, they could not purchase new efficient technologies because their priorities were centered on fundamental needs, which would favor the usage of polluting enterprises (Eléazar, 2015).

Because real income, energy consumption, and carbon dioxide (CO_2) emissions are all linked, one school of thought suggests that they should all be considered together (Arouri et al., 2012). For example, according to an EKC study, growing income does not always result in lower CO_2 emissions, and rising wages result in increased pollution of the environment (Salahuddin et al., 2020); Balsalobre-Lorente, Shahbaz (Balsalobre-Lorente et al., 2018). Furthermore, because energy consumption impacts environmental quality, it is prudent to analyze these two variables using a unified procedure to decrease errors. Similarly, because these factors are interconnected, their relationships should be investigated concurrently using a combined procedure, as suggested by Pao and Tsai (Pao and Tsai, 2010) in BRICS nations, Keppler and Mansanet-Bataller (Keppler and Mansanet-Bataller, 2010) in the UK, Ghosh (2010) in India, and Zhang et al. (2009) in China. Despite this, their conclusions differed due to the diverse techniques, data, and countries participating in the study. A large body of past research on the relationship between income and pollution has backed up the reversed U-shaped relationship, often known as the EKC theory. In their papers, Saboori and Sulaiman (Saboori and Sulaiman, 2013),Chien, Hsu (Chien et al., 2022) investigated the EKC hypothesis, yet their findings were mixed. For example, an N-shaped association, a linear relationship, and a U-shaped correlation were discovered. The detection of omitted-variable bias is a major flaw in these earlier investigations. As a result, some recent studies have incorporated numerous elements that have influenced environmental pollution, such as openness to trade, urbanization, energy consumption, and financial development, into the varied research conducted. However, as a result of this multivariate study, different results concerning EKC theory have been developed (Ozturk and Acaravci, 2010; Omri, 2013; Acheampong, 2018; Qamruzzaman, 2022c), employing panel vector Autoregression (PVAR) in conjunction with a system known as the generalized method of moment (GMM) for 116 nations from 1990 to 2014 to investigate the changing relationship between economic growth, energy consumption, and carbon dioxide emissions. The outcomes of their study reveal that real GDP does not affect the territorial and global use of energy. Finally, except for the MENA nations, contamination of the environment had little effect on energy use in the global panel, with some evidence of the EKC theory in SSA countries. Gorus and Aydin (Gorus and Aydin, 2019) implements multiple Granger causality models to analyze the causality between energy use, real GDP, and pollution in eight MENA oil-rich nations from 1975 to 2014. In comparison to the causal relationships of the time domain, the analysis of the panel frequency domain reveals a cause-and-effect relationship among the fundamental variables in various occurrences. Previous studies did not categorize countries by area or income level, making it difficult to determine how real income and energy use influence environmental degradation in this cluster of countries.

In Sub-Saharan Africa, Congo, for example, has negative values for both the short and long term, indicating that economic expansion leads to reduced emissions (Narayan and Narayan, 2010). From 1975 to 2008, income elasticity in Mauritius, for instance, has been steadily increasing. The EKC pattern could not be verified in this way. Mauritius' energy usage heavily relies on imported fossil fuels, with an estimated 82 percent reliance at the time. Almost all energy use is for the provision of power and/or as a liquid for transportation, accounting for 81 percent of the country's total CO_2 emissions (Matadeen et al., 2011).

In another study, Ethiopian time-series data from 1970 to 2010 were reviewed. The findings reveal that while economic expansion increases energy consumption equally in the medium and long run, CO_2 emissions are decoupled from growth in the long run. Ethiopia achieved this by utilizing hydrodynamic and geothermal energy, which aided in developing a green economy (Musah et al., 2022).

Because different pollutants respond differently to numerous trade factors, and because the effect of trade on the environment is nation-specific, which could depend on the level of income and political institutions of the countries involved, inconclusive empirical research may have occurred as a result of some omitted variables, if any (Yang et al., 2021). As a result, we included Nitrous Oxide (N_2O) and Agricultural Methane (agricultural CH_4) emissions in our model, although many earlier studies have focused solely on the relationship between trade and CO_2 emissions. Furthermore, no research has been conducted on the relationship between Nitrous Oxide (N_2O) emissions, Agricultural Methane (agricultural CH_4) emissions, CO_2 emissions, and trade in Sub-Saharan African countries as a whole or its sub-groups; this inspired the present study (Qamruzzaman, 2021).

3 Methodology

3.1 Specification of the model

We assumed that the main determinants of economic development were trade and energy usage; therefore, we, in turn, defined environmental pollution as an outcome of energy consumption in connection with trade and economic growth. That being the case, we defined our models as follows:

$$N_2O_{it} = f\left(TRD_{it}, Y_{it}, EI_{it}, FDI_{it}, HC_{it}\right) \quad (1a)$$

$$CO_{2it} = f\left(TRD_{it}, Y_{it}, EI_{it}, FDI_{it}, HC_{it}\right) \quad (1b)$$

$$ACH_{4it} = f\left(TRD_{it}, Y_{it}, EI_{it}, FDI_{it}, HC_{it}\right) \quad (1c)$$

We include natural logarithms to our selected variables to reduce the heteroscedasticity problem and be able to observe the growth level of the parameters by their log differences to compute Eqs 1a–c, thus using it to study the correlation between the independent and dependent variables, following the modification of the KAYA or I=PAT model by regressing GHG emissions (CO_2, N_2O, and ACH_4) on trade, income per capita growth, energy intensity, foreign direct investment, and human capital:

$$\ln\ (N_2O)_{it} = \alpha 1 + \beta_1\, ln(TRD)_{it,} + \lambda_1\, ln(Y)_{it} + \lambda_2\, ln(EI)_{it} + \lambda_3\, ln(FDI)_{it} + \lambda_4\, ln(HC)_{it} + \eta_{1i} + \varepsilon_{1it} \quad (2a)$$

$$ln(CO2)_{it} = \alpha 2 + \beta_2\, ln(TRD)_{it,} + \lambda_5\, ln(Y)_{it} + \lambda_6\, ln(EI)_{it} + \lambda_7\, ln(FDI)_{it} + \lambda_8\, ln(HC)_{it} + \eta_{2i} + \varepsilon_{2it} \quad (2b)$$

$$ln(ACH_{4it}) = \alpha 3 + \beta_3\, ln(TRD)_{it,} + \lambda_9\, ln(Y)_{it} + \lambda_{10}\, ln(EI)_{it} + \lambda_{11}\, ln(FDI)_{it} + \lambda_{12}\, ln(HC)_{it} + \eta_{3i} + \varepsilon_{3it} \quad (2c)$$

Where:

$\ln\ (N_2O)_{it}$ = the natural log of Nitrous Oxide emissions in country i and time t

$\ln\ (CO_2)_{it}$ = the natural log of CO_2 emissions in country i and time t

$\ln\ (ACH_4)_{it}$ the natural log of Agricultural Methane Emissions in country i and time t

$\ln\ (TRD)_{it}$ = the natural log of trade in the percentage of GDP

$\ln(Y)_{it}$ = the natural log of Income Per Capita Growth (constant 2010 U.S. dollars) in country i and time t

$\ln\ (EI)_{it}$ = the natural log of Energy Intensity (Energy Supply/GDP- measured at purchasing power parity) in country i and time t

$\ln\ (FDI)_{it}$ = the natural log of Foreign Direct Investment in country i and time t

$\ln\ (HC)_{it}$ = the natural log of Human Capital (measured as the rate of secondary school graduation) in country I and time t

β_i measures the relative effects of trade on environmental quality.

λ_i = set of parameters indicating the relative effects of the control variables.

3.2 Estimation techniques

In line with the works of Ghani, Kerr (Ghani et al., 2011), Vlastou (Vlastou, 2010), and Madsen (Madsen, 2009), the study employs a dynamic panel technique in addressing potential endogeneity problems in the data using the methods of Arellano and Bover (Arellano and Bover, 1995) and Blundell and Bond (Blundell and Bond, 1998). This type of dynamic panel framework is developed by the application of the first difference transformation portrayed by the following Eq. 3:

$$ep_{it} - ep_{i,t-i} = (\alpha - 1)ep_{i,t-1} + \beta' X_{i,t} + \eta_i + \varepsilon_{i,t} \tag{3}$$

Where $ep_{it} - ep_{i,t-i}$ is the growth of environmental pollution, $X_{i,t}$ denotes the set of independent variables, including our measure of natural resources revenues, income per capita growth, energy intensity, foreign direct investment, and human capital; η_i Denotes the unobserved country-specific effect, and $\varepsilon_{i,t}$ denotes the error term. We further expressed Eq. 3 as follows:

$$ep_{i,t} = \alpha' ep_{i,t-1} + \beta' X_{i,t} + \eta_i + \varepsilon_{i,t} \tag{4}$$

Changing Eq. 4 into the first difference gives the Equation seen below:

$$ep_{i,t} - ep_{i,t-1} = \alpha' \left[ep_{i,t-1} - ep_{i,t-2}\right] + \beta' \left[X_{i,t} - X_{i,t-1}\right] + \left[\varepsilon_{i,t} - \varepsilon_{i,t-1}\right] \tag{5}$$

It is seen from Eq. 5 that the lagged difference in environmental pollution is correlated with the error term, which suggests the potential existence of endogeneity of the independent variable X, which prompts the use of instrumental variables. In an attempt to address this problem, the system difference estimator includes the lagged levels of the independent variables as instruments in the supposition that the lagged level of the independent variables is weakly exogenous and that the error term is not serially correlated. In the empirical analysis, a positive and significant coefficient of natural resources revenues, income per capita growth, energy intensity, foreign direct investment, and human capital suggest that the independent variables increase pollution, hence deterioration of the environment in the countries under consideration. On the contrary, a negative and significant coefficient implies a reduction in emissions, thereby improving the environment.

Lastly, following the theory behind the EKC analysis, we investigate the existence of an inverted U-shape correlation between income per capita growth and N_2O, ACH_4, and CO_2 emissions. We included the square of income per capita growth into Eq. 2 to compute Eq. 6, using these equations to ascertain the existence of the EKC hypothesis in our model. Consistent with the work of Shahbaz, Van Hoang (Shahbaz et al., 2017b), Andriamahery and Qamruzzaman (Andriamahery and Qamruzzaman, 2022a), we modeled our EKC theory as follows:

$$\ln\,(N_2O)_{it} = \alpha 1 + \beta_1\, ln(TRD)_{it,} + \lambda_1\, ln(Y)_{it} + \lambda_2\, ln(Y^2)_{it}\, \lambda_3\, ln(EI)_{it} + \lambda_4\, ln(FDI)_{it} + \lambda_5\, ln(HC)_{it} + \eta_{1i} + \varepsilon_{1it} \tag{6a}$$

$$ln(CO2)_{it} = \alpha 2 + \beta_2\, ln(TRD)_{it,} + \lambda_6\, ln(Y)_{it} + \lambda_7\, ln(Y^2)_{it} + \lambda_8\, ln(EI)_{it} + \lambda_9\, ln(FDI)_{it} + \lambda_{10}\, ln(HC)_{it} + \eta_{2i} + \varepsilon_{2it} \tag{6b}$$

$$ln(ACH_{4it}) = \alpha 3 + \beta_3\, ln(TRD)_{it,} + \lambda_{11}\, ln(Y)_{it} + \lambda_{12}\, ln(Y^2)_{it} + \lambda_{13}\, ln(EI)_{it} + \lambda_{14}\, ln(FDI)_{it} + \lambda_{15}\, ln(HC)_{it} + \eta_{3i} + \varepsilon_{3it} \tag{6c}$$

The estimated turning points are determined by Eqs 7a–c

$$x_1^* = \exp\left(-\frac{\lambda_1}{2\lambda_2}\right) \tag{7a}$$

$$x_2^* = \exp\left(-\frac{\lambda_6}{2\lambda_7}\right) \tag{7b}$$

$$x_3^* = \exp\left(-\frac{\lambda_{11}}{2\lambda_{12}}\right) \tag{7c}$$

3.3 Data and its sources

This section looks at the data used for the empirical analysis of the relationship between trade and the environment. We compiled data on N_2O, CO_2 emissions, and Agricultural Methane emissions and used them as dependent variables; whereas trade in the percentage of GDP, income per capita growth, energy intensity, foreign direct investment, and human capital from the World Bank online data bank for 33 Sub-Saharan African countries were used as independent variables. We used the yearly data for the period 1990–2017. We put the data into income groups (upper-middle-income, lower-middle-income, and low-income countries). Concerning the previous statement, the first panel of countries consists of Botswana, Equatorial Guinea, Gabon, Mauritius, Namibia, Seychelles, and South Africa. The second panel consists of Angola, Cameroon, Comoros, Congo Rep, Ivory Coast, Ghana, Kenya, Nigeria, Senegal, and Sudan. The third panel contains Benin, Burkina Faso, Burundi, CAR, Chad, Congo Dem Rep, Ethiopia, Guinea, Madagascar, Malawi, Mozambique, Niger, Rwanda, Sierra Leone, Tanzania, and Uganda. The literature has used different variables to measure pollution, including N_2O, SO_2, CO_2, etc. However, our analysis used N_2O emissions, CO_2 emissions, and Agricultural Methane (agricultural CH4) emissions because of their global effects.

4 Analysis of results

4.1 Presentation of results

In estimating the equations at a certain level, the study applies the Hausman specification test to pick between the random and fixed effects models. We use the total sample, which includes nations in Sub-Saharan Africa. We classify Sub-Saharan African countries into three groupings to capture

TABLE 1 Panel estimation results: LNN_2O as the dependent variable.

Variables	SSA			UMIC			LMIC			LIC		
	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS
Constant	6.7802 (16.40)***	6.5665 (13.58)***	-----	6.4919 (11.91)***	-8.8075 (-42.03)***	-----	8.0243 (15.40)***	7.8931 (11.41)***	-----	7.1147 (6.84)***	6.7892 (6.26)***	-----
$LNN_2O(-1)$	-----	-----	0.7706 (74.38)***	-----	-----	0.784,065 (12.45)***	-----	-----	11.3899 (3.71)***	-----	-----	0.8542 (22.84)***
LNTRD	0.06931 (4.49)***	0.0775 (5.08)***	0.0214 (6.04)***	0.0638 (2.56)**	0.3973 (81.18)***	0.0394 (2.23)**	0.0707 (4.03)***	0.0750 (4.30)***	0.1222 (2.19)**	0.1242 (3.00)***	0.1359 (3.32)***	0.0457 (2.96)***
LNY	-0.0603 (-3.48)***	-0.0445 (-0.88	0.0257 (5.72)***	-0.1726 (-2.68)***	0.3407 (16.67)***	-0.1034 (-1.82)*	-0.1701 (-3.043)***	0.1695 (3.03)***	-2.3644 (1.79)*	0.0905 (2.11)**	0.0918 (2.14)**	0.0209 (4.79)***
LNEI	-0.0372 (-0.68)***	-0.0096 (-0.17)	-0.0012 (-0.07)	-0.2823 (-14.11))***	1.2941 (37.84)***	-0.0313 (-0.73)	-0.4822 (-4.62)***	-0.4601 (-4.42)***	-0.0523 (-0.15)	-0.1068 (-2.63)***	-0.0817 (-0.97)	0.0946 (2.12)**
LNFDI	-0.0289 (-0.82)	-0.0328 (-0.93)	-0.0288 (-8.38)***	-0.0217 (-0.71)	-1.0295 (-38.11)***	0.0435 (1.32)	0.0857 (2.08)**	0.0834 (2.03)**	0.2090 (0.79)	-0.1116 (-2.59)***	-0.1120 (-2.61)***	-0.0208 (-10.43)***
LNHC	-0.1079 (-3.73)***	-0.1078 (-3.74)***	-0.0455 (-3.16)***	0.0362 (0.51)	1.7773 (58.12)***	0.0211 (0.63)	-0.0841 (-1.72)*	-0.0848 (-1.73)*	-0.5994 (-1.80)*	-0.1554 (-3.03)***	-0.1490 (-2.92)***	-0.1074 (-1.75)
No. of Obs	892	892	827	168	168	162	280	280	270	448	448	416
R^2	0.9625	0.07	-----	0.9941	0.7057	-----	0.9682	0.2298	-----	0.9210	0.0712	-----
F-Statistics	608.822 (0.000)***	13.950 (0.000)***	-----	2654.663 (0.000)***	77.692 (0.000)***	-----	576.331 (0.000)***	16.354 (0.000)***	-----	249.029 (0.000)	6.777 (0.000)***	-----
Hausman Test	Chi^2 (5) = 20.60 (0.0010)***		-----	Chi^2 (5) = 7701.88 (0.0000)***		-----	Chi^2 (5) = 10.18 (0.0703)*		-----	Chi^2 (5) = 4.72 (0.4506)		-----
AR (2)	-----	-----	0.9987	-----	-----	0.9889	-----	-----	0.9866	-----	-----	0.9966
Sargan Test	-----	-----	$\chi2$ = 31.52 (0.5648)	-----	-----	$\chi2$ = 21.22 (0.6921)	-----	-----	$\chi2$ = 24.66 (0.734)	-----	-----	$\chi2$ = 82.52 (0.772)

Note. The variables are expressed in log form, and t–values are reported in parenthesis (except for the Hausman test and F-statistics where probabilities are reported in parenthesis), ----- implies not applicable, (*) (**) and (***) represent significance at the 10%, 5%, and 1% levels respectively. The variables entering the Dynamic model are in first difference, and their coefficients are interpreted as growth elasticities. Both the fixed and random-effects models are in levels.

disparities in income levels: Upper-Middle-Income Countries (UMIC), Lower-Middle-Income Countries (LMIC), and Low-Income Countries (LIC). As dependent variables, three environmental quality measurements were used. The regression is then conducted for each of the sub-economic groups concerning each measure of environmental quality to see if differences in income levels across sub-regions impact the relative effects of the independent variables on the dependent variables.

Tables 1–3 show the results of the panel dynamic model analysis of the long-term effects of trade, income per capita growth, energy intensity, foreign direct investment, and human capital on the three environmental quality measures (N_2O, ACH_4, and CO_2). Estimates for the Environmental Kuznets Curve (EKC) hypothesis were also made; the results are presented in Tables 4–6. These panel regression findings are calculated for all nations in Sub-Saharan Africa and the three sub-income groups.

Individual unobserved country-specific effects are not correlated with the explanatory variables for SSA, UMIC, and LMIC, meaning that the fixed-effects model is superior to the random-effects model for levels regression in these groups, as demonstrated in the lower areas of Tables 1,2. However, in the LIC, it is proposed that the random-effects model be favored over the fixed-effects model. Furthermore, the Hausman specification test results in the lower section of Table 3 consistently show that the fixed-effects model is preferred over the random-effects model for all groups (SSA, UMIC, LMIC, and LIC), as the tests show that individual unobserved country-specific effects are uncorrelated with the explanatory variables.

The results of the Sargan tests in the lower sections of Tables 1–3 show that the instruments are valid in all dynamic panel

TABLE 2 Panel estimation results: $LNACH_4$ as the dependent variable.

Variables	SSA			UMIC			LMIC			LIC		
	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS
Constant	6.2148 (12.40)***	5.9628 (10.32)***	-----	6.2929 (13.33)***	-12.695 (-69.99)***	-----	9.2487 (16.73)***	9.0914 (12.58)***	-----	2.2717 (1.80)*	1.9631 (1.53)	-----
$LNACH_4$(-1)	-----	-----	0.7707 (74.38)***	-----	-----	6.1023 (12.94)***	-----	-----	13.9089 (3.68)***	-----	-----	0.8016 (8.29)***
LNTRD	0.0947 (5.07)***	0.1045 (5.66)***	0.0214 (6.05)***	-0.0451 (-2.54)**	0.5113 (120.67)***	0.0429 (2.42)**	0.0541 (2.9095)***	0.0589 (3.19)***	0.7894 (2.07)**	0.2995 (5.13)***	0.3142 (5.48)***	0.1212 (2.86)***
LNY	-0.1368 (-2.23)**	-0.1386 (-2.25)**	0.0257 (5.72)***	0.3835 (21.43)***	0.4434 (25.07)***	-0.2089 (-3.13)***	-0.1656 (-2.79)***	-0.1646 (-2.77)***	-1.3071 (-3.96)***	-0.0032 (-0.04)	0.3477 (7.12)***	-0.0389 (-4.98)***
LNEI	-0.1694 (-2.53)**	-0.1356 (-2.04)**	-0.0012 (0.07)	-0.0839 (-1.33)	1.3994 (47.27)***	-0.0602 (-0.95)	-1.1373 (-10.26)***	-1.1084 (-10.04)***	-0.9691 (-2.15)**	-0.0903 (-0.83)	-0.0801 (-0.7485)	-0.0939 (-0.46)
LNFDI	0.1230 (2.89)***	0.1182 (2.78)***	-0.0288 (-8.38)***	-0.6404 (-100.82)***	-1.2681 (-54.22)***	-0.0158 (-0.61)	0.1879 (4.30)***	0.1847 (4.23)***	0.5473 (2.02)**	-0.0231 (-0.44)	-0.3143 (-2.87)***	-0.0312 (-4.43)***
LNHC	-0.1385 (-3.94)***	-0.1378 (-3.94)***	-0.0455 (-3.16)***	0.0652 (1.07)	2.0729 (78.31)***	0.0932 (1.48)	0.0840 (1.62)	0.0853 (1.64)	-0.6549 (-1.89)*	0.0776 (1.25)	0.0681 (1.10)	-0.0969 (-2.38)**
No. of Obs	892	892	827	168	168	162	280	280	270	448	448	416
R^2	0.9567	0.1263	-----	0.9972	0.6561	-----	0.9652	0.4102	-----	0.8840	0.1603	-----
F-Statistics	524.982 (0.000)***	25.624 (0.000)***	-----	5654.345 (0.000)***	61.817 (0.000)***	-----	525.190 (0.000)***	38.114 (0.000)***	-----	162.730 (0.000)***	16.876 (0.000)***	-----
Hausman Test	Chi^2 (5) = 19.67 (0.0014)***		-----	Chi^2 (5) = 19341.51 (0.0000)***		-----	Chi^2 (5) = 12.37 (0.0301)**		-----	Chi^2 (5) = 2.83 (0.7267)		-----
AR (2)	-----	-----	0.9987	-----	-----	0.9984	-----	-----	0.9909	-----	-----	0.4166
Sargan Test	-----	-----	χ2 = 55.33 (0.633)	-----	-----	χ2 = 30.07 (0.701)	-----	-----	χ2 = 24.84 (0.774)	-----	-----	χ2 = 23.24 (0.375)

Note. The variables are expressed in log form, and t–values are reported in parenthesis (except for the Hausman test and F-statistics where probabilities are reported in parenthesis), ---- implies not applicable, (*) (**) and (***) represent significance at the 10%, 5%, and 1% levels respectively. The variables entering the Dynamic model are in first difference, and their coefficients are interpreted as growth elasticities. Both the fixed and random-effects models are in levels.

regressions for the dynamic model. Finally, the tests for second-order serial correlation in the residuals reveal no severe problem with serial correlation in the dynamic panel's regressions.

4.2 Discussion of results

Starting with one of the environmental quality indicators (nitrous oxide emissions), we examine the impact of trade (as measured by natural resource revenues), income per capita growth, energy intensity, foreign direct investment, and human capital on N_2O emissions. Table 1 shows that the trade (NRR) coefficient for the fixed-effects model is positive and significant for the SSA, UMIC, and LMIC for the SSA, UMIC, and LMIC. According to the results of the random-effects model, trade has a positive and significant impact on Nitrous Oxide Emissions in the LIC exclusively. This means that an increase in trade in any of these groups leads to an increase in N_2O, lowering the environmental quality. Table 1 also includes the results of the panel dynamic model study of the long-term consequences. The empirical findings reveal that trading raises N_2O emissions in all populations (SSA countries, UMIC, LMIC, and LIC). This means that a 10% increase in trade in SSA, UMIC, LMIC, and LIC increases N_2O emissions by 0.2, 0.4, 1.2, and 0.5 percent, respectively, when all other explanatory variables are held constant. This effect of trade on the environment could be explained by the fact that nearly 70% of people in Sub-Saharan Africa work in agriculture, which increases the generation of nitrous oxide through soil cultivation, nitrogen fertilizer use, and the management of animal manure. Furthermore, because fossil

TABLE 3 Panel estimation results: $LNCO_2$ as the dependent variable.

Variables	SSA			UMIC			LMIC			LIC		
	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS
Constant	3.4127 (8.02)***	3.1629 (6.91)***	-----	-3.4775 (-2.09)**	-6.6102 (-10.32) ***	-----	4.0351 (7.43)***	3.4062 (5.97)***	-----	-1.1494 (-1.56)	-1.5133 (-2.05)**	-----
$LNCO_2$(-1)	-----	-----	0.8250 (84.37)***	-----	-----	-1.7424 (-1.21)	-----	-----	-1.6045 (-0.48)	-----	-----	0.8035 (7.21)***
LNTRD	0.2179 (13.74)***	0.2266 (14.58)***	0.0951 (28.44) ***<	0.4377 (6.99)***	0.3988 (26.66)***	0.4585 (8.49)***	0.1287 (7.05)***	0.1518 (8.50)***	0.5473 (2.02)**	0.4207 (12.37)***	0.4328 (13.00)***	0.0613 (6.90)***
LNY	-0.1172 (-2.25)**	-0.1161 (-2.23)**	0.0141 (3.36)***	-0.1326 (-2.04)**	-0.0189 (-0.30)	-0.1642 (-2.99)***	0.1549 (2.66)***	0.1562 (2.6836) ***	2.4000 (1.66)*	0.0693 (1.99)**	-0.0712 (-1.63)	0.1035 (1.38)
LNEI	-0.4854 (-8.55)***	-0.4569 (-8.19)***	-0.0073 (-0.84)	0.4139 (1.87)*	1.3089 (12.53)***	0.2114 (1.09)	-0.2079 (-1.91)*	-0.1042 (-0.97)	-0.3954 (-0.99)	-0.5220 (-8.23) ***<	-0.4836 (-7.78)***	-0.1164 (-1.78)*
LNFDI	-0.0976 (-2.70)***	-0.1027 (-2.84)***	0.0376 (5.79)***	-0.2668 (-2.86)***	-0.6164 (-7.47)***	-0.2964 (-3.77)***	-0.0156 (-0.36)	-0.0304 (-0.71)	0.1168 (0.3919)<	0.0358 (1.18)	0.0370 (1.22)	0.0278 (1.66)*
LNHC	-0.4374 (-14.69) ***	-0.4433 (-14.97) ***	-0.0721 (-7.26)***	-0.9570 (-4.46)***	-1.7219 (-18.43) ***	-0.5577 (-2.91)***	-0.4723 (9.27)***	-0.4641 (-9.16)***	0.3552 (0.94)	-0.2440 (-6.73)***	-0.2472 (-6.87)***	-0.0627 (-2.08)**
No. of Obs	892	892	827	168	168	162	280	280	270	448	448	416
R^2	0.9520	0.5585	-----	0.9317	0.7939	-----	0.9593	0.4538	-----	0.9295	0.7004	-----
F-Statistics	471.052 (0.000)***	224.164 (0.000)***	-----	214.066 (0.000)***	124.857 (0.000)***	-----	447.238 (0.000)***	45.538 (0.000) ***	-----	281.283 (0.000)***	206.675 (0.000)***	-----
Hausman Test	Chi^2 (5) = 22.93 (0.0003)***		-----	Chi^2 (5) = 316.39 (0.0000)***		-----	Chi^2 (5) = 41.95 (0.0000)***		-----	Chi^2 (5) = 12.94 (0.0239)***		-----
AR (2)	-----	-----	0.3705	-----	-----	0.9985	-----	-----	0.9978	-----	-----	0.7923
Sargan Test	-----	-----	$\chi2 = 43.01$ (0.6471)	-----	-----	$\chi2 =$ 48.32 (0.637)	-----	-----	$\chi2 =$ 28.33 (0.548)	-----	-----	$\chi2 =$ 20.46 (0.558)

Note. The variables are expressed in log form, and t–values are reported in parenthesis (except for the Hausman test and F-statistics where probabilities are reported in parenthesis), ----- implies not applicable, (*) (**) and (***) represent significance at the 10%, 5%, and 1% levels respectively. The variables entering the Dynamic model are in first difference, and their coefficients are interpreted as growth elasticities. Both the fixed and random-effects models are in levels.

TABLE 4 Environmental Kuznets Curve (EKC) results.

	Dependent variable: D (LNN_2O)			
Variables	SSA	UMIC	LMIC	LIC
LNTRD	0.0305 (3.62)***	0.4956 (2.88)***	-0.2329 (-1.61)	-0.0608 (-3.52)***
LNY	0.0239 (4.65)***	0.9311 (3.87)***	1.4584 (1.43)	0.0227 (4.41)***
LNY^2	-0.0086 (-4.05)***	-0.1539 (-2.84)***	0.0072 (0.16)	-0.0026 (-0.75)
LNEI	-0.0237 (-1.26)	0.5974 (2.39)**	1.0934 (3.24)***	0.1203 (1.53)
LNFDI	-0.0377 (-6.66)***	-0.4325 (-2.20)**	1.0939 (3.74)***	0.0462 (0.69)
LNHC	0.0315 (1.07)	0.7167 (4.12)***	2.0009 (7.36)***	0.1040 (2.50)**
TURNING POINT	4.01 %	20.59 %	NS	NS

Note. ***, **, * indicate significance at the 1%, 5%, and 10% levels respectively; NS means not significant.

fuel combustion and industrial processes are two of the most significant contributors to anthropogenic emissions, this could indicate that more fossil fuel has been used in the production and sale of natural resources, given the fact that many Sub-Saharan African countries rely on natural resources to boost their economies.

TABLE 5 Environmental Kuznets Curve (EKC) results.

	Dependent variable: D ($LNACH_4$)			
Variables	**SSA**	**UMIC**	**LMIC**	**LIC**
LNTRD	0.0415 (3.56)***	0.0785 (0.64)	-0.1713 (0.47)	0.1505 (2.07)**
LNY	0.0319 (4.81)***	-0.0721 (-0.36)	1.6822 (0.65)	-0.0315 (-2.83)***
LNY^2	-0.0067 (-1.74)*	-0.1030 (-1.97)*	-0.0278 (-0.28)	-0.0076 (-0.64)
LNEI	0.0819 (2.37)**	1.4480 (5.68)***	0.7152 (1.32)	-0.0297 (-0.17)
LNFDI	0.0305 (2.43)**	1.4059 (4.79)***	0.6536 (1.56)	-0.1479 (-0.52)
LNHC	0.0338 (1.08)	-0.3126 (-0.43)	1.5336 (2.42)**	-0.3390 (1.16)
TURNING POINT	10.81 %	0.70 %	NS	NS

Note. ***, **, * indicate significance at the 1%, 5%, and 10% levels respectively; NS means Not Significant.

TABLE 6 Environmental Kuznets Curve (EKC) results.

	Dependent variable: D ($LNCO_2$)			
Variables	**SSA**	**UMIC**	**LMIC**	**LIC**
LNTRD	0.0954 (12.34)***	0.1342 (0.94)	0.4065 (2.98)***	0.0370 (0.82)
LNY	0.0987 (5.59)***	-0.0104 (-0.0324)	1.7537 (2.27)**	0.1051 (1.17)
LNY^2	-0.0101 (-3.77)***	0.0393 (0.39)	-0.0713 (-1.96)*	0.0032 (0.53)
LNEI	0.0389 (5.72)***	0.0674 (0.08)	-0.0697 (-0.16)	-0.0305 (-0.17)
LNFDI	0.0232 (3.05)***	-1.2849 (-2.38)**	0.3129 (0.84)	0.0421 (0.64)
LNHC	0.0922 (10.05)***	1.9730 (1.74)*	1.6673 (4.54)***	0.0683 (1.72)*
TURNING POINT	132.44 %	NS	219,257.04 %	NS

Note. ***, **, * indicate significance at 1%, 5%, and 10% levels respectively; NS means Not Significant.

The mixed results regarding the association between the Income Per Capita Growth (Y) and Nitrous Oxide (N_2O) emissions. The results of the fixed-effects regressions for the entire SSA member nations, UMIC, and LMIC, reveal that income per capita growth hurts N_2O emissions. On the other hand, we published the random-effects model for the LIC. The regression results demonstrate that Income Per Capita Growth and Nitrous Oxide Emissions have a positive association. In the dynamic model, income per capita growth in the UMIC and LMIC has a negative and large impact on N_2O emissions. In relative magnitude, the results reveal that a 10% rise in GDP per capita reduces N_2O emissions in the atmosphere by 1% and 23.6 percent in UMIC and LMIC, thus enhancing environmental quality. The panel data, on the other hand, show that income per capita growth positively and significantly affects N_2O emissions in Sub-Saharan African (SSA) and Low-Income Countries (LIC). This means that a 10% increase in Nitrous Oxide emissions raises the N_2O level in the atmosphere by 0.3 percent and 0.2 percent, respectively, while keeping the other control variables constant.

For the whole sample of Sub-Saharan African (SSA) countries, UMIC, and LMIC, the connection between N_2O emissions and Energy Intensity (EI) is negative and significant in the fixed-effects model. In Low-Income Countries, however, it is not significant for the random-effects model (LIC). The coefficient of energy intensity is only positive and significant for the Low-Income Nations (LIC) in the panel dynamic model; it is not significant for the SSA countries, UMIC, and LMIC. This means that a 10% increase in energy intensity (while keeping the other explanatory factors fixed) increases N_2O emissions in the atmosphere by about 1% in LIC.

While using the fixed-effects model, the association between foreign direct investment (FDI) and N_2O is positive and significant for only the LMIC; when using the random-effects model, the relationship is negative and significant for the LIC. Only the total Sub-Saharan African (SSA) countries and LIC have a negative and substantial association in the dynamic model. In terms of N_2O emissions, a 10% increase in FDI reduces them by 0.3 percent and 0.2 percent in SSA and LIC, respectively.

For the whole sample of Sub-Saharan African (SSA) nations, LMICs, and LICs, the link between Nitrous Oxide (N_2O) emissions and Human Capital (HC) is negative and significant in both fixed and random-effects models. However, it is not important in the Upper-Middle-Income Countries (UMIC). In the dynamic model, the link between N_2O emissions and HC in SSA, LMIC, and LIC is inverse and statistically significant. In the UMIC, it is of minor significance. This suggests that strengthening human capital reduces N_2O emissions in SSA, LMIC, and LIC, but not UMIC. This means that in SSA, LMIC, and LIC, a 10% increase in human capital reduces N_2O emissions by 0.5 percent, approximately 6% and 1%, respectively.

The estimations in Table 2 demonstrate the relative effects of trade, income per capita growth, energy intensity, foreign direct investment, and human capital on ACH_4 emissions, which is another measure of environmental quality. The trade variable (NRR) coefficient for the overall SSA nations, LMICs, and LICs are positive and significant for the fixed/random-effects model, according to Table 2. In the UMIC panel, however, it is negative and substantial. Table 2 also includes the results of the panel dynamic model study of the long-term consequences. The empirical findings reveal that trade increases agricultural methane (ACH_4) emissions in the SSA countries and UMICs, LMICs, and LICs. With the other explanatory factors held constant, a 10% increase in trade in SSA, UMIC, LMIC, and LIC raises ACH_4 emissions by 0.2 percent, 0.4 percent, 7.9 percent, and 1.2 percent, respectively. These findings are in line with the conclusion of Dario, LoPresti (Dario et al., 2014). Increased demand for livestock products could explain the negative impact of commerce on the environment.

The mixed results regarding the association between income per capita growth (Y) and agricultural methane (ACH_4) emissions. The results from the entire SSA member nations and LMIC for the fixed/random-effects model show that the income per capita growth negatively influences ACH_4 emissions, which is significant. The regression results, on the other hand, demonstrate that in the UMIC and LIC, income per capita growth has a positive and substantial effect on ACH_4 emissions. In the dynamic model, income per capita increase in the UMIC, LMIC, and LIC has a negative and significant impact on ACH_4 emissions. In relative magnitude, a 10% rise in income per capita growth reduces ACH_4 emissions in the atmosphere by 2.1 percent, 13.7 percent, and 0.4 percent in the UMIC, LMIC, and LIC, respectively, which is an indication of environmental quality improvement. To reduce ACH_4 pollution, these countries within these income groups need to boost economic growth. The panel data, on the other hand, show that income per capita growth positively and significantly affects ACH_4 emissions across the Sub-Saharan African (SSA) nations. This implies that a 10% increase in per capita income (while leaving all other explanatory variables constant) raises the ACH_4 level in the atmosphere by 0.3 percent.

When looking at the relationship between energy intensity (EI) and agricultural methane (ACH_4) emissions and looking at the regression results in Table 2, it can be seen that the coefficient of the energy intensity (EI) variable is negative for all panels (SSA, UMIC, LMIC, and LIC), but only significant in the SSA and LMIC panels. According to the panel dynamic model, the coefficient of energy intensity is negative in all four panels (SSA, UMIC, LMIC, and LIC), but only in the LMIC panel is it significant. According to the results of the dynamic model, a 10% increase in energy intensity (while leaving the other control variables constant) reduces ACH_4 emissions in the atmosphere by 9.7% in the LMIC at the 5% level. These results could be explained by a situation in which the use of renewable energy, such as solar energy for agricultural activities, is increasing in these countries (LMIC).

The link between foreign direct investment (FDI) and ACH_4 emissions is positive and significant for the total SSA countries and LMIC but negative and significant for the UMIC and LIC in the fixed/random-effects model. The dynamic model shows a negative connection in the total Sub-Saharan African (SSA) countries, UMIC and LIC. However, only the countries of Sub-Saharan Africa (SSA) and the LIC are noteworthy. A 10% increase in FDI in relative emissions reduces ACH_4 emissions by 0.3 percent in SSA and 0.3 percent in LIC, respectively. Nonetheless, it is significant and favorable for the LMIC. In LMIC, a 10% increase in FDI results in a 5.5 percent increase in ACH_4 emissions.

For the whole sample of Sub-Saharan African (SSA) nations, the association between ACH_4 emissions and human capital (HC) is negative and significant using the fixed/random-effects model. However, it is positive but insignificant in the UMIC, LMIC, and Low-Income Countries (LIC). The dynamic model's association between ACH_4 emissions and HC in SSA, LMIC, and LIC is inverse and statistically significant. In the UMIC, it is both positive and insignificant. This suggests that, at the 1%, 10%, and 5% levels of significance, strengthening human capital reduces ACH_4 emissions in SSA, LMIC, and LIC, respectively. This means that in SSA, LMIC, and LIC, a 10% increase in human capital reduces ACH_4 emissions by 0.5 percent, 6.5 percent, and 1 percent, respectively.

CO_2 emissions are also considered a metric of environmental quality. We also examine how to trade (NRR), income per capita growth, energy intensity, foreign direct investment, human capital, and CO_2 emissions are related. According to the regression results in Table 3, the trade variable (NRR) coefficient is positive and significant in all of the panels for the fixed-effects model (SSA, UMIC, LMIC, and LIC). Table 3 also includes the results of the panel dynamic model investigation of the long-term consequences. In all of the panels, the empirical results reveal that trade raises CO_2 emissions significantly. Keeping the control variables constant, we see a 10% increase in trade in SSA, UMIC, and LMIC and an increase in CO_2 emissions by approximately 1%, 4.6 percent, 5.5 percent, and

0.6 percent in LIC, respectively. These figures back up Shahbaz, Topcu (Shahbaz et al., 2021), Zhuo and Qamruzzaman (Zhuo and Qamruzzaman, 2021), Managi, Hibiki (Managi et al., 2009), Xu, Qamruzzaman (Xu et al., 2021). This trade effect on CO_2 emissions could be explained by reliance on coal or fossil-fuel-powered manufacturing methods, household usage of more conventional energy (fossil fuel), and numerous pollutant-producing sectors in these regions.

The mixed results regarding the association between income per capita growth (Y) and CO_2 emissions. The total SSA member nations and UMIC for the fixed-effects model show that rising income per capita hurts CO_2 emissions. And they are important. The regression results, on the other hand, reveal that income per capita growth positively and significantly impacts CO_2 emissions in LMICs and LICs. The income per capita increase has a negative and large impact on CO_2 emissions in the UMIC in the dynamic model. In relative magnitude, the findings reveal that a 10% rise in per capita income reduces CO_2 emissions by 1.6 percent in the atmosphere, improving environmental quality. Countries at these income levels should boost their economic growth to reduce CO_2 emissions and improve environmental quality. This result backs Frankel and Rose's conclusions (2005). The panel results, on the other hand, show that income per capita growth positively and considerably impacts CO_2 emissions in Sub-Saharan African (SSA) and LMIC nations. This means that a 10% increase in income per capita growth (while keeping the control variables constant) raises CO_2 levels in the atmosphere by 0.1 percent in SSA countries and 24% in LMICs. These findings corroborate those of Omri (Omri, 2013), Aka (Aka, 2008), Xia, Qamruzzaman (Xia et al., 2022), JinRu and Qamruzzaman (JinRu and Qamruzzaman, 2022) and Fodha and Zaghdoud (Fodha and Zaghdoud, 2010). The LIC's income per capita growth coefficient is positive but not statistically significant.

Given the relationship between energy intensity (EI) and CO_2 emissions, and based on the regression results in Table 3, the coefficient of the energy intensity (EI) variable is negative and significant in the overall SSA, LMIC, and LIC nations for the fixed-effects model. In the UMIC, on the other hand, it is positive and important. The coefficient of energy intensity is negative and significant only in the LIC panel, according to the panel dynamic model. The dynamic model shows that increasing energy intensity by 10% (while keeping the control variables constant) reduces CO_2 emissions in the atmosphere by 1.2 percent in the LIC at the 10% level.

The link between foreign direct investment (FDI) and CO_2 emissions in the fixed effects model is positive but not significant for the LIC, negative and significant for the total SSA nations and UMIC, and negative but negligible for the LMIC. In the UMIC, the link is negative and significant for the dynamic model. In terms of CO_2 emissions, a 10% increase in FDI reduces CO_2 emissions by about 3% in UMIC. It is, however, positive and significant for the SSA countries and the LIC. This means that a 10% increase in FDI raises CO_2 emissions by 0.4 percent in SSA nations and 0.3 percent in LIC countries. This could be explained by the fact that SSA countries have abundant natural resources, which is seen by natural resources exports as a percentage of GDP. Furthermore, it is widely accepted that most FDI inflows into SSA nations are directed to the natural resources sector, which MNCs dominate. However, these multinational corporations are not likely to employ sophisticated methods in exploiting and mining these resources, resulting in environmental devastation. More studies should be done in this field to better understand the relationship between CO_2 emissions and FDI. In the LMIC, the FDI coefficient is likewise positive but small.

The link between CO_2 emissions and human capital (HC) is consistently negative and significant for all panels in the fixed-effects model (SSA, UMIC, LMIC, and LIC). In the dynamic model, CO_2 emissions and HC in the aggregate SSA countries, UMIC, and LIC have an inverse and statistically significant association. This suggests that strengthening human capital reduces CO_2 emissions by 1%, 1%, and 5% in the SSA countries, UMIC and LIC, respectively. This means that a 10% increase in human capital reduces the CO_2 emissions by 0.7 percent, 5.6 percent, and 0.6 percent in SSA, UMIC, and LIC countries, respectively.

The income per capita growth variable's association with the three environmental quality measurements (N_2O, ACH_4, and CO_2), which has to do with the environmental Kuznets curve, is of higher interest (EKC). Only the most important panels will be covered in this report. For the sample of SSA nations and UMIC, the calculated coefficient on the squared term of income per capita growth (see Table 4) is negative for N_2O. In both panels, they are statistically significant. The calculated coefficient on the squared term of income per capita growth for the total sample of SSA nations and UMIC is negative for agricultural methane (ACH_4) emissions (Table 5). It is statistically insignificant for both panels. The calculated coefficient on the squared term of income per capita growth to CO_2 (Table 6) is negative for the whole sample of SSA and LMIC countries. It is statistically significant for the entire SSA panel and very weakly significant for the LMIC panel. This verifies the EKC theory, but with distinct turning points: constant income per capita increase diminishes these environmental parameters after a specific percentage of growth (reported in percentages at the bottom of Tables 4–6 as "turning points") (N_2O, ACH_4, and CO_2). As other academics have done, the tipping points are measured in percentages rather than dollars. This is conceivable because, instead of the mere income per capita, we add income per capita growth in our model, measured in percentages. The findings of the estimations in Tables 4–6 show that the EKC for the three environmental quality metrics in the overall SSA countries is consistently confirmed. The EKC was only validated for N_2O and ACH_4 emissions in the upper-middle-income nations (UMIC). The EKC was only marginally confirmed in the LMIC for CO_2 emissions and was not confirmed in the LIC panel for any of the three environmental quality parameters. Concerning our EKC data, Omri (Omri, 2013), Qamruzzaman (Qamruzzaman, 2022b) and Li and Qamruzzaman (Li and Qamruzzaman, 2022) came to a similar conclusion. These findings suggest that as countries within these groupings boost their economic growth to a specific percentage of continuous income per capita growth, environmental emissions will rise first, then reduce after the maximum percentage point is reached.

5 Implications and conclusion

5.1 Implications for policy

The outcomes of this study show that trade has similar environmental effects in Sub-Saharan African countries. The panel Dynamic model's results demonstrate that trade raises emissions (N_2O, ACH_4, and CO_2) significantly in the total sample of SSA, UMIC, LMIC, and LIC. In the long run, even though trade affects the environment in the total sample of SSA, its influence on the environment is relatively stronger in the LMIC than in the UMIC and LIC for all environmental variables, according to one of the research's primary findings (N_2O, ACH_4, and CO_2). In the short run, trade raises all emissions (N_2O, ACH_4, and CO_2) in the SSA, UMIC, and LMIC's general sample; trade increases CO_2 but decreases N_2O and ACH_4 emissions in LIC. However, the presence of the EKC indicates a possibility of reducing such emissions in the future, as shown by the study. The findings of this study imply that, for the environmental policies to be effective in achieving the desired results in terms of enhancing environmental quality, SSA nations' trade policies must be considered for environmental reforms. Unpredictability in trade situations among multiple countries, while enacting environmental policy improvements could result in various outcomes, the policies are often kept at their embryonic phases. The gradual implementation of environmental policies is crucially important; it could play an essential role in achieving the desired outcomes. That being the case, policies focused on trade reforms that will improve environmental quality must be implemented as a priority because environmental deterioration is a significant result of anthropogenic actions. Furthermore, initiatives to improve the environment, such as supporting green investment, may lower emissions and improve environmental quality. Previous findings, such as those of Copeland and Taylor (Copeland and Taylor, 2004), Qamruzzaman (Qamruzzaman, 2022b) and Frankel and Rose (Frankel and Rose, 2005), are supported by our findings. Because different income groups have varied inclinations to impact environmental quality through trade, multiple policies and policy strategies are required to improve environmental quality and increase economic growth sustainability. For example, the notion of green investment aims to ensure eco-friendliness, global warming adaptability, and economic diversification. It raises governments' awareness and interest in including green investment in their budgetary planning, taking into account the fiscal and monetary systems, as well as establishing and strengthening effective climate change policies, generating clean/green jobs through reducing or eliminating fiscal taxes. Beneficiaries and stakeholders as a whole must, however, work together for this to happen. The EKC findings show that distinct turning points exist among the groupings and that countries should alter their local environmental laws to achieve universal development goals. As a result, policymakers must adopt major reforms in a step-by-step manner, beginning with trade policies before moving on to environmental measures (Andriamahery and Qamruzzaman, 2022b; Qamruzzaman, 2022b; Xia et al., 2022).

5.2 Conclusions

This research aims to empirically establish the relationship between trade and pollutant emissions (N_2O, ACH4, and CO_2) and other relevant control variables, including income per capita growth, energy intensity, foreign direct investment, and human capital. For robust analysis, data were obtained from a cross-section of Sub-Saharan African countries and sub-divided into income groups (UMIC, LMIC, and LIC). To determine the presence of EKC, this paper looks for an inverted U-shape link between income per capita growth and nitrous oxide (N_2O), agricultural methane (ACH_4), and carbon dioxide (CO_2) emissions. The Hausman specification tests consistently reject the null hypothesis that individual unobserved country-specific effects are not correlated with the explanatory variables for the CO_2 variable, implying that the fixed-effects model is preferred over the random-effects model for all regressions at the level in all panels (SSA, UMIC, LMIC, and LIC). The Hausman specification tests prefer the fixed-effect model for N_2O and ACH_4 variables in the overall SSA countries, UMIC and LMIC; however, the test favors the random effects model in the LIC. In all of the dynamic regressions, the Sargan tests estimates for over-identification constraints reveal that the instruments utilized in correcting for the presence of probable endogeneity are valid.

The findings of this study back up the assumption that commerce has a consistently negative impact on the environment in Sub-Saharan African countries, regardless of wealth level. This study has a clear policy implication: trade policies that support a cleaner environment should be adequately implemented before environmental reforms are implemented to improve the Sub-Saharan region's environment. The findings of this study show that the overall impact of environmental reforms in the SSA area has been ineffective in terms of enhancing the environment. This is hardly surprising, given that many of these countries have enacted weak trade and environmental policies in the region, resulting in environmental damage. As a result, attempts to enhance environmental well-being through environmental policies must be coordinated with trade reforms or rules that promote environmental improvement in the Sub-Saharan African region. Furthermore, we can deduce that the air quality will be lowered due to commerce which, in turn, increases pollution in the atmosphere. International environmental cooperation will almost certainly continue to exist on the list of the regular necessities of the SSA. Under such circumstances, reducing transboundary greenhouse gas emissions and their negative environmental consequences is essential. Cooperation prioritizes technology dissemination and improves environmental quality by enhancing efficiency gains and modernization (Beghin et al., 1995). Various countries have identified the inclusion of environmental measures in trade agreements as one of the most effective ways to promote the global economy while improving environmental quality. As a result, trade agreements should increase governments' abilities to handle environmental concerns. Similarly, reducing trade obstacles related to environmentally friendly items could encourage green technology innovation at a sustainable cost. Renewable energy development must be aided by reducing trade and economic barriers, providing enough subsidies to developers, lowering the risks associated with green investments, and gradually developing and implementing renewable energy markets.

In conclusion, this analysis shows that the effectiveness of environmental reforms is largely dependent on, among other things, the major trade reform policies that promote a cleaner environment. Governments must enact trade policies to increase environmental quality before pursuing environmental changes. This is because poor trade policies are likely to degrade environmental quality. Although this study contributes to a better understanding of this topic, it should be noted that enacting and implementing trade agreements geared toward reducing the environmental pollution in the atmosphere while maintaining real GDP growth should take into account other macroeconomic determinants than the ones used in our study. In addition, a slew of other environmental indicators must be evaluated to thoroughly examine the environment's quality. Other control variables such as innovation, commerce based on consumption and production, urbanization, transportation, and environmental regulation laws could be considered in future expansions of this study in Sub-Saharan African countries.

The present study is not out of certain limitations that can be addressed in future research. First, the study has overlooked the effects of cross-sectional dependency fact in empirical estimation, which may lead to spurious estimation for coefficient assessment. Second, advanced econometrical tools such as CS-ARDL and nonlinear assessment, that is, Panel–NARDL, can be implemented in documenting the explanatory effects of environmental sustainability.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://data.worldbank.org https://wdi.worldbank.org/ https://wdi.worldbank.org/ https://data.worldbank.org.

Author contributions

MQ: Introduction, Methodology, Empirical model estimation; AA: Data Accumulation, Literature Survey, First draft preparation, Final Preparation; JD: Methodology, Empirical model estimation.

Funding

This study received financial support from the Institute for Advanced Research (IAR), United International University, and Publication Grant: IAR/2022/Pub/029.

Acknowledgments

We sincerely thank the associate editor and two esteemed reviewers for their constructive suggestions and guidance during the revision process. We firmly believe that the inclusion of reviewer suggestions has tremendously improved the quality of our submission.

Conflict of interest

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Acheampong, A. O., Amponsah, M., and Boateng, E. (2020). Does financial development mitigate carbon emissions? Evidence from heterogeneous financial economies. *Energy Econ.* 88, 104768. doi:10.1016/j.eneco.2020.104768

Acheampong, A. O. (2018). Economic growth, CO2 emissions and energy consumption: What causes what and where? *Energy Econ.* 74, 677–692. doi:10.1016/j.eneco.2018.07.022

Aka, B. F. (2008). Effects of trade and growth on air pollution in the aggregated sub-saharan africa. *Int. J. Appl. Econ. Quantitative Stud.* 5 (1), 5–14.

Alola, A. A. (2019). Carbon emissions and the trilemma of trade policy, migration policy and health care in the US. *Carbon Manag.* 10 (2), 209–218. doi:10.1080/17583004.2019.1577180

Alvarado, R., and Toledo, E. (2017). Environmental degradation and economic growth: Evidence for a developing country. *Environ. Dev. Sustain.* 19 (4), 1205–1218. doi:10.1007/s10668-016-9790-y

Andriamahery, A., and Qamruzzaman, M. (2022a). A symmetry and asymmetry investigation of the nexus between environmental sustainability, renewable energy, energy innovation, and trade: Evidence from environmental Kuznets curve hypothesis in selected MENA countries. *Front. Energy Res.* 9. doi:10.3389/fenrg.2021.778202

Andriamahery, A., and Qamruzzaman, M. (2022b). Do access to finance, technical know-how, and financial literacy offer women empowerment through women's entrepreneurial development? *Front. Psychol.* 12 (5889), 776844. doi:10.3389/fpsyg.2021.776844

Antweiler, W., Copeland, B. R., and Taylor, M. S. (2001). Is free trade good for the environment? *Am. Econ. Rev.* 91 (4), 877–908. doi:10.1257/aer.91.4.877

Apergis, N., and Payne, J. (2010). Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. *Energy Policy* 38 (1), 656–660. doi:10.1016/j.enpol.2009.09.002

Arellano, M., and Bover, O. (1995). Another look at the instrumental variable estimation of error-components models. *J. Econ.* 68 (1), 29–51. doi:10.1016/0304-4076(94)01642-d

Arouri, M. E. H., Ben Youssef, A., M'henni, H., and Rault, C. (2012). Energy consumption, economic growth and CO2 emissions in Middle East and North African countries. *Energy Policy* 45, 342–349. doi:10.1016/j.enpol.2012.02.042

Balsa-Barreiro, J., Li, Y., Morales, A., and Pentland, A. S. (2019). Globalization and the shifting centers of gravity of world's human dynamics: Implications for sustainability. *J. Clean. Prod.* 239, 117923. doi:10.1016/j.jclepro.2019.117923

Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., and Farhani, S. (2018). How economic growth, renewable electricity and natural resources contribute to CO2 emissions? *Energy Policy* 113, 356–367. doi:10.1016/j.enpol.2017.10.050

Banday, U. J., and Aneja, R. (2020). Renewable and non-renewable energy consumption, economic growth and carbon emission in BRICS. *Int. J. Energy Sect. Manag.* 14 (1), 248–260. doi:10.1108/ijesm-02-2019-0007

Bangwayo-Skeete, P. F. (2012). Do common global economic factors matter for africa's economic growth? *J. Int. Dev.* 24 (3), 304–315. doi:10.1002/jid.1704

Bashir, M. F., Ma, B., Bilal, and Shahzad, L. (2021). Scientific data-driven evaluation of academic publications on environmental Kuznets curve. *Environ. Sci. Pollut. Res.* 28 (14), 16982–16999. doi:10.1007/s11356-021-13110-6

Beghin, J., Roland-Holst, D., and Mensbrugghe, D. v. d. (1995). Trade liberalization and the environment in the pacific basin: Coordinated approaches to Mexican trade and environment policy. *Am. J. Agric. Econ.* 77 (3), 778–785. doi:10.2307/1243251

Blundell, R., and Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data models. *J. Econ.* 87 (1), 115–143. doi:10.1016/s0304-4076(98)00009-8

Boleti, E., Garas, A., Kyriakou, A., and Lapatinas, A. (2021). Economic complexity and environmental performance: Evidence from a world sample. *Environ. Model. Assess. (Dordr).* 26 (3), 251–270. doi:10.1007/s10666-021-09750-0

Bölük, G., and Mert, M. (2014). Fossil & renewable energy consumption, GHGs (greenhouse gases) and economic growth: Evidence from a panel of EU (European Union) countries. *Energy* 74, 439–446. doi:10.1016/j.energy.2014.07.008

Brunnschweiler, C. N. (2010). Finance for renewable energy: An empirical analysis of developing and transition economies. *Environ. Dev. Econ.* 15 (3), 241–274. doi:10.1017/s1355770x1000001x

Chakraborty, C., and Basu, P. (2002). Foreign direct investment and growth in India: A cointegration approach. *Appl. Econ.* 34 (9), 1061–1073. doi:10.1080/00036840110074079

Chien, F., Hsu, C. C., Ozturk, I., Sharif, A., and Sadiq, M. (2022). The role of renewable energy and urbanization towards greenhouse gas emission in top Asian countries: Evidence from advance panel estimations. *Renew. Energy* 186, 207–216. doi:10.1016/j.renene.2021.12.118

Cole, M. A., and Elliott, R. J. R. (2003). Determining the trade–environment composition effect: The role of capital, labor and environmental regulations. *J. Environ. Econ. Manag.* 46 (3), 363–383. doi:10.1016/s0095-0696(03)00021-4

Copeland, B. R., and Taylor, M. S. (2004). Trade, growth, and the environment. *J. Econ. literature* 42 (1), 7–71. doi:10.1257/.42.1.7

Dario, C., LoPresti, A., Davis, S. J., Bastianoni, S., and Caldeira, K. (2014). CH4 and N2O emissions embodied in international trade of meat. *Environ. Res. Lett.* 9 (11), 114005. doi:10.1088/1748-9326/9/11/114005

Dinda, S. (2004). Environmental Kuznets curve hypothesis: A Survey. *Ecol. Econ.* 49 (4), 431–455. doi:10.1016/j.ecolecon.2004.02.011

Dogan, B., and Deger, O. (2016). How globalization and economic growth affect energy consumption: Panel data analysis in the sample of BRIC countries. *Int. J. Energy Econ. Policy* 6 (4), 806–813.

Dollar, D., and Kraay, A. (2003). Institutions, trade, and growth. *J. monetary Econ.* 50 (1), 133–162. doi:10.1016/s0304-3932(02)00206-4

Elbadawi, I. A., and Rocha, R. R. (1992). *Determinants of expatriate workers' remittances in north Africa and europe*. Washington, DC: Country Economics Department, World Bank.

Eléazar, Z. (2015). *Document de Travail consumption and foreign trade in Sub-Sahara African countries*. hal-01110769.

Eriksen, T. H. (2014). "The public sphere and the dialectics of globalization," in *Reclaiming the public sphere: Communication, power and social change*. Editors T. Askanius and L. S. Østergaard (London: Palgrave Macmillan UK), 64–78.

Farhani, S., Chaibi, A., and Rault, C. (2014). CO2 emissions, output, energy consumption, and trade in Tunisia. *Econ. Model.* 38, 426–434. doi:10.1016/j.econmod.2014.01.025

Ferdaous, J., and Qamruzzaman, A. (2014). Impact of international trade, remittances and industrialization on the economic growth of Bangladesh. *Editor. Board Members* 13 (8), 485–495.

Fodha, M., and Zaghdoud, O. (2010). Economic growth and pollutant emissions in Tunisia: An empirical analysis of the environmental Kuznets curve. *Energy Policy* 38 (2), 1150–1156. doi:10.1016/j.enpol.2009.11.002

Frankel, J., and Rose, A. (2005). Is trade good or bad for the environment? Sorting out the causality. *Rev. Econ. Statistics* 87 (1), 85–91. doi:10.1162/0034653053327577

Ghani, E., Kerr, W., and O'Connell, S. (2011). "Promoting entrepreneurship, growth, and job creation," in *In reshaping tomorrow: Is south asia ready for the big leap?* New Delhi: Oxford University Press, 168–201.

Gnangnon, S. K. (2020). Trade openness and diversification of external financial flows for development: An empirical analysis. *South Asian J. Macroecon. Public Finance* 9 (1), 22–57. doi:10.1177/2277978719898974

Gorus, M. S., and Aydin, M. (2019). The relationship between energy consumption, economic growth, and CO2 emission in MENA countries: Causality analysis in the frequency domain. *Energy (Oxford)* 168, 815–822. doi:10.1016/j.energy.2018.11.139

Grossman, G. M., and Krueger, A. B. (1991). *Environmental impacts of a North American free trade agreement*. Cambridge, MA, USA: National Bureau of Economic Research, 3914.

Hamid, I., Alam, M. S., Kanwal, A., Jena, P. K., Murshed, M., and Alam, R. (2022a). Decarbonization pathways: The roles of foreign direct investments, governance, democracy, economic growth, and renewable energy transition. *Environ. Sci. Pollut. Res.* 29 (33), 49816–49831. doi:10.1007/s11356-022-18935-3

Hamid, I., Alam, M. S., Murshed, M., Jena, P. K., Sha, N., and Alam, M. N. (2022b). The roles of foreign direct investments, economic growth, and capital investments in decarbonizing the economy of Oman. *Environ. Sci. Pollut. Res.* 29 (15), 22122–22138. doi:10.1007/s11356-021-17246-3

Helbling, T., Batini, N., and Cardarelli, R. (2005). "Globalization and external imbalances," in *IMF world economic outlook* (Washington, DC: International Monetary Fund), 109–156.

Hye, Q. M. A., and Lau, W.-Y. (2015). Trade openness and economic growth: Empirical evidence from India. *J. Bus. Econ. Manag.* 16 (1), 188–205. doi:10.3846/16111699.2012.720587

Iwata, H., Okada, K., and Samreth, S. (2010). Empirical study on the environmental Kuznets curve for CO2 in France: The role of nuclear energy. *Energy policy* 38 (8), 4057–4063. doi:10.1016/j.enpol.2010.03.031

Jänicke, M., Binder, M., and Mönch, H. (1997). 'Dirty industries': Patterns of change in industrial countries. *Environ. Resour. Econ. (Dordr).* 9 (4), 467–491. doi:10.1007/bf02441762

Jayanthakumaran, K., Verma, R., and Liu, Y. (2012). CO_2 emissions, energy consumption, trade and income: A comparative analysis of China and India. *Energy Policy* 42, 450–460. doi:10.1016/j.enpol.2011.12.010

Jiang, X., and Green, C. (2017). The impact on global greenhouse gas emissions of geographic shifts in global supply chains. *Ecol. Econ.* 139, 102–114. doi:10.1016/j.ecolecon.2017.04.027

Jianguo, W., and Qamruzzaman, M. (2017). Financial innovation and economic growth: A casual analysis. *Innovation Manag*., in Proceedings of the 14th International Conference on Innovation & Management, China, 1100.

JinRu, L., and Qamruzzaman, M. (2022). Nexus between environmental innovation, energy efficiency, and environmental sustainability in G7: What is the role of institutional quality? *Front. Environ. Sci.* 10, 860244. doi:10.3389/fenvs.2022.860244

Kaya, Y., and Yokobori, K. (1997). *Environment, energy, and economy : Strategies for sustainability*. Tokyo: Tokyo: United Nations University Press.

Keppler, J. H., and Mansanet-Bataller, M. (2010). Causalities between CO2, electricity, and other energy variables during phase I and phase II of the EU ETS. *Energy policy* 38 (7), 3329–3341. doi:10.1016/j.enpol.2010.02.004

Khan, D., and Ullah, A. (2019). Testing the relationship between globalization and carbon dioxide emissions in Pakistan: Does environmental Kuznets curve exist? *Environ. Sci. Pollut. Res.* 26 (15), 15194–15208. doi:10.1007/s11356-019-04913-9

Kuznets, S. (1955). Economic growth and income inequality. *Am. Econ. Rev.* 45 (1), 1–28.

Li, J., and Qamruzzaman, M. (2022). Dose tourism induce Sustainable Human capital development in BRICS through the channel of capital formation and financial development: Evidence from Augmented ARDL with structural Break and Fourier TY causality. *Front. Psychol.* 13, 1260. doi:10.3389/fpsyg.2022.804349

Liu, X., Klemes, J. J., Varbanov, P. S., Cucek, L., and Qian, Y. (2017). Virtual carbon and water flows embodied in international trade: A review on consumption-based analysis. *J. Clean. Prod.* 146, 20–28. doi:10.1016/j.jclepro.2016.03.129

López-Menéndez, A. J., Pérez, R., and Moreno, B. (2014). Environmental costs and renewable energy: Re-Visiting the environmental Kuznets curve. *J. Environ. Manag.* 145, 368–373. doi:10.1016/j.jenvman.2014.07.017

Madsen, J. (2009). Trade barriers, openness, and economic growth. *South. Econ. J.* 76 (2), 397–418. doi:10.4284/sej.2009.76.2.397

Managi, S., Hibiki, A., and Tsurumi, T. (2009). Does trade openness improve environmental quality? *J. Environ. Econ. Manag.* 58 (3), 346–363. doi:10.1016/j.jeem.2009.04.008

Matadeen, J., Matadeen, S., and Seetanah, B. (2011). *Trade openness and economic growth: Evidence from Mauritius*. ICITI.

Mia, A. H., Qamruzzaman, M., and Ara, L. A. (2014). Stock market development and economic growth of Bangladesh-A causal analysis. *Bangladesh J. MIS* 6 (2), 62–74.

Murshed, M., Haseeb, M., and Alam, M. S. (2022). The environmental Kuznets curve hypothesis for carbon and ecological footprints in South asia: The role of renewable energy. *GeoJournal* 87 (3), 2345–2372. doi:10.1007/s10708-020-10370-6

Musah, M., Owusu-Akomeah, M., Kumah, E. A., Mensah, I. A., Nyeadi, J. D., Murshed, M., et al. (2022). Green investments, financial development, and environmental quality in Ghana: Evidence from the novel dynamic ARDL simulations approach. *Environ. Sci. Pollut. Res.* 29 (21), 31972–32001. doi:10.1007/s11356-021-17685-y

Musila, J. W., and Yiheyis, Z. (2015). The impact of trade openness on growth: The case of Kenya. *J. policy Model.* 37 (2), 342–354. doi:10.1016/j.jpolmod.2014.12.001

Narayan, P. K., and Narayan, S. (2010). Carbon dioxide emissions and economic growth: Panel data evidence from developing countries. *Energy policy* 38 (1), 661–666. doi:10.1016/j.enpol.2009.09.005

Omri, A. (2013). CO2 emissions, energy consumption and economic growth nexus in MENA countries: Evidence from simultaneous equations models. *Energy Econ.* 40, 657–664. doi:10.1016/j.eneco.2013.09.003

Otekunrin, A. O., Chinoda, T., and Matowanyika, K. (2021). The nexus between economic growth, financial development, financial inclusion and financial innovation in africa. *Asian Econ. Financial Rev.* 11 (8), 672–681. doi:10.18488/journal.aefr.2021.118.672.681

Ozturk, I., and Acaravci, A. (2010). CO2 emissions, energy consumption and economic growth in Turkey. *Renew. Sustain. Energy Rev.* 14 (9), 3220–3225. doi:10.1016/j.rser.2010.07.005

Pao, H.-T., and Tsai, C.-M. (2010). CO2 emissions, energy consumption and economic growth in BRIC countries. *Energy policy* 38 (12), 7850–7860. doi:10.1016/j.enpol.2010.08.045

Pei, J., Sturm, B., and Yu, A. (2021). Are exporters more environmentally friendly? A re-appraisal that uses China's micro-data. *World Econ.* 44 (5), 1402–1427. doi:10.1111/twec.13024

Peters, G. P., Minx, J. C., Weber, C. L., and Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. U. S. A.* 108 (21), 8903–8908. doi:10.1073/pnas.1006388108

Qamruzzaman, M., and Ferdaous, J. (2014). Building a knowledge-based economy in Bangladesh. *Asian Bus. Rev.* 4 (3), 41–49. doi:10.18034/abr.v4i3.266

Qamruzzaman, Md (2022b). "Nexus between economic policy uncertainty and institutional quality: Evidence from Indian and Pakistan," in *Macroeconomics and finance in emerging market economies*. doi:10.1080/17520843.2022.2026035

Qamruzzaman, M. (2022c). Nexus between environmental innovation, energy efficiency and environmental sustainability in the lower-income economy. *GSC Adv. Res. Rev.* 12 (1), 068–083. doi:10.30574/gscarr.2022.12.1.0190

Qamruzzaman, M. (2021). Nexus between environmental quality, institutional quality and trade openness through the channel of FDI: An application of common correlated effects estimation (CCEE), NARDL, and asymmetry causality. *Environ. Sci. Pollut. Res.* 28, 52475–52498. doi:10.1007/s11356-021-14269-8

Qamruzzaman, M. (2022a). Nexus between renewable energy, foreign direct investment, and agro-productivity: The mediating role of carbon emission. *Renew. Energy* 184, 526–540. doi:10.1016/j.renene.2021.11.092

Saboori, B., and Sulaiman, J. (2013). Environmental degradation, economic growth and energy consumption: Evidence of the environmental Kuznets curve in Malaysia. *Energy Policy* 60, 892–905. doi:10.1016/j.enpol.2013.05.099

Salahuddin, M., Gow, J., and Vink, N. (2020). Effects of environmental quality on agricultural productivity in sub saharan african countries: A second generation panel based empirical assessment. *Sci. Total Environ.* 741, 140520. doi:10.1016/j.scitotenv.2020.140520

Shahbaz, M., Hoang, T. H. V., Mahalik, M. K., and Roubaud, D. (2017b). Energy consumption, financial development and economic growth in India: New evidence from a nonlinear and asymmetric analysis. *Energy Econ.* 63, 199–212. doi:10.1016/j.eneco.2017.01.023

Shahbaz, M., Hye, Q. M. A., Tiwari, A. K., and Leitao, N. C. (2013). Economic growth, energy consumption, financial development, international trade and CO2 emissions in Indonesia. *Renew. Sustain. Energy Rev.* 25, 109–121. doi:10.1016/j.rser.2013.04.009

Shahbaz, M., Kumar Mahalik, M., Jawad Hussain Shahzad, S., and Hammoudeh, S. (2019). Testing the globalization-driven carbon emissions hypothesis: International evidence. *Int. Econ.* 158, 25–38. doi:10.1016/j.inteco.2019.02.002

Shahbaz, M., Nasreen, S., Ahmed, K., and Hammoudeh, S. (2017a). Trade openness–carbon emissions nexus: The importance of turning points of trade openness for country panels. *Energy Econ.* 61, 221–232. doi:10.1016/j.eneco.2016.11.008

Shahbaz, M., Topcu, B. A., Sarigul, S. S., and Vo, X. V. (2021). The effect of financial development on renewable energy demand: The case of developing countries. *Renew. Energy* 178, 1370–1380. doi:10.1016/j.renene.2021.06.121

Shahzadi, I., Javed, A., Pirzada, S. S., Nasreen, S., and Khanam, F. (2014). Impact of employee motivation on employee performance. *Eur. J. Bus. Manag.* 6 (23), 159–166.

Sharif Hossain, M. (2011). Panel estimation for CO2 emissions, energy consumption, economic growth, trade openness and urbanization of newly industrialized countries. *Energy policy* 39 (11), 6991–6999. doi:10.1016/j.enpol.2011.07.042

Skellern, K., Markey, R., and Thornthwaite, L. (2017). Identifying attributes of sustainable transitions for traditional regional manufacturing industry sectors – a conceptual framework. *J. Clean. Prod.* 140, 1782–1793. doi:10.1016/j.jclepro.2016.07.183

Sohag, K., Begum, R. A., Abdullah, S. M. S., and Jaafar, M. (2015). Dynamics of energy use, technological innovation, economic growth and trade openness in Malaysia. *Energy* 90, 1497–1507. doi:10.1016/j.energy.2015.06.101

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. *World Dev.* 32 (8), 1419–1439. doi:10.1016/j.worlddev.2004.03.004

Sun, H., Edziah, B. K., Kporsu, A. K., Sarkodie, S. A., and Taghizadeh-Hesary, F. (2021). Energy efficiency: The role of technological innovation and knowledge spillover. *Technol. Forecast. Soc. Change* 167, 120659. doi:10.1016/j.techfore.2021.120659

Syed, A. A., Kamal, M. A., Ullah, A., and Grima, S. An asymmetric analysis of the influence that economic policy uncertainty, institutional quality, and corruption level have on India's digital banking services and banking stability. *Sustainability*, 2022. 14(6): p. 3238. doi:10.3390/su14063238

Tucker, M. (1995). Carbon dioxide emissions and global GDP. *Ecol. Econ.* 15 (3), 215–223. doi:10.1016/0921-8009(95)00045-3

Vlastou, I. (2010). Forcing africa to open up to trade: Is it worth it? *J. Dev. areas* 44 (1), 25–39. doi:10.1353/jda.0.0086

Vongpraseuth, T., and Choi, C. G. (2015). Globalization, foreign direct investment, and urban growth management: Policies and conflicts in Vientiane, Laos. *Land Use Policy* 42, 790–799. doi:10.1016/j.landusepol.2014.10.003

Xia, C., Qamruzzaman, M., and Adow, A. H. (2022). An asymmetric nexus: Remittance-led human capital development in the top 10 remittance-receiving countries: Are FDI and gross capital formation critical for a road to sustainability? *Sustainability* 14 (6), 3703. doi:10.3390/su14063703

Xu, S., Qamruzzaman, M., and Adow, A. H. (2021). Is financial innovation bestowed or a curse for economic sustainably: The mediating role of economic policy uncertainty. *Sustainability* 13 (4), 2391. doi:10.3390/su13042391

Yamaji, K., Matsuhashi, R., Nagata, Y., and Kaya, Y. (1993). A study on economic measures for CO2 reduction in Japan. *Energy policy* 21 (2), 123–132. doi:10.1016/0301-4215(93)90134-2

Yang, Y., Qamruzzaman, M., Rehman, M. Z., and Karim, S. (2021). Do tourism and institutional quality asymmetrically effects on FDI sustainability in BIMSTEC countries: An application of ARDL, CS-ARDL, NARDL, and asymmetric causality test. *Sustainability* 13 (17), 9989. doi:10.3390/su13179989

Yingjun, Z., Jahan, S., and Qamruzzaman, M. (2021). Access to finance and legal framework in female entrepreneurship development in Bangladesh: The mediating role of self-leadership. *Asian Econ. Financial Rev.* 11 (9), 762–780. doi:10.18488/journal.aefr.2021.119.762.780

Zhang, X.-P., and Cheng, X.-M. (2009). Energy consumption, carbon emissions, and economic growth in China. *Ecol. Econ.* 68 (10), 2706–2712. doi:10.1016/j.ecolecon.2009.05.011

Zhao, L., and Qamruzzaman, M. (2022). Do urbanization, remittances, and globalization matter for energy consumption in belt and road countries: Evidence from renewable and non-renewable energy consumption. *Front. Environ. Sci.* 10. doi:10.3389/fenvs.2022.930728

Zhuo, J., and Qamruzzaman, M. (2021). Do financial development, FDI, and globalization intensify environmental degradation through the channel of energy consumption: Evidence from belt and road countries. *Environ. Sci. Pollut. Res.* 29, 2753–2772. doi:10.1007/s11356-021-15796-0

frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 19 September 2022
DOI 10.3389/fenvs.2022.990238

Check for updates

OPEN ACCESS

EDITED BY
Jose Balsa-Barreiro,
Massachusetts Institute of Technology,
United States

REVIEWED BY
Xiaodong Yang,
Xinjiang University, China
Fengtao Guang,
China University of Geosciences
Wuhan, China

*CORRESPONDENCE
Peiji Shi,
xbsdspj@163.com

SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal Frontiers in Environmental Science

RECEIVED 09 July 2022
ACCEPTED 29 August 2022
PUBLISHED 19 September 2022

CITATION
Yin J, Shi P, Feng H, Tong H and Chao M (2022), Dynamic evolution and influencing factors of coupling coordination between innovation environment and transformation development of resource-based cities in Gansu province, China.
Front. Environ. Sci. 10:990238.
doi: 10.3389/fenvs.2022.990238

Dynamic evolution and influencing factors of coupling coordination between innovation environment and transformation development of resource-based cities in Gansu province, China

Junfeng Yin[1], Peiji Shi[1,2]*, Haoyuan Feng[3], Huali Tong[1,2] and Meng Chao[4]

[1]College of Geography and Environmental Science, Northwest Normal University, Lanzhou, China,
[2]Key Laboratory of Resource Environment and Sustainable Development of Oasis, Lanzhou, China,
[3]School of Ecological and Environmental Science, East China Normal University, Shanghai, China,
[4]College of Minning, Guizhou University, Guiyang, China

Studying the internal relationship between the innovation environment and the transformation development of resource-based cities from the perspective of coupling and coordination helps reveal the mechanism between them, which is of great significance to sustainable development of resource-based cities. This study reconstructs the index system for innovative environment and transformation development. We used the coupling coordination degree model, Epanechnikov function, and panel quantile regression model to analyze the coupling coordination level, dynamic evolution characteristics, and influencing factors of innovative environment and transformation development of resource-based cities in Gansu Province from 2009 to 2019. The study shows that the innovation environment index and the transformation development index of resource-based cities increased significantly during the study period. The innovation environment index of resource-based cities has been greatly improved, showing a dynamic evolution trend of rapid growth and development characteristics of "low-level, fast growth". There are differences in the characteristics of transformation development in resource-based cities, but on the whole, it shows a trend of increasing fluctuation. The state of coupling coordination has changed from a severely unbalanced state to a moderately unbalanced state; some cities have turned to a low-level coordination state, and the overall trend is presented to optimize the process continuously. The quantile regression results show that the level of economic development and industrial structure has a significant positive effect on improving the coupling coordination degree of the two. The degree of government intervention has a negative impact. The level of capital investment has a negative effect at a high score but has no significant impact at a low score. This study tries to provide a scientific basis for formulating the policy of coordinated development between an innovation environment and transformation development of resource-based cities and also provides a reference for high-quality development of other resource-based cities.

KEYWORDS

innovation environment, transformation development, coupling mechanism, resource-based city, Gansu province

1 Introduction

Resource-based cities are defined as cities built or developed into leading industries relying on the region's exploitation and processing of natural resources, such as minerals and forests (Li et al., 2013; Yu et al., 2015; Chen and Zhang 2021). Since the founding of New China, resource-based cities, as an essential energy supply base in China, have made historic contributions to formation of the national industrialization development system and the map of industrialization development (Li and Dewan 2017; Li et al., 2020). Under economic globalization and dynamic population transfer, world GDP and CO_2 emissions are moving eastward. Currently, China has shown a certain phenomenon of economic maturity, but the consumption efficiency of resources and energy is relatively high (Balsa-Barreiro et al., 2019), which puts pressure on sustainable development of resource-based cities. The report to the 19th National Congress of the Communist Party of China (2017) pointed out that China's economic development has shifted to a stage of high-quality development (Deng et al., 2022), The key to high-quality development of resource-based cities is how to achieve the transformation and upgrading of industrial structure and effective transformation of old and new driving forces, transforming the original model of scale expansion led by natural resources and at the expense of the environment sacrifice into a model of high-quality development driven by technological innovation, changing from factor-driven development to innovation-driven development (Jiang et al., 2020) to overcome the instability problem in the development of resource-based cities. Resource-based cities have strong resource dependence and development inertia, and forming industrial development path dependence is easy (Zhang and Brouwer 2020), which leads to failure of resource-abundance cities to play a good "Resource Gospel" role in the high-quality development of the regional economy. On the contrary, the phenomenon of "Resource Curse", which is negatively related to regional economic development, is likely to occur to a certain extent (Sachs and Warner 1995), causing regional resources to dry up, deteriorating ecological environment, and lack of economic industry development and sustainable urban development problems (Hooved 2012; Martinez-Fernandez et al., 2012). Also, the challenges and transformation of sustainable development of resource-based cities in China have become core issues (Chen et al., 2018). In addition, the essence of the economic transformation and development of resource-based cities is to guide the transformation of economic structure and reduce the dependence on resource-based cities' industries (Kuai et al., 2015; Chen et al., 2018; Zhang et al., 2020). Transformation and upgrading of resource-based cities are not simply about economic development but the leapfrog development of regional economies caused by technological progress and institutional changes. Therefore, exploring a path for renewal and breakthroughs is an inevitable problem faced by resource-based cities.

The regional innovation environment plays a vital role in promoting regional industrial development or economic development of the whole region (Maurseth and Verspagen 2002; Hasan and Tucci 2010), such as building a high-quality regional innovation system, creating a suitable environment for regional technological innovation, and enhancing regional innovation capabilities, which are the fundamental ways to improve regional transformation development capabilities and regional competitiveness significantly (Gong 2021). A review of the successful transformation development experiences of resource-based cities in the world shows that regional transformation development cannot be separated from the construction and support of a regional innovation environment. As a supportive environment for innovation activities, the regional innovation environment promotes socio-economic development by expanding the regional innovation scale, increasing innovation activity quantity, and improving innovation efficiency, ultimately realizing urban transformation upgrading and sustainable development. Resource-based cities in the process of development need to rely on a regional innovation system and a regional innovation environment to constantly explore new economic growth points and growth poles, explore new models of regional development paths, and unlock realization of the creation of a new way of regional industry evolution, thus promoting the whole area into a new high-quality economic development orbit to achieve high-quality sustainable development.

The research on the innovation environment and transformation development of resource-based cities has become a hot topic in the academic circle with great achievements. Presently, some research studies on the innovation environment and transformation development of resource-based cities mainly focuses on the following aspects: 1) pay attention to the impact of the innovation environment on the transformation development process of resource-based cities. For example, the calculation of the innovation environment index shows that the urban innovation environment has a positive role in promoting the industrial transformation development of resource-based cities (Li and Lin 2018). Technological innovation improves resource utilization efficiency through technological progress, thus promoting the transformation development of resource-based cities (Porter 1991). Also, on this basis, some studies discuss the influence of the government institutional environment (Shao et al., 2021), science and technology environment (Xie et al., 2020), and network facility environment (Zhu et al., 2021) on the transformation development of resource-based cities. 2) Focus on evaluating innovation environment and transformation development level, collaborative development path, and countermeasures. For example, a comprehensive evaluation index system was constructed to measure the level of urban transformation development (Chen et al., 2018; Liu et al., 2021) and innovation environment (Chen and Zhang 2021). On this basis, some scholars combine the innovation environment and transformation development to explore the coupling process of resource-based cities (Chen and Zhang 2021), further putting forward synergistic development paths (Xing and Luo 2018; Wang Q. et al., 2021) and development countermeasures (Li et al., 2013; Yu et al., 2016; Yan et al., 2019). 3) Attribution analysis of regional transformation development level caused by innovation environment change in resource-based cities, and analysis of its influence effect and driving mechanism. For example, regional technological innovation plays a positive role in the green transformation development of resource-based cities, and technological innovation plays a more significant role in urban transformation development and promotes the technical innovation path of regional transformation (Xie et al., 2020). The regional innovation environment continues to promote regional economic development and plays a crucial role in upgrading urban industrial structure through technological innovation knowledge and a technological spillover effect (Doytch and Narayan 2016). The innovation environment can promote resource cities' green industrial transformation by improving traditional industries' production technology and resource utilization efficiency (Li and Lin 2018; Miao et al., 2018). Other studies have shown that the increase in revenue from the resource sector will cause innovators to prefer the resource sector over the R&D sector (Sachs and Warner 2001), and the crowding effect of innovation may reduce the efficiency of regional resource utilization (Sun et al., 2017), thus affecting regional transformation development. Jin et al. (2019) also confirmed that technological innovation restricts the green transformation development of regional industries. In summary, from the perspective of regional distribution, existing research on resource-based cities is mainly concentrated in the whole country, northeast China, and Shanxi Province. At the same time, there are few relevant research results on resource-based cities in northwest China, especially in Gansu province. Therefore, conducting relevant research on resource-based cities in Gansu province is significant.

The main purpose of this study is to demonstrate the coupling coordination between the innovation environment and transformation development of resource-based cities in Gansu Province from 2009 to 2019. The objectives are proposed at three levels: 1) a coupling mechanism between innovation environment and transformation development is analyzed. 2) The coupling coordination degree of resource-based cities in Gansu province is measured. 3) Explore the influencing factors of coupling coordination degree of resource-based cities in Gansu Province. Possible academic contributions to this study are as follows: The coupling mechanism of regional innovation environment and transformation development is expounded, and a mathematical model is used to explore the influencing factors of coupling coordination degree, which enriches the research on coupling coordination between innovation environment and transformation development of resource-based cities.

2 Coupling mechanism of regional innovation environment and transformation development

There is a close interaction between the regional innovation environment and regional transformation development (Appio et al., 2021). The regional innovation environment provides sufficient conditions for regional innovation development, is the main driving force for regional transformation development, and is critical to enhancing regional sustainable development (Fang et al., 2014) so that the regional economy can develop healthily and with high quality. Regional innovation environment refers to the sum of external factors that influence the various innovation activities of regional innovation subjects in a specific region in the process of innovation development. It mainly includes the planning and strategy of the state for regional innovation development; the diversified investment of the state in regional innovation development; and the social attitude to innovation behavior and so on. Based on the perspective of innovation environment elements, this study considers that the regional innovation environment is the concentrated embodiment of regional innovation development based on the infrastructure environment, driven by the human resource environment, guaranteed by the financial market environment, keyed by the technology service environment, and mainlined by the policy institutional environment. At the same time, the innovation environment is also a concrete representation of the leading power of emerging industries, the influence of scientific and technological achievements, and the gathering power of innovation resources. Regional transformation development is mainly reflected in three aspects: economy, society, and ecology, that is, to realize scientific control and

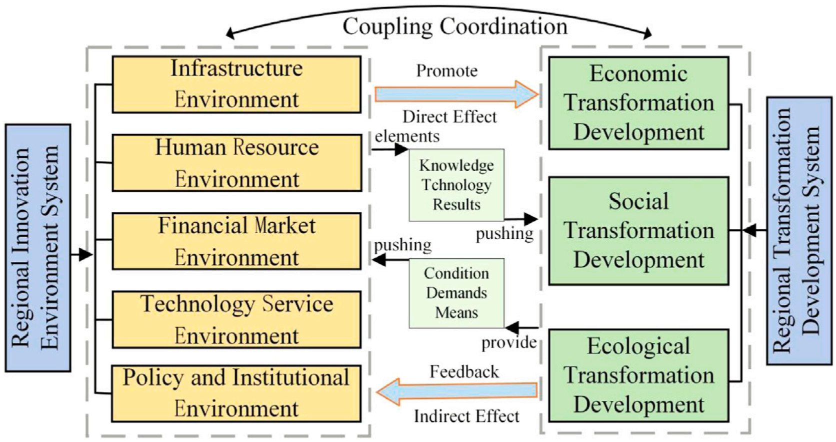

FIGURE 1
Coupling mechanism of the innovation environment and the transformation development.

high unity between economic development and environmental protection, natural ecology and human ecology, and people's livelihood and social development in the complex system of economy–society–ecology (Figure 1).

The response degree of regional transformation development caused by the change in the regional innovation environment reflects the fit degree of the regional innovation environment for regional transformation development. The level of the regional innovation environment has been improved effectively, and the speed of regional transformation development has been fast, which reflects that regional transformation development has a solid response to improvement of the regional innovation environment, and vice versa. The regional innovation environment gathers innovative elements such as knowledge, capital, and technology in multiple ways and constantly forms new technologies and products in a region, which promotes high-level rationalization and modernization of regional industrial development and then promotes the development of regional transformation and upgrading. Regional transformation development can effectively promote the improvement of the regional innovation environment, and the regional innovation environment is the guaranteeing factor for improving regional innovation ability, which has a positive effect on the improvement of regional innovation ability. Regional transformation development can not only promote high-quality development of the regional economy but also provide the development foundation for the regional innovation environment, optimize the regional innovation environment, form the regional innovation atmosphere, improve the regional innovation output, and then feed the regional transformation development. Therefore, the regional innovation environment and regional transformation development promote each other and develop cooperatively.

On the one hand, the regional innovation environment can improve technical routes, workflows, and process equipment of the original production, thus forming a new industrial mode based on digitalization, intelligence, green, and security, extended by networking, personalization, and service. The regional innovation environment can effectively induce the emergence of new industries, new technologies, new forms of business, and new models and then promote regional transformation development. A regional innovation environment effectively aggregates innovation resources, accelerates the pace of regional transformation and upgrading, and elevates regional transformation development. In addition, the regional innovation environment can promote industry (chain) technology level to continuously improve, drive the deep integration of innovative technologies and traditional industries, and promote industry from low value-added links to high value-added links to ascend, laying a solid foundation maintenance industry (chain) stable industry and changing the development mode and path of regional industry. On the other hand, regional transformation development will stimulate the regional demand for the innovation of new technology and new methods, and the innovation demand cannot leave the fertile soil of the innovation environment. The surge in innovation demand will prompt the government and enterprises to invest a large amount of human, material, and financial resources in quantity and quality, which will play a positive role in promoting the transformation of old and new industrial driving forces and upgrading the economic structure. Regional transformation development can effectively improve the level of the regional innovation environment. The transformation development will put higher requirements on regional infrastructure, capital resources, institutions, and policies; will prompt the government to perfect relevant policy support; increase

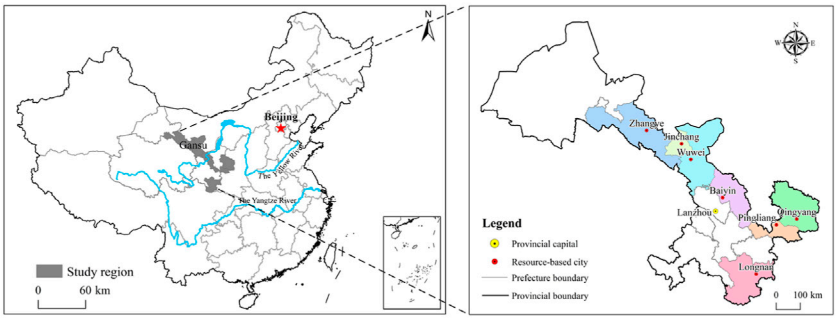

FIGURE 2
Geographical location of resource-based cities in Gansu Province.

diversified capital investment; and improve the regional innovation environment. At the same time, regional transformation development will drive the accumulation of more talents, technology, capital, facilities, and other resources, providing a good development environment for regional innovation. Regional transformation development can improve regional innovation output, and its essence is to enhance the process of industrial evolution and change, aiming at product economic added value and product competitiveness. Therefore, resource-based cities should coordinate and integrate innovation environments and transformation development to make resource-based cities green and sustainable.

3 Study area and data source

3.1 Study area

Gansu province is a vital hinge province in northwest China and an important economic growth pole in western China. The GDP of Gansu province increased from 326.83 billion yuan in 2009 to 871.83 billion yuan in 2019, showing a fast economic growth rate. In terms of strategic position, it is an important transportation hub and a financial channel connecting central and western China with eastern China and numerous trunk railways and national highways. Gansu province is located at the intersection of the Qinghai–Tibet Plateau, Loess Plateau, and Inner Mongolia Plateau. The landforms within Gansu province are complex and diverse, including mountains, plateaus, plains, river valleys, deserts, and gobi; with complete types and staggered distribution, Gansu province is representative in terms of natural conditions. But, the economic development of resource-based cities in Gansu province is slow, and the transformation development is difficult. From 2009 to 2019, the GDP of resource-based cities in the province increased from 148.52 billion yuan in 2009 to 340.84 billion yuan in 2019, with an average annual growth rate of 11.77%. However, the proportion of resource-based cities in the province's GDP decreased from 43.24% in 2009 to 39.09% in 2019. According to the National Sustainable Development Plan for Resource-Based Cities (2013–2020) issued by the State Council in December 2013 (Council 2013), Gansu Province involves seven resource-based cities, as shown in Figure 2.

3.2 Construction of the evaluation index system

The comprehensive evaluation index system of resource-based city innovation environments selects 23 evaluation indexes from five aspects: infrastructure environment, human resource environment, financial market environment, technology service environment, and policy institutional environment. The goal of the transformation development of resource-based cities is to get rid of excessive dependence of economic development on resources to achieve high-quality sustainable development of the cities. The transformation development situation mainly selects 13 evaluation indexes from three aspects: economic transformation development, social transformation development, and ecological transformation development. Finally, the comprehensive evaluation index system of the innovation environment and transformation development of resource-based cities is obtained (Table 1).

3.3 Research methods

Figure 3 shows the analysis framework of this research. The theoretical basis of the coupling mechanism between innovation environment and transformation development is analyzed. The relevant data are collected and sorted, and a comprehensive evaluation index system is constructed. At the same time, the data are preliminarily processed by the standardized method. The entropy method calculates the subsystem index of the

TABLE 1 Resource-based city innovation environment and transformation development evaluation index system.

imension	Indicators	Specific indicators
Innovation environment (u_1)	Infrastructure environment	Number of beds in health institutions per 10,000 people. Road area per capita. Total amount of urban post and telecommunications. Number of broadband internet users in the city. Afforestation coverage rate of built-up area. The number of books in public libraries per 10,000 people.
	Human resource environment	R&D personnel equivalent to full-time equivalent. Number of students in regular institutions of higher learning. Number of teachers in regular institutions of higher learning. Number of colleges and universities.
	Financial market environment	Total loans of financial institutions. Total deposits of financial institutions. Average wage of urban workers on the job. The transaction amount of technology market contracts.
	Technology service environment	R&D investment intensity. The proportion of education expenditure in public finance expenditure. Number of units in a city with RD activity. Number of patented inventions. Number of articles in *Web of Science.*
	Policy institutional environment	Number of urban key laboratories. Number of scientific and technological innovation service platforms. Number of science and technology innovation centers. Number of international scientific and technological cooperation bases.
Transformation development (u_2)	Economic transformation development	The GDP growth rate. per capita gross domestic product. The proportion of tertiary industry in GDP Total import and export trade as a proportion of GDP. Total consumption of retail goods. High-level industrial structure level.
	Social transformation development	Engel coefficient. Per capita disposable income of urban residents. Per capita disposable income of rural residents. The number of people having difficulty finding jobs in urban areas reemployed. Registered urban unemployment rate.
	Ecological transformation development	The proportion of days with air quality above grade two in the whole year. Comprehensive utilization of general industrial solid waste. Afforestation coverage rate of built-up area. Total industrial waste water discharge.

Note: Technology market contracts include technology development contracts, technology transfer contracts, technical consulting contracts and technical service contracts; Key laboratories include national key laboratories and provincial key laboratories.

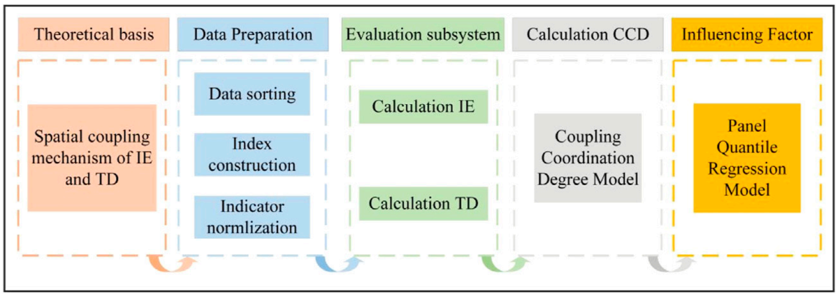

FIGURE 3
Analysis framework for evaluating coupling coordination degree between innovation environment and transformation development. Note: IE innovation environment), TD (transformation development), CCD (coupling coordination degree).

innovation environment and transformation development, and the coupling coordination degree model calculates the coupling coordination degree of innovation environment and transformation development. The Panel Quantile Regression model calculates the influencing factors of the coupling coordination degree of the innovation environment and transformation development.

3.3.1 Entropy method

The entropy method is used to calculate the comprehensive measure of the innovation environment and transformation development of resource-based cities. The entropy method has the advantage of objective weighting, avoids the deviation caused by subjective factors to a certain extent, and can realistically reflect the importance of various indicators in the comprehensive

TABLE 2 Classification criterion of coupling coordination degree.

Type	Criteria	Systematic comparison	Sub-type
Severe Imbalance (SI)	0.0 < D ≤ 0.2	$u_1(x)$- $u_2(x)$ > 0.1	Lagging transformation development SI(I-1)
		$u_2(x)$- $u_1(x)$ > 0.1	Lagging innovation environment SI(I-2)
		0< $\|u_1(x)$- $u_2(x)\|$<0.1	Systematic Balanced SI (I-3)
Moderate Imbalance (MI)	0.2 < D ≤ 0.4	$u_1(x)$- $u_2(x)$ > 0.1	Lagging transformation development MI(II-1)
		$u_2(x)$- $u_1(x)$ > 0.1	Lagging innovation environment MI(II-2)
		0< $\|u_1(x)$- $u_2(x)\|$<0.1	Systematic Balanced MI (II-3)
Low Coordination (LC)	0.4 < D ≤ 0.6	$u_1(x)$- $u_2(x)$ > 0.1	Lagging transformation development LC(III-1)
		$u_2(x)$- $u_1(x)$ > 0.1	Lagging innovation environment LC(III-2)
		0< $\|u_1(x)$- $u_2(x)\|$<0.1	Systematic Balanced LC (III-3)
Moderate Coordination (MC)	0.6 < D ≤ 0.8	$u_1(x)$- $u_2(x)$ > 0.1	Lagging transformation development MC(IV-1)
		$u_2(x)$- $u_1(x)$ > 0.1	Lagging innovation environment MC(IV-2)
		0< $\|u_1(x)$- $u_2(x)\|$<0.1	Systematic Balanced MC (IV-3)
High Coordination (HC)	0.8 < D ≤ 1.0	$u_1(x)$- $u_2(x)$ > 0.1	Lagging transformation development HC(V-1)
		$u_2(x)$- $u_1(x)$ > 0.1	Lagging innovation environment HC(V-2)
		0< $\|u_1(x)$- $u_2(x)\|$<0.1	Systematic Balanced HC (V-3)

indicators. The specific calculation process and steps can be found in the literature (Dong et al., 2021).

3.3.2 Coupling degree and coordination degree

The concept of "coupling" is borrowed from the concept of system coupling in physics, which is referred to by geoscience researchers as the relationship between two or more systems interacting and influencing each other (Liu et al., 2020; Yin et al., 2021). We used the coupling degree and coordination degree to explore the possible relationship between the innovation environment and transformation development of resource-based cities. The formula is as follows:

$$C = \sqrt{\frac{u_1 \times u_2}{(u_1 + u_2)^2}}, \tag{1}$$

where C represents the coupling degree, u_1 represents the innovation environment index, and u_2 is the transformation development index. Because the coupling degree calculation method may produce the situation where the subsystem development level is low but the coupling degree is high, it cannot truly reflect the overall comprehensive coordination level. Therefore, coupling coordination degree is further introduced:

$$D = \sqrt{C \times T}, \tag{2}$$

$$T = \alpha u_1 + \beta u_2, \tag{3}$$

where D represents the coordination degree; T represents the comprehensive evaluation index of the two systems, and α and β represent the undetermined coefficient, and the sum is 1 (we assumed that the two systems are equally important; both α and β were assigned 1/2). Referring to previous research (Chen and Zhang 2021), the coupling degree and coordination degree were classified, as listed in Table 2.

3.3.3 Panel quantile regression model

In previous studies, scholars mainly focused on the influence of explanatory variables on the conditional expectation of the explained variables, which is actually the central tendency of describing the conditional distribution. However, this study focuses on the influence of explanatory variables on the whole conditional distribution, so the quantile regression model is selected to provide comprehensive information on the conditional distribution to reflect the overall picture of the entire conditional distribution and to explore the influencing factors of the coupling coordination degree between innovation environment and transformation development in resource-based cities. The panel quantile regression model was introduced by Koenker and Bassett Jr. (Koenker and Bassett, 1978) and became a comprehensive method for statistical analysis models in various fields (Koenker and Hallock 2001; Cheng et al., 2021). In this study, a panel quantile regression model was further introduced to estimate the linear relationship between explanatory variables and explained variables under different quantiles (Li et al., 2021; Salari et al., 2021). The traditional ordinary least squares regression model (OLS) can get the conditional expectation between explanatory variables and explained variables (Cheng et al., 2021). That is, it can provide a unique conclusion for all resource-based cities in Gansu Province. However, there are spatial differences in the degree of coupling coordination between the innovation

TABLE 3 Comprehensive scores of resource-based cities' innovation environment from 2009 to 2019.

Year	Jinchang	Baiyin	Wuwei	Zhangye	Pingliang	Qingyang	Longnan	Mean
2009	0.059	0.039	0.062	0.047	0.048	0.042	0.036	0.048
2010	0.066	0.058	0.065	0.084	0.067	0.071	0.047	0.066
2011	0.099	0.063	0.062	0.084	0.057	0.068	0.047	0.068
2012	0.112	0.072	0.067	0.100	0.069	0.085	0.041	0.078
2013	0.125	0.106	0.097	0.148	0.081	0.097	0.046	0.100
2014	0.165	0.145	0.115	0.194	0.090	0.116	0.070	0.128
2015	0.206	0.145	0.136	0.221	0.089	0.130	0.066	0.142
2016	0.211	0.158	0.145	0.235	0.110	0.141	0.081	0.154
2017	0.211	0.150	0.131	0.323	0.095	0.131	0.069	0.159
2018	0.336	0.163	0.340	0.594	0.388	0.134	0.272	0.318
2019	0.346	0.189	0.374	0.620	0.396	0.173	0.371	0.353
Mean	0.176	0.117	0.145	0.241	0.136	0.108	0.104	0.147
Average annual growth rate	19.30%	17.19%	19.78%	29.47%	23.39%	15.26%	26.26%	21.52%

TABLE 4 Comprehensive scores of resource-based cities' transformation development from 2009 to 2019.

Year	Jinchang	Baiyin	Wuwei	Zhangye	Pingliang	Qingyang	Longnan	Mean
2009	0.270	0.092	0.131	0.123	0.068	0.103	0.136	0.132
2010	0.438	0.167	0.121	0.149	0.111	0.100	0.153	0.177
2011	0.428	0.219	0.130	0.222	0.119	0.122	0.178	0.203
2012	0.376	0.228	0.140	0.241	0.138	0.118	0.145	0.198
2013	0.226	0.217	0.153	0.255	0.152	0.153	0.177	0.190
2014	0.292	0.253	0.151	0.269	0.162	0.289	0.185	0.229
2015	0.255	0.249	0.179	0.286	0.190	0.182	0.176	0.217
2016	0.284	0.288	0.183	0.324	0.221	0.197	0.208	0.244
2017	0.312	0.315	0.214	0.413	0.217	0.197	0.214	0.269
2018	0.347	0.338	0.220	0.267	0.221	0.361	0.190	0.278
2019	0.378	0.336	0.259	0.280	0.229	0.190	0.212	0.269
Mean	0.328	0.246	0.171	0.257	0.166	0.183	0.179	0.219
Average annual growth rate	3.44%	13.87%	7.11%	8.57%	12.99%	6.33%	4.56%	7.42%

environment and transformation development of resource-based cities in Gansu Province. Therefore, the quantile regression model is selected to investigate the influence of explanatory variables on cities with different degrees of coupling coordination. The formula is as follows:

$$Quant_{\tau}(Y_{it}X_{it}) = \beta(\tau)X_{it} + \mu_i(\tau) + e_{it}. \quad (4)$$

In the formula, the left side of the equation is the τ conditional quantile of coupling coordination; X_{it} stands for the explanatory variable; τ stands for quantile, ranging from 0 to 1; $\beta(\tau)$ denotes the regression coefficient at the τ quantile; $\mu_i(\tau)$ denotes the individual effect at the τ quantile; e_{it} represents the model disturbance term.

3.4 Data sources

The research period of this study is 2009–2019, and the relevant data involved in this study are mainly obtained from The Statistical Yearbook of Chinese Cities, China Statistical Yearbook, China Urban Economic Yearbook, Gansu Development Yearbook, statistical yearbook of seven resource-based cities, and the Statistical Bulletin of National Economic and Social Development of corresponding cities. Some data were obtained from the Science and Technology Department of Gansu Province's official website (https://kjt.gansu.gov.cn/). The missing data of some indicators in very few years were obtained by interpolation of the existing year's data.

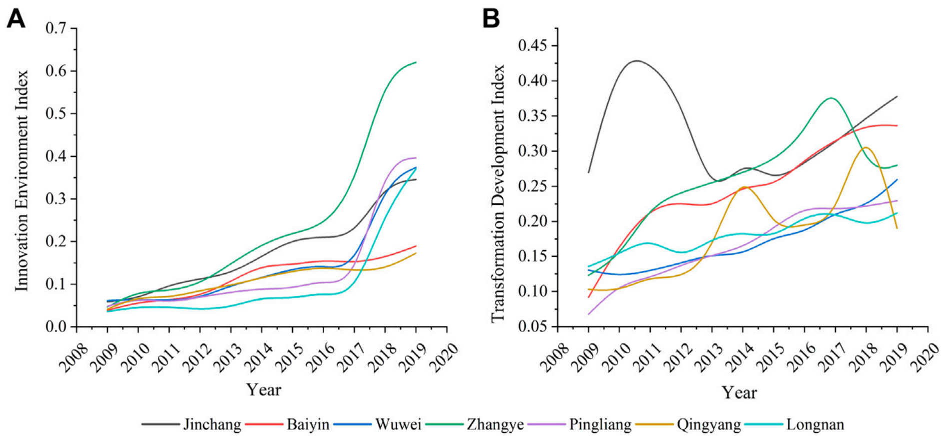

FIGURE 4
Innovation environment and transformation development index of resource-based cities.

4 Results

4.1 Comprehensive evaluation of the innovation environment

On the time scale, the innovation environment index of resource-based cities in Gansu Province has greatly improved from 2009 to 2019, showing a dynamic evolution trend of rapid growth. With the increase of time, the innovation environment index of resource-based cities is unbalanced in the development process, and the gap among cities increases (Figure 4A). This is reflected in the fact that the innovation environment index scores for resource-based cities increased from 0.048 to 0.353 during the study period, and the average annual growth rate reached 21.52%. In 2009, the innovation environment gap of resource-based cities in Gansu province was small and basically in the same development stage. From 2009 to 2017, the growth of the innovation environment in all cities was relatively slow, with Zhangye City having the most significant growth range (0.277) and Longnan City having the smallest growth range (0.033). From 2017 to 2019, except for Qingyang and Baiyin, other cities' innovation environment indexes realized a significant growth trend. The increasing range of Zhangye, Pingliang, and Longnan reached about 0.30, and the growing fields of Jinchang and Wuwei were 0.135 and 0.243, respectively. During this period, the gap in the innovation environment index of various cities gradually widened.

The innovation environment level of resource-based cities in Gansu province is not high, showing the development characteristics of "low level, fast growth." The main reasons for this are that resource-based cities have a low level of economic and social development and relatively insufficient innovation development motivation, and it is challenging to create an improved regional innovation environment in terms of innovation element concentration and input. At the same time, the relatively backward infrastructure environment in the region also puts tremendous pressure on the improvement of the regional innovation environment, which results in the level of innovation development being low for a long time. In recent years, with the deepening of the innovation-driven development strategy, the central and local governments have increased efforts to create a regional innovation environment from various aspects, such as funds and policies, put forward to drive high-quality regional development through scientific and technological innovation, and actively improve regional innovation level so that resource-based cities in Gansu province usher in rapid development opportunities. In terms of regions, Zhangye has been actively implementing the innovation-driven development strategy in recent years, focusing on promoting regional scientific and technological progress and innovation level, and the comprehensive index of regional scientific and technical progress has been steadily increasing, and several high-tech enterprises have been identified as leading in the province, which has dramatically improved the innovation environment of the region in recent years. Baiyin and Qingyang are relatively rich in resources and have a relatively good industrial base, but the lack of diversified capital investment in innovation, science, and technology service environments to be further optimized makes the innovation environment of these two cities show a slow-growth trend. Other cities have also actively accelerated the construction of regional innovation environments and created an excellent regional innovation environment to promote local economic development, industrial transformation, and upgrading. For example, Jinchang has actively constructed an innovation city and demonstration area for the transfer and transformation of scientific and technological achievements, significantly improving the level of the regional innovation environment.

4.2 Comprehensive evaluation of transformation development

On the time scale, there are differences in the transformation development characteristics of resource-based cities from 2009 to 2019. However, in general, they show a fluctuating upward trend (Figure 4B). The score of the transformation development index of resource-based cities increased from 0.132 to 0.269 during the study period, with an average annual growth rate of 7.42%. The transformation development of Baiyin is the fastest, with a numerical increase from 0.092 in 2009 to 0.336 in 2019; its average annual growth rate is the largest; the growth rate is 13.87%. Pingliang followed with an annual growth rate of 12.99%. Wuwei, Zhangye, and Qingyang's average annual growth rates are between 6% and 9%, which is in the middle. The transformation development index of Jinchang presents an "*N*" type, taking 2013 as the timing breakpoint, with the range of change in the early stage being significant and showing a sharp growth followed by a sharp decline and a relatively stable change in the late stage, presenting a trend of fluctuating growth. It is worth noting that Qingyang's transformation development index fluctuates wildly and shows a downward trend after 2018. From the perspective of regional industrial structure, the typical "two, three, one" industrial structure in 2009 gradually changed to the coexistence pattern of "three, two, one" and "two, three, one" in 2019. The proportion of the output value of the primary and secondary industries showed a decreasing trend during the study period, while the ratio of the output value of the tertiary industry increased year by year. With time, the industrial structure of each city gradually changed from a lower level to a higher level. However, the output value of the secondary industry in Jinchang and Qingyang has always been in the first place for a long time, and the urban industrial structure is still dominated by the secondary industry. However, in Jinchang and Qingyang, the proportion of the output value of the secondary industry in the total GDP has always been the first, and the secondary sector still dominates the urban industrial structure.

Although the transformation development of resource-based cities in Gansu province fluctuates wildly, there is steady progress, and the overall trend is rising. The main reason is that, in recent years, resource-based cities in Gansu province have actively implemented innovation-driven strategies and industrial transformation and upgrading strategies, gradually promoting the coordinated development of various industries in the city and the effective use of natural resources, significantly improving the level of transformation development. The level of transformation development in Wuwei, Pingliang, and Longnan has increased steadily, mainly because these cities are relatively less reliant on resources. The industrial structure transformation was achieved earlier, forming an industrial structure development form dominated by the tertiary industry. At the same time, it also promotes rational division of labor and benign interaction of local industries through the centralized utilization and development of resources. Qingyang is rich in mineral, agricultural, and tourism resources, but in recent years, the quality of resources has declined, and mining is challenging. Meanwhile, it has always been an industrial city dominated by the secondary industry, and the urban transformation development fluctuates wildly, and it has entered the critical stage of transformation development. Jinchang has a more extensive, sizeable industrial foundation and good resource endowment, but it is also faced with excessive dependence on resources and a shortage of emerging industry development prominent question. For this, Jinchang puts forward the development idea of "two districts, two cities, and two integration," which cultivates the new driving force of green development, gets rid of the dependence on path development, and speeds up the urban transformation and upgrading.

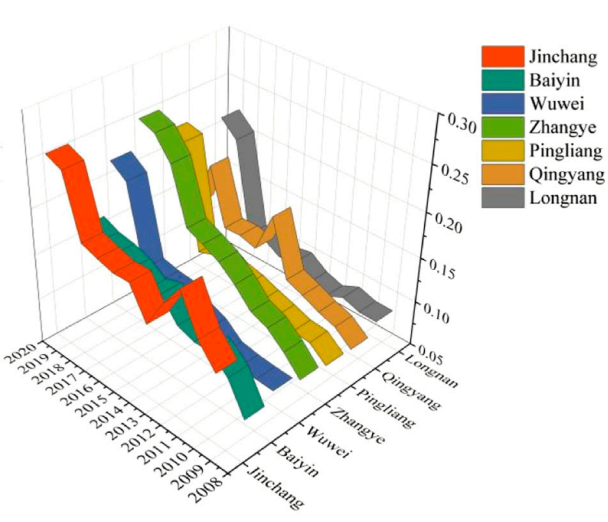

FIGURE 5
Time variation of coupling coordination degree between innovation environment and transformation development of resource-based cities.

4.3 Coupling coordination analysis of innovation environment and transformation development

4.3.1 Coupling coordination degree analysis

The coupling coordination degree between the innovation environment and transformation development of all resource-

TABLE 5 Coupling coordination types of innovation environment and transformation development of resource-based cities in Gansu province from 2009 to 2019.

City	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Jinchang	II-2	II-2	II-2	II-2	II-2	II-2	II-3	II-3	II-2	III-3	III-3
Baiyin	I-3	II-3	II-2	II-2	II-2	II-2	II-2	II-2	II-2	III-2	III-2
Wuwei	I-3	II-3	II-3	II-3	II-3	II-3	II-3	II-3	II-3	II-1	II-1
Zhangye	I-3	II-3	II-2	II-2	II-2	II-3	II-3	II-3	III-3	III-1	III-1
Pingliang	I-3	II-3	II-3	II-3	II-3	II-3	II-2	II-2	II-2	II-1	II-1
Qingyang	I-3	II-3	II-3	II-3	II-3	II-3	II-3	II-3	II-3	II-2	II-3
Longnan	I-3	II-2	II-2	I-2	II-2	II-2	II-2	II-2	II-2	II-3	II-1

SI | MI | LC | MC | HC

Low coupling coordination level ⇨ High coupling coordination level

based cities shows fluctuating growth during the study period. The coupling coordination state changes from a severe imbalance state to a moderate imbalance state. Some cities have changed to a low coordination state, and the overall trend of the continuous optimization process is shown in Figure 5. The starting point of the coupling coordination degree of each city is relatively low, but it shows a significant improvement during the study period. According to the increase in amplitude of coupling coordination degree, the rank from large to small is as follows: Zhangye > Pingliang > Baiyin > Longnan > Wuwei > Jinchang > Qingyang, and the overall increase amplitude was more than 66%, among which, Zhangye increased from 0.195 in 2009 to 0.457 in 2019, and the increase was the first among all cities, reaching 134.22%. Qingyang saw the smallest increase, from 0.181 in 2009 to 0.301 in 2019.

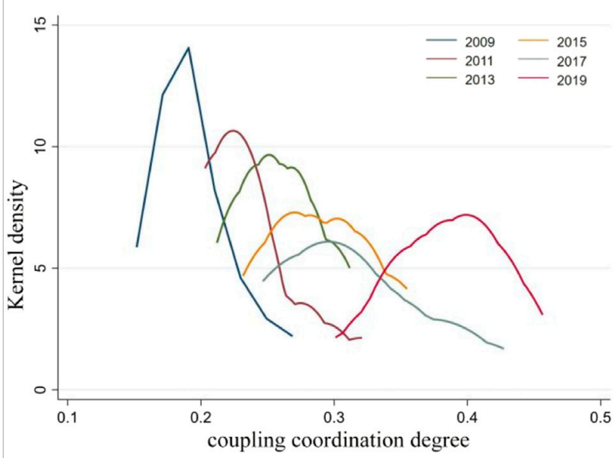

FIGURE 6
Core density curve of the coupling coordination degree between innovation environment and transformation development of resource-based cities in Gansu Province from 2009 to 2019.

4.3.2 Type of coupling coordination and analysis of shortboard

From the perspective of the long-term coordinated development of the system, it is essential to identify the shortcomings and influencing factors of the subsystem development balance. System Science Theory believes that development of composite systems does not require the complete synchronous development of subsystems. When the development difference of subsystems is within a certain buffer zone, it is considered that the development of subsystems tends to be synchronous, showing coordinated development. Based on the abovementioned considerations, this study classifies the coupling coordination degree and coordinated development type between innovation environment and transformation development of resource-based cities (Table 5). It can be seen from the figure that the coupling coordination degree between the innovation environment and transformation development of resource-based cities from 2009 to 2019 is in a moderate imbalance state in most cities. The short board form of coupling coordination between the two shows prominent stage characteristics, which is basically manifested as "synchronous development" or "moderate imbalance-innovation environment lag" development. Jinchang changed from "moderate imbalance-innovation environment lag" to "low coordination". In 2017, Wuwei changed from "moderate imbalance" to "low coordination-transformation development

TABLE 6 Indicator system for the coupled and coordinated development of innovation environment and transformation development in resource-based cities.

Driving factor	Indicator system	Variable code
Economic development	Per capita gross domestic product	*Inecon*
Industrial structure	Proportion of tertiary industry in GDP	*Inind*
Capital investment	Ratio of social fixed asset investment to GDP	*Incap*
Government intervention	Local government expenditure as a percentage of GDP	*Ingov*

lag"; Baiyin changed from "moderate imbalance" to "low coordination" in time series, but it always presents the shortboard of innovation environment lagging development. The main reason lies in the lack of innovation development motivation, innovation environment support, innovation talents, and capital investment in these cities, which leads to slow innovation development of these cities and lagging development of the innovation environment. Due to the limitations of natural resources, traffic location, and social and economic development level, the innovation environment and transformation development of Longnan City started late. Under the condition that the internal and external environment has not changed significantly, the development process of the two is difficult to present long-term synchronous development, and the coordinated development degree of the two is low.

4.3.3 Dynamic evolution characteristics of coupling coordination degree

The Epanechnikov function was used to analyze the dynamic evolution characteristics of the coupling coordination degree between the innovation environment and the transformation development of resource-based cities in Gansu Province from 2009 to 2019. The time sections of 2009, 2011, 2013, 2015, 2017, and 2019 were selected as the research sections. Based on the kernel density distribution curve's distribution location, morphology, and ductility, the dynamic evolution process of the coupling coordination degree from 2009 to 2019 was described in detail, and the kernel density curve was finally drawn (Figure 6). From the distribution position, the kernel density distribution curve shows a prominent right-shift characteristic, which indicates that the coupling coordination degree of innovation environment and transformation development of resource-based cities in Gansu province shows an increasing trend and keeps moving toward a high level. In terms of distribution morphology, the peak value of the kernel density curve experienced a "decline–rise" evolution trend, with the width continuously expanding, indicating that in the early stage of the study, the absolute gap within the region was further expanding. However, the absolute gap was narrowed in the later stage, and the central trend was strengthened. Regarding kurtosis of the kernel density distribution curve, the top of the kernel density curve in 2009 is relatively sharp and has a large kurtosis. The peak values of kernel density curves of coupling coordination degree in each year gradually slow down with time, indicating that the outliers of coupling coordination degree show a reducing trend with the increase of years. Regarding the kernel density distribution curve, the coupling coordination degree presents a "single-peak" distribution. In 2009, the coupling coordination degree was concentrated at about 0.18, and most cities (except Jinchang) were severely imbalanced, consistent with the previous research. In 2019, the coupling coordination degree of all cities was concentrated between 0.37 and 0.45, mainly distributed in Jinchang, Wuwei, Pingliang, and Zhangye.

4.4 Driving factor analysis

4.4.1 Identification of driving factors and variable selection

First, ITD was used to represent the coupling coordination degree between the innovation environment and transformation development of resource-based cities as the explained variable. Based on the abovementioned research and analysis, the influencing factors of the difference in the coupling coordination degree between the innovation environment and transformation development of resource-based cities are selected from four dimensions: economic development, industrial structure, capital investment, and government intervention (Table 6). 1) Economic development. The level of regional economic development is closely related to regional transformation (Wang L. et al., 2021). The level of economic development can affect the quality of the urban innovation environment and the process of transformation development and then affect the degree of synergistic development between the two. So, per capita gross domestic product is selected to represent the level of economic development. 2) Industrial structure. Relevant research results (Wang L. et al., 2021) show that scientific and technological innovation is of great significance to the optimization and upgrading of regional industrial structures, and the upgrading of regional industrial structures also has a significant impact on the improvement of regional scientific and technological innovation level and the quality of regional transformation development. Therefore, the proportion of the tertiary industry in GDP is selected as a proxy

TABLE 7 Quantile regression and OLS regression results of coupled coordination degree driving factors.

OLS regression/quantile	*cons*	*lnecon*	*lnind*	*lnscap*	*lngov*
OLS	−5.922*** (0.430)	0.188*** (0.0311)	0.669*** (0.105)	−0.0937** (0.0402)	−0.269*** (0.100)
0.1 quantile	−5.774*** (0.752)	0.203*** (0.0544)	0.543*** (0.184)	0.105 (0.0703)	−0.270 (0.176)
0.2 quantile	−5.942*** (0.717)	0.191*** (0.0519)	0.615*** (0.175)	0.0608 (0.0671)	−0.351** (0.167)
0.3 quantile	−5.986*** (0.661)	0.179*** (0.0478)	0.660*** (0.162)	0.00466 (0.0618)	−0.389*** (0.154)
0.4 quantile	−5.818*** (0.567)	0.169*** (0.0410)	0.655*** (0.139)	−0.0513 (0.0530)	−0.381*** (0.132)
0.5 quantile	−6.240*** (0.547)	0.184*** (0.0395)	0.731*** (0.134)	−0.0609 (0.0511)	−0.404*** (0.128)
0.6 quantile	−6.185*** (0.485)	0.199*** (0.0351)	0.704*** (0.119)	−0.112** (0.0454)	−0.320*** (0.113)
0.7 quantile	−6.184*** (0.458)	0.233*** (0.0331)	0.654*** (0.112)	−0.161*** (0.0429)	−0.197*** (0.107)
0.8 quantile	−6.425*** (0.386)	0.251*** (0.0279)	0.679*** (0.0945)	−0.163*** (0.0361)	−0.192** (0.0902)
0.9 quantile	−6.479*** (0.897)	0.296*** (0.0649)	0.608*** (0.219)	−0.173*** (0.0839)	−0.0802 (0.209)

variable. 3) Capital investment. Referring to the neoclassical economic theory, an increase in capital investment can promote the improvement of urban economic aggregates, scientific and technological progress, and industrial transformation and upgrading. The social fixed asset investment ratio to GDP is selected as a proxy variable. 4) Government intervention. Government intervention can compensate for inadequacy of the regional economic market and the real economy. Moderate government intervention has significant positive effects on regional economic development, but excessive government intervention will also not be conducive to regional industrial restructuring (Zhang et al., 2018). So, the impact of government intervention on the urban innovation environment and transformation development depends on the situation. From the research perspective of this study, local government expenditure as a percentage of GDP is selected as a proxy variable. The more considerable local government expenditure as a percentage of GDP is, the higher the degree of government intervention is and the lower the role of the market plays. Natural logarithmic processing is carried out to analyze and study the coupling coordination degree between the innovation environment and transformation development of resource-based cities, per capita gross domestic product, and the proportion of tertiary industry in GDP.

4.4.2 Quantile regrression analysis

As can be seen from Table 7, with the increase of quantiles, the quantile regression coefficient of the economic development level shows a trend of first decreasing and then increasing, which indicates that the influence of economic development on both ends of the conditional distribution of coupling coordination degree is more significant than that on the middle part. In other words, improving economic development significantly impacts cities with low or high coupling coordination degree between innovation environment and transformation development, while benefiting the middle part less. Specifically, for every 1% increase in the economic development level of resource-based cities, the level of coupling coordination at the 10, 40, and 90% quantiles increases by 0.203, 0.169, and 0.296%, respectively. The level of industrial structure promotes the improvement of the coupling coordination degrees between the innovation environment and transformation development of resource-based cities to a certain extent at each quantile, and all pass the 1% level test. The regression coefficient showed an increasing trend of fluctuation with the increase of quantile. This indicates that the industrial structure significantly influences the coupling coordination degree, and the influence degree is greater than that of the economic development level. To be specific, the coupling coordination degree of innovation environment and transformation development will increase by 0.543, 0.731, and 0.608% in cities at 10, 50, and 90% of the quantile when the level of industrial structure increases by 1%, indicating that the level of industrial structure will have a strong impact on the coupling coordination degree only within a certain floating range. The level of capital investment has different effects on different quantiles of coupling coordination degree. There is a positive correlation in the low quantiles, but it does not pass the significance test. In high quantiles, there is a negative correlation, and it passes the 1% significance test, the negative effect increased with the increase of quantile. The main reason may be that capital investment is a double-edged sword, and capital investment exceeding actual social demand will lead to slow regional economic development and will not show a linear growth relationship. Driven by capital investment, resource-based cities fail to promote advantages and eliminate disadvantages and fail to combine capital investment with a regional innovation environment and regional transformation development. The influence of government intervention degree on coupling coordination degree is negative, indicating that the stronger the government intervention degree, the worse the coupling coordination degree between innovation environment and transformation development of resource-based cities. As shown in Table 7, government intervention has no significant influence on coupling coordination degree at the 10 and 90% quantile. At the 20%–80% quantile, the regression coefficient increases first and then decreases and reaches its maximum at the 50% quantile, indicating

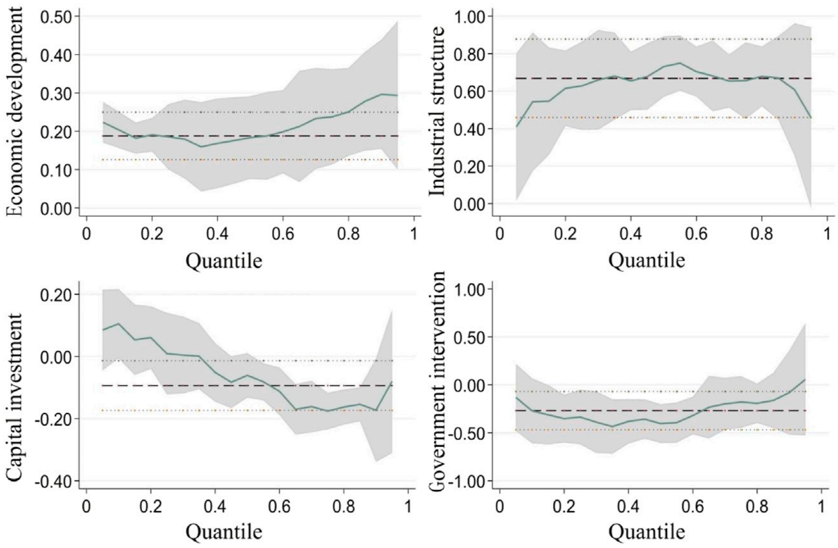

FIGURE 7
Differences in the coupling coordination degree of various explanatory factors in different quantile models.

that government intervention has the strongest influence on cities in the middle of the coupling coordination degree. The main reason is that the innovation environment of resource-based cities itself is low, and the transformation development is relatively tricky. As a result, the degree of government intervention does not match the development conditions of backward resource-based cities, which hinders the coordinated development degree of innovation environments and transformation development of resource-based cities. Figure 7 shows the differences in the coupling coordination degree of each explanatory factor in different quantiles from 2009 to 2019.

5 Discussion

5.1 Policy recommendations

While improving the quality of the innovation environment in resource-based cities, innovation achievements should be transformed and applied to regional transformation development. Based on the current development situation, we should give full play to the advantages of urban resources and selectively develop industries with comparative advantages. At the same time, we will adhere to the direction of green, intelligent, and high-end industries; actively promote the extension of the industrial chain; and speed up the upgrading of traditional industries by centering on the advantages of featured minerals, petroleum, and other resources such as making full use of Jinchang's nonferrous metal new material industry base, Qingyang, Pingliang's oil and coal industry base, Zhangye's big data cloud platform, as well as Baiyin's Lanbai National Independent Innovation Demonstration Zone and Lanbai Science and Technology Innovation Reform Pilot Zone, strengthening the resource-based cities' cooperation with well-known colleges and universities and research institutions, expanding and enhancing strategic emerging industries such as new energy and new materials, and realize their development in a concentrated, clustered, and intensive manner. Relying on regional, national, and provincial cultural tourism resources and cultural brands, we enlarge the comprehensive effect of the cultural tourism industry, promote in-depth integration of cultural tourism, and strive to build strategic pillar industries of cultural tourism to promote high-quality development of resource-based cities in transformation.

While accelerating the transformation development level of resource-based cities, efforts should be made to create a regional innovation environment. All resource-based cities take advantage of their geographical advantages to participate in major infrastructure construction actively and promote internal and external connectivity of infrastructure. For example, Qingyang and Pingliang should accelerate the formation of Ping-Qing metropolitan, actively integrate into the Guanzhong Plain urban agglomeration, and speed up intercity transportation facility interconnection. Longnan should actively integrate into the Chengdu–Chongqing urban agglomeration, deepen inter-provincial cooperation with Chengdu and other places, strengthen regional linkage development, and build new growth points and poles for regional development. Jinchang, Wuwei, Zhangye, and Baiyin actively integrated into the economic circle of Lanzhou and accelerated the planning and construction of high-grade highways and the layout planning of a high-speed intercity railway with Lanzhou, reducing the time cost and logistics cost of all cities and major cities and promoting the coordinated development of innovation environment optimization and industrial structure transformation. Encouraging research institutes and institutions of higher learning to set up research institutes in resource-dependent cities, introducing state-level key laboratories and technology engineering centers, encouraging local governments to build regional bases for technological venture capital and bases for entrepreneurship and innovation of small and medium-sized enterprises and selectively train high-level innovative scientific and technical personnel, and creating good innovation environment for the high-quality development of resource-based city industry transformation.

5.2 Research deficiencies and future research directions

The innovation environment and transformation development of resource-based cities discussed in this study are only discussed from the perspective of coupling coordination, but in fact, the internal relationship between the innovation environment and transformation development of resource-based cities is highly complex. In the future, it is necessary to comprehensively and systematically discuss the deep-seated essential problems existing in developing resource-based cities from a multi-directional and multi-perspective. Whether the relationship between an innovation environment and transformation development in resource-based cities in Gansu Province is universal needs to be tested by using other regions or provinces as examples, and it is necessary to explore further the mechanism of technology, talent, capital, and policy on the transformation development and upgrading development of resource-based cities, as well as the transformation development and upgrading development mode of resource-based cities under the background of the "3,060" dual carbon target.

6 Conclusions

1) During the study period, both the innovation environment index and the transformation development index of resource-based cities increased significantly. The innovation environment index of resource-based cities has been greatly improved, showing a dynamic evolution trend of rapid growth and showing the development characteristics of "low level, fast growth". There are differences in the characteristics of transformation development resource-based cities, but on the whole, it shows a trend of increasing fluctuation. Although the fluctuation is significant, there is steady progress.
2) The coupling coordination degree of innovation environment and transformation development in various resource-based cities was significantly developed during the study period. The coupling coordination state shows the transformation from the severe imbalance state to the moderate imbalance state, and some cities have changed to the low coordination state. The overall trend is to optimize the process continuously. The process of the coupling coordination degree between innovation environment and transformation development in resource-based cities is not synchronous, and the short form of the coupling coordination between the two generally shows obvious stage characteristics, which is manifested as "synchronous development" or "moderate imbalance—innovation environment lag" development. The kernel density distribution curve showed an obvious right-shift characteristic, and the coupling coordination degree showed an increasing trend and continuously advanced to a high level.
3) Improving economic development significantly impacts the innovation environment and transformation development of resource-based cities with low and high coupling coordination degrees. Industrial structure promotes the coupling coordination between an innovation environment and the development of resource-based cities to a certain extent at each decimal point. Capital investment has different effects on different quartiles of coupling coordination degree, with positive correlation in low quartiles and negative correlation in high quartiles. The stronger the government's intervention degree, the worse the coupling coordination degree between the innovation environment and transformation development of resource-based cities.

Data availability statement

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

Author contributions

Junfeng Yin: conceptualization, methodology, software, visualization, writing—original draft, and writing—review and editing. Peiji Shi: conceptualization, writing review, and supervision. Haoyuan Feng, Huali Tong, and Meng Chao: writing—review and modified language.

Funding

This work was supported by the National Natural Science Foundation of China (Grant No. 41771130).

Conflict of interest

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Appio, F. P., Frattini, F., Petruzzelli, A. M., and Neirotti, P. (2021). Digital transformation and innovation management: A synthesis of existing research and an agenda for future studies. *J. Prod. Innov. Manage.* 38, 4–20. doi:10.1111/jpim.12562

Balsa-Barreiro, J., Li, Y., Morales, A., and Pentland, A. S. (2019). Globalization and the shifting centers of gravity of world's human dynamics: Implications for sustainability. *J. Clean. Prod.* 239, 117921–117923. 117917. doi:10.1016/j.jclepro.2019.117923

Chen, W., Shen, Y., and Wang, Y. (2018). Evaluation of economic transformation and upgrading of resource-based cities in Shaanxi province based on an improved TOPSIS method. *Sustain. Cities Soc.* 37, 232–240. doi:10.1016/j.scs.2017.11.019

Chen, Y., and Zhang, D. (2021). Multiscale assessment of the coupling coordination between innovation and economic development in resource-based cities: A case study of northeast China. *J. Clean. Prod.* 318, 128597. doi:10.1016/j.jclepro.2021.128597

Cheng, C., Ren, X., Dong, K., Dong, X., and Wang, Z. (2021). How does technological innovation mitigate CO2 emissions in OECD countries? Heterogeneous analysis using panel quantile regression. *J. Environ. Manag.* 280, 111818. doi:10.1016/j.jenvman.2020.111818

Council, T. S. (2013). *The plan for the sustainable development of resource-based cities in China (2013–2020). China.* Available online at: http://www.gov.cn/zwgk/-12/03/content_2540070.htm.

Deng, X., Liang, L., Wu, F., Wang, Z., and He, S. (2022). A review of the balance of regional development in China from the perspective of development geography. *J. Geogr. Sci.* 32 (1), 3–22. doi:10.1007/s11442-021-1930-0

Dong, L., Longwu, L., Zhenbo, W., Liangkan, C., and Faming, Z. (2021). Exploration of coupling effects in the economy–society–environment system in urban areas: Case study of the ebeiu river delta urban agglomeration. *Ecol. Indic.* 128, 107858. doi:10.1016/j.ecolind.2021.107858

Doytch, N., and Narayan, S. (2016). Does FDI influence renewable energy consumption? An analysis of sectoral FDI impact on renewable and non-renewable industrial energy consumption. *Energy Econ.* 54, 291–301. doi:10.1016/j.eneco.2015.12.010

Fang, C., Ma, H., Wang, Z., and Li, G. (2014). The sustainable development of innovative cities in China: Comprehensive assessment and future configuration. *J. Geogr. Sci.* 24 (6), 1095–1114. doi:10.1007/s11442-014-1141-z

Gong, C. (2021). Government R&D investment, knowledge accumulation, and regional innovation capability: Evidence of a threshold effect model from China. *Complexity* 2021, 8963237. doi:10.1155/2021/8963237

Hasan, I., and Tucci, C. L. (2010). The innovation–economic growth nexus: Global evidence. *Res. Policy* 39 (10), 1264–1276. doi:10.1016/j.respol.2010.07.005

Hoekveld, J. J. (2012). Time-space relations and the differences between shrinking regions. *Built Environ.* 38 (2), 179–195. doi:10.2148/benv.38.2.179

Jiang, Z., Lyu, P., Ye, L., and wenqian Zhou, Y. (2020). Green innovation transformation, economic sustainability and energy consumption during China's new normal stage. *J. Clean. Prod.* 273, 123044. doi:10.1016/j.jclepro.2020.123044

Jin, W., Zhang, H.-q., Liu, S.-s., and Zhang, H.-b. (2019). Technological innovation, environmental regulation, and green total factor efficiency of industrial water resources. *J. Clean. Prod.* 211, 61–69. doi:10.1016/j.jclepro.2018.11.172

Koenker, R., and Bassett, G., Jr. (1978). Regression quantiles. *Econometrica* 46, 33–50. doi:10.2307/1913643

Koenker, R., and Hallock, K. F. (2001). Quantile regression. *J. Econ. Perspect.* 15 (4), 143–156. doi:10.1257/jep.15.4.143

Kuai, P., Li, W., Cheng, R., and Cheng, G. (2015). An application of system dynamics for evaluating planning alternatives to guide a green industrial transformation in a resource-based city. *J. Clean. Prod.* 104, 403–412. doi:10.1016/j.jclepro.2015.05.042

Li, B., and Dewan, H. (2017). Efficiency differences among China's resource-based cities and their determinants. *Resour. Policy* 51, 31–38. doi:10.1016/j.resourpol.2016.11.003

Li, K., and Lin, B. (2018). How to promote energy efficiency through technological progress in China? *Energy* 143, 812–821. doi:10.1016/j.energy.2017.11.047

Li, H., Long, R., and Chen, H. (2013). Economic transition policies in Chinese resource-based cities: An overview of government efforts. *Energy Policy* 55, 251–260. doi:10.1016/j.enpol.2012.12.007

Li, H., Lo, K., and Zhang, P. (2020). Population shrinkage in resource-dependent cities in China: Processes, patterns and drivers. *Chin. Geogr. Sci.* 30 (1), 1–15. doi:10.1007/s11769-019-1077-4

Li, W., Elheddad, M., and Doytch, N. (2021). The impact of innovation on environmental quality: Evidence for the non-linear relationship of patents and CO2 emissions in China. *J. Environ. Manag.* 292, 112781. doi:10.1016/j.jenvman.2021.112781

Liu, H., Fang, C., and Fang, K. (2020). Coupled human and natural cube: A novel framework for analyzing the multiple interactions between humans and nature. *J. Geogr. Sci.* 30 (3), 355–377. doi:10.1007/s11442-020-1732-9

Liu, E. N., Wang, Y., Chen, W., Chen, W., and Ning, S. (2021). Evaluating the transformation of China's resource-based cities: An integrated sequential weight and TOPSIS approach. *Socio-Economic Plan. Sci.* 77 (17), 101022. doi:10.1016/j.seps.2021.101022

Martinez-Fernandez, C., Audirac, I., Fol, S., and Cunningham-Sabot, E. (2012). Shrinking cities: Urban challenges of globalization. *Int. J. Urban Reg. Res.* 36 (2), 213–225. doi:10.1111/j.1468-2427.2011.01092.x

Maurseth, P. B., and Verspagen, B. (2002). Knowledge spillovers in ebei: A patent citations analysis. *Scand. J. Econ.* 104 (4), 531–545. doi:10.1111/1467-9442.00300

Miao, C., Fang, D., Sun, L., Luo, Q., and Yu, Q. (2018). Driving effect of technology innovation on energy utilization efficiency in strategic emerging industries. *J. Clean. Prod.* 170, 1177–1184. doi:10.1016/j.jclepro.2017.09.225

Porter, M. E. (1991). Towards a dynamic theory of strategy. *Strateg. Manag. J.* 12 (S2), 95–117. doi:10.1002/smj.4250121008

Sachs, D. J., and Warner, M. A. (2001). Natural resource and economic development: The curse of natural resources. *Eur. Econ. Rev.* 46, 827–838. doi:10.1016/s0014-2921(01)00125-8

Sachs, J. D., and Warner, A. (1995). *Natural resource abundance and economic growth*. USA: National bureau of economic research Cambridge, Mass.

Salari, T. E., Roumiani, A., and Kazemzadeh, E. (2021). Globalization, renewable energy consumption, and agricultural production impacts on ecological footprint in emerging countries: Using quantile regression approach. *Environ. Sci. Pollut. Res.*, 1–15.

Shao, W., Yin, Y., Lu, S., and Taghizadeh-Hesary, F. (2021). Analysis of the upgrading effect of the industrial structure of environmental regulation—evidence from 113 cities in China. *Front. Environ. Sci.* 28 (36), 49627–49641. doi:10.3389/fenvs.2021.692478

Sun, D., Lu, D., Li, Y., Zhou, L., and Zhang, M. (2017). Energy abundance and China's economic growth: 2000–2014. *Chin. Geogr. Sci.* 27 (5), 673–683. doi:10.1007/s11769-017-0901-y

Wang, L., Su, M., Kong, H., and Ma, Y. (2021a). The impact of marine technological innovation on the upgrade of China's marine industrial structure. *Ocean. Coast. Manag.* 211, 105792. doi:10.1016/j.ocecoaman.2021.105792

Wang, Q., Liu, M., Tian, S., Yuan, X., Ma, Q., and Hao, H. (2021b). Evaluation and improvement path of ecosystem health for resource-based city: A case study in China. *Ecol. Indic.* 128, 107852. doi:10.1016/j.ecolind.2021.107852

Xie, W., Yan, T., Xia, S., and Chen, F. (2020). Innovation or introduction? The impact of technological progress sources on industrial green transformation of resource-based cities in China. *Front. Energy Res.* 8, 301. doi:10.3389/fenrg.2020.598141

Xing, M., and Luo, F. (2018). Comparative study on the optimization path of industrial value chain in China's resource-based cities. *Sustainability* 10 (5), 1338. doi:10.3390/su10051338

Yan, D., Kong, Y., Ren, X., Shi, Y., and Chiang, S. (2019). The determinants of urban sustainability in Chinese resource-based cities: A panel quantile regression approach. *Sci. total Environ.* 686, 1210–1219. doi:10.1016/j.scitotenv.2019.05.386

Yin, J., Liu, H., Shi, P., and Zhang, W. (2021). Exploring coupling relationship between urban connection and high-quality development using the case of ebeiu-xining urban agglomeration. *Complexity* 2021, 1–12. doi:10.1155/2021/9933582

Yu, C., Li, H., Jia, X., and Li, Q. (2015). Improving resource utilization efficiency in China's mineral resource-based cities: A case study of chengde, ebei province. *Resour. Conservation Recycl.* 94, 1–10. doi:10.1016/j.resconrec.2014.10.013

Yu, C., de Jong, M., and Cheng, B. (2016). Getting depleted resource-based cities back on their feet again–the example of Yichun in China. *J. Clean. Prod.* 134, 42–50. doi:10.1016/j.jclepro.2015.09.101

Zhang, H., Xiong, L., Li, L., and Zhang, S. (2018). Political incentives, transformation efficiency and resource-exhausted cities. *J. Clean. Prod.* 196, 1418–1428. doi:10.1016/j.jclepro.2018.06.093

Zhang, H., Shen, L., Zhong, S., and Elshkaki, A. (2020). Coal resource and industrial structure nexus in energy-rich area: The case of the contiguous area of Shanxi and Shaanxi Provinces, and Inner Mongolia Autonomous Region of China. *Resour. Policy* 66, 101646. doi:10.1016/j.resourpol.2020.101646

Zhang, Q., and Brouwer, R. (2020). Is China affected by the resource curse? A critical review of the Chinese literature. *J. Policy Model.* 42 (1), 133–152. doi:10.1016/j.jpolmod.2019.06.005

Zhu, D., Li, T., Zhang, C., Ren, Y., Wang, H., and Duan, X. (2021). Role of internet of things technology in promoting the circulation industry in the transformation of a resource-based economy. *Wirel. Commun. Mob. Comput.* 2021, 7124086. doi:10.1155/2021/7124086

frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 18 October 2022
DOI 10.3389/fenvs.2022.955954

Check for updates

OPEN ACCESS

EDITED BY
Martin Siegert,
Imperial College London,
United Kingdom

REVIEWED BY
Morteza Maleki,
Georgia Institute of Technology,
United States
Jose Balsa-Barreiro,
Massachusetts Institute of Technology,
United States

*CORRESPONDENCE
Yongchun Sun,
zixiaoronger@163.com

SPECIALTY SECTION
This article was submitted to
Environmental Economics and
Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 29 May 2022
ACCEPTED 03 October 2022
PUBLISHED 18 October 2022

CITATION
Sun Y (2022), Environmental regulation, agricultural green technology innovation, and agricultural green total factor productivity.
Front. Environ. Sci. 10:955954.
doi: 10.3389/fenvs.2022.955954

Environmental regulation, agricultural green technology innovation, and agricultural green total factor productivity

Yongchun Sun *

School of Economics and Management, Guangzhou Nanyang Polytechnic College, Guangzhou, China

In order to promote the green transformation of agricultural development, we used a partial linear function coefficient panel model to measure the impact of environmental regulations in 30 provinces and cities in China on agricultural green technology innovation and agricultural green total factor productivity. The advantage of this model is that it can take into account the heterogeneity of regional economic development levels, that is, by introducing variables that are functions of regional economic development levels as coefficients of environmental regulation. The research results show that: when the level of regional economic development is low, environmental regulation has a limited impact on agricultural green technology innovation and agricultural green total factor productivity, but as the level of regional economic development gradually increases, environmental regulation has a more significant impact on the two. And environmental regulation has a greater impact on agricultural green total factor productivity than on agricultural green technology innovation. Based on the research results, policy recommendations are suggested.

KEYWORDS

agricultural green total factor productivity, agricultural green technology innovation, environmental regulation, agricultural green transformation, partial linear function coefficient panel model

1 Introduction

The rapid development of China's agriculture is also accompanied by the emergence of environmental problems (Zhou and Li, 2021). An article in China Guangming Daily reported, The Institute of Geographical Sciences and Natural Resources Research released the research results of its Key Laboratory of Land Surface Pattern and Simulation (Xu et al., 2020), there is a 21.49 percent soil heavy metal spot in the main grain-producing areas of China, according to the Chinese Academy of Sciences. There were 13.97% of moderate pollution, 2.50% of heavy pollution, and 5.02% of very heavy pollution. Considering that soil pollution is often irreversible, the future cost of treatment and ecological pressure will be considerable. In this context, over the course of the "13th Five-Year Plan," the word "green" was identified as the "development concept" for the first

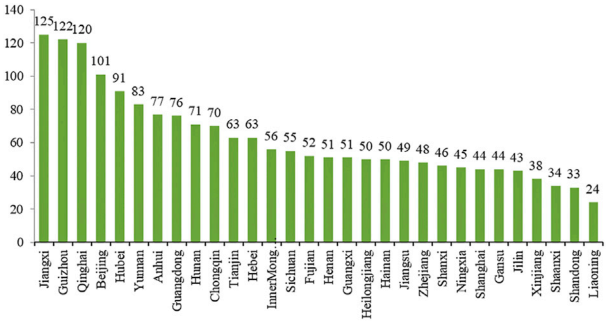

FIGURE 1
The total number of environmental vocabularies in the work reports of the provincial governments from 2009 to 2019.

time, and one of the key sectors to achieve green growth Agriculture and rural areas are the top priority. General Secretary Xi Jinping has also repeatedly emphasized the need to fully realize the green transformation of agricultural development. In September 2021, China's first special plan for agricultural green development was issued by six national ministries and commissions, the "14th Five-Year Plan for National Agricultural Green Development," Showing China's determination and courage to fully realize the comprehensive green transformation of agricultural development. At present, China's economy has progressed from a stage of high-speed growth to a stage of high-quality development (Hao et al., 2021; Rauf et al., 2021; Abbasi et al., 2022). China has been highly valued by government departments in terms of green development. Figure 1 is a summary of the environmental vocabulary that appeared in the work reports of the provincial governments in China from 2009 to 2019. Low carbon, "carbon dioxide," "sulfur dioxide," "chemical oxygen demand," "environmental protection," "environmental protection," "emission reduction," "air," "green," "energy consumption," "pollution," "Ecology," "Pollution," a total of 15. According to Figure 1, the country's attention to the environment is increasing overall. While lamenting the country's urgent attention to green development, it is impossible not to think deeply about how to achieve the coordinated development of economic growth and environmental protection (Du et al., 2021). Balsa-Barreiro et al. (2019) can help us realize how was coupled the economic model of China with the emissions, and how in the last years these factors were decoupled. In this study, the study examined the location of the centers of gravity of four basic indicators over the period 1960–2016: GDP, CO_2 emissions, total population, and urban population. As an important sector of green development, agriculture and rural areas, in the event that agricultural economic growth and ecological environment are coordinated, the green transformation of China's agricultural development relies heavily on environmental regulation.

Many previous studies by scholars have confirmed the important role of environmental regulation in the environmental field, but most of the literature studies only focus on a single indicator, the role of environmental regulation in promoting agricultural development's green transformation comes from agricultural green technology innovation and agricultural green total factor productivity (Yu et al., 2022). Therefore, the paper integrates environmental regulation, agricultural green technology innovation, and agricultural green total factor productivity into a research framework, which enriches the current research and is of great significance.

In agricultural production, green technology innovation reduces pollution emissions from fossil fuels and increases the use of clean energy. Green total factor productivity balances agricultural production efficiency without exceeding environmental carrying capacity, this indicator measures the transformation of China's agricultural green development. However, environmental regulation is controversial in the research on agricultural green technology innovation and agricultural green total factor productivity. The specific manifestations are as follows.

At present, Academic circles disagree on the impact of environmental regulation on green innovation (Liu et al., 2022). Some scholars such as (Porter, 1991) believe that environmental regulation can enable enterprises to avoid penalties due to environmental problems, update technical equipment, and expand R&D investment. As a result, many scholars have confirmed the "Porter Hypothesis" (Pang et al., 2019; Yu et al., 2019; Zhou et al., 2019; Zhang et al., 2020; Xie et al., 2021). Several scholars believe that environmental regulation is important, it makes enterprises increase their investment in environmental inspections and fines at a limited cost, which will squeeze corporate resources, reduce corporate R&D investment, and inhibit regional green innovation (Gollop and Roberts, 1983; Grey and Shadbegian, 2003; Ambec et al., 2013; Li et al., 2019).

Among the many factors affecting agricultural green total factor productivity, one of the simplest and most straightforward ways to address the issue of excessive factor use and the externality of environmental damage is through environmental legislation. There is conflicting evidence in the literature regarding whether environmental regulation affects agricultural green total factor productivity, and if so, whether it has a positive or negative impact. According to some studies (Cochard et al., 2005; Shadbegian and Gray, 2005), environmental regulation will have a negative impact on agricultural green total factor productivity. However, according to other studies (Jorge

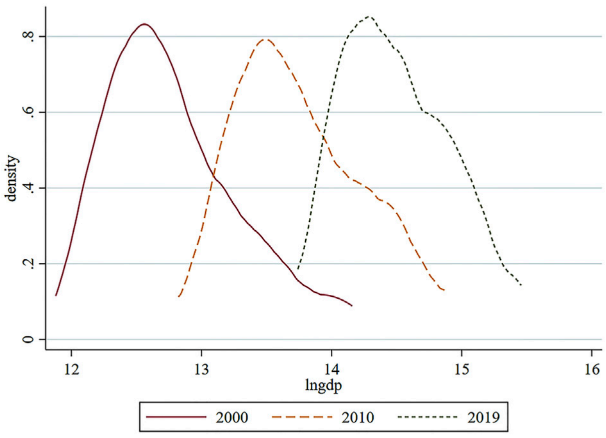

FIGURE 2
Kernel density evolution of lnGDP in various provinces.

et al., 2015; Ye et al., 2018), environmental regulation is conducive to improving agricultural green total factor productivity. Still other researchers noted that environmental regulation did not significantly affect agricultural green TFP (Liang et al., 2012a).

Secondly, most of the research literature on environmental regulation only regards environmental regulation as a control variable in the empirical test, and pays no attention to how the internal environmental regulation system affects the production of green total factor in agriculture; and the existing literature only uses linear regression. The model is used to test the relationship between the two. In fact, with the dynamic change of regulatory intensity, environmental regulations' effects on agricultural green TFP may also exhibit nonlinear traits. However, both the linear regression model and the nonlinear model research may be biased. Therefore, this paper uses a partial linear function coefficient model that takes into account both linear and nonlinear characteristics to describe the method by which environmental legislation affects agricultural development's transition to a more sustainable model.

In addition, restricted by the level of economic development, there may be regional variations in how environmental legislation affects the development of agricultural green technologies and the productivity of agricultural green total factors (Liu et al., 2021a). Specifically, Investment in resources is crucial for the development of agricultural green technology. For areas with low levels of economic growth, due to limited resources, innovation and research and development will face greater challenges. Conversely, there are more resources and expertise available for R&D in areas with higher economic development levels. In addition, agricultural machinery is a necessary material and equipment for agricultural modernization, but it will also cause energy consumption and increase agricultural carbon emissions due to its large-scale use. Therefore, in order to reduce pollution, ER will inevitably affect the efficiency of agricultural production. In areas with low economic development levels, enterprises producing these machines may be squeezed out of the market due to ER, It will ultimately have an impact on the increase in productivity of the green total factor in agriculture (Yu et al., 2022). Figure 2 depicts the evolution of the real PGDP per capita log distribution across Chinese provinces. As can be seen from Figure 2, the differences in the level of economic development among provinces are quite significant however, the level of regional economic development as a whole is rising. Therefore, considering the different levels of economic development in different provinces, In this research, the heterogeneity of ER's effects on the development of agricultural green technologies and agricultural green total factor productivity will be examined (Yu et al., 2022).

The following is a summary of the study's major contributions: First, using the two key indicators of agricultural green technology innovation and agricultural green total factor productivity (Yu et al., 2022), this paper thoroughly analyzes the impact of agricultural environmental regulation (ER) on the green development of agriculture in 30 provinces and cities in China (Zhou and Li, 2022), which contributes to more Clear and more comprehensive understanding of the important role of ER in the transition of agricultural development to green. This is not studied in the previous literature and enriches the current research. Secondly, this paper examines the hypothesis that whether the favorable Different levels of regional economic growth will have different effects on how environmental regulations affect the green transition of agricultural production, which is rarely studied in the current agricultural literature. Third, In order to examine the nonlinear link between ER and two green development indicators, this paper makes use of Mr. Du Kerui's partial linear function coefficient panel model. The model can guard against model miscalculation and improve the accuracy of the estimation outcome.

The following describes the paper's organizational structure: the introduction is the first section, which introduces the research background, etc.; in the second part, it summarizes the related literature of agricultural environmental regulation and its relationship with agricultural green technology innovation and agricultural green total factor productivity (Yu et al., 2022). Section 3 provides a description of the models, variables, and data sources used in this study. Analyses and empirical findings are presented in Section 4. Conclusion and policy repercussions are presented in Section 5.

2 Literature review

2.1 Research on environmental regulation and agricultural green technology innovation

Du et al. (2021) think that many scholars at home and abroad have confirmed the positive role of environmental regulation in the field of energy and environment. Such as green efficiency (Galloway and Johnson, 2016; Curtis and Lee, 2019; Wang et al., 2019; Su and Zhang, 2020; Du et al., 2021), carbon emissions (Zhao et al., 2020a; Zhao et al., 2020b; Wang and Wei, 2020; Du et al., 2021), Environmental regulation plays a beneficial role in the fields of energy and the environment, according to numerous academics domestically and internationally (Li et al., 2022). For instance, carbon emissions (Zhao et al., 2020a; Zhao et al., 2020b; Wang and Wei, 2020); green efficiency (Curtis and Lee, 2019; Wang et al., 2019; Su and Zhang, 2020; Du et al., 2021); energy efficiency (Liu et al., 2018).

In different studies, Different studies have come to different findings about how environmental regulation affects technological innovation. Many academics think that environmental regulation can encourage innovation. For instance, researchers (Brunnermeier and Cohen, 2003) demonstrate that greater environmental innovation will result from an increase in pollution reduction spending; (Turken et al., 2020) believes that due to the promotion effect of green technology, Industry should prioritize investing in green technology. However, some scholars believe that environmental regulation can only take effect under certain conditions. According to Borsatto and Amui (2019), there is no consistent connection between environmental legislation and green innovation. According to Song et al. (2018), businesses can only attempt to raise the caliber of their workforce and continue to pursue green innovation by putting strong environmental rules into place.

Based on the above literature research, it is evident that there is ongoing disagreement on the research finding regarding the impact of environmental regulation on the development of green technologies (Wang and Yan, 2022). However, for the green technology innovation in the agricultural field, this indicator has not been utilized by any academics to evaluate the success of agricultural green development.

2.2 Environmental regulation and agricultural green total factor productivity

The Chinese governments have developed a number of environmental regulation measures to achieve the green transformation of agricultural development in line with the idea of agricultural green development. (Picazo-Tadeo et al., 2011; Deng and Gibson, 2019; Liu et al., 2021b; Iqbal et al., 2021; Irfan et al., 2021; Jiang, 2022). At present, the factors impacting agricultural green total factor productivity have been the subject of much investigation by both domestic and foreign academics. Agricultural pollution is one of many influencing elements that greatly jeopardize agricultural ecological efficiency (Irfan and Ahmad, 2022).

The most immediate and efficient factor is environmental regulation. However, there are not many studies looking at the effects of environmental regulation on agricultural green TFP. Moreover, there is conflicting evidence in the available research on the link between environmental legislation and agricultural green TFP. A fair agricultural environmental regulation, according to certain studies, can increase agricultural green total factor productivity (Zhan and Xu, 2019), and while believe that the impact of agricultural environmental regulation on agricultural green total factor productivity is that with the continuous increase of the threshold value (Yu et al., 2022), some scholars (Liang et al., 2012b) believe that the impact of ER on agricultural green total factor productivity is negative, the negative impact factors are gradually reduced (Yu et al., 2022). Environmental regulation is frequently used as a control variable in literature. This study examines environmental control as a significant explanatory factor.

In addition, the selection of environmental regulation variables varies greatly among different scholars. For example, the number of agricultural environmental protection policies is used to measure environmental regulation; (Zhan and Xu, 2019) using agricultural command and control (Xie et al., 2021) use agricultural carbon emissions and pollution emissions to measure. It is clear that there is still a significant gap in the literature on the two's relationship.

3 Research models, variables, and data

3.1 Research model

In order to study the impact of environmental regulation ER on agricultural green total factor productivity and agricultural green innovation, this paper first considers the linear model shown below

$$Y_{it} = \gamma X_{it-1} + \alpha' Z_{it-1} + \delta_i + \mu_{it} \tag{1}$$

Among them, X_{it-1} represents the ER level of environmental regulation in the ith city at t − 1. In order to consider the lag of environmental regulation, the key explanatory variable ER is lagged by one period. The variable Z_{it-1} is a control variable, in order to avoid being affected by t − 1 At the same time, the influence of explanatory variables makes the empirical results biased, so the control variables are also lagged by one period. δ_i

represents the unobserved individual effect and μ_{it} is the random error assumed to be i.i.d (0, σ_μ^2).

However, considering that the impact of ER on agricultural green development may be affected by the level of economic development, most scholars may construct an interaction term between the level of economic development and environmental regulation ER, but this strategy may lead to model errors and estimation biases. For details, refer to (Du et al., 2020a; Du et al., 2020b; Du et al., 2021). Therefore, this paper introduces the variable coefficient U_{it-1} for the model. U_{it-1} specifically refers to the level of regional economic development in this paper, that is, PGDP. Part of the variable coefficient panel model is as follows:

$$Y_{it} = \gamma(U_{it-1})X_{it-1} + \alpha' Z_{it-1} + \delta_i + \mu_{it} \tag{2}$$

The heterogeneity effect of different regional economic development levels on my country's agricultural green transformation is expressed as $\gamma(U_{it-1})$. Based on the nonparametric kernel method, (An et al., 2016) further extended the model, and extended the cross-sectional model to a partial linear variable coefficient panel data model with fixed effects using the series method. Specifically, please refer to the research methodology (An et al., 2016; Du et al., 2021).

First, use the difference to eliminate the fixed effect δ

$$\Delta Y_{it} = \Delta\left(\gamma(U_{it-1})X_{it-1}\right) + \alpha' Z_{it-1} + \Delta\mu_{it} \tag{3}$$

Second, the substitution function coefficients $\gamma(U_{it-1})$ are approximated by a linear combination of the k basis functions:

$$p(U_{it-1})'\theta = \left[p_1(U_{it-1}), \cdots, p_k(U_{it-1})\right]\begin{bmatrix}\theta_1\\ \vdots \\ \theta_k\end{bmatrix} \tag{4}$$

where $p(U_{it-1})$ is a $k \times 1$ basis function, and θ is an unknown parameter of k × 1. When k is large enough, there is a linear combination of $p_i(U_{it-1})$ that can approximately replace any smoothing coefficient $\gamma(U_{it-1})$, and the mean square error MSE is the smallest. Eq. 4 can be rewritten as:

$$\Delta Y_{it} = \Delta(X_{it-1}p(U_{it-1})'\theta + \alpha'\Delta Z_{it-1} + \Delta\varepsilon_{it} \tag{5}$$

Among them, the error term $\Delta\epsilon_{it} = \Delta\mu_{it} + \Delta(\gamma(U_{it-1})X_{it-1}) - \Delta(X_{it-1}p(U_{it-1})'\theta)$.

Finally, the least squares estimate:

$$\left(\hat{\alpha}', \hat{\theta}'\right) = \left[\Delta\tilde{Z}'\Delta\tilde{Z}\right]^{-1}\Delta\tilde{Z}'\Delta\tilde{Y} \tag{6}$$

in, $$\Delta\tilde{Y} = \begin{bmatrix}\Delta Y_{12}\\ \vdots \\ \Delta Y_{NT}\end{bmatrix}, \Delta\tilde{Z} = \begin{bmatrix}\Delta Z_{11}, \Delta(X_{11}p(U_{11}))\\ \vdots \\ \Delta Z'_{N(T-1)}, \Delta(X_{N(T-1)}p(U_{N(T-1)})\end{bmatrix}$$

Furthermore, the coefficient function γ(•) is estimated as:

$$\hat{\gamma}(U_{it-1}) = p(U_{it-1})'\hat{\theta} \tag{7}$$

Therefore, based on the research of (An et al., 2016) and with reference to (Du et al., 2020c) to estimate the partial linear panel model of the function coefficients, the Stata software package estimates the following models. The specific estimation equation in this paper is set as follows with reference to the reference model Eq. 2:

$$\ln GTFP_{it} = \gamma(lnPGDP_{it-1}) \times ER_{it-1} + \alpha' Z_{it-1} + \delta_i + \mu_{it} \tag{8}$$

$$\ln GP_{it} = \gamma(lnPGDP_{it-1}) \times ER_{it-1} + \alpha' Z_{it-1} + \delta_i + \mu_{it} \tag{9}$$

Among them, the following table i and t are the corresponding 30 provinces in China and the corresponding year, t − 1 is the corresponding year with a lag period, there are two explained variables in this paper, namely agricultural green total factor productivity (GTFP) and agricultural green For innovative GP, considering the lag of the impact of environmental regulation on ER, the key explanatory variable ER lag one period is expressed as ER_{it-1}, And $\gamma(lnPGDP_{it-1})$ is the function coefficient of ER_{it-1}. The variable Z_{it-1} is the control variable, including HUMAN, EG, DR, TRA, MAC, and IND, Which are expressed as: the level of rural human capital, the intensity of environmental pollution control, the degree of disaster, the density of agricultural machinery, the gap between urban and rural income distribution, and the level of rural economic openness. Considering the consistency of the explanatory variables, there is also a lag of one period.

3.2 Research variables

3.2.1 Explained variable

The BMLPI (Biennial Malmquist-Luenberger productivity index) proposed by Pastor et al. (2011), Wang (2011) is used to measure the agricultural green total factor productivity of the explanatory variables in this paper, that is, the two-period Manquist-Luenberger productivity index. GMLPI (Global MLPI), that is, the similarity of the global Manquist-Luenberger productivity index, is to solve the problem of unfeasible solutions for measuring green productivity with undesired output. Although GMLPI can solve the problem of infeasible solutions, when new data is added, for example, when data is added every year, the entire frontier needs to be rebuilt, and the overall technology changes accordingly. And miscellaneous, the model calculation number is not stable. However, BMLPI is different. It is a productivity index that can be used as a production technology to calculate efficiency and variables every two periods. Therefore, there is no need to repeat the calculation for each additional year of data. The already calculated data will not change, only the newly added data will be calculated. Once, its additional advantage is that it can take into account technological regressions, which are much looser than the harsh assumptions of previous models. Therefore, the BMLPI model formula for calculating agricultural green total factor productivity based on DDF is as follows:

$$BML_t^{t+1} = \frac{1+\vec{D}_O^B(x^t, y^t, b^t; y^t, -b^t)}{1+\vec{D}_O^B(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}$$
$$= \left[\frac{1+\vec{D}_O^t(x^t, y^t, b^t; y^t, -b^t)}{1+\vec{D}_O^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}\right] \times$$
$$\left[\frac{1+\vec{D}_O^B(x^t, y^t, b^t; y^t, -b^t)}{1+\vec{D}_O^t(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}\right] \times \left[\frac{1+\vec{D}_O^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}{1+\vec{D}_O^B(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}\right] \quad (10)$$

The software for calculating agricultural green total factor productivity is the latest version of Stata17, which cannot be calculated in previous versions of Stata. The input indicators of the productivity are as follows: X_1 represents the input of chemical fertilizers, which is measured by the amount of agricultural chemical fertilizers calculated by the pure method; X_2 represents the input of agricultural machinery, which is measured by the total power of agricultural machinery; X_3 represents the agricultural irrigation Input, this indicator is measured by the effective agricultural irrigation area; X_4 represents land input, which is measured by the sown area of crops; X_5 represents labor input, which is measured by the employees of agriculture, forestry, animal husbandry and fishery. The output indicators include the expected output expressed by the total output value of agriculture, forestry, animal husbandry and fishery, which takes 2000 as the base period to calculate the constant price; the non-expected output indicator is the measurement method of agricultural carbon emissions. Refer to Section 3.2.2 for the calculation method.

Another explanatory variable in this paper, agricultural green innovation, is expressed by the number of agricultural green patents (GP) in each province. The IPC classification number of the number of agricultural green technology patents is based on the "IPC Green Inventory" guidelines formulated by the IPC Committee[1], obtained with reference to the agricultural part of the green patent list issued by the World Intellectual Property Organization (WIPO), and obtained through screening in the Patent Search and Analysis System (PSS-System) of the China Intellectual Property Office. Since patent examination takes a long time and there is a time lag in patent granting, the number of green patents is the sum of the data of invention patents and utility patent applications, rather than the data of patent grants.

3.2.2 Explanatory variables

The key explanatory variable studied in this paper is environmental regulation (ER). At present, scholars measure various types of environmental regulation variables. Specifically, some scholars in the field of agriculture use the number of agricultural environmental protection policies at the end of each year in each province in my country. In the same way, agricultural carbon emissions are used to measure the intensity of environmental regulation. The calculation method is based on. The formula for calculating carbon emissions is as follows:

$$\mathrm{ER} = \sum E_i = \sum T_i \cdot \delta_i \quad (11)$$

In the formula, ER is the total amount of agricultural carbon emissions, and E_i is expressed as the emissions of six carbon sources, including the use of chemical fertilizers, pesticides, agricultural film, and diesel in agricultural production, as well as ploughing (measured by the actual sown area of crops) and The amount of carbon emissions produced by the use of machinery and equipment in the agricultural production process due to irrigation, T_i is the amount emitted by each carbon source, and δ_i is the coefficient of each carbon emission, which are fertilizers ($0.8956\ \mathrm{kg\ kg^{-1}}$), pesticides ($4.9341\ \mathrm{kg\ kg^{-1}}$), agricultural film ($5.18\ \mathrm{kg\ kg^{-1}}$), diesel oil ($05927\ \mathrm{kg\ kg^{-1}}$), tillage ($312.6\ \mathrm{kg\ km^{-1}}$), agricultural irrigation ($25\ \mathrm{kg\ hm^{-1}}$), but according to Li Bo's calculation method of agricultural irrigation carbon emissions, this paper uses the data of China Statistical Yearbook from 2015 to 2019 to calculate the actual average thermal power coefficient of 0.7316, and the final calculation of the actual coefficient of agricultural irrigation is $18.291\ \mathrm{kg\ hm^{-1}}$.

3.2.3 Control variables

According to the current situation of agricultural development in my country, the control variables selected in this paper are as follows:

1) The level of rural human capital (HUMAN). In general, the higher the level of rural labor culture, the more conducive to the mastery of agricultural production technology and the rational use of pesticides, fertilizers and other factors, so theoretically, it will have a positive impact on agricultural green innovation and agricultural total factor productivity. This article is based on the calculation method of (Qiao, 2018) Human = prim × 6 + midd × 9 + high × 12 + univ × 16, of which 6, 9, 12, and 16 are the primary, junior high, and high schools for workers in agricultural production, respectively. The number of years of education of secondary school and college education above, prim, midd, high, and univ respectively represent the proportion of residents aged six and above in each education stage.
2) Environmental pollution control intensity (EG). The quality of rural agricultural environment is closely related to the intensity of local environmental governance, so it is measured by the proportion of environmental pollution control investment in GDP.
3) Agricultural production environment (DR). In general, the more serious the agricultural disaster in a certain area is, the

1 IPC Green Inventory website: https://www.wipo.int/classifications/ipc/green-inventory/home.

TABLE 1 Descriptive statistics of each variable.

Variable implication	Variable	N	Mean	S.D.	Min	Max
Agricultural green technology innovation	lnGP	570	5.971	1.508	2.398	9.728
Agricultural Green Total Factor Productivity	lnGTFP	570	4.757	0.501	3.733	6.632
environmental regulation	ER	570	23.708	15.537	0.918	62.455
Rural human capital level	lnHUAMN	570	3.854	0.927	1.22	5.573
Income distribution gap between urban and rural areas	lnIND	570	5.644	0.207	5.218	6.316
The level of opening up of the rural economy	lnTRA	570	3.997	1.499	1.166	8.592
Degree of disaster	lnDR	570	7.539	0.927	2.313	11.858
Intensity of Environmental Pollution Control	lnEG	570	4.779	0.493	2.532	6.856
Agricultural Machinery Density	lnMAC	570	6.198	0.586	2.112	9.172

greater the damage to the local agricultural production environment. Therefore, this paper uses the proportion of the affected area of land in regional agricultural production to the total sown area of crops to measure.

4) Agricultural Machinery Density (MAC). Generally speaking, the higher the density of agricultural machinery may lead to an increase in carbon emissions and affect the way of local agricultural green transformation. Therefore, this paper uses the proportion of the total power of agricultural machinery to the sown area to measure.
5) Urban-rural income ratio (IND). Generally speaking, the size of the income gap between urban and rural residents indicates the degree of support of the local government for agricultural development. Therefore, this paper uses the ratio of the per capita net income of urban residents to rural residents in the region to measure this indicator.
6) Rural economic opening level (TRA). Generally speaking, the trade status of agricultural products in the region will affect the agricultural production environment, which in turn affects the green development of local agriculture. Therefore, this paper uses the proportion of the total import and export of agricultural products in the region to the total agricultural production to measure this indicator.

TABLE 2 Estimated results of the fixed effects panel model.

	lnGP	lnGTFP
ER	0.065***	0.023***
	(0.015)	(0.005)
lnHUMAN	−0.249***	−0.137***
	(0.088)	(0.043)
lnIND	−1.437***	−0.411***
	(0.339)	(0.122)
lnTRA	0.763***	0.239***
	(0.177)	(0.079)
lnDR	−0.379***	−0.124***
	(0.083)	(0.032)
lnEG	0.078	−0.079
	(0.125)	(0.047)
lnMAC	1.171***	0.378***
	(0.155)	(0.048)
_cons	5.686**	5.061***
	(2.081)	(0.945)
N	570	570
R^2	0.5839	0.5917
F value	38.25	54.56

Note: Values in parentheses are cluster robust standard errors. ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

3.3 Research data

The main explanatory variable in this paper is agricultural green total factor productivity, which is calculated based on the data of "China Statistical Yearbook" and "China Rural Statistical Yearbook" and takes 2000 as the base period. Search and analysis system (PSS-System) screening. The data from 2001 to 2020 are selected for the two explained variables, and the environmental regulation and control variables are calculated using the data from 2000 to 2019. The data sources are China Statistical Yearbook, China Rural Statistical Yearbook, and China Population and Employment Statistical Yearbook. "China Agricultural Yearbook," "China Environmental Yearbook," and "China Agricultural Products Trade Development Report" and so on.

In addition, in order to study whether there is heterogeneity in the impact of environmental regulation on agricultural total factor productivity and agricultural green technology innovation under different economic development levels, this paper uses per capita GDP to represent the level of economic development (PGDP). And the base period is 2000. Except for the environmental regulation (ER) variable, all other variables are logarithmic, and the descriptive statistics of all variables are shown in Table 1.

4 Empirical researche

4.1 Estimation results of the linear panel model

The panel model estimation results with fixed effects in Eq. 1 are shown in Table 2. The ER estimated coefficients on both lnGP and lnGTFP are positive and significant, suggesting that if environmental regulation increases by 0.01, GP and GTFP will increase by 0.065% and 0.023%, respectively. These results preliminarily show that environmental regulation contributes to the green transition of agricultural development. On the one hand, environmental regulation can promote green technology innovation in the field of agricultural production and stimulate the application of green technology; on the other hand, environmental regulation can promote the improvement of agricultural green total factor productivity. As far as control variables are concerned, the significance of the effects of control variables on lnGP and lnGTFP in the previous period is basically the same. The estimated result in Table 2 is the impact of environmental regulation ER on the green development of agriculture without considering the level of economic development. In the next section, this paper will discuss the heterogeneity of two important indicators of ER in the development of agricultural green transformation at different levels of economic development.

Among the control variables, the variable of interest, the level of rural human capital (HUMAN), has a negative coefficient on both lnGP and lnGTFP. Theoretically, the higher the education level of farmers, the more favorable the development of green transformation in rural areas, but in fact, during the early development of China, the government focused more on economic development at the expense of environmental protection, and the phenomenon of "pollution first and treatment later" emerged. In recent years, however, the government has begun to pay more attention to environmental protection and the concept of green water and green mountains has begun to take root in people's minds. It is believed that in the near future, the positive effects of human capital will be brought into full play. In fact, the coefficients of agricultural machinery density on lnGP and lnGTFP are both significantly positive, meaning that the higher the degree of agricultural mechanization, the more it contributes to the green transformation of agriculture. As the degree of agricultural mechanization increases, agricultural development is scaled up and resource utilization is maximized, reducing carbon emissions from agricultural production as the efficiency of agricultural production increases, thus protecting the ecological environment.

TABLE 3 Estimated results of the linear part of partially linear function-coefficient panel models.

	lnGP	lnGTFP
lnHUMA	−0.112	−0.081***
	(0.096)	(0.026)
lnIND	−1.004***	−0.212***
	(0.272)	(0.074)
lnTRA	0.563***	0.173***
	(0.089)	(0.028)
lnDR	−0.309***	−0.092***
	(0.047)	(0.014)
lnEG	0.017	−0.101***
	(0.095)	(0.024)
lnMAC	0.717***	0.233***
	(0.092)	(0.026)
N	570	570
R^2	0.6482	0.7030
F value	144.55	184.60

Note: The value in parentheses is the standard error of the bootstrap method (1,000 times). ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

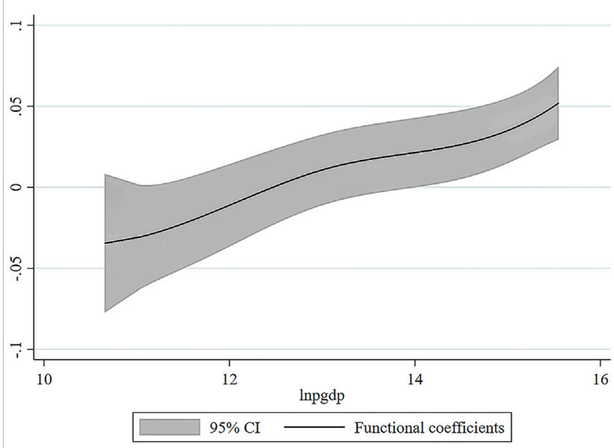

FIGURE 3
The functional coefficient of environmental regulation ER to agricultural green technology innovation.

4.2 Estimation results of the partial linear panel model with function coefficients

This section analyzes the impact of environmental regulation ER on agricultural green technology innovation and agricultural green total factor productivity under different economic development levels based on a partial linear panel model with functional coefficients. The estimation results of Eqs 2, 3 are shown in Table 3. Figures 3, 4 show the heterogeneous effects of environmental regulation of ER at different levels of economic

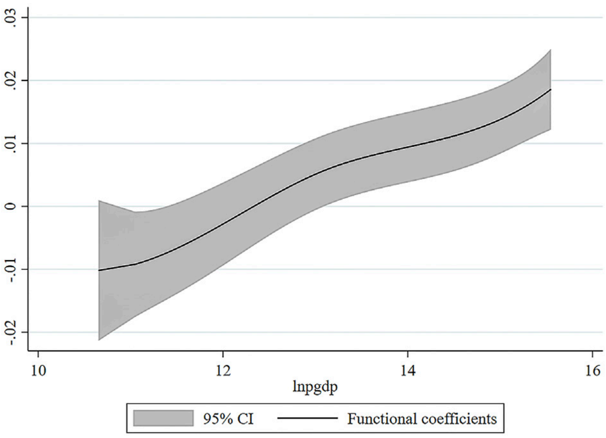

FIGURE 4
The functional coefficient of environmental regulation ER on agricultural GTFP.

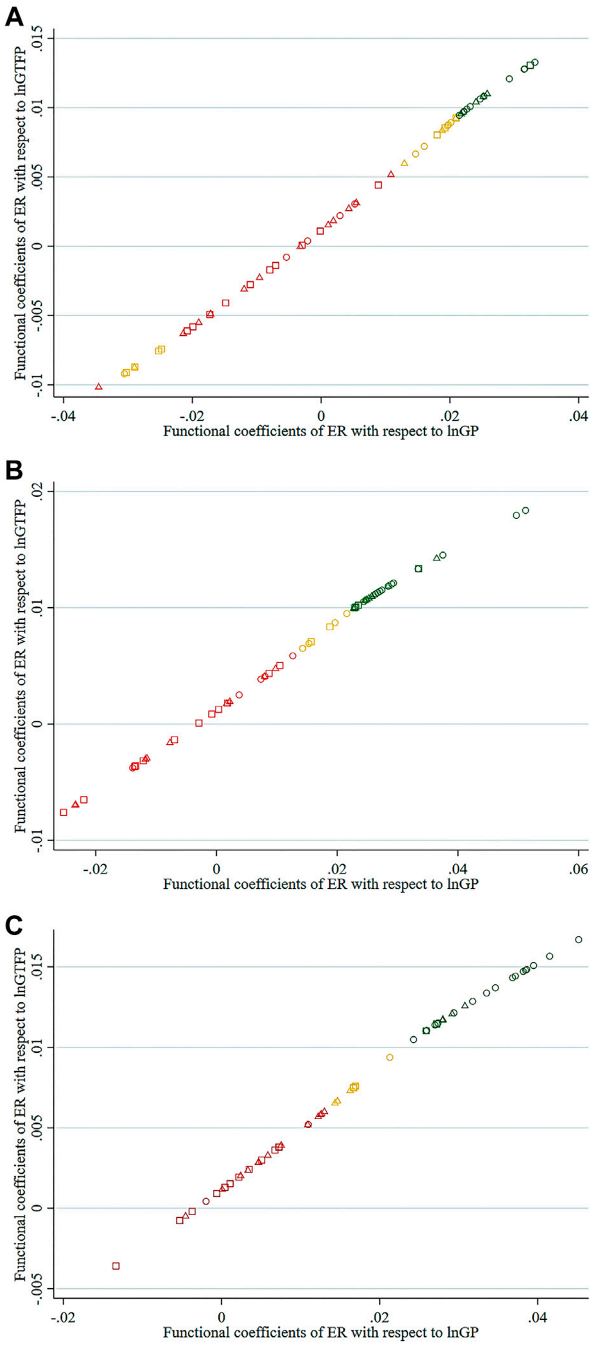

FIGURE 5
Functional coefficients of ER with respect to lnGP. **(A)** Function coefficients of ER in 2001-2002. **(B)** Function coefficients of ER in 2009-2010. **(C)** Function coefficients of ER in 2018-2019. Note: Squares indicate when real PGDP is low; triangles indicate when actual PGDP is moderate; circles indicate when actual PGDP is high. Red indicates that the effect of ER on lnGTFP and lnGP is not significant; yellow indicates that ER has a significant effect on lnGTFP; blue indicates that ER has a significant effect on lnGP; green indicates that ER has a significant effect on both lnGTFP and lnGP.

development, that is, the impact of ER on agricultural green technology innovation and agricultural green TFP will vary with different levels of economic development. The 95% confidence interval indicates that the effect of ER in these intervals is significant and positively contributing. As far as the control variables are concerned, the coefficient of agricultural production environment (DR) is negative, and the deterioration of agricultural environment inhibits the development of lnGP and lnGTFP; therefore, it is necessary to develop ecological agriculture and disaster-avoidance agriculture to change the disadvantage into advantage and promote the green transformation of agricultural development. In addition, the coefficient of environmental pollution control intensity (EG) on lnGTFP is insignificant in Table 2, while it is significant in Table 3, but the coefficient is negative, increasing the strength of environmental control has a positive role in promoting green development, but in the early stage, with the increase of investment in green industries, there is an inhibitory effect on the development of green economy, but with the concept of universal energy conservation as well as ecological and environmental protection gradually It is believed that the development of green economy will be actively promoted in the future.

For agricultural green technology innovation, when the level of economic development is relatively low, the implementation of environmental regulation ER has an inhibitory effect, which is not conducive to the development of green innovation. However, with the further development of my country's high-quality economy and the strong awareness of people's environmental protection, the inhibitory effect will gradually weaken.

When economic development reaches a higher level, ER will play a positive role, and people will begin to actively save energy and reduce emissions, green environmental protection, and low-carbon life. Therefore, the innovation of agricultural green technology can promote the realization of environmental protection in agriculture and rural areas, and there are always clear waters and lush mountains.

For agricultural green total factor productivity, when the level of economic development is low, environmental regulation ER not only has a crowding-out effect on economic development, but also has a crowding-out effect on non-green R&D companies because of increased R&D costs. Energy industry technology will be limited due to environmental regulation ER, so in the initial stage, agricultural green total factor productivity will be inhibited. However, with the continuous improvement of the level of economic development and the enhancement of people's awareness of environmental protection, ER will instead stimulate the innovation and development of green production technology, improve environmental protection capabilities, product quality, and ultimately improve agricultural green productivity, so that the social economy and the environment can develop harmoniously.

4.3 Statistics by province

This section will explore the impact of ER on agricultural green development based on the heterogeneity of economic development levels in each province. Referring to (Du at al., 2021), for the classification of the economic development level of each city in China, this paper divides 30 provinces and cities in China into three categories based on the average value of real per capita GDP. It shows the impact of ER on agricultural green technology innovation and agricultural green total factor productivity in three different time periods, 2001-2002, 2009-2010, and 2018-2019.

It can be seen from Figure 5A that in 2001-2002, for most provinces with low and medium levels of economic development, the impact of ER on agricultural green technology innovation and agricultural green TFP was not significant. In a few provinces with low levels of economic development, ER has a significant impact on agricultural green total factor productivity, but hardly contributes to agricultural green technology innovation. For most provinces with a high level of economic development, ER can significantly promote agricultural green technology innovation and agricultural green total factor productivity.

It can be seen from Figure 5B that in 2009-2010, for most provinces with low and medium economic development levels, the contribution of ER to agricultural green technology innovation and agricultural green TFP increased. For provinces with a higher level of economic development, the positive effect of ER on the impact of the two is also increasing.

From Figure 5C, in 2018-2019, in almost all provinces with higher economic development levels, ER can significantly promote agricultural green technology innovation and agricultural green total factor productivity. Due to the balance between the east and west of my country's economic development level, there are still many provinces with low economic development levels. The impact of ER on agricultural green technology innovation and agricultural green total factor productivity is not significant. The pulling effect of technological innovation and agricultural green total factor productivity is increasing.

From Figures 5A–C, we can tell that, as time goes by, the economic role of ER's agricultural green transition is increasing, and the impact is becoming more and more prominent. From 2000 to 2019, the economic development level of each province has been continuously improved, which verifies that the green transformation of my country's agricultural development is affected by the level of economic development. A higher level of economic development will help ER play a more active role in agricultural green technology innovation and agricultural green total factor productivity, and promote the green transformation of my country's agricultural development.

5 Conclusion and policy implications

5.1 Conclusion

Agricultural green technology innovation and agricultural green total factor productivity are the two main indicators for the green transformation of agricultural development, while environmental regulation is a key measure to prevent and control pollution as well as agricultural green sustainable development goals.

Taking into account the differences in regional economic development levels, this paper adopts a partial linear panel model with functional coefficients to study the heterogeneous impact of environmental regulation on agricultural green technology innovation and agricultural green total factor productivity. The main conclusions are as follows: 1) With the improvement of the level of economic development, the role of environmental regulation in promoting agricultural green technology innovation and agricultural green total factor productivity has been significantly enhanced, and environmental regulation has played an increasingly active role. The impact of total factor productivity is more significant than that of agricultural green technology innovation. 2) This paper takes 2001-2002, 2009-2010, and 2018-2019 as examples, and empirically analyzes that with the passage of time, the role of environmental regulation in promoting the green transformation of agricultural development has become more and more prominent. . From the initial period of 2001-2002, only a few provinces with a relatively high level of economic development did environmental regulation significantly promote the development of agricultural green technology innovation and agricultural green total factor productivity. In lower provinces, the contribution of environmental regulation is not obvious.

5.2 Policy implications

The above empirical results show that under different levels of economic development, environmental regulation has different effects on agricultural green technology innovation and agricultural green total factor productivity. Therefore, agricultural green environmental protection policies should be adapted to regional economic development, so that relevant supporting policies can be promulgated to cooperate with the implementation of environmental regulations.

First of all, in order to better promote the innovation of agricultural green technology, the differences in the level of economic development in different regions should be considered. For regions with low economic development levels, appropriate policy support should be given to stimulate the innovation of agricultural green technology. The tools of policy regulation and gradual transformation of environmental regulation have changed from imperative to incentive. For example, the government provides financial support for agricultural green technology innovation and research and development capabilities, increases compensation for environmental protection, increases investment in agricultural green development from different channels, enhances the power of green technology to develop agriculture, and reduce the constraints of energy saving and emission reduction clean and environmental protection technologies. At the same time, strengthen regional cooperation and give full play to the spillover effect of technological innovation in regions with high economic development levels.

Secondly, the difference in the level of economic development makes the impact of environmental regulation on agricultural green total factor productivity heterogeneous. Going back to the past development experience, the green development of my country's agriculture should avoid maintaining growth at the expense of the environment, and formulate a prudent and appropriate agricultural Green environmental protection policies, regulations and standards, vigorously promote green ecology, enable agriculture to develop circularly, and continuously increase the development and subsidies of agricultural green production behaviors. For example: replacing chemical fertilizers with organic fertilizers, promoting the development of green and energy-saving agricultural machinery, reducing energy consumption in agricultural production, developing comprehensive planting and breeding, aquaponics and other green measures to make the production model greener. Design a market-oriented operation system for environmental protection and ecological construction in line with the green development of agriculture, and at the same time cooperate with the government's "visible hand" to jointly promote energy conservation, emission reduction, green and low carbon in the agricultural and rural sectors. An important part of carbon neutrality. Ultimately, the comprehensive green transformation of agricultural development will be achieved.

Finally, in order to promote the large-scale development of agricultural green planting technology, the government should take incentive measures to encourage relevant green planting enterprises to join in the promotion of green agricultural planting technology, further expand the development of import and export trade of agricultural products, increase farmers' income, and strengthen The training on green production technology for agricultural and rural producers will increase the production and income of agricultural farmers, improve the efficiency of various agricultural production factors, save energy and reduce emissions, and accelerate the transformation and development of my country's agriculture to green (Galloway and Johnson, 2016; Liu et al., 2018; Xiao et al., 2022).

Data availability statement

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

Author contributions

CS: The author contributed to the drafting of the paper, participated in the conception and design of the study, collected the data, and performed the statistical analysis. The author has reviewed and approved the manuscript's published form.

Funding

I am very grateful to the Guangzhou Office of Philosophy and Social Science (2021GZGJ29), Guangdong Provincial Key Scientific Research Platform Project (2020ZDZX1064), Guangdong Educational Science Planning Project (2022GXJK673).

Acknowledgments

I appreciate the editors' and the two reviewers' insightful comments of a previous draft of this manuscript.

Conflict of interest

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.955954/full#supplementary-material

References

Abbasi, K. R., Shahbaz, M., Zhang, J., Irfan, M., and Alvarado, R. (2022). Analyze the environmental sustainability factors of China: The role of fossil fuel energy and renewable energy. *Renew. Energy* 187, 390–402. doi:10.1016/j.renene.2022.01.066

Ambec, S., Cohen, M. A., Elgie, S., and Lanoie, P. (2013). The porter hypothesis at 20: Can environmental regulation enhance innovation and competitiveness? *Rev. Environ. Econ. Policy* 7 (1), 2–22. doi:10.1093/reep/res016

An, Y., Hsiao, C., and Li, D. (2016). Semiparametric Estimation of Partially Linear Varying Coefficient Panel Data Models *Emerald Publishing Ltd.* 36, 47–65. doi:10.1108/S0731-905320160000036011

Balsa-Barreiro, J., Li, Y., Morales, A., and Pentland, A. S. (2019). Globalization and the shifting centers of gravity of world's human dynamics: Implications for sustainability. *J. Clean. Prod.* 239, 117923. doi:10.1016/j.jclepro.2019.117923

Borsatto, J. M. L. S., and Amui, L. B. L. (2019). Green innovation: Unfolding the relation with environmental regulations and competitiveness. *Resour. Conserv. Recycl.* 149, 445–454. doi:10.1016/j.resconrec.2019.06.005

Brunnermeier, S. B., and Cohen, M. A. (2003). Determinants of environmental innovation in US manufacturing industries. *J. Environ. Econ. Manag.* 45 (2), 278–293. doi:10.1016/S0095-0696(02)00058-X

Cochard, F., Willinger, M., and Xepapadeas, A. (2005). Efficiency of nonpoint source pollution instruments:an experimental study. *Environ. Resour. Econ. (Dordr).* 30 (4), 393–422. doi:10.1007/s10640-004-5986-y

Curtis, E. M., and Lee, J. M. (2019). When do environmental regulations backfire? Onsite indus trial electricity generation, energy efficiency and policy instruments. *J. Environ. Econ. Manage.* 96, 174–194. doi:10.1016/j.jeem.2019.04.004

Deng, X., and Gibson, J. (2019). Improving eco-efficiency for the sustainable agricultural production: A case study in shandong, China. *Technol. Forecast. Soc. Change* 144, 394–400. doi:10.1016/j.techfore.2018.01.027

Du, K., Yu, Y., and Li, J. (2020a). Does international trade promote CO_2 emission performance? An empirical analysis based on a partially linear functional-coefficient panel data model. *Energy Econ.* 92, 104983. doi:10.1016/j.eneco.2020.104983

Du, K., Yu, Y., and Wei, C. (2020b). Climatic impact on China's residential electricity consumption: Does the income level matter? China econ. *China Econ. Rev.* 63, 101520. doi:10.1016/j.chieco.2020.101520

Du, K., Zhang, Y., and Zhou, Q. (2020c). Fitting partially linear functional-coefficient panel-data models with Stata. *Stata J.* 20 (4), 976–998. doi:10.1177/1536867X20976339

Du, K., Cheng, Y., and Yao, X. (2021). Environmental regulation, green technology innovation, and industrial structure upgrading: The road to the green transformation of Chinese cities. *Energy Econ.* 98, 105247. doi:10.1016/j.eneco.2021.105247

Galloway, E., and Johnson, E. P.(2016). Teaching an old dog new tricks: Firm learning from environmental regulation. *Energy Econ.* 59, 1–10. doi:10.1016/j.eneco.2016.06.023

Gollop, F. M., and Roberts, M. J. (1983). Environmental regulations and productivity growth: The case of fossil-fueled electric power generation. *J. Polit. Econ.* 91 (4), 654–674. doi:10.1086/261170

Grey, W. B., and Shadbegian, R. J. (2003). Plant vintage, technology, and environmental regulation. *J. Environ. Econ. Manage.* 46 (3), 384–402. doi:10.1016/S0095-0696(03)00031-7

Hao, Y., Gai, Z., Yan, G., Wu, H., and Irfan, M. (2021). The spatial spillover effect and nonlinear relationship analysis between environmental decentralization, government corruption and air pollution: Evidence from China. *Sci. Total Environ.* 763, 144183. doi:10.1016/j.scitotenv.2020.144183

Iqbal, W., Tang, Y. M., Chau, K. Y., Irfan, M., and Mohsin, M. (2021). Nexus between air pollution and NCOV-2019 in China: Application of negative binomial regression analysis. *Process Saf. Environ. Prot.* 150, 557–565. doi:10.1016/j.psep.2021.04.039

Irfan, M., and Ahmad, M. (2022). Modeling consumers' information acquisition and 5G technology utilization: Is personality relevant? Personality individ. *Pers. Individ. Dif.* 188, 111450. doi:10.1016/j.paid.2021.111450

Irfan, M., Elavarasan, R. M., Hao, Y., Feng, M., and Sailan, D. (2021). An assessment of consumers' willingness to utilize solar energy in China: End-users' perspective. *J. Clean. Prod.* 292, 126008. doi:10.1016/j.jclepro.2021.126008

Jiang, G. (2022). How does agro-tourism integration influence the rebound effect of China's agricultural eco-efficiency? An economic development perspective. *Front. Environ. Sci.* 10, 921103. doi:10.3389/fenvs.2022.921103

Jorge, M. L., Madueño, J. H., Martinez-Martinez, D., and Sancho, M. P. L. (2015). Competitiveness and environmental performance in Spanish small and medium enterprises: Is there a direct link? *J. Clean. Prod.* 101, 26–37. doi:10.1016/j.jclepro.2015.04.016

Li, J. T., Ji, J. Y., and Zhang, Y. (2019). Non-linear effects of environmental regulations on economic outcomes. *Manag. Environ. Qual.* 30 (2), 368–382. doi:10.1108/MEQ-06-2018-0104

Li, X., Shaikh, P. A., and Ullah, S. (2022). Exploring the potential role of higher education and ICT in China on green growth. *Environ. Sci. Pollut. Res.* 29, 64560–64567. doi:10.1007/s11356-022-20292-0

Liang, L., Qu, F., and Feng, S. (2012a). Measurement of agricultural technical efficiency based on the perspective of environmental pollution constraints. *J. Nat. Resour.* 27 (9), 1580–1589. doi:10.11849/zrzyxb.2012.09.015

Liang, L., Qu, F., and Feng, S. (2012b). Agricultural technical efficiency measurement under the environmental constraints. *J. Nat. Resour.* 27 (9), 1580–1589. doi:10.11849/zrzyxb.2012.09.015

Liu, Y., Li, Z. H., and Yin, X. M. (2018). Environmental regulation, technological innovation and energy consumption—A cross-region analysis in China. *J. Clean. Prod.* 203, 885–897. doi:10.1016/j.jclepro.2018.08.277

Liu, L., Yang, X., Meng, Y., Ran, Q., and Liu, Z. (2021a). Does the construction of national eco-industrial demonstration parks improve green total factor productivity? Evidence from prefecture level cities in China. *Sustainability* 14 (1), 26. doi:10.3390/su14010026

Liu, D., Zhu, X., and Wang, Y. (2021b). China's agricultural green total factor productivity based on carbon emission: An analysis of evolution trend and influencing factors. *J. Clean. Prod.* 278, 123692. doi:10.1016/j.jclepro.2020.123692

Liu, Q., Zhu, Y., Yang, W., and Wang, X. (2022). Research on the impact of environmental regulation on green technology innovation from the perspective of regional differences: A quasi-natural experiment based on China's new environmental protection law. *Sustainability* 14 (3), 1714. doi:10.3390/su14031714

Pang, R., Zheng, D., Shi, M. J., and Zhang, X. L. (2019). Pollute first, control later? Exploring the economic threshold of effective environmental regulation in China's context. *J. Environ. Manage.* 248, 109275. doi:10.1016/j.jenvman.2019.109275

Pastor, J. T., Asmild, M., and Lovell, C. A. K. (2011). The biennial malmquist productivity change index. *Socio-Economic Plan. Sci.* 45, 10–15. doi:10.1016/j.seps.2010.09.001

Picazo-Tadeo, A. J., Gómez-Limón, J. A., and Reig-Martínez, E. (2011). Assessing farming eco-efficiency: A data envelopment analysis approach. *J. Environ. Manage.* 92 (4), 1154–1164. doi:10.1016/j.jenvman.2010.11.025

Porter, M. E. (1991). Towards a dynamic theory of strategy. *Strateg. Manag. J.* 12 (S2), 95–117. doi:10.1002/smj.4250121008

Qiao, M. (2018). Dual effects of environmental regulation on R&D innovation efficiency:an empirical study based on inter-provincial industrial panel data. *Mod. Econ. Discuss.* 09, 79–89. doi:10.13891/j.cnki.mer.2018.09.012

Rauf, A., Ozturk, I., Ahmad, F., Shehzad, K., Chandiao, A. A., Irfan, M., et al. (2021). Do tourism development, energy consumption and transportation demolish sustainable environments? Evidence from Chinese provinces. *Sustainability* 13 (22), 12361. doi:10.3390/su132212361

Shadbegian, R. J., and Gray, W. B. (2005). Pollution abatement expenditures and plant-level productivity: A production function approach. *Ecol. Econ.* 54 (2-3), 196–208. doi:10.1016/j.ecolecon.2004.12.029

Song, M., Wang, S., and Sun, J. (2018). Environmental regulations, staff quality, green technology, R&D efficiency, and profit in manufacturing. *Technol. Forecast. Soc. Change* 133, 1–14. doi:10.1016/j.techfore.2018.04.020

Su, S., and Zhang, F. (2020). Modeling the role of environmental regulations in regional green economy efficiency of China: Empirical evidence from super efficiency DEA-Tobit model. *J. Environ. Manag.* 261, 110227. doi:10.1016/j.jenvman.2020.110227

Turken, N., Carrillo, J., and Verter, V. (2020). Strategic supply chain decisions under environmental regulations: When to invest in end-of-pipe and green technology. *Eur. J. Operational Res.* 283 (2), 601–613. doi:10.1016/j.ejor.2019.11.022

Wang, C. (2011). Sources of energy productivity growth and its distribution dynamics in China. *Resour. Energy Econ.* 33, 279–292. doi:10.1016/j.reseneeco.2010.06.005

Wang, H., and Wei, W. (2020). Coordinating technological progress and environmental regulation in CO2 mitigation: The optimal levels for OECD countries & emerging economies. *Energy Econ.* 87, 104510. doi:10.1016/j.eneco.2019.104510

Wang, L., and Yan, Y. (2022). Environmental regulation intensity, carbon footprint and green total factor productivity of manufacturing industries. *Int. J. Environ. Res. Public Health* 19 (1), 553. doi:10.3390/ijerph19010553

Wang, Y., Sun, X., and Guo, X. (2019). Environmental regulation and green productivity growth: Empirical evidence on the Porter Hypothesis from OECD industrial sectors. *Energy Policy* 132, 611–619. doi:10.1016/j.enpol.2019.06.016

Xiao, S., He, Z., Zhang, W., and Qin, X. (2022). The agricultural green production following the technological progress: Evidence from China. *Int. J. Environ. Res. Public Health* 19 (16), 9876. doi:10.3390/ijerph19169876

Xie, C., Huang, C., and Xu, H. (2021). Regional disparity and influencing factors of agricultural technology efficiency in China: Based on dual constraint of agricultural carbon and agricultural non-point source pollution. *Sci. Technol. Manag. Res.* 41 (15), 184–190. doi:10.3969/j.issn.1000-7695.2021.15.024

Xu, Z., Chen, J., Jin, Z., Li, H., and Chen, F. (2020). Representing model uncertainty by multi-stochastic physics approaches in the GRAPES ensemble. *Adv. Atmos. Sci.* 37 (4), 328–346. doi:10.1007/s00376-020-9171-1

Ye, C., Sun, C., and Chen, L. (2018). New evidence for the impact of financial agglomeration on urbanization from a spatial econometrics analysis. *J. Clean. Prod.* 200, 65–73. doi:10.1016/j.jclepro.2018.07.253

Yu, K., Hu, Y., and Song, Z. (2019). Environmental regulation, government support and green technological innovation: An empirical study based on resource—Based enterprises. *J. Yunnan Univ. Finance Econ.* 35 (04), 100–112. doi:10.16537/j.cnki.jynufe.000434

Yu, D., Liu, L., Gao, S., Yuan, S., Shen, Q., and Chen, H. (2022). Impact of carbon trading on agricultural green total factor productivity in China. *J. Clean. Prod.* 367, 132789. doi:10.1016/j.jclepro.2022.132789

Zhan, J., and Xu, Y. (2019). Environmental regulation, agricultural green productivity and food security. *China Popul. Resour. Environ.* 29 (03), 167–176. Available at: http://agri.ckcest.cn/file1/M00/0F/71/Csgk0F4RmkeAXD9wAAYj8fqX3bg639.pdf.

Zhang, M., Sun, X. R., and Wang, W. W. (2020). Study on the effect of environmental regulations and industrial structure on haze pollution in China from the dual perspective of independence and linkage. *J. Clean. Prod.* 256, 120748. doi:10.1016/j.jclepro.2020.120-748

Zhao, J., Jiang, Q. Z., Dong, X. C., and Dong, K. Y. (2020a). Would environmental regulation improve the greenhouse gas benefits of natural gas use? A Chinese case study. *Energy Econ.* 87, 104712. doi:10.1016/j.eneco.2020.104712

Zhao, X. M., Liu, C. J., Sun, C. W., and Yang, M. (2020b). Does stringent environmental regulation lead to a carbon haven effect? Evidence from carbon-intensive industries in China. *Energy Econ.* 86, 104631. doi:10.1016/j.eneco.2019.104631

Zhou, A., and Li, J. (2021). Impact of anti-corruption and environmental regulation on the green development of China's manufacturing industry. *Sustain. Prod. Consum.* 27, 1944–1960. doi:10.1016/j.spc.2021.04.031

Zhou, Q., Zhang, X. L., Shao, Q. L., and Wang, X. L. (2019). The non-linear effect of environmental regulation on haze pollution: Empirical evidence for 277 Chinese cities during 2002–2010. *J. Environ. Manage.* 248, 109274. doi:10.1016/j.jenvman.2019.109274

TYPE Original Research
PUBLISHED 07 November 2022
DOI 10.3389/fenvs.2022.972354

Check for updates

OPEN ACCESS

EDITED BY
Jose Balsa-Barreiro,
Massachusetts Institute of Technology,
United States

REVIEWED BY
Solomon Prince Nathaniel,
University of Lagos, Nigeria
Yacouba Kassouri,
Leipzig University, Germany

*CORRESPONDENCE
Hummera Saleem,
humairasaleem@numl.edu.pk

SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 18 June 2022
ACCEPTED 27 September 2022
PUBLISHED 07 November 2022

CITATION
Chen M, Jiandong W and Saleem H (2022), The role of environmental taxes and stringent environmental policies in attaining the environmental quality: Evidence from OECD and non-OECD countries.
Front. Environ. Sci. 10:972354.
doi: 10.3389/fenvs.2022.972354

The role of environmental taxes and stringent environmental policies in attaining the environmental quality: Evidence from OECD and non-OECD countries

Mingliu Chen[1], Wen Jiandong[2] and Hummera Saleem[3]*

[1]Center for Economic Development Research and Economics and Management School, Wuhan University, Wuhan, China, [2]Professor, Center for Economic Development Research and Economics and Management School, Wuhan University, Wuhan, China, [3]National University of Modern Languages (NUML) Islamabad, Islamabad, Pakistan

Numerous economies focus on attaining a clean environment by applying environmental policies and green technology. This study examined the impact of GDP growth, non-renewable, technological change, environmental tax, and strict regulations on an ecological footprint for the Organization for Economic Cooperation and Development (OECD) and Non-OECD (not members of OECD) economies from 1990 to 2015. This analysis applied the Cross-Sectionally Augmented Auto-Regressive Distributed Lag (CS-ARDL) to identify the role of GDP, and environmental taxes, with selected control factors on ecological degradation. These CS-ARDL techniques resolve the issues of slope heterogeneity, endogeneity, and cross-sectional dependence. For robustness, this study used Augmented Mean Group (AMG), and Common Correlated Effect Mean Group (CCEMG) tests to check the long-run association between variables. The empirical findings of CS-ARDL have confirmed that environmental taxes, stringent environmental policies, and ecological innovation significantly improve environmental quality in OECD compared to the Non-OECD countries. The D-H panel Granger causality test results show the unidirectional causality moving from environmental tax to ecological footprint, which referred to the "green dividend" hypothesis of minimizing environmental degradation. Using AMG and CCEMG tests for Robustness checks indicates that environmental taxes and tight environmental policy can effectively improve the environment's quality in both regions. Hence, environmental protection awareness is forcing policymakers to minimize the impact of environmental degradation to achieve sustainable growth.

KEYWORDS

CO2 emission, ecological footprint, GDP growth, energy, environmental taxes, environmental policy

10.3389/fenvs.2022.972354

1 Introduction

Over the last 20 years, environmental initiatives have been aimed to promote the transition of the economy into low-carbon economies significantly to minimize the adverse environmental effects (such as global warming, greenhouse gas (GHG) emissions, air pollution, and climate change) (Agbugba and Iheonu 2018). By establishing and executing energy plans like the Kyoto Protocol and the Paris Climate Accord, which regulate the policies related to climate and energy consumption, and the transformation of the economy towards low-carbon industrialization and attaining energy-efficient policies. Eco-technology and Environmental regulations are significant features of the Paris Climate Agreement and Kyoto Protocol policies, including carbon trading, environmental taxes, and energy-efficient and eco-friendly technologies as the primary strategy plans (Alberini and Filippini, 2011; Ang et al., 2015). Additionally, researchers have discussed various determinants that mitigate environmental pollution (He et al., 2019). GHG emissions are considered the most significant global threat to the entire ecosystem, especially human health. The main contributor to anthropogenic GHG is carbon dioxide (CO2 emissions), used as the proxy for environmental degradation in various prior Literature. However, massive criticism is faced by the CO2 emissions as a proxy to identify the environmental degradation caused by GDP growth. On the other hand, the use of CO2 emissions as a proxy for capturing the ecological damage caused by economic expansion has been widely criticised by various studies.

In this context, the ecological footprint proposed by (Rees, 1992) satisfies all of the above characteristics for a comprehensive, progressive, and integrative assessment of environmental degradation. A few empirical works have evaluated the ecological footprint factor (Neagu, 2020). Estimating the sustainability of an economy's consumption is related to the ecological footprint (EFP), developed by Wackernagel and Rees (1998). According to the Global Footprint Network (2022) definition, the ecological footprint indicates how much water and land is naturally essential to produce different products required by the population. Altintas and Kassouri, 2020 examined that validity of EKC depends on the environmental indicators. Their study used the two other environmental proxies, i.e. CO2 emissions and ecological footprint, for 14 European countries from 1990–2014. They concluded that the proxy of the environmental curve could significantly affect the existence of the EKC hypothesis. Their finding shows that the prediction of EKC is highly sensitive to an appropriate environmental tool; thus, the ecological footprint is a reasonable proxy to detect environmental pollution. Their findings exhibit fossil fuels significantly increase environmental pollution, and clean energy use substantially improves the environment's quality. Moran et al. (2008) and Shahzad et al. (2020); statistical results found a positive and significant relationship between economic growth and ecological footprint. The importance of environmental regulations and a non-carbon ecological footprint for 87 economies from 2004 to 2010 is highlighted by (Asici and Acar 2016). Their statistical findings indicate that ecological constraints significantly improve environmental quality.

Based on contradicting empirical and theoretical analyses of the previous studies, to resolve the inconsistency in the preliminary analysis thus, we required more investigations in this regard. Most of the existing Literature is just on the connection between toxin outflows, for instance, air quality and Sulfur and CO2 emissions discharges, which is an essential restriction of these investigations (Burnett and Madariaga, 2017). In this regard, we found limited research examining a comprehensive analysis and globally analogous factors, especially those containing the study of environmental taxes and policies and economic growth, under the premises of the environmental Kuznets curve (EKC). This study used the newly announced measure of environmental degradation by ecological footprint (EFP). The EFP contains cropland, forest land, grazing land, fishing grounds, CO2 emission, and infrastructure footprint (Charfeddine, 2017). In addition, the utilization of ecological footprint compared to the traditional measure (CO2) of environmental degradation is the motivation of the current analysis in the context of OECD and Non-OECD countries. These economies are facing environmental challenges. Thus further investigation is required to overcome worse climatic challenges. The ecological footprint directly points to the fact that much land and water are naturally needed to yield all products, considering soil, forestry, mining, and oil reserves. As a result, our research examines whether environmental taxes and regulations can reduce an ecological footprint as a proxy for the destruction of the environment.

The OECD and Non-OECD countries are selected for this study as the consumption of non-renewable is still so high in these economies with a high rate of CO2 emissions. The OECD is accountable for 35% of fossil fuel by-products worldwide. Energy-based industries account for 29% of global emissions outflows in these nations because of natural resources (OECD, 2021). These all selected countries face severe environmental issues regarding unexpected outcomes in the ecological system. Various countries have adopted environment-friendly policies such as environmental taxes, renewable sources, green financing, and innovation. But still, many developed countries are polluting the environment badly; thus, global warming and the destruction of the ecosystem are putting pressure on developed countries to minimize CO2 emissions. Recently, various studies concluded a positive and significant relationship between non-renewable energy consumption and environmental degradation (Huang et al., 2020; Saleem et al., 2020.). The study of Abbasi et al. (2021), focused on efficient energy policies to protect the environment from fossil fuel consumption. Additionally, Shen et al. (2020) highlighted the excess utilization of non-renewable energy sources, which leads to the destruction of the environment in developing and developed countries.

The environmental activist had long imagined that environment-related regulations and taxes must endorse ecological objectives in numerous world regions. Since the start of the 21st century, environmental protection awareness has realized the execution of environmental taxes as a plausible choice, particularly among developed countries. As of late, other developed countries like France, Germany, the UK, and Italy have followed this way. Creating countries like Poland, Estonia, and Hungary have had the option to incorporate ecological regulations (OECD, 2019). Non-OECD modern economies like South Korea, Thailand, Taiwan, Singapore, and Malaysia have endorsed instruments (market-based) with the conventional command and control guidelines (adding environmental regulations) as they try to improve the quality of the environment (Saleem et al., 2020). The results of Shen et al. (2020) highlighted the excess utilization of non-renewable energy sources, which leads to the destruction of the environment in developing and developed countries.

The existing Literature identifies various determinants of environmental degradation. For instance, prior studies concluded that technological innovations were a mediating determinant in improving the quality of the environment. Technological change can enhance environmental quality through energy conservation (Cheng et al., 2021). Technological innovation improves energy efficiency, optimizing production processes (Jin et al., 2017). Numerous Literature claims that the primary sources of environmental degradation are non-renewable energy (Saidi and Hammami, 2015; Saleem et al., 2020). Thus, technological advancement upsurge the use of renewable energy through energy efficiency. This background is advantageous and appropriate for governments and policymakers in OECD economies are related to the great importance of addressing the challenges of environmental degradation. In addition, a large portion of the world accounts for OECD economies, which play a significant role in the world economy and technologically advanced economies.

Based on the statements mentioned earlier, this analysis aims to identify the environmental Kuznets curve with the restriction of environmental taxes and regulations used to highlight environmental degradation issues in the context of OECD and Non-OECD economies. These countries are the world's leading growth economies with high consumption of global energy, thus significantly increasing the level of CO2 emission. For policy recommendation, numerous variables, e.g., green growth, environmental taxes, and environmental regulation policies, are essential to discuss their influential role and different strategies to minimize the effect of environmental degradation in these economies. Consequently, this research analysis addresses a few significant contributions. Initially, the current study certifies uncovering the determinants of an ecological footprint as an alternate factor for environmental deterioration rather than only single carbon dioxide emissions. This is a significant issue since few studies examined the role of ecological footprint, especially since these developed and transitional economies are more answerable for poorly utilizing natural resources. Second, the current study presents a few plausible variables essential to policy implications. This environmental destruction motivates us to reinvestigate the role of non-renewable energy use with some control variables, e.g., environmental taxes, technological innovation, strict environmental regulations that would impact the quality of the environment, with the latest methodologies to check their impact on the ecological footprint. Third, this study is unique as it has both OECD and Non-OECD economies under the umbrella of a single model. This study provides a new insight that contributes to existing studies to examine the effect of technological change, environmental taxes, economic growth, and environmental regulations on the ecological footprint hypothetically. Fourth, the OECD and Non-OECD nations have been investigated using modern econometric approaches and the latest data set from 1990 to 2016. Thus, to identify the stationarity of ecological footprint, economic growth, non-renewable energy consumption, technological change, environmental tax, and regulation, the second generation panel unit root (augmented cross-sectional IPS (CIPS)) tests are used. The panel data analysis also has a cross-sectional dependence. Thus, the traditional panel unit root test (e.g., IPS, LLC, and Hadri tests) give erroneous and inconsistent results. Cross-section dependence (CSD) is a common issue in panel data analysis (Baltagi and Hashem Pesaran, 2007), and due to this, the validation of the traditional estimation of panel test is not accepted (Gengenbach et al., 2009). This study applied the latest Pesaran LM normal, Friedman chi-square, Pesaran CD normal, and Breusch-Pagan chi-square test to avoid spurious results. This review presents advanced econometrics, for example, a second generation unit root statistical test, Westerlund (2008) co-integration test, CS ARDL, for robustness check the methods of Augmented Mean Group (AMG) and Common Correlated Effect Mean Group (CCEMG), and board Dumitrescu and Hurlin's (D-H) causality test. The current study provides important policy suggestions for OECD and Non-OECD economies. Finally, this study will identify the following research questions. Firstly, Do technological change, environmental taxes, and regulations significantly improve the ecological footprint in these OECD and Non-OECD countries?

The remaining part of the research is organized as follows. Section 2) is presented the literature review on environmental degradation with its few control variables. Section 3) gives the theoretical background methodology and our technique, including the assessment procedure. Section 4) shows our analysis's results, discussion, and interpretation. Finally, Section 5) discusses a conclusion and policy suggestions for sustainability.

2 Literature review

2.1 Theoretical literature

Based on the theoretical Literature, in the early 1940s, the idea of technological innovation was presented by Josef Schumpeter. Technological innovation should be replaced by old traditional methods in the capitalist economy. According to their theory, temporary monopoly power can be raised in the society, but they benefit from excess profits for a short period, but then the market will be replaced by old products with new ones. Three stages of market transformation are described by Schumpeter, where the latest technologies are introduced in the market to replace the old ones. Schumpeter introduced three steps, i.e., invention, innovation, and diffusion. A newly developed product is called an invention; when the brand new goods are commercialized in the market, are related to innovation, and research and development (R&D) is essential to invention and innovation. Diffusion is the third stage where new technology is used by individuals or firms significantly (Jaffe et al., 2003). Therefore, technological innovation is the mutual environmental and economic influence of the three of these stages. Similarly, the endogenous growth theory also focused on technological change and argued that these changes could significantly improve environmental issues in the long term. Technological innovation can be enhanced through R&D, especially in the energy sector, by introducing renewable and energy-efficient technologies that mitigate ecological destruction (Saleem et al., 2020).

In the early, Josef Schumpeter described the theoretical framework for technological change. However, the theoretical framework for clean energy use is represented by the framework of green Keynesianism. Based on this framework, the analysis could identify the contribution of clean energy use in achieving environmental sustainability and reducing the destruction of the environment. The expansion of the Keynesian theory is described as green Keynesianism; this indicates that sustaining environmental sustainability is highly associated with achieving a high economic growth rate. The key objective of green Keynesianism is to boost economic growth and development by finding solutions to environmental issues. Environmental mitigating goals and active macroeconomic policy are jointly discussed in the green Keynesianism theory. These objectives can be achieved by environmentally friendly technologies, clean energy, and environmental protection policies.

2.2 Empirical literature

Based on the empirical Literature, this analysis categorized the prior existing Literature that examined the main determinants of environmental destruction into four different strands of Literature. The environment-economic growth nexus is explained in the first strand of the Literature. The Literature on the environment-technological change nexus is defined in the second strand of the review. The Literature on the environmental taxes-environmental degradation nexus is examined in the third strand of the evaluation. The Literature on environmental degradation-environmental policy stringency nexus is discussed in the third strand of the review.

2.2.1 Literature on environmental degradation and economic growth

The first strand of the literature review indicates the environmental degradation-income level nexus. This association is well presented by Grossman and Krueger (1995); in their research thereon, the link between income level and environmental degradation is defined in their inverted U-shaped EKC hypothesis. Their hypothesis is explained the inverse relationship between environmental degradation and economic growth. Over the last 20 years, the EKC framework has been used in numerous empirical analyses to identify the relationship between environmental quality and income level (Lapinskiene et al., 2017; Auci and Trovato, 2018), while for the same purpose, this framework is also used with the addition of energy use (Pablo-Romero and Sanchez-Brada, 2017). Many empirical analyses provide evidence for the existence of EKC in European countries (e.g., Auci and Trovato, 2018); their findings confirmed the presence of EKC in 25 European economies from 1997 to 2005. By contrast, some studies did not verify the existence of EKC in European economies (e.g., Mazur et al., 2015); their results could not confirm the existence of EKC for 28 European economies from 1995 to 2006. However, the findings of Pablo-Romero and Sanchez-Brada (2017) confirmed the presence of EKC in the residential sector from 1990 to 2013. Several empirical analyses usually discussed the EKC by utilizing CO2 as a proxy of environmental degradation, but less attention has been given to the ecological footprint and its role in the environmental degradation-economic growth nexus. Al-Mulali et al. (2015) examined the model of EKC for 93-panel countries and confirmed the existence of EKC for middle and upper-income countries, and the ecological footprint was used as the dependent variable. Ozturk et al. (2016) also examined the validity of the EKC framework for upper-middle-income economies by using ecological footprint. Uddin et al. (2017) employed an ecological footprint and confirmed the existence of EKC for Pakistan, India, Nepal and Malaysia. Pata (2021) used the CO2 emission and environmental footprint to identify the validity of EKC premises for the United States of America. Balsalo-bre-Lorente et al. (2019) confirmed the validity of EKC for Mexico, Nigeria, Indonesia, and Turkey economies.

Balsa-Barreiro et al. (2019) analysed the impact of GDP growth on CO2 emissions. Urban population and population for global level from 1960–2016. The world's human dynamics changes are essential to discuss in the scenario of population growth dynamics, GDP growth, and environmental destruction. All these challenges mentioned above are highly associated with globalisation and measured with the center of gravity (reallocation trends initiated by globalization). The statistical findings concluded that Japan, China, the European Union, and the United States are top emitters and the world's largest economies. The results also indicate the decoupling effect, when the GDP trace is affected faster than the CO2 trace. Asian countries (especially India and China) and a few African countries are the most populated in the world. Due to the largest megalopolises and cities extended in Europe, southeastern Asia and America significantly increased the urban population. The policies suggested to the policymakers to solve the global challenges primarily related to GDP growth and its influence on the quality of the environment. Wang et al. (2019) examined the coupling/decoupling of GDP growth from energy use in India and China. These countries and other developing nations are trying to achieve sustainable economic growth by using fewer energy sources. This study investigated the GDP growth-energy nexus for China and India from 1990 to 2015 using the Log-Mean Divisia Index and Cobb Douglas function methods. The statistical results concluded that China's decoupling efforts significantly improve energy efficiency, and by using technological innovation, India is also trying to contribute to the decoupling effort.

2.2.2 Literature on environmental degradation and technological innovation

The second strand of the Literature is based on the relationship between environmental degradation and technological innovation. Many researchers recommended that CO2 emissions can be significantly reduced by technological innovation, especially in the process of production, without damaging GDP growth. Lin and Zhu (2019) examined the environmental degradation-renewable technology nexus in the context of China. Their statistical findings concluded that technological change through renewable energy sources is improving the environmental quality in China and promoting a low-carbon society. Ahmad et al. (2020) investigated technological innovation and its impact on ecological footprint for twenty-two emerging economies, and their statistical findings concluded that ecological footprint reduction is possible due to technological innovation. Wang et al. (2020) analysed that technological innovation is a critical factor in achieving environmental sustainability in the N-11 economies. Similarly, Guo et al. (2021) examined the impact of technological innovation on the quality of the environment in China, and their findings concluded that sustainable development goals (SDGs) could be achieved through technological innovation. The results of Samargandi (2017) described the relationship between technological change and environmental pollution in Saudi Arabia and could not provide the influential role of technological innovation in minimising environmental degradation. Kassouri et al. (2022) examined the development of renewable energy, oil utilization, and natural capital in the European countries between 1996 and 2016. Their empirical findings concluded that growth in renewable energy consumption is significantly discouraged by the different use of oil utilization by inelastic proportions. Different carbon sequestration techniques can be minimized the use of non-renewable energy sources. Moreover, this region's energy transitional policy should be enhanced by an adequate supply of renewable energy. Bilgili et al. (2021) investigated the environment-disaggregated energy R&D nexus in 13 developed economies from 2002 to 2018. Their findings exhibit the presence of EKC only in higher carbon-emitting economies. But in the case of lower carbon-emitting economies, the EKC is more predominant. They also found no dynamic association between environmental pollution and economic growth. The impact of research and development on clean energy and technological innovation to curb environmental pollution is a prerequisite in these countries.

2.2.3 Literature on environmental taxes and environmental degradation

The third strand of the Literature is based on the relationship between environmental degradation and environmental taxes. Recently, countries have been trying to attain sustainable economic growth by controlling environmental issues. They are implementing various policies (to increase sustainability) such as environmental taxes, green innovation, and innovative sources of energy (e.g., photovoltaic cells). Ecological destruction and energy consumption are significantly reduced by Environmental tax. Miceikiene et al. (2018) examined the significant role of a carbon tax in the economies and focused on renewable energy innovations.

A comprehensive analysis of Wissema and Dellink (2007) examined the statistical data of Ireland's economy and concluded that CO2 emissions are reduced by 25% if 15 Euros per ton carbon taxes are imposed. Similarly, Sterner (2007) also explored that use of non-renewable energy can be reduced through the imposition of environmental taxes. Convery et al. (2007) described that environmental taxes collected 13 billion in revenue to the Irish economy in the same line. It is estimated that a 90% decline in CO2 emissions can be possible in this country. Lin and Li (2011) investigated a statistical analysis of Scandinavian economies, found a negative connotation between environment-related taxes and CO2 emissions in Finland, and investigated that the economy of Norway is heavily dependent on petroleum and the rate of CO2 emission is higher in this country. Morley (2012) examined the environmental tax and CO2 emissions nexus in EU member nations, and their statistical findings show the inverse relationship between environmental taxes and CO2 emissions. Borozan (2019) examined the association between energy taxes and residential energy consumption. Their results concluded that energy taxes could efficiently reduce residential energy use in European Union countries. Along the same line, He et al. (2019) also found the influential role of environmental taxes in minimising the CO2 emissions in OECD economies and China.

2.2.4 Literature on environmental degradation and environmental policy stringency

The fourth strand of the Literature is based on the relationship between environmental degradation and environmental regulations. Stringent environmental laws and policies are being prompted to minimize the worse environmental quality; thus, strict environmental policy is essential for mitigating CO2 emissions. The core purpose of this indicator is to divert the producer and consumer behaviour to environmental-friendly products by making environmental pollution services more expensive. Neves et al. (2020) described that environmental restrictions would increase the cost of polluted (dirty) goods and activities Mulatu (2018) highlighted the importance of environmental outcomes and regulations. They concluded that CO2 emissions could be reduced by implementing environmental policies and eco-friendly technology. According to Cohen and Tubb (2018), environmentally “dirty” technologies should be replaced by eco-friendly technologies as stringent environmental policies and environmental taxes significantly impose positive effects on environmental pollution (Lagreid and Povitkina 2018).

The empirical analyses of the nexus between environmental quality and policy are discussed in the studies of Dechezleprêtre and Sato (2017) and van Leeuwen and Mohnen (2017), but the findings are not conclusive. Shapiro and Walker (2018) examined that between 1990 and 2008, a reduction in CO2 emissions was found in the United States. Similarly, Wolde-Rufael and Mulat-Weldemeskel (2021) analyzed the role of environmental policies for the few emerging economies from 1994 to 2015 and the effectiveness of environmental policies in reducing environmental destruction. In the same vein, de Angelis et al. (2019) examined environmental stringency and its impact on environmental quality for OECD economies. They found a significant reduction in CO2 emissions due to environmental stringency regulations. But Wang and Wei (2020) found that stringency environmental policy does not improve environmental quality by reducing CO2 emissions.

3 Econometric model and data

3.1 Theoretical framework and model construction

This current topic represents our theoretical framework depending on these preliminary analyses. Additionally, the Literature of literature section discussed a few research analyses that have been done on ecological footprint. Though, limited research studies examine the combined impact of environmental taxes and environmental regulations on environmental quality under the EKC scheme for Non-OECD and OECD nations. The theoretical framework is presented based on the double-dividend hypothesis of environmental taxation and the premises of the environmental Kuznets curve (EKC) (Dinda, 2005). Theoretically, natural resources depletion for consumption purposes will source in higher ecological footprints and more ecological deficit. According to this description, the emerging and developed countries endeavour to implement stringent policy implications and regulations (energy and environmental-related taxes) and governmental controls to regulate non-renewable energy sources and resource consumption. The theoretical framework channel describes energy resource consumption for industrial production as significantly associated with resource consumption and resource generation. Consequently, excess utilization of natural resources causes ecological issues. Following this, ample use of natural resources with environmental destruction motivates the policymakers to implement environmental regulations and taxes to minimize the use of non-renewable.

Thus, identifying the main contribution of this study to the mitigation of environmental issues, this study explores the effects of environmental taxes, strict environmental regulations, and the efficient role of technological innovation on the ecological footprint (EPF) of OECD Non-OECD economies. Thus, in this line, we presume that strict environmental regulations and taxes are efficient indicators of minimizing the deterioration of environmental quality (He et al., 2019; Xiong and Li, 2019). Moreover, the modeling of our study also comprises some plausible control variables based on prior research and Literature. Similarly, other control factors such as non-renewable energy use and GDP growth also increase environmental degradation. The energy use-environmental destruction nexus is well discussed in EKC premises. The contribution of this study is by analyzing the impact of energy on the improvement in ecological footprint, which can significantly improve environmental quality. Many researchers discuss sustainable growth-environment nexus regulations and policies, and their main objective is to achieve less environmental deterioration with sustainable growth (Hao et al., 2021; Saleem 2022). This theory is designed by Grossman and Krueger (1995) as it determines the trade-off between the environment and growth. In this sense, our study incorporated plausible control variables under the umbrella of the EKC framework.

Theoretical description of all the variables mentioned above (Eq. 1) and the ecological footprint-GDP growth nexus with control factors are employed under the scheme of the EKC test in the following equations.

$$\mathbf{EFP_t = f\left(GDP_t, GDP_t^2, NREW, GTEC_t, ETX_t, ERL_t\right)} \quad (1)$$

3.2 Description of data

Table 1 represents the list of variables. This study finds the association between ecological footprint (EFP) and growth with other control factors from 1990 to 2016 for twenty-seven OECD and six Non-OECD countries. The data on GDP growth is used as GDP per capita (constant 2010US$). Non-renewable are used as (a percentage of total final energy consumption). The data on GDP growth and non-renewable energy use has been obtained from the World Development Indicator (WDI, 2021). *CO2* represents the carbon emission (per capita) obtained from WDI (2021). Technological innovation is estimated as eco-friendly technology as a % of all technologies. EFP represents the values of EFP to identify environmental degradation. EFP quantitative indicator is designed by Rees (1992), especially determining natural resources consumption and their production. EFP is calculated in the generation of waste of various resources, depletion of natural resources, rapid utilization of natural resources and waste absorption rate of nature, and the growth of new resources. The data of EFP as metric tons (per capita) is obtained from the Global Footprint Network (2021). The data and countries are selected according to the availability of data. The statistical data on environmental regulation (as an index of stringency ecological policy) and environmental tax are taken from an OECD (2021) statistics database. Furthermore, Appendix A describes the list of OECD and Non OECD economies of the world.

3.3 Methods

3.3.1 Cross-section dependence unit root test

Initially, the present analysis tries to identify the cross-sectional dependence (CSD) among various model factors. In doing so, the test of CSD is designed by Pesaran (2007). Moreover, numerous indicators are linked with CSD. Spurious results will be attached if the CSD problem is not considered during estimation (Westerlund and Edgerton, 2008; Flores, 2019). The authors used different CSD tests to identify the CSD in the analysis of panel data among the factors, namely, Breusch-Pagan chi-square, Friedman chi-square, Pearson CD normal, and Pearson LM standard test.

3.3.2 Tests of slope homogeneity

The second step of the study tries to identify the data analysis's slope homogeneity. We used Pesaran and Yamagata's test (2008) to find out the slope homogeneity of the model. This test can significantly identify the heterogeneity or homogeneity of the data analysis. We used the Pesaran and Yamagata (2008) statistics to determine the slope homogeneity. Thus, the homogeneity and heterogeneity of the panel data would be checked with this test. The importance of the slope homogeneity test cannot be denied in the empirical analysis.

3.3.3 Panel unit root tests

The third step is to check the non-stationarity issue in time series analysis was discussed in various empirical analyses (Cheung et al., 2019; Jiang et al., 2020). The study investigates the unit root problem; thus, the second-generation stationary techniques are used to identify the unit root problem (Pesaran 2007). The test permits the presence of CSD in the study. The augmented cross-sectional IPS (CIPS) test detects the stationary issue of various factors under consideration. This study used Pesaran (2007) (i.e., cross-sectional augmented IPS).

3.3.4 Co-integration tests

The fourth step of the study is to identify the co-integration between the variables. Co-integration is demarcated as the long-run association between different factors of the model. In this method, various variables can be analysed for long-run relationships. The modern panel co-integration test was designed by Westerlund (2008), and we applied this in our analysis to designate robust revelations. The presence of CSD, non-stationarity of data, and heterogeneity in the panel data analysis can be handled by Westerlund and Edgerton (2008).

$$\alpha_1\,(L)\Delta y_{it} = y2it + \beta_i\left(y_{it} - 1 - \alpha_i' x_{it}\right) + \lambda_i\,(L)v_{it} + \eta_{it} \tag{2}$$

TABLE 1 List of variables.

Variables	Description	Units	Sources
EPF	Ecological Footprint	Metric tonnes (per capita)	Global Footprint Network (2021)
GDP	Gross domestic product	Constant 2010 US$	(WDI, 2021)
NREW	Non-renewable energy consumption	Total final energy consumption in %	(WDI, 2021)
ETX	Environment taxes	% of GDP	OECD (2021)
GTEC	Environment clean technology, and innovation	% of all technologies	OECD (2021)
ERL	Stringency environmental policy	Index of stringency environmental policy	OECD (2021)

$$\text{Where, } \delta_{1i} = \beta_i(1)\widehat{o}_{21} - \beta_i\lambda_{1i} + \beta_i(1)\widehat{o}_{2i} \text{ and } y2i = \beta_i\lambda_{2i} \quad (3)$$

The equation of Westerlund co-integration statistics is given below,

$$G_t = 1/N\sum_{i=1}^{N}\alpha_i'/SE(\alpha_i'), \quad (4)$$

$$G_a = 1/N\sum_{i=1}^{N}T\alpha_i'/\alpha_i'(1), \quad (5)$$

$$P_t = \alpha_i'/SE(\alpha_i'), \quad (6)$$

$$P_a = T\alpha', \quad (7)$$

The value of group statistics is shown as Ga and Gt, and panel statistics are represented by P_t and P_a. The null hypothesis represents no cointegration, and the alternative hypothesis indicates the long-run association between the variables.

3.3.5 Cross-section augmented autoregressive distributed lags

The fifth step is to use the CS-ARDL method to identify the association between environmental degradation and its control variables due to the panel data set and the presence of cross-sectional dependency in the variables of this analysis. This CS-ARDL technique resolves the issues of slope heterogeneity, endogeneity, and CSD (Chudik and Pesaran, 2013). This test compresses various descriptive elements with unexplained components and a small sample size that is unpredictable and sensitive sample size. Different explanatory variables with undetected details, unexpected and sensitive small size of the sample are compact by this test. Based on the theoretical framework, this study incorporated the impact of environmental tax, strict environmental regulations, non-renewable energy use, technological change, and GDP growth on environmental degradation. We rewrite the model as follows:

$$EFP_{2it} = \beta_1 + \beta_2 GDP_{it} + \beta_3(GDP_{it})^2 + \beta_4 NREW + \beta_5 REW_{it} + \beta_6 GTEC_{it} + \beta_7 EXT_{it} + \beta_8 ERL_{it} + \epsilon_{it} \quad (8)$$

Where β_1 represents the slope of coefficient, $\beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$ parameters of economic growth (GDP), square of GDP, non-renewable energy consumption (NREW), technological innovation (GTEC), environmental tax (ETX), strict ecological regulations (ERL). Similarly, 'i' represents the country, and 't' represents the period.

The equation given below defines the model of CSD-ARDL.

$$\Delta EDG_{it} = \Omega_i + \sum_{1=0}^{m}\Phi_{1il}\Delta EDG_{it,t-1} + \sum_{1=0}^{m}\Phi_{2il}X_{i,t-i} \quad (9)$$

$$\Delta EDG_{it} = \Omega_i + \sum_{1=0}^{m}\Phi_{1il}\Delta EDG_{it,t-1} + \sum_{1=0}^{m}\Phi_{2il}X_{i,t-i} + \sum_{1=0}^{m}\Phi_{3il}Y_{it-1} + \epsilon_t \quad (10)$$

Where EDG is related to the dependent variable (environmental degradation), Y represents the average value of dependent variables, and X indicates the importance of main determinants such as GDP, GDP square, GTEC, NREW, EXT, and ERL, l, and m related to the lag values of the dependent variable.

The following equation represents the long-run analysis of CS-ARDL through the mean group estimator as given below,

$$\pi\, CS - ARDL,\ i = \sum_{1=0}^{m}\Phi_{1il},\ m/1 - \sum_{1=0}^{m} \quad (11)$$

Meanwhile, the following equation represents the mean group of the study.

$$\pi MG = 1/N - \sum_{i=1}^{N}\pi i \quad (12)$$

Though, the study also presents the short-run coefficients in the following equation,

$$\Delta EDG_{it} = \varnothing_i\left[EDG_{i,t-1} - \pi X_{i,t}\right] + \sum_{1=0}^{m}\Phi_{1il}\Delta EDG_{it,t-1} + \sum_{1=0}^{m}\Phi_{2il}\Delta EDG_{it,t-i} + \sum_{1=0}^{m}\Phi_{3il}Y_{it-1} + \epsilon_t \quad (13)$$

Eq. 13 represents the short-run co-efficient of CS-ARDL analysis. Where *EDG* is related to the dependent variable (environmental degradation), Y represents the average value of dependent variables, and X indicates the importance of crucial determinants such as GDP, GDP square, GTEC, REW, NREW, EXT, and ERL, l and m related to the lag values of the GDP growth.

3.3.6 Robustness estimators

For robustness check, this study used the tests of applying the Augmented Mean Group (AMG) designed by Eberhardt (2012) Common Correlated Effect Mean Group (CCEMG) designed by Pesaran (2006). These tests significantly deal with the endogeneity, CSD, and heterogeneity concerns. In addition, the correlation among different cross-section units is also controlled by these estimators.

3.3.7 Panel causality test

Although, the results of the CS-ARDL estimators confirm the association's magnitude and direction. However, our final step of the study analyses the causality between variables. Thus, Dumitrescu and Hurlin's (2012) test is used to scrutinise the causal association between environmental quality (EFP) and other control variables like GDP, non-renewable energy, environmental tax, and strict environmental regulations. By identifying the model of the study, this analysis tests the bivariate causality among different variables by handling the heterogeneity all over the CSD (in the short run). In this test, H0 represents that there is no causality, and H1 represents that there is causality among the factors. Finally, to test the non-causality Granger analysis for each cross-section, the study focused on examining the Wald estimate. The inconsistent non-causal theory recognises that heterogeneous panel causality links to the normal distribution. Figure 1 illustrates the Route of

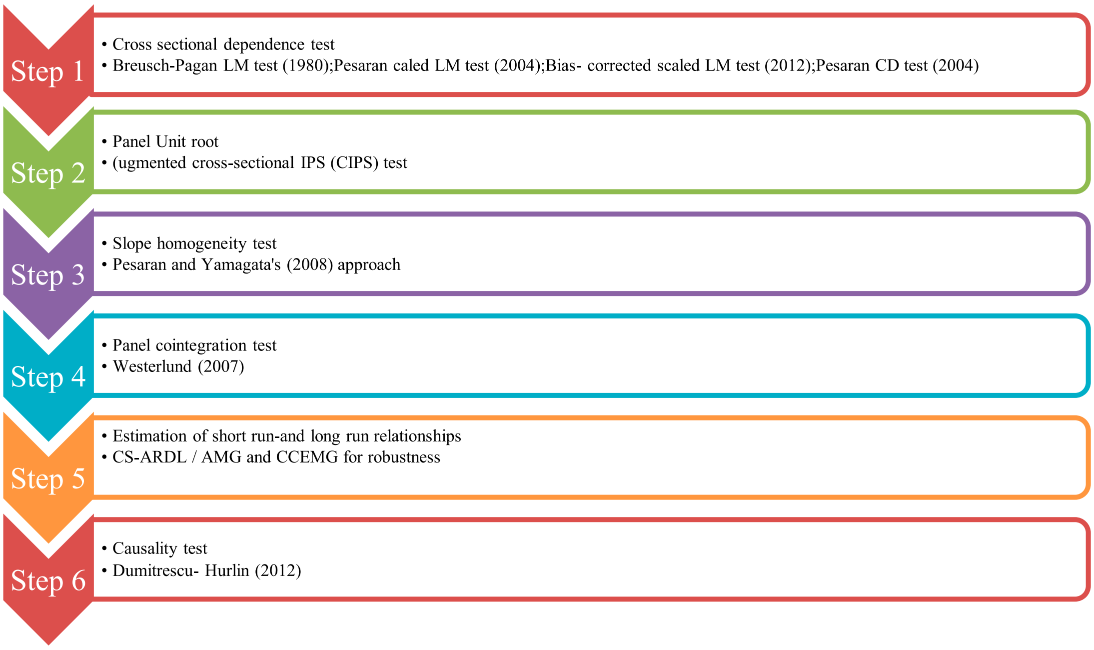

FIGURE 1
Route of methodology.

methodology, where different methods are applied in this analysis, e.g., Cross-sectional dependence test, panel unit test, slope homogeneity test, panel cointegration test, and Causality test Dumitrescu and Hurlin's (2012).

4 Empirical results and discussion

The empirical findings of the CSD test are presented in Table 2; the presence of CSD is confirmed in the panel data analysis as this study used the Pesaran LM normal, Friedman chi-square, Pesaran CD normal, and Breusch-Pagan chi-square test, respectively, and rejected the null hypothesis (no existence of CSD)/accepted the alternative hypothesis (presence of CSD).

After employing the CSD test, it is essential to use the test of slope homogeneity; thus, we used Pesaran and Yamagata's (2008) approach. Table 3 shows that this study rejected the null hypothesis and accepted the alternative hypothesis (heterogeneous slope coefficients).

Additionally, the statistical findings of the unit root test are presented in Table 4, identifying the stationarity of the data addressing the heterogeneity and the CSD test. To determine the unit root issue under the observation of alternative or null hypotheses, we concluded that few variables found the stationarity issue in the panel data analysis and rejected the null hypothesis for all the variables.

The current analysis applied the method of Westerlund and Edgerton (2008) to identify the existence of cointegration in the research; the statistical findings are reported in Table 5. The results showed that we accepted the alternative hypothesis (presence of cointegration) and rejected the null hypothesis (no cointegration exists). Thus, the study indicates a long-run association between the variables and justifies the study's arguments. Additionally, the long-run association was found between variables for Westerlund and Edgerton (2008) under the dependent variables EFP.

The present analysis applied the CS-ARDL test to determine the impact of economic growth, non-renewable, technological innovation, environmental tax, and strict environmental regulations on environment quality under the scheme of EKC with dependent variables (EFP). Table 6 indicates the long-run and short-run results for OECD and Non-OECD countries. The GDP growth and GDP square were found to be positively and negatively, respectively, in the context of OECD and Non-OECD countries for environmental quality (EFP); thus, the existence of EKC is confirmed for both OECD and Non-OECD economies. The results are consistent with prior studies (Destek and Sinha, 2020; Saleem et al., 2022). A short-run analysis (OECD countries) shows that a 1 unit change in GDP will increase EFP by 0.52 units. The findings of our study are similar to the results of Ahmed et al. (2020) examined China, Ahmed et al. (2020) for G7 countries, and Shahbaz et al. (2013) for Indonesia. Salahuddin et al. (2016) concluded the contradict findings, and no association

TABLE 2 Test of residual cross-section dependence.

Test	Statistic	Prob	Null hypotheses	Conclusion
Breusch-Pagan Chi-square	6.674	0.000	No CSD in residuals	Reject
Pesaran LM Normal	3.486	0.001	No CSD in residuals	Reject
Pesaran CD Normal	-5.097	0.000	No CSD in residuals	Reject
Friedman Chi-square	16.760	0.000	No CSD in residuals	Reject

Rejection means that the null hypothesis is rejected at a 1% significance level.

TABLE 3 The heterogeneity and homogeneity testing of slope co-efficient.

Model 1	
$RFP_t = f(GDP_t, GDP_t^2, NREW, GTEC_t, ETX_t, ERL_t)$	
Delta (*p*-value)	Adjusted—Delta (*p*-value)
30.098*** (0.000)	45.008*** (0.000)
MODEL 2	
$EFP_t = f(GDP_t, GDP_t^2, NREW, GTEC_t, ETX_t, ERL_t)$	
Delta (*p*-value)	Adjusted—Delta (*p*-value)
20.876*** (0.000)	28.567*** (0.000)

*** represents the level of significance at 1%.

was found between environmental quality and GDP growth in OECD countries. On the other side, Ozcan et al. (2020) oppose the result found in their analysis and conclude an inverse association between GDP growth and environmental degradation.

The values of GDP square were negative and significant, which shows that if there is one unit change in GDP square, it will bring a 0.34 unit change in EFP. The long-run estimates also concluded a significant inverse relationship between GDP square and environmental quality, as I unit increase in GDP square will lead to a 0.50 unit decline in EFP. The high rate of GDP growth enriched the excess utilization of resources in these OECD economies. The positive association between GDP growth and ecological footprint in OECD economies suggested that the worse consequences of GDP growth on the quality of the environment can be mitigated through initiatives and effective government policies that consider worse environmental quality. Our findings are consistent with those (Saleem et al., 2021; Wenbo and Yan, 2018), However, the results of Destek and Sarkodie (2020) could not support the EKC's presence in Pakistan.

Moreover, a significant and positive association was found between NREW energy and environmental degradation in OECD countries; this means ecological footprint destruction is accelerating by using non-renewable energy consumption in the long and short run. The findings can be justified: still developed countries heavily rely on non-renewable energy consumption. The hypothetical testing of the study stated that environmental quality is deteriorating by excess non-renewable energy use. More specifically, the results indicate 0.49 units increase in EFP, as a 1 unit change found in NREW energy use. The long-run estimates also found a positive association between environmental quality and NREW energy, and an I unit increase in NREW will lead to a 0.41 unit upsurge seen in EFP, respectively. This study concluded a positive association between NREW energy use and ecological footprint at a 1% significance level. This hypothesis is justified as higher NREW energy use accelerates the destruction of ecological footprint. Numerous researchers have recently investigated the relationship between environmental quality and NREW energy use (e.g., Sharif et al., 2019, Saleem et al., 2021). Similarly, the findings of Bekun et al. (2019) and Inglesi-Lotz and Dogan (2018) also investigated a positive association between renewable energy use and the quality of the environment. These statistical results are supported by the empirical evidence of Wolde-Rafael and Mulat-Weldemeskel 2021; Adewuyia and Awodumi 2017; Ben Jebli and Kahia 2020).

Technological change through efficient utilization of energy sources and technological change can significantly improve the quality of the environment. A significant negative correlation was found between technological innovation and environmental degradation in OECD countries. More precisely, the results indicate that unit 0.08 unit decreases were seen in EFP, as there was 1 unit change in GTEC. The long-run estimates also found a positive association between environmental quality and GTEC. An I unit increase in GTEC will lead to 0.29 unit decreases in EFP. Moreover, this is comprehensible that environmental quality can be improved through more innovation then fewer resources will be utilized, leading to a lower ecological footprint. Similarly, technological innovation developed the production process of green technology, efficient energy utilization, less utilization of natural resources, and an upsurge of renewable energy sources. These findings align with existing Literature (Saleem et al., 2020; Islam et al., 2022). Various empirical findings (Chen and Lee, 2020; Usman and Hammar, 2021) concluded that technological change exerts a detrimental impact on the quality of the environment. The findings of our study are also endorsed by the studies of (Hao et al., 2021; Saleem et al., 2022). This statement is also vindicated by preliminary analysis, e.g., the

TABLE 4 Statistical analysis of Panel unit root test.

	At level		First differences	
Variable names	CIPS	Mip	CIPS	Mip
OECD Economies				
Ecological Footprint	-0.002	-0.061	-0.765	-4.858***
Economic Growth	-0.599	-0.012	-0.894	8.754***
Non-Renewable energy use	-0.307	-0.970	-0.726	6.430***
Environmental Tax	-8.561***	-4.423***	-	-
Technological change	-4.812***	-5.413***	-	-
Stringency environmental policy	-3.768***	-4.507***	-	-
Non-OECD Economies				
Ecological Footprint	-0.020	-0.011	-0.089***	-7.841***
Economic Growth	-0.172	-6.78	-0.479	9.097***
Non-Renewable energy use	-0.438	-0.600	-0.335	4.689***
Environmental Tax	-8.429***	-4.785***	-	-
Technological Innovation	-5.876***	-7.564***	-	-
Stringency environmental policy	-5.968***	-4.895***	-	-

**** indicates a 1% level of significance.

study of Tobelmann and Wendler (2020) concluded that technological change could significantly reduce carbon dioxide emissions in European economies. Kassouri et al. (2022) concluded that technological advancement in terms of clean energy in the long run substantially supports the worldwide convergence of energy technology. Their results show that advanced countries should use effective technology-driven energy policies to accelerate clean energy technological innovation.

Environmental effectiveness can be accomplished through the imposition of environmental taxes, and these taxes can decline environmental degradation. The short-run estimation of the study indicates that a 1 unit increase in ETX would lead to a 0.05 unit decline found in EFP. The long-run estimates also found a negative association between ETX and environmental quality. An I unit increase in ETX will lead to 0.32 unit decreases in EFP. The findings of our analysis are endorsed by the studies of (Saleem et al., 2022; Wolde-Rufael and Mulat-Weldemeskel 2021; Ulucak et al., 2020; Andersson 2019; Criqui et al., 2019), and the statistical findings of all these authors found the inverse relationship between environmental tax and environmental degradation.

TABLE 5 Statistical findings of panel cointegration test (Westerlund, 2007).

Statistics	Value	Z-value
G_t	-4.765***	-3.890***
G_a	-6.987***	-3.654***
P_t	-8.356***	-4.924***
P_a	-9.685***	-5.087***

Where *** represents the 1% level of significance.

The short-run estimation of the study indicates that a 1 unit increase in ERL would lead to a 0.05 unit decline found in EFP. The long-run estimates also found a negative association between environmental quality and ERL. An I unit increase in ERL will lead to 0.25 unit decreases found in EFP. Thus, in this line, strict environmental regulations and taxes are efficient factors in abating the deterioration of environmental quality (He et al., 2019; Xiong and Li, 2019). The findings of our analysis are endorsed by the studies of (Wolde-Rufael and Mulat-Weldemeskel 2021); the statistical results of all these authors found the inverse relationship between tight environmental rules and regulations and environmental degradation. The Error of correction technique (ECT) (-1) indicates the speed of adjustment, the findings of ETC (-1) concluded that at a 1% level of significance, 60% modification is required to move towards the equilibrium point of the research study for OECD economies.

Table 6 also designates the long-run and short-run results for Non-OECD economies in model 1 (EFP). The GDP growth and GDP square were positive and negative in Non-OECD economies for environmental quality (EFP). There is a 1 unit change in GDP in the short-run analysis, which will increase EFP by 0.05 units. The values of GDP square were negative and significant, which shows that if one unit change brings in GDP square, it will bring a 0.03 unit change in EFP. The long-run estimates also found the inverse relationship between environmental quality and GDP; an I unit increase in GDP

10.3389/fenvs.2022.972354

TABLE 6 Statistical findings of CS-ARDL.

Model 1 (OECD)				
EFPt = *f* (GDPt, GDPt2, NREWt, GTECt, ETXt, ERLt)				
Variables	**Short-run analysis**	**Long run-analysis**		
	Co-efficient	**Standard deviation**	**Co-efficient**	**Standard deviation**
GDPit	-0.524***	0.570	-0.356***	0.001
(GDPit)2	-0.340***	0.047	-0.501***	0.019
NREWit	0.050***	0.012	-0.410***	0.002
GTECit	-0.080**	0.002	-0.293***	0.012
ETXit	-0.050**	0.020	-0.320**	0.013
ERLit	-0.049***	0.032	-0.249***	
ECT (-1)	0.601***			
Model 2 (Non-OECD)				
GDPit	0.050**	0.022	0.264***	3.1845
(GDPit)2	-0.030***	0.001	-0.542***	0.004
NREWit	0.038***	0.003	0.20***	0.006
GTECit	-0.037**	0.090	-0.132**	0.0479
ETXit	-0.029***	0.070	-0.177***	0.0815
ERLit	-0.020**	0.056	-0.198***	0.0417
ECT (-1)	-0.450***			

***, ** represents the 1% and 5% level of significance.

square will lead to a 0.26 unit decline in EFP. The long-run estimates also found the inverse relationship between environmental quality and GDP square, as an I unit increase in GDP square will lead to a 0.49 unit decline in EFP. The findings of our study are consistent with the empirical evidence of (Sharif et al., 2019; Saleem 2020).

Moreover, a significant and positive association was found between NREW energy and environmental degradation in Non-OECD countries. More specifically, the results indicate 0.03 EFP, respectively, as a 1 unit change was found in NREW energy use. The long-run estimates also found a positive association between environmental quality and NREW energy. An I unit increase in NREW will lead to a 0.20 unit upsurge in EFP. These findings can be justified: as most Non-OECD economies are developing economies and heavily depend on non-renewable energy sources. These economies are early stages of economic development and actively moving towards rapid economic growth; thus, the impact of non-renewable energy consumption on environmental quality is worse. The results are consistent with the study of Shafiei and Salim (2014), whose study concluded that excess use of fossil fuels significantly deteriorates the quality of the environment.

Technological change through efficient utilization of energy sources and technological change can significantly improve the quality of the environment. Additionally, a significant negative correlation was found between technological innovation and environmental degradation in Non-OECD countries. The results indicate that unit 0.04 unit decreases were seen in EFP, as a 1 unit change was found in GTEC. The long-run estimates also found a positive association between environmental quality and GTEC. An I unit increase in GTEC will lead to 0.13 unit decreases in EFP. The statistical results of the analysis follow the analyses of Solarin and Bello, (2021), and Usman and Hammar, (2021); these studies concluded that technological innovation *via* renewable energy use significantly mitigates environmental degradation. These Non-OECD economies are facing the challenges of environmental degradation and putting pressure on ecological footprint due to the negative impact of non-renewable energy use. Thus, the government should encourage investments in technological innovation and provide financial assistance to the firms to promote green technology innovation to combat environmental degradation.

The short-run estimation of the study indicates that a 1 unit increase in ETX would lead to a 0.03 unit decline found in EFP. The long-run estimates also found a negative association between environmental quality and ETX. A 1 unit increase in ETX will lead to 0.18 unit decreases in EFP. The short-run estimation of the study indicates that a 1 unit increase in ERL would lead to a

TABLE 7 Long run AMG and CCEMG for robustness check.

Model 1 (OECD)/	Augmented mean group (AMG.)		Common correlated effect mean group (CCEMC)	
GDP_{it}	-0.429***	3.570	-0.586***	13.070
$(GDP_{it})^2$	-0.280***	3.047	-0.380***	8.098
$NREW_{it}$	0.060***	4.102	0.049***	5.182
$GTEC_{it}$	-0.088***	4.002	-0.095***	8.872
ETX_{it}	-0.060***	5.020	-0.070***	12.870
ERL_{it}	-0.050***	6.032	-0.060***	16.032
Model 2 (Non-OECD)/Dependent variable (EFP)				
GDP_{it}	0.046***	3.022	0.060***	4.022
$(GDP_{it})^2$	-0.028***	7.701	-0.035***	8.701
$NREW_{it}$	0.030***	14.303	0.027***	9.903
$GTEC_{it}$	-0.046***	4.090	-0.039***	5.320
ETX_{it}	-0.039***	15.070	-0.030***	9.870
ERL_{itf}	-0.025***	12.056	-0.031***	6.316

*** shows the level of significance at 1%.

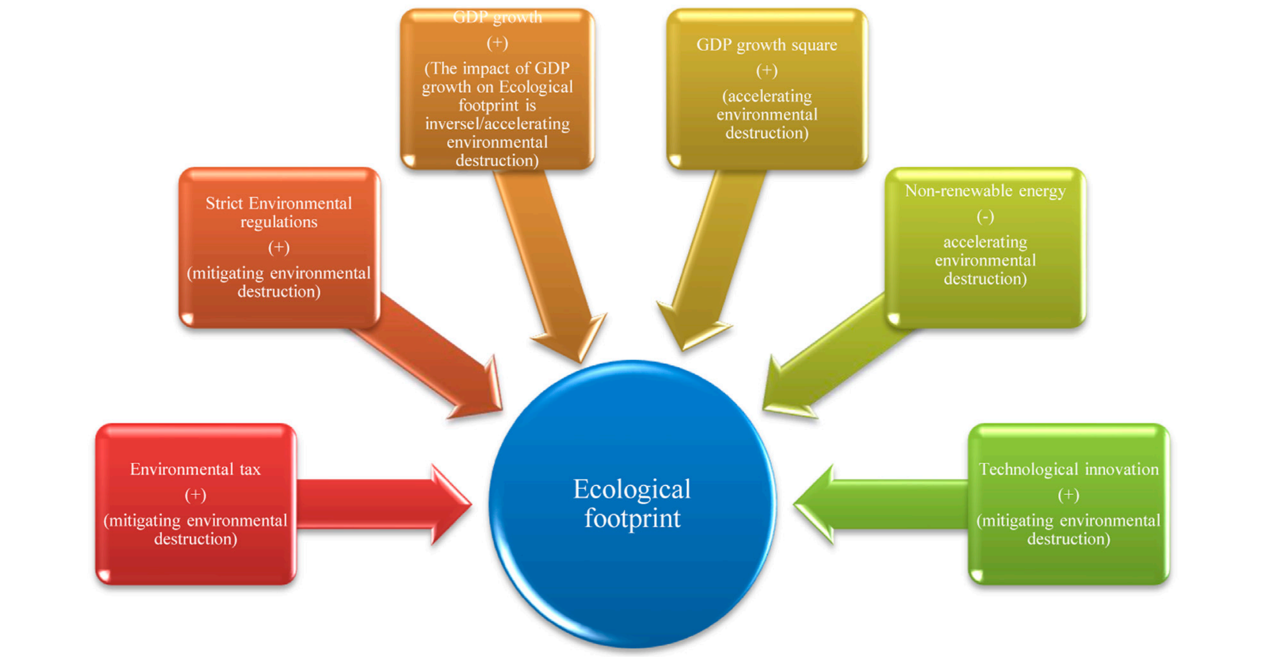

FIGURE 2
Graphical representation of statistical findings.

0.02 unit decline found in EFP. The long-run estimates also found a negative association between environmental quality and ERL An I unit increase in ERL will lead to 0.18 unit decreases in EFP. These results confirmed EXT and ERL's positive contribution to mitigating environmental degradation. These findings are consistent with the line of Hao et al. (2021) and Zhang et al. (2016); they also analysed that strict environmental regulation can significantly improve the quality of the environment. However, Shahzad et al. (2020) concluded that an environmental degradation-environmental regulation policies nexus finding still requires more research and investigation. The Error of correction technique (ECT) (-1) indicates the speed of adjustment; the results of ETC (-1) concluded that at a 1% significance level, 45% modification is required to move

TABLE 8 The statistical findings of the Dumitrescu Hurlin panel test.

S.no.	Hypothesis	W-stat	Z-stat	P-value	Statistical results	Decision
1	LEFPϕLGDP	3.877	0.806	0.419	No	
	LGDPϕLEFP	4.983	3.104	0.035	Yes	Unidirectional Causality
2	LEFPϕLGDP2	1.847	0.77	0.441	No	
	LGDP2ϕLEFP	4.931	3.043	0.041	Yes	Unidirectional Causality
3	LEFPϕLNREW	5.098	4.125	0	Yes	
	LNREWϕLEFP	3.322	2.902	0.012	Yes	Bidirectional Causality
4	LEFPϕLGTEC	6.612	5.009	0.01	Yes	
	LGTECϕLEFP	3.267	2.837	0.014	Yes	Bidirectional Causality
5	LEFPϕLETX	3.759	0.543	0.489	No	
	LETXϕLEFP	5.825	4.092	0	Yes	Unidirectional Causality
6	LEFPϕLERL	5.89	3.965	0	Yes	
	LERLϕLEFP	7.815	6.725	0	Yes	Bidirectional Causality
7	LGDPϕLGDP2	4.877	3.006	0.07	Yes	
	LGDP2ϕLGDP	7.903	6.123	0	Yes	Bidirectional Causality
8	LGDPϕLNREW	8.047	7.778	0	Yes	
	LNREWϕLGDP	5.536	4.09	0	Yes	Bidirectional Causality
9	LGDPϕLGTEC	8.098	8.78	0	Yes	
	LGTECϕLGDP	7.034	6.236	0	Yes	Bidirectional Causality
10	LGDPϕLEXT	4.612	3.679	0.08	Yes	
	LEXTϕLGDP	9.298	8.677	0	Yes	Bidirectional Causality
11	LGDPϕLERL	0.709	0.543	0.659	No	
	LERLϕLGDP	6.825	5.092	0	Yes	Unidirectional Causality
12	LGDP2ϕLNREW	7.65	6.905	0	Yes	
	LNREWϕLGDP2	8.905	7.78	0	Yes	Bidirectional Causality
13	LGDP2ϕLGTEC	4.322	3.902	0.04	Yes	
	LGTECϕLGDP2	5.985	4.674	0	Yes	Bidirectional Causality
14	LGDP2ϕLEXT	7.985	6.674	0	Yes	
	LEXTϕLGDP2				Yes	Bidirectional Causality
15	LGDP2ΦLRL	1.847	0.77	0.441	No	
	LERLϕLGDP2	4.931	3.043	0.041	Yes	Unidirectional Causality
16	LNREWϕLEXT	8.438	7.784	0	Yes	
	LEXTϕLNREW	6.976	5.805	0	Yes	Bidirectional Causality
17	LERLϕLNREW	1.767	0.55	0.341	No	
	LNREWϕLERL	5.931	4.043	0.001	Yes	Unidirectional Causality
18	LEXTϕLERL	1.564	0.35	0.761	No	
	LERLϕLEXT	5.931	4.043	0	Yes	Unidirectional Causality

Where, GDP = GDP, growth; NREW, non-renewable energy consumption; EFP = ecological foot print; EXT, environmental tax; GTEC, technological innovation.

towards the equilibrium point of the research study for Non-OECD economies.

4.1 Robustness checks

The statistical findings of AMG and CCEMC are reported in Table 7. The GDP and GDP square values under the AMG and CCEMC were positive and negatively associated with EFP and confirmed the existence of EKC in the context of OECD and Non-OECD economies. The results indicate that level of significance and magnitude are changed, but the findings of the estimated co-efficient have the same direction under these two estimation methods (like the former estimation). The panel data consists of slope heterogeneity and cross-section dependence, which can be considered in the CS-ARDL approach. For robustness, this study applied long-run AMG and the CCEMG tests that also considered the slope heterogeneity and cross-section dependence issues. The results of CS-ARDL are endorsed

FIGURE 3
Graphical depiction of D-H panel causality.

by the findings of AMG and CCEMG tests. The findings of the AMG (CCEMG) tests show that if held all other factors remains constant, if there is 1% change in GDPt, GDPt2,NREWt, GTECt, ETXt, and ERLt, it will bring -0.43 (-0.58),0,28 (-0.38),0,06 (-0.05), 0.08(0.09), 0.06(-0.07),0.05(-0.06) % change in EFP for OECD economies. On the other hand, the findings of the AMG (CCEMG) tests for Non-OECD economies exhibit that if there is one % change in GDPt, GDPt2, NREWt, GTECt, ETXt, and ERLt, it will leads to 0.04 (0.06),0,03 (-0.03), 0.03 (0.03), -0.05(-0.04), -0.04(-0.03),-0.02(-0.03) % change in EFP. Figure 2 represents a graphical illustration of the statistical conclusions; we concluded that the impact of GDP growth, and Nonrenewable energy on Ecological footprint is inverse/ accelerating environmental destruction. Moreover, the Environmental tax, strict environmental regulations and technological innovation mitigate ecological destruction.

Table 8 represents the Dumitrescu Hurlin panel test findings to test the causality between the variables. The estimation describes that any policy shock in GDP, GDP square, non-renewable, technological change, environmental tax, and tight environmental regulations will be significantly essential to identifying the quality of the environment. Furthermore, significant variation can be found in GDP, GDP square, non-renewable, technological change, environmental tax, and tight environmental regulations if any policy changes in worse quality of the environment. The findings of technological change are endorsed by Saleem et al. (2022), Hao et al. (2021), and Can et al. (2021). Adopting technological innovation leads to a significant decline in environmental degradation; thus, the environment-renewable energy use nexus found the causal relationship. These empirical findings are sustained by (Morawska et al., 2018; and Shen et al., 2020). Figure 3 represents the D-H panel causality test; statistical findings indicate that bi-directional causality found between GTEC*EFP, ERL*EFP, NREW*EFP and unidirectional causality found between EXT*EFP, GDP2*EFP and GDP*EFP.

5 Conclusion

This analysis examined the impact of GDP growth, non-renewable, technological change, environmental tax, and tight environmental regulations on an ecological footprint from 1990–2016. The current study applied the method of CS-ARDL to identify the role of GDP on environmental degradation with some control factors under the premises of the environmental Kuznets curve. The findings of this study indicate that an inverted U–shaped EKC was found between GDP growth and environmental quality for OECD and Non-OECD economies (as EFP suggests that GDP growth initially deteriorates the ecological quality, but after the threshold level, GDP growth square leads to less deteriorating environmental quality). The empirical results are robust and consistent in terms of model specification. The analysis explains that the successful implementation of most current policies and work regarding improving environmental quality, such as technological innovation, use of renewable energy, environmental tax, and stringent environmental regulations, significantly contributes to protecting the environment in these economies. The findings of this study concluded that OECD economies are transforming their economies from non-renewable energy to renewable energy use (*via* technological innovation) faster than Non-OECD economies. Moreover, the impact of environmental tax and regulations impact is more significant for OECD economies than Non-OECD economies. The finding shows that the ecological footprint is significantly deteriorating by increasing GDP growth, especially for OECD economies, compared to the Non-OECD economies.

Based on a comprehensive investigation, this study recommends that environmental taxes discourage fossil fuel energy use and invest in energy-saving and eco-friendly innovations. Environmental protection policies depend on implementing environmental taxes and effective institutional procedures (Implementation of rules) for OECD and Non-OECD economies. Under these checks and balances (by institutions) frameworks confirm preserving the environment through environment-friendly innovation. Additionally, the technological-ecological footprint nexus indicates that bidirectional causality is found between these variables, supporting the feedback hypothesis. This feedback hypothesis shows that economies are moving toward environmental sustainability; these findings align with (Sadorsky 2009a; and Chein et al., 2021). Using fossil fuels could be discouraged by increased technological innovation through efficient and renewable use. Thus, the policymakers and governments in the OECD and Non-OECD economies must adopt energy policies and suitable places that desire marketability and technological change towards accomplishing environmentally sustainable goals. Interestingly, the empirical findings of the current study align with these economies' recently implemented efficiency and revised transitional energy policies.

Similarly, the statistical findings of this analysis also analyzed that the impact of environmental policies adopted by these economies is working successfully as technological innovation, ecological taxes, and regulation are improving the quality of the environment. However, these economies should reexamine their policies to control the excessive use of nonrenewable energy, and Non-OECD economies require more attention to convert their energy from non-renewable to renewable. This analysis provides practical strategies for regulators to less utilization of non-renewable energy (mitigating environmental degradation) through the development of effective policies. Thus, to overcome the harmful impact of environmental pollution in these selected economies, this study suggested that it is essential to focus on ecological innovation to move towards environmental sustainability and prosperity.

Furthermore, for future research and significant suggestions/policy implications, this current analysis has some limitations that should be addressed. Further research can be done by adding financial inclusion's role in mitigating environmental degradation by providing financial assistance (green financing) to the firms to produce green products. Scholars can enhance the Literature by scrutinizing the association between research and development (R&D), the role of institutional quality, and ecological footprint. Institutional reforms-environment nexus may bring diverse outcomes, which are not mentioned in the current analysis. Additionally, determinants like human capital, remittance inflows, and economic complexity can be added while investigating the connection between ecological footprint and environmental degradation.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: World Bank (2021), World Development Indicators. The World Bank, Accessed on: 28 January2022 from http://data.worldbank.org/ and Global Footprint Network 2021. How the Footprint Works, Ecological Footprint, Global Footprint Network, https://www.footprintnetwork.org/our-work/ecological-footprint/#:~:text=Ecological%20Footprint%20accounting%20measures%20the%20demand%20on%20and%20supply%20of%20nature.&text=On%20the.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abbasi, K. R., Hussain, K., Redulescu, M., and Ozturk, I. (2021). Does natural resources depletion and economic growth achieve the carbon neutrality target of the UK? A way forward towards sustainable development. *Resour. Policy* 74, 102341. doi:10.1016/j.resourpol.2021.102341

Adewuyi, A. O., and Awodumi, O. B. (2017). Renewable and non-renewable energy-growth-emissions linkages: Review of emerging trends with policy implications. *Renew. Sustain. Energy Rev.* 69, 275–291. doi:10.1016/j.rser.2016.11.178

Agbugba, I., Iheonu, C., and Onyeaka, K. (2018). Homogeneous and heterogeneous effect of exchange rate on economic growth in African countries. *Int. J. Econ. Commer. Manag.* 6 (9), 1–14.

Ahmad, M., Jiang, P., Majeed, A., Umar, M., Khan, Z., and Muhammad, S. (2020). The dynamic impact of natural resources, technological innovations and economic growth on ecological footprint: An advanced panel data estimation. *Resour. Policy* 69, 101817. doi:10.1016/j.resourpol.2020.101817

Al-Mulali, U., Weng-Wai, C., Sheau-Ting, L., and Mohammed, A. H. (2015). Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation. *Ecol. Indic.* 48, 315–323. doi:10.1016/j.ecolind.2014.08.029

Alberini, A., and Filippini, M. (2011). Response of residential electricity demand to price: The effect of measurement error. *Energy Econ.* 33 (5), 889–895. doi:10.1016/j.eneco.2011.03.009

Altıntaş, H., and Kassouri, Y. (2020). Is the environmental Kuznets Curve in Europe related to the per-capita ecological footprint or CO2 emissions? *Ecol. Indic.* 113, 106187. doi:10.1016/j.ecolind.2020.106187

Andersson, J. J. (2019). Carbon taxes and CO 2 emissions: Sweden as a case study. *Am. Econ. J. Econ. Policy* 11 (4), 1–30. doi:10.1257/pol.20170144

Ang, B. W., Choong, W. L., and Ng, T. S. (2015). Energy security: Definitions, dimensions and indexes. *Renew. Sustain. energy Rev.* 42, 1077–1093. doi:10.1016/j.rser.2014.10.064

Aşıcı, A. A., and Acar, S. (2016). Does income growth relocate ecological footprint? *Ecol. Indic.* 61, 707–714. doi:10.1016/j.ecolind.2015.10.022

Auci, S., and Trovato, G. (2018). The environmental Kuznets curve within European countries and sectors: Greenhouse emission, production function and technology. *Econ. Polit.* 35 (3), 895–915. doi:10.1007/s40888-018-0101-y

Balsa-Barreiro, J., Li, Y., Morales, A., and Pentland, A. S. (2019). Globalization and the shifting centers of gravity of world's human dynamics: Implications for sustainability. *J. Clean. Prod.* 239, 117923. doi:10.1016/j.jclepro.2019.117923

Balsalobre-Lorente, D., Gokmenoglu, K. K., Taspinar, N., and Cantos-Cantos, J. M. (2019). An approach to the pollution haven and pollution halo hypotheses in MINT countries. *Environ. Sci. Pollut. Res.* 26 (22), 23010–23026. doi:10.1007/s11356-019-05446-x

Baltagi, B. H., and Hashem Pesaran, M. (2007). Heterogeneity and cross section dependence in panel data models: Theory and applications introduction. *J. Appl. Econ. Chichester. Engl.* 22 (2), 229–232. doi:10.1002/jae.955

Ben Jebli, M., and Kahia, M. (2020). The interdependence between CO2 emissions, economic growth, renewable and non-renewable energies, and service development: Evidence from 65 countries. *Clim. Change* 162 (2), 193–212. doi:10.1007/s10584-020-02773-8

Bilgili, F., Nathaniel, S. P., Kuşkaya, S., and Kassouri, Y. (2021). Environmental pollution and energy research and development: An environmental Kuznets curve model through quantile simulation approach. *Environ. Sci. Pollut. Res.* 28 (38), 53712–53727. doi:10.1007/s11356-021-14506-0

Borozan, D. (2019). Unveiling the heterogeneous effect of energy taxes and income on residential energy consumption. *Energy Policy* 129, 13–22. doi:10.1016/j.enpol.2019.01.069

Burnett, J. W., and Madariaga, J. (2017). The convergence of US state-level energy intensity. *Energy Econ.* 62, 357–370. doi:10.1016/j.eneco.2016.03.029

Can, M., Ahmed, Z., Mercan, M., and Kalugina, O. A. (2021). The role of trading environment-friendly goods in environmental sustainability: Does green openness matter for OECD countries? *J. Environ. Manag.* 295, 113038. doi:10.1016/j.jenvman.2021.113038

Charfeddine, L. (2017). The impact of energy consumption and economic development on ecological footprint and CO2 emissions: Evidence from a markov switching equilibrium correction model. *Energy Econ.* 65, 355–374. doi:10.1016/j.eneco.2017.05.009

Cheng, Y., Awan, U., Ahmad, S., and Tan, Z. (2021). How do technological innovation and fiscal decentralization affect the environment? A story of the fourth industrial revolution and sustainable growth. *Technol. Forecast. Soc. Change* 162, 120398. doi:10.1016/j.techfore.2020.120398

Cheung, W. C., Simchi-Levi, D., and Zhu, R. (2019). "Learning to optimize under non-stationarity," in The 22nd International Conference on Artificial Intelligence and Statistics (PMLR), 1079–1087.

Cohen, M. A., and Tubb, A. (2018). The impact of environmental regulation on firm and country competitiveness: A meta-analysis of the porter hypothesis. *J. Assoc. Environ. Resour. Econ.* 5 (2), 371–399. doi:10.1086/695613

Convery, F., McDonnell, S., and Ferreira, S. (2007). The most popular tax in Europe? Lessons from the Irish plastic bags levy. *Environ. Resour. Econ. (Dordr).* 38 (1), 1–11. doi:10.1007/s10640-006-9059-2

Criqui, P., Jaccard, M., and Sterner, T. (2019). Carbon taxation: A tale of three countries. *Sustainability* 11 (22), 6280. doi:10.3390/su11226280

De Angelis, E. M., Di Giacomo, M., and Vannoni, D. (2019). Climate change and economic growth: The role of environmental policy stringency. *Sustainability* 11 (8), 2273. doi:10.3390/su11082273

Dechezleprêtre, A. (2017). The impacts of environmental regulations on competitiveness antoine Dechezleprêtre and misato Sato review of environmental economics and policy, volume 11, issue 2, 1 july 2017, pages 183–206, https://doi. org/10.1093/reep/rex013 (1) there was an error in the text citations on page 185, lines 34-35, and page 195, line 24. *J. Assoc. Environ. Resour. Econ.* 1 (4), 521–553.

Destek, M. A., and Sinha, A. (2020). Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: Evidence from organisation for economic Co-operation and development countries. *J. Clean. Prod.* 242, 118537. doi:10.1016/j.jclepro.2019.118537

Dinda, S. (2005). A theoretical basis for the environmental Kuznets curve. *Ecol. Econ.* 53 (3), 403–413. doi:10.1016/j.ecolecon.2004.10.007

Dumitrescu, E. I., and Hurlin, C. (2012). Testing for Granger non-causality in heterogeneous panels. *Econ. Model.* 29 (4), 1450–1460. doi:10.1016/j.econmod.2012.02.014

Eberhardt, M. (2012). Estimating panel time-series models with heterogeneous slopes. *Stata J.* 12 (1), 61–71. doi:10.1177/1536867x1201200105

Flores, A. (2019). Relationship between transport demand and economic growth: Dynamic analysis using the ARDL model. *Cuad. Econ.* 43, 105.

Gengenbach, C., Palm, F. C., and Urbain, J. P. (2009). Panel unit root tests in the presence of cross-sectional dependencies: Comparison and implications for modelling. *Econ. Rev.* 29 (2), 111–145. doi:10.1080/07474930903382125

Global Footprint Network (2020). *How the footprint works*. California, USA: Ecological Footprint, Global Footprint Network. Availabel at: https://www.footprintnetwork.org/our-work/ecologicalfootprint/#:~:text=Ecological%20Footprint%20accounting%20measures%20the%20demand%20on%20and%20supply%20of%20nature.&text=On%20the (Accessed April, 2022).

Grossman, G. M., and Krueger, A. B. (1995). Economic growth and the environment. *Q. J. Econ.* 110 (2), 353–377. doi:10.2307/2118443

Guo, J., Zhou, Y., Ali, S., Shahzad, U., and Cui, L. (2021). Exploring the role of green innovation and investment in energy for environmental quality: An empirical appraisal from provincial data of China. *J. Environ. Manag.* 292, 112779. doi:10.1016/j.jenvman.2021.112779

Hao, L. N., Umar, M., Khan, Z., and Ali, W. (2021). Green growth and low carbon emission in G7 countries: How critical the network of environmental taxes, renewable energy and human capital is? *Sci. Total Environ.* 752, 141853. doi:10.1016/j.scitotenv.2020.141853

He, P., Ning, J., Yu, Z., Xiong, H., Shen, H., and Jin, H. (2019). Can environmental tax policy really help to reduce pollutant emissions? An empirical study of a panel ARDL model based on OECD countries and China. *Sustainability* 11 (16), 4384. doi:10.3390/su11164384

Huang, S. Z., Chau, K. Y., Chien, F., and Shen, H. (2020). The impact of startups' dual learning on their green innovation capability: The effects of business executives' environmental awareness and environmental regulations. *Sustainability* 12 (16), 6526. doi:10.3390/su12166526

Islam, M., Hossain, M., Khan, M., Rana, M., Ema, N. S., and Bekun, F. V. (2022). Heading towards sustainable environment: Exploring the dynamic linkage among selected macroeconomic variables and ecological footprint using a novel dynamic ARDL simulations approach. *Environ. Sci. Pollut. Res.* 29 (15), 22260–22279. doi:10.1007/s11356-021-17375-9

Jaffe, A. B., Newell, R. G., and Stavins, R. N. (2003). "Technological change and the environment," in *Handbook of environmental economics* (Amsterdam, Netherlands: Elsevier), Vol. 1, 461–516.

Jiang, J., Li, X., and Zhang, J. (2020). *Online stochastic optimization with wasserstein based non-stationarity. arXiv preprint arXiv:2012.06961.*

Jin, L., Duan, K., Shi, C., and Ju, X. (2017). The impact of technological progress in the energy sector on carbon emissions: An empirical analysis from China. *Int. J. Environ. Res. Public Health* 14 (12), 1505. doi:10.3390/ijerph14121505

Kassouri, Y., Bilgili, F., and Peter Majok Garang, A. (2022). Are government energy technology research, development, and demonstration budgets converging or diverging? Insights from OECD countries. *Technol. Analysis Strategic Manag.* 34 (5), 563–577. doi:10.1080/09537325.2021.1914330

Laegreid, O. M., and Povitkina, M. (2018). Do political institutions moderate the GDP-CO2 relationship? *Ecol. Econ.* 145, 441–450. doi:10.1016/j.ecolecon.2017.11.014

Lapinskienė, G., Peleckis, K., and Slavinskaitė, N. (2017). Energy consumption, economic growth and greenhouse gas emissions in the European Union countries. *J. Bus. Econ. Manag.* 18 (6), 1082–1097. doi:10.3846/16111699.2017.1393457

Lin, B., and Li, X. (2011). The effect of carbon tax on per capita CO2 emissions. *Energy policy* 39 (9), 5137–5146. doi:10.1016/j.enpol.2011.05.050

Lin, B., and Zhu, J. (2019). Determinants of renewable energy technological innovation in China under CO2 emissions constraint. *J. Environ. Manag.* 247, 662–671. doi:10.1016/j.jenvman.2019.06.121

Mazur, C., Contestabile, M., Offer, G. J., and Brandon, N. P. (2015). Assessing and comparing German and UK transition policies for electric mobility. *Environ. Innovation Soc. Transitions* 14, 84–100. doi:10.1016/j.eist.2014.04.005

Miceikiene, A., Ciuleviciene, V., Rauluskeviciene, J., and Streimikiene, D. (2018). Assessment of the effect of environmental taxes on environmental protection. *Ekon. Cas.* 66, 286–308.

Moran, D. D., Wackernagel, M., Kitzes, J. A., Goldfinger, S. H., and Boutaud, A. (2008). Measuring sustainable development—nation by nation. *Ecol. Econ.* 64 (3), 470–474. doi:10.1016/j.ecolecon.2007.08.017

Morawska, L., Thai, P. K., Liu, X., Asumadu-Sakyi, A., Ayoko, G., Bartonova, A., et al. (2018). Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? *Environ. Int.* 116, 286–299. doi:10.1016/j.envint.2018.04.018

Morley, B. (2012). Empirical evidence on the effectiveness of environmental taxes. *Appl. Econ. Lett.* 19 (18), 1817–1820. doi:10.1080/13504851.2011.650324

Mulatu, A. (2018). Environmental regulation and international competitiveness: A critical review. *Int. J. Glob. Environ. Issues* 17 (1), 41–63. doi:10.1504/ijgenvi.2018.10011732

Neagu, O. (2020). Economic complexity and ecological footprint: Evidence from the most complex economies in the world. *Sustainability* 12 (21), 9031. doi:10.3390/su12219031

Neves, S. A., Marques, A. C., and Patrício, M. (2020). Determinants of CO2 emissions in European union countries: Does environmental regulation reduce environmental pollution? *Econ. Analysis Policy* 68, 114–125. doi:10.1016/j.eap.2020.09.005

OECD (2021). *Environmental tax (indicator)*. Available at: https://www.oecd.org/ (Accessed April 10, 2022).

Ozturk, I., Al-Mulali, U., and Saboori, B. (2016). Investigating the environmental Kuznets curve hypothesis: The role of tourism and ecological footprint. *Environ. Sci. Pollut. Res.* 23 (2), 1916–1928. doi:10.1007/s11356-015-5447-x

Pablo-Romero, M., and Sanchez-Brada, A. (2017). Residential energy environmental Kuznets curve in the EU-28. *Energy* 125, 44–54. doi:10.1016/j.energy.2017.02.091

Pata, U. K., Aydin, M., and Haouas, I. (2021). Are natural resources abundance and human development a solution for environmental pressure? Evidence from top ten countries with the largest ecological footprint. *Resour. Policy* 70, 101923. doi:10.1016/j.resourpol.2020.101923

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *J. Appl. Econ. Chichester. Engl.* 22 (2), 265–312. doi:10.1002/jae.951

Pesaran, M. H. (2006). Estimation and inference in large heterogeneous panels with a multifactor error structure. *Econometrica* 74 (4), 967–1012. doi:10.1111/j.1468-0262.2006.00692.x

Pesaran, M. H., and Yamagata, T. (2008). Testing slope homogeneity in large panels. *J. Econ.* 142 (1), 50–93. doi:10.1016/j.jeconom.2007.05.010

Rees, W. E. (1992). Ecological footprints and appropriated carrying capacity: What urban economics leaves out. *Environ. Urban.* 4 (2), 121–130. doi:10.1177/095624789200400212

Saidi, K., and Hammami, S. (2015). The impact of CO2 emissions and economic growth on energy consumption in 58 countries. *Energy Rep.* 1, 62–70. doi:10.1016/j.egyr.2015.01.003

Saleem, H., Khan, M. B., and Mahdavian, S. M. (2022). The role of green growth, green financing, and eco-friendly technology in achieving environmental quality: Evidence from selected asian economies. *Environ. Sci. Pollut. Res.* 29, 57720–57739. doi:10.1007/s11356-022-19799-3

Saleem, H., Khan, M. B., and Shabbir, M. S. (2020). The role of financial development, energy demand, and technological change in environmental sustainability agenda: Evidence from selected asian countries. *Environ. Sci. Pollut. Res.* 27 (5), 5266–5280. doi:10.1007/s11356-019-07039-0

Shahbaz, M., Ozturk, I., Afza, T., and Ali, A. (2013b). Revisiting the environmental Kuznets curve in a global economy. *Renew. Sustain. Energy Rev.* 25, 494–502. doi:10.1016/j.rser.2013.05.021

Shahzad, U. (2020). Environmental taxes, energy consumption, and environmental quality: Theoretical survey with policy implications. *Environ. Sci. Pollut. Res.* 27 (20), 24848–24862. doi:10.1007/s11356-020-08349-4

Shapiro, J. S., and Walker, R. (2018). Why is pollution from US manufacturing declining? The roles of environmental regulation, productivity, and trade. *Am. Econ. Rev.* 108 (12), 3814–3854. doi:10.1257/aer.20151272

Sharif, A., Raza, S. A., Ozturk, I., and Afshan, S. (2019). The dynamic relationship of renewable and nonrenewable energy consumption with carbon emission: A global study with the application of heterogeneous panel estimations. *Renew. Energy* 133, 685–691. doi:10.1016/j.renene.2018.10.052

Shen, N., Wang, Y., Peng, H., and Hou, Z. (2020). Renewable energy green innovation, fossil energy consumption, and air pollution—Spatial empirical analysis based on China. *Sustainability* 12 (16), 6397. doi:10.3390/su12166397

Sterner, T. (2007). Fuel taxes: An important instrument for climate policy. *Energy policy* 35 (6), 3194–3202. doi:10.1016/j.enpol.2006.10.025

Toebelmann, D., and Wendler, T. (2020). The impact of environmental innovation on carbon dioxide emissions. *J. Clean. Prod.* 244, 118787. doi:10.1016/j.jclepro.2019.118787

Uddin, G. A., Salahuddin, M., Alam, K., and Gow, J. (2017). Ecological footprint and real income: Panel data evidence from the 27 highest emitting countries. *Ecol. Indic.* 77, 166–175. doi:10.1016/j.ecolind.2017.01.003

Ulucak, R., and Kassouri, Y. (2020). An assessment of the environmental sustainability corridor: Investigating the non-linear effects of environmental taxation on CO_2 emissions. *Sustain. Dev.* 28 (4), 1010–1018. doi:10.1002/sd.2057

Usman, M., and Makhdum, M. S. A. (2021). What abates ecological footprint in BRICS-T region? Exploring the inuence of renewable energy, nonrenewable energy, agriculture, forest area and financial development. *Renew. Energy* 179, 12–28. doi:10.1016/j.renene.2021.07.014

Van Leeuwen, G., and Mohnen, P. (2017). Revisiting the porter hypothesis: An empirical analysis of green innovation for The Netherlands. *Econ. Innovation New Technol.* 26 (1-2), 63–77. doi:10.1080/10438599.2016.1202521

Wackernagel, M., and Rees, W. (1998). *Our ecological footprint: Reducing human impact on the earth (vol. 9)*. Gabriola, BC, Canada: New society publishers.

Wang, H., and Wei, W. (2020). Coordinating technological progress and environmental regulation in CO2 mitigation: The optimal levels for OECD countries & emerging economies. *Energy Econ.* 87, 104510. doi:10.1016/j.eneco.2019.104510

Wang, Q., Jiang, R., and Zhan, L. (2019). Is decoupling economic growth from fuel consumption possible in developing countries? A comparison of China and India. *J. Clean. Prod.* 229, 806–817. doi:10.1016/j.jclepro.2019.04.403

Wenbo, G., and Yan, C. (2018). Assessing the efficiency of China's environmental regulation on carbon emissions based on Tapio decoupling models and GMM models. *Energy Rep.* 4, 713–723. doi:10.1016/j.egyr.2018.10.007

Westerlund, J., and Edgerton, D. L. (2008). A simple test for cointegration in dependent panels with structural breaks. *Oxf. Bull. Econ. Statistics* 70 (5), 665–704. doi:10.1111/j.1468-0084.2008.00513.x

Wissema, W., and Dellink, R. (2007). AGE analysis of the impact of a carbon energy tax on the Irish economy. *Ecol. Econ.* 61 (4), 671–683. doi:10.1016/j.ecolecon.2006.07.034

Wolde-Rufael, Y., and Mulat-Weldemeskel, E. (2021). Do environmental taxes and environmental stringency policies reduce CO2 emissions? Evidence from 7 emerging economies. *Environ. Sci. Pollut. Res.* 28 (18), 22392–22408. doi:10.1007/s11356-020-11475-8

World Bank (2021). *World development indicators*. Washington, DC, USA: The World Bank. Available at: http://data.worldbank.org/(Accessed January 28, 2022).

Xiong, Z., and Li, H. (2019). Ecological deficit tax: A tax design and simulation of compensation for ecosystem service value based on ecological footprint in China. *J. Clean. Prod.* 230, 1128–1137. doi:10.1016/j.jclepro.2019.05.172

Zhang, X., Guo, Z., Zheng, Y., Zhu, J., and Yang, J. (2016). A CGE analysis of the impacts of a carbon tax on provincial economy in China. *Emerg. Mark. Finance Trade* 52 (6), 1372–1384. doi:10.1080/1540496x.2016.1152801

10.3389/fenvs.2022.972354

Appendix A: mentions the list of the OECD and Non-OECD countries.

OECD countries	OECD countries	Non-OECD countries
Australia	Norway	Brazil
Austria	Poland	China
Belgium	Portugal	India
Canada	Slovak Republic	Indonesia
Czech Republic	Slovenia	Russia
Denmark	Spain	South Africa
Finland	Sweden	
France	Switzerland	
Germany	Turkey	
Greece	United Kingdom	
Hungary	United States	
Ireland	Korea	
Italy	Netherlands	
Japan		

frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 23 November 2022
DOI 10.3389/fenvs.2022.985719

The asymmetric effect of technological innovation on CO_2 emissions in South Africa: New evidence from the QARDL approach

Maxwell Chukwudi Udeagha *‡ and Nicholas Ngepah ‡

School of Economics, College of Business and Economics, University of Johannesburg, Johannesburg, South Africa

OPEN ACCESS

EDITED BY
Yingcheng Li,
Southeast University, China

REVIEWED BY
Umer Shahzad,
Anhui University of Finance and Economics, China
Jose Balsa-Barreiro,
Massachusetts Institute of Technology, United States

*CORRESPONDENCE
Maxwell Chukwudi Udeagha,
maxwelluc@yahoo.com

‡These authors have contributed equally to this work

SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal Frontiers in Environmental Science

RECEIVED 04 July 2022
ACCEPTED 25 October 2022
PUBLISHED 23 November 2022

CITATION
Udeagha MC and Ngepah N (2022), The asymmetric effect of technological innovation on CO_2 emissions in South Africa: New evidence from the QARDL approach.
Front. Environ. Sci. 10:985719.
doi: 10.3389/fenvs.2022.985719

The asymmetric impact of technological innovation on carbon dioxide (CO_2) emissions in South Africa from 1960 to 2020 is evaluated in this study. We apply the newly established quantile autoregressive distributed lag (QARDL) methodology to deal with distributional asymmetry based on the location of CO_2 emissions within its own distribution. This distinguishes our analysis from earlier studies in the following way. In contrast to other studies, this research uses the QARDL technique to assess the long-term stability across the quantiles, resulting in a more adaptable econometric analysis than the traditional frameworks. In order to capture the trade share in South Africa's GDP and the quantity of trade compared to world trade, we employ a novel measure of trade openness. We find that 1) technological innovation helps reduce CO_2 emissions in the short term and over the long term; 2) the scale effect worsens CO_2 emissions, whereas the technique effect enhances it, supporting the existence of an environmental Kuznets curve (EKC) hypothesis; 3) energy consumption, foreign direct investment (FDI), and industrial added value degrade environmental quality; and 4) increasing trade openness is glaringly harmful to the environment over the long term, despite being beneficial in the short term; 5) there are long-term, asymmetric linkages between CO_2 emissions, scale effect, technique effect, technological innovation, energy use, FDI, and trade openness; 6) industrial value-added, scale effect, technique effect, technical innovation, energy usage, FDI, and trade openness Granger-cause CO_2 emissions over the medium, long, and short terms indicate the significance of these variables in determining CO_2 emissions. Based on our empirical findings, this study makes the case that South Africa's government and policymakers should consider the importance of innovative technologies as a sustainable source of advancements in attaining energy security and promoting ecological integrity in the nation.

KEYWORDS

CO_2 emissions, QARDL, energy consumption, EKC, economic growth, industrial value-added, South Africa, trade openness

Introduction

Governments all over the world are becoming more and more concerned about environmental degradation as it has an impact on global warming and has the potential to disrupt the planet's carbon cycle. Climate change is currently one of the most important issues facing humanity. Unparalleled threats to growth and human existence are shown by climate change brought on by greenhouse gas emissions (GHGs), primarily carbon dioxide (CO_2) pollution. These risks include extreme weather, the extinction of species, and a food crisis (Bales and Sovacool, 2021; Udeagha and Ngepah, 2022a). The main human activity that contributes to CO_2 emissions is the combustion of fossil fuels (coal and natural gas) for transportation and energy. However, some manufacturing processes and alterations to land usage still result in CO_2 emissions. Extreme weather occurrences, such as floods, heatwaves, storms, droughts, rising sea levels, disruptions to water systems, and stunted plant growth are just a few of the many possible health, physical, and ecological repercussions of climate change and global warming (Udeagha and Muchapondwa, 2022). A nation may endure environmental deterioration as a result of the enormous cost of saving endangered species and cleaning up landfills, which might have detrimental economic repercussions. Thus, one of the contemporary global challenges included in the political frameworks of many countries is environmental protection. With the expectation that these studies will shed light on the macroeconomic drivers of climate change, several scientific investigations have been conducted to identify the components that influence pollution to comprehend the economic aspects of environmental degradation.

In recent years, climate change and ecological degradation have become the most urgent economic issues. The fundamental causes of climate change and global warming are GHGs. Conversely, as the primary greenhouse gas, CO_2 emissions have attracted considerable attention in the environmental literature (Abid et al., 2022). As shown by the International Energy Agency, rising fossil fuel consumption has caused CO_2 emissions to soar, necessitating a swift transition to lower CO_2 emissions and meet sustainable goals. Additionally, the sustainable development goals (7, 8, 9, 12, and 13) established by the United Nations, which must be achieved by the year 2030, emphasize the urgent need for solutions to combat climate change, including affordable clean energy, sustainable economic growth, technological innovation, sustainable consumption, and production (Wang et al., 2022a). As a result, many nations now place a high priority on lowering carbon emissions, and the advancement of technology has also played an important role in promoting changes to the direction of global economic development (Udeagha and Ngepah, 2022b). It is recognized that the idea of technological innovation is a factor that may reduce energy consumption, cut pollutant emissions, enhance environmental quality, and encourage the growth of a greener economy (Li et al., 2022). The use of innovative methods to create eco-friendly products that consume less energy and pollute the environment is referred to as technological innovation. Creating clean energy, using renewable energies, and manufacturing techniques that are less environmentally destructive than fossil fuels are all examples of technological breakthroughs (Chhabra et al., 2022). Additionally, technological advancement helps governments maximize their use of renewables and develop alternative fuels (Adebayo et al., 2022). It has been stated that the advancement of technological improvements and alternative energies in emerging economies will be an effective tool for reducing environmental emissions and achieving long-term environmental sustainability (Udeagha and Breitenbach, 2021; Kuang et al., 2022). Consequently, investing in eco-friendly technological innovations can increase the sustainability of production and economic engagement and offer a viable remedy for lowering carbon emissions in emerging economies such as South Africa. Therefore, technological innovation is acknowledged as one of the tactics the nation may employ to improve the sustainability of the environment and accomplish sustainable economic development because it provides an opportunity to drastically cut energy consumption (EC) and increase energy efficiency.

Technological innovations are important in increasing energy efficiency, reducing energy consumption, and minimizing CO_2 emissions (Erdogan, 2021). Fisher-Vanden et al. (2004), Hang and Tu (2007), Zhou et al. (2010), and Jiahua et al. (2010) showed that technological innovation provides strong opportunities to fulfill the energy mandate by allowing the country to switch from exhaustible energy sources to renewable ones, allows the country to achieve higher production levels with a minimum of energy, and improves innovation, which leads to more entrepreneurship *via* improved market access and increased competition. Technological innovation by opening up international commodity markets is a way to generate new investment, increase productivity, and improve employment and real wages (Berg and Krueger, 2003). It also promotes resource allocation efficiency, which brings about better economic growth. This could ultimately lead to massive factor accumulation, information spillovers, and the spread of technology (Das and Paul, 2011; Zahonogo, 2017; Udeagha and Ngepah, 2020; Udeagha MC. and Ngepah, N. 2021). Improved use of technological innovations is important in promoting a green economy and reducing emissions of growing CO_2. Improved use of electric vehicles, hybrid technology, and renewable energy sources reduces pollution and fossil fuels. In the process of becoming a reality, sustainable innovation highlights the interplay between scientific and technical advancement and the atmosphere. Moreover, the country's natural environment and economic gains will be directly impacted by innovation capacity. In order to

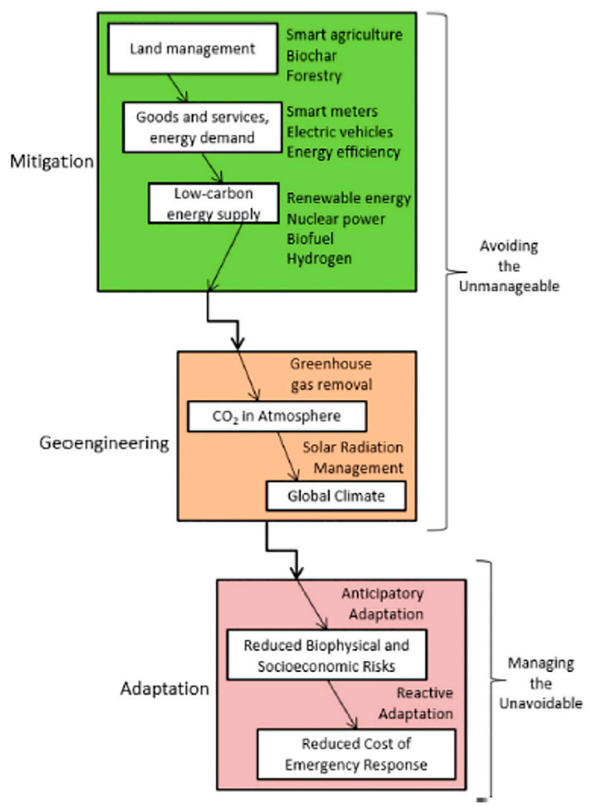

FIGURE 1
Conceptualizing climate change mitigation, geoengineering, and adaption.

"decouple" the rate of scientific and technical advancement from resource utilization, the catalyst for environmental sustainability in South Africa is to encourage sustainable urban economic innovation and competitiveness.

Decoupling theory is the fundamental hypothesis put out by the Organization for Economic Co-operation and Development (OECD) to break the relationship between economic development and resource use or ecological damage (OECD, 2002). The phrase "decoupling" refers to a break in the link between economic development and resource usage or environmental damage (Enevoldsen et al., 2007). The environmental Kuznets curve (EKC) may be used to describe how the decoupling trajectory manifests. The EKC theory argues that early economic development is accompanied by an increase in environmental pressure. Notwithstanding, in the medium term, under the combined effects of economic, structural, technological, and governmental environmental regulations, a progression trend appears after environmental pollution attains a maximum point, finally realizing the best state of strong decoupling between economic development and environmental pollution (Xia and Zhong, 2016). The burden of resource extraction on the atmosphere is measured by this idea's ability to assess the coupling fracture connection between human pursuits (the driving force) and that load. In academics, the study of decoupling has recently gained popularity. Economic development and transportation (Tapio, 2005), environmental quality and economic growth (Yang and Meng, 2019), and energy utilization and economic growth (Roman-Collado et al., 2018) have been the key themes of decoupling investigations. The level of reliance between innovation and resource consumption is primarily what is meant by the decoupling between innovation capabilities and resource consumption. The act of dependence building shifts from a strong to a weak connection, diminishing with time, before eventually showing a reversal change. The precise occurrence of this process is the progressive strengthening of innovation in the urban economy and the shift in the urban economy's growth pattern to a green mode. For instance, Balsa-Barreiro et al. (2019) demonstrated how some pertinent human indicators (e.g., wealth production, GDP, environmental costs, and CO_2 emissions) described different trajectories at a global level, highlighting the decoupling effect brought on by technological innovation at this point. At the global level, the shifting of the GDP and CO_2 emissions traces from west to east may be explained by the decreasing importance of the western nations, where wealth is typically accumulated, as well as the growing significance of Southeast Asia. Grether and Mathys (2009) stated that it is crucial to underline that the CO_2 emission trace is found farther to the east. This concerns the economy's prospective coupling or decoupling with the energy sector. The western nations have gone through an industrial and economic transition, concentrating their economies on the services sector. In an international setting, several nations have transplanted their traditional industries in emerging nations to reduce prices and ecological deterioration (Balsa-Barreiro et al., 2019). As a result, most of them have entered what is known as the "strong decoupling phase," during which they are growing their GDP while simultaneously lowering their ecological impact in absolute terms (Szigeti et al., 2017).

In recent years, the impact of technological innovation on the environment has attracted considerable attention from various researchers and scholars around the world. The innovation activities can be defined as the production of modern and best products (goods and services) or processes, a new marketing plan, or a modern organizational approach to business activities, workplace organization, or close relationships (Destek and Manga, 2021; Ibrahim and Vo, 2021). The minimum requirement for innovation is that the production process, marketing approach must be new or highly developed by the company. In this context, some empirical works have found that technological innovation improves the quality of the environment (Udeagha and Ngepah, 2021a; Udeagha and Ngepah, 2021b). However, some studies have concluded that technological innovations have added to the growing levels of environmental degradation (Atsu et al., 2021). According to a

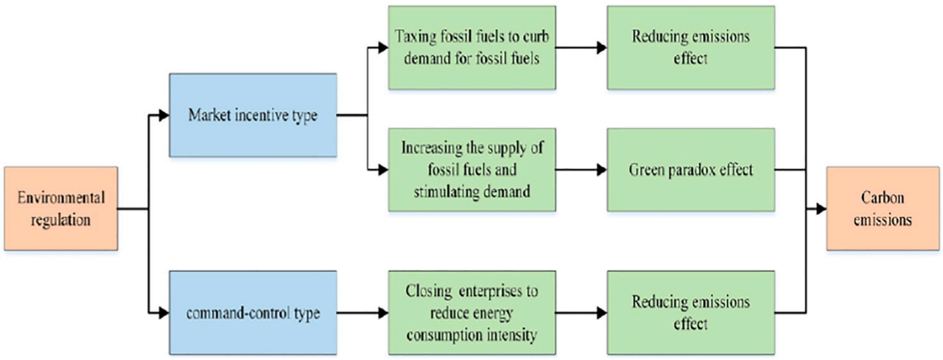

FIGURE 2
Direct functional path of environmental regulation on carbon (CO_2) emissions.

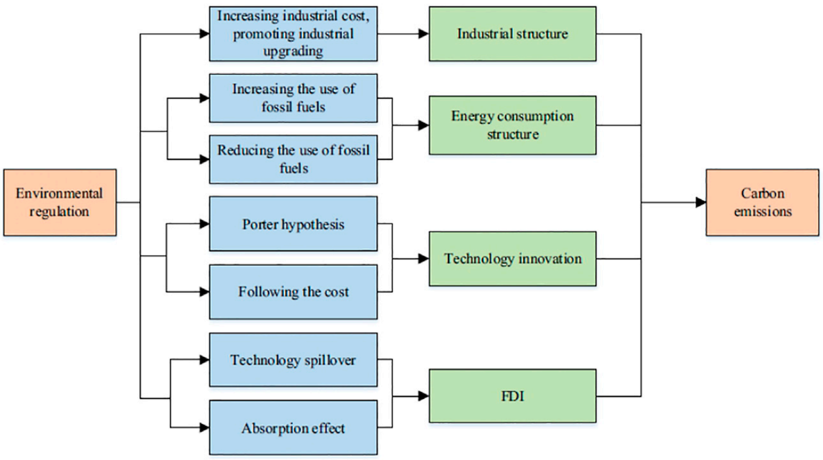

FIGURE 3
Indirect functional path of environmental regulation on carbon emissions.

report by the Intergovernmental Panel on Climate Change (IPCC 2018), the number of anthropogenic emissions from the air could be reduced through measures to develop technological innovations and environmental policies. However, the most widely used and improved indicators are research and development activities (R&D) and patent applications. Technological innovations are an important factor in this dynamic integration that can contribute to transforming energy resources from non-renewable sources to more efficient and sustainable sources (Zameer et al., 2020; Usman and Hammar, 2021).

Numerous studies have examined how South Africa's environmental quality is impacted by trade openness, energy intensity, foreign direct investment (FDI), and an enhanced financial system. For instance, Adebayo and Odugbesan (2021), who used ARDL-based bounds and wavelet coherence methods to examine the relationship between financial development, real growth, urbanization, and CO_2 emissions in South Africa, discovered that financial development and real growth worsen environmental quality, whereas urbanization helps lower CO_2 emissions. In a multivariate framework, Joshua and Bekun (2020) evaluated the long-term relationships between several factors and environmental quality and discovered feedback causation among the variables analyzed. Joshua and Bekun (2020) used the dynamic autoregressive distributed lag method to investigate the link between FDI and economic growth in carbon emissions, considering the effect of urbanization and coal consumption in South Africa. The results show that long-term and short-term CO_2 emissions increase with economic expansion. A bidirectional causal relationship between urbanization and FDI is also Joshua and Bekun (2020), who hypothesized that

TABLE 1 A summary of the selected articles on the innovation–CO_2 emissions nexus based on different regions.

S/N	Authors	Period/sample	Methods	Main findings
Region: EU countries				
1	Töbelmann and Wendler (2020)	1992–2014	GMM	Innovation reduces CO_2 emissions
2	Anser et al. (2021)	2000–2017	PFE, PQR	Innovation reduces CO_2 emissions
Region: BRICS economies				
3	Brandão Santana et al. (2015)	1996–2008	Chow test	Innovation increases CO_2 emissions
4	Azevedo et al. (2018)	1980–2011	OLS	Innovation has different environmental effects across the BRICS economies
5	Khan et al. (2020a)	1985–2014	AMG, FMLS	Innovation reduces CO_2 emissions
6	Khattak et al. (2020)	1980–2016	CCEMG, AMG	Innovation increases CO_2 emissions
7	Santra (2017)	2005–2012	OLS, LSDV	Innovation increases CO_2 emissions
8	Rafique et al. (2022)	1990–2017	AMG	Innovation reduces CO_2 emissions
9	Dauda et al. (2021)	1990–2016	FMOLS, DOLS	Innovation increases CO_2 emissions
10	Yang et al. (2021)	1990–2016	DSUR, FMOLS	Innovation reduces ecological footprint
11	Haseeb et al. (2019)	1994–2014	DSUR, FMOLS	Innovation reduces CO_2 emissions
12	Erdogan (2021)	1992–2018	DCCE, PMG	Innovation reduces CO_2 emissions
Country: Turkey				
13	Demir et al. (2020)	1971–2013	ARDL	Innovation increases CO_2 emissions
14	Shan et al. (2021)	1990–2018	ARDL	Innovation reduces CO_2 emissions
Region: African countries				
15	Ibrahie (2020)	1971–2014/Egypt	ARDL	Innovation reduces CO_2 emissions
16	Asongu (2018)	2002–2012/44 SSA	GMM	Innovation reduces CO_2 emissions
17	Dauda et al. (2021)	1990–2016	FE, GMM	Innovation increases CO_2 emissions
Region: America				
18	Dinda (2018)	1963–2010/USA	VAR and Engle and Granger	Innovation reduces CO_2 emissions
19	Ahmad and Raza (2020)	1984–2018/Brazil	ARDL	Innovation reduces CO_2 emissions
Region: OECD countries				
20	Álvarez-Herránz et al. (2017)	1990–2014	Lagged Distributive models	Innovation reduces CO_2 emissions
21	Mensah et al. (2018)	1990–2014	STIRPAT and ARDL	Innovation has different environmental effects across the BRICS economies
22	Ahmad et al. (2016)	1990–2014	FMOLS	Innovation reduces CO_2 emissions
23	Baloch et al. (2020)	1990–2017	PMG/ARDL	Innovation reduces CO_2 emissions
Region: Asian countries				
24	Zameer et al. (2020)	1985–2017/India	VECM	Innovation reduces CO_2 emissions
25	Zhang et al. (2017a), Zhang et al. (2017b)	2000–2013/China	System GMM	Innovation reduces CO_2 emissions
26	Long et al. (2017)	2015–2016/ Korean MNCs in China	Analysis through factors	Innovation reduces CO_2 emissions
27	Jin et al. (2019)	1995–2012/China	Multiple regression	Innovation reduces CO_2 emissions
28	Khan et al. (2020a)	1991–2015/China	ARDL and NARDL	Innovation reduces CO_2 emissions
29	Usman and Hammar (2021)	1990–2017/APEC	FGLS, AMG	Innovation increases CO_2 emissions
30	Godil et al. (2020)	1995–2018/Pakistan	QARDL	Innovation reduces CO_2 emissions
31	Arshad et al. (2020)	1990–2014/SSEA	DOLS, GM-FMOLS	Innovation increases CO_2 emissions
32	Villanthenkodath and Mahalik (2022)	1980–2018/India	ARDL	Innovation increases CO_2 emissions
33	Guo et al. (2021)	1995–2017	AMG/CS-ARDL	Innovation reduces CO_2 emissions
Region: Belt and Road host countries				
34	Razzaq et al. (2021)	2003–2018	FMOLS, DOLS, FE-OLS	Innovation reduces CO_2 emissions

(Continued on following page)

TABLE 1 (*Continued*) A summary of the selected articles on the innovation–CO_2 emissions nexus based on different regions.

S/N	Authors	Period/sample	Methods	Main findings
Region: G7 countries				
35	Awaworyi Churchill et al. (2019)	1870–2014	CCEMG	Innovation reduces CO_2 emissions
36	Khan et al. (2020b)	—	CS-ARDL	Innovation reduces CO_2 emissions
Region: BEM countries				
37	Destek and Manga (2021)	1995–2016	ECM-based cointegration test	Innovation reduces CO_2 emissions
38	Ozcan and Apergis (2018)	1990–2015	MG, AMG, GM-FMOLS	Innovation reduces CO_2 emissions
40	Faisal and Idris (2020)	1993–2014	FMOLS, DOLS	Innovation increases CO_2 emissions
41	Altinoz et al. (2020)	1995–2014	Panel VAR/GMM	Innovation reduces CO_2 emissions
42	Ibrahim and Vo (2021)	1991–2014	GMM	Innovation reduces CO_2 emissions

Note: GMM, generalized method of moments; PFE, panel fixed effect; PQR, panel quantile regression; OLS, ordinary least squares; AMG, augmented mean group; FMLS, fully modified least squares: CCEMG, common correlated effects mean group; AMG, augmented mean group; LSDV, least squares dummy variables; FMOLS, fully modified ordinary least squares; DOLS, dynamic ordinary least squares; DSUR, dynamic seemingly unrelated cointegrating regression; DCCE, dynamic common correlated effects; PMG, pooled mean group; ARDL, autoregressive distributed lag; FE, fixed effects; FGLS, feasible generalized least square; QARDL, quantile autoregressive distributed lag; GM-FMOLS, group mean-fully modified ordinary least square; CS-ARDL, cross-sectionally augmented autoregressive distributed lag; FE-OLS, fixed effects ordinary least squares; EU, European Union; BRICS, Brazil, Russia, India, China, and South Africa; OECD, Organization for Economic Co-operation and Development; BEM, big emerging market; SSEA, South and Southeast Asian region; APEC, Asia Pacific Economic Cooperation; SSA, Sub-Saharan Africa.

urban growth encourages FDI in South Africa. Bekun et al. (2019) used Bayer and Hanck's (2013) combined cointegration framework, Pesaran et al.'s (2001) bounds analysis, Kripfganz and Schneider's (2018) critical values, and an approximate *p*-value to examine the relationship between EC and economic growth in South Africa from 1960 to 2020. The findings corroborate the theory of energy-led growth in South Africa by showing a one-way causal relationship between EC and economic growth.

However, the role of technological innovation in promoting environmental quality has been largely ignored, especially in South Africa. Although a few studies have examined the link between innovation and environmental quality, such as EU countries (Anser et al., 2021), the BRICS economics (Erdogan, 2021; Yang et al., 2021), Turkey (Shan et al., 2021), Egypt (Ibrahiem, 2020), US (Dinda, 2018), Brazil (Ahmad and Raza, 2020), OECD countries (Baloch et al., 2020), India (Zameer et al., 2020), China (Khan et al., 2020a), Asia-Pacific Economic Cooperation (APEC) countries (Guo et al., 2021; Usman and Hammar, 2021), G7 countries (Khan et al., 2020b), and Big Emerging Market (BEM) economies (Faisal and Idris, 2020; Destek and Manga, 2021; Ibrahim and Vo, 2021), to our knowledge, no study has examined this relationship in South Africa. Therefore, this paper aims to fill this important gap in the literature.

The following are justifications for technological innovation and climate change in this study: first, understanding the interconnectedness of sociotechnical elements in the context of climate change and innovation is made possible by insights from energy policy and the broader business literature. One finding is that, in recent years, the deployment of novel technologies, such as distributed energy storage, smart grids, and renewable energy (particularly solar photovoltaics and microinverters), has resulted in significant cost savings and climate change mitigation (IRENA, 2021). Second, in addition to energy efficiency, low-carbon and non-carbon, carbon reduction, and carbon capture and storage technologies are advancements in preventing climate change (Khalfaoui et al., 2022). More contentious technologies include "geoengineering" techniques that aim to halt or lessen global warming by purposefully altering the environment on a big scale (Sovacool, 2021). The geoengineering concepts include introducing reflecting particles into the atmosphere, burying CO_2 beneath the surface, or erecting massive mirrors in space to reflect sunlight (Sovacool, 2021). Third, Figure 1 helps conceptualize these various climate routes or approaches. Basically, mitigation and geoengineering possible alternatives attempt to "prevent the uncontrollable" by effectively reducing CO_2 or comparable greenhouse gases or improving the ability of natural and technical sinks to store them; adaptation strives to "handle the inevitable" by increasing adaptability and reducing vulnerability to cater for climate variability currently in progress, consistent with earlier levels of pollution and probable emission levels. Therefore, each pathway incorporates different commercial marketplaces, established actors, and underlying management logic. Fourth, mitigation is frequently seen as a public good with little-to-no financial value outside the direct selling of energy technology or services. The business model is based on fuel substitution or encouraging low-carbon alternatives to replace fossil fuel systems. The extractive and mining sectors, the hydrocarbon industry, retrofit businesses, and energy service providers are the main protagonists in this scenario. Emerging renewable energy and electric vehicle companies are also important players. When it comes to

TABLE 2 Definition of variables and data sources.

Variable	Description	Expected sign	Source
CO_2	CO_2 emissions (kg per 2010 US$ of GDP)	N/A	WDI
EC	Energy consumption, million tons of oil equivalent	Positive	BP Statistical Review of World Energy
TECH	Technological innovation measured by gross domestic spending on R&D (%GDP)	Negative	WDI
OPEN	Trade openness computed as composite trade intensity introduced by Squalli and Wilson (2011) capturing trade effect	Positive or negative	WDI, authors
SE	Real GDP per capita capturing scale effect	Positive	WDI
TE	Real GDP per capita squared capturing technique effect	Negative	WDI, authors
FDI	Foreign direct investment, net inflows (%of GDP)	Positive	WDI
IGDP	Industry, value added (%of GDP)	Positive or negative	WDI

N/A, not available; WDI, world development indicator.

TABLE 3 Descriptive statistics.

Variables	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	J-B stat	Probability
CO_2	0.264	0.238	0.477	0.084	0.120	0.217	1.652	4.682	0.000
SE	7.706	7.959	8.984	6.073	0.843	−0.511	2.156	4.102	0.029
TE	60.316	63.754	80.717	36.880	12.663	−0.387	2.082	3.422	0.000
TECH	9.360	9.255	10.545	8.210	0.766	0.082	1.634	4.499	0.005
EC	4.220	4.422	4.840	3.177	0.527	−0.558	1.921	5.621	0.060
FDI	13.203	13.286	14.659	11.913	0.738	0.056	2.463	0.702	0.004
IGDP	3.513	3.580	3.813	3.258	0.161	−0.215	1.697	4.474	0.007
OPEN	6.060	6.512	7.665	2.745	1.329	0.636	2.077	5.757	0.000

Source: authors' calculations.

improving resilience, investing in infrastructure, or diversifying other local assets such as agriculture or buildings, climate adaptation is frequently seen as having significant local co-benefits and a market value; incumbent actors here include those already pushing large development or community benefit projects. With no established actors and the least robust commercial model, geoengineering has the prospect of upending the fundamental economic principles that underlie mitigation and adaptation. Last but not least, addressing the environmental threats brought on by climate change would be made easier with an awareness of its inconsistencies and dynamics. Adopting suitable technological innovation should be emphasized as a possible route in that direction. Most of the factors influencing the course and effects of climate change are human-related. Mitigation and control of the impacts of global warming would be exceedingly difficult without reputable instruments and systems for constant assessments and evaluation. Without management, humanity would be forced to deal with the looming cruelty that it has unintentionally caused *via* its own actions and inactions. This demonstrates the importance of contemporary technological innovation as a game-changing method for reducing carbon emissions and addressing climate change.

In contrast, the Technological Innovation Agency (TIA) of South Africa was established on 29 October 2010 to assist the government in promoting and accelerating technological innovation so that it may be developed and utilized to boost economic growth and the standard of living for all South Africans. The agency's mission is to foster innovation to meet the particular circumstances in South Africa and the whole African continent because the creation of fresh, context-specific knowledge is a crucial component of innovation. The young population of South Africa, with a median age of roughly 20 years, is a crucial component of this exceptional circumstance. This distinctive cohort offers fascinating potential for innovation in the format and subject matter of postsecondary education and training. Additionally, it emphasizes the significance of a government-industry-led consolidated technical education system. The developing ties between South Africa and Brazil, China, Russia, and India, which were formalized by the recent request of South Africa to join these BRIC nations, suggest another move for rapid technological innovation and

TABLE 4 Unit root analysis.

Variable	Dickey–Fuller GLS	Phillips–Perron	Augmented Dickey–Fuller	Kwiatkowski–Phillips–Schmidt–Shin	The Narayan and Pop (2010) unit root test			
	(DF-GLS)	(PP)	(ADF)	(KPSS)	Model 1		Model 2	
Level	Test–Statistics value	—	—	—	Break-Year	ADF-stat	Break-Year	ADF-stat
InCO$_2$	−0.570	−0.464	−1.152	0.966	1982:1985	−3.132	1987:1994	−8.160***
InSE	−0.116**	−0.079	−1.308	0.833***	1979:1988	−2.914	1982:1990	−7.601***
InTE	−0.112*	−0.076	−1.268	0.848***	1979:1990	−1.939	1982:1994	−6.791***
InTECH	−0.254***	−0.284***	−2.999	0.255***	1995:2000	−4.318	2008:2019	−7.821***
InEC	−0.011	−0.014	−0.366	1.300***	1982:1989	−4.372**	1985:1991	−8.521***
InFDI	−0.032*	−0.001	−0.012	0.640	2001:2006	−2.021	2004:2010	−8.362***
InOPEN	−0.072	−0.082	−1.335	1.080*	1996:2001	−3.053	2003:2020	−7.318***
InIGDP	−0.046	−0.071*	−1.718	1.060**	1972:1985	−3.815	1982:1991	−7.521***
First difference					Critical value (1%, 5%, and 10%)			
Δ InCO$_2$	−0.995***	−0.996***	−7.176***	0.705***	1999:2005	−4.801**	1980:2020	−5.832***
Δ InSE	−0.695***	−0.707***	−5.319***	0.585***	1983:1997	−5.831***	1985:1995	−6.831***
Δ InTE	−0.694***	−0.707***	−5.316***	0.589***	1991:2000	−8.531***	1987:1996	−5.893***
Δ InTECH	−1.023***	−1.034***	−7.473***	0.424***	1999:2003	−4.841**	2006:2010	−5.983***
Δ InEC	−1.105***	−1.121***	−8.142***	0.586***	1985:1993	−5.921***	1989:1997	−7.942***
Δ InFDI	−0.207**	−0.209**	−6.443***	0.609***	2005:2008	−6.831***	2001:2017	−6.973***
Δ InOPEN	−0.935***	−0.938***	−6.699***	0.626***	1996:2004	−6.842**	2001:2007	−8.942***
Δ InIGDP	−0.799***	−0.801***	−5.878***	0.431***	1975:1990	−7.742***	1988:1992	−7.892***

Source: authors' calculations.

Note: *, ** and *** denote statistical significance at 10%, 5%, and 1% levels, respectively. MacKinnon (1996) one-sided *p*-values. Lag length based on SIC and AIC. Probability based on Kwiatkowski–Phillips–Schmidt–Shin (1992). The critical values for the Narayan–Popp unit root test with two breaks are followed by Narayan and Pop (2010). All the variables are trended.

10.3389/fenvs.2022.985719

TABLE 5 Quantile co-integration test results.

Model	Coefficient	$Sup_{\tau}/V_n(\tau)$	Critical value 1%	Critical value 5%	Critical value 10%
CO_2 emissions vs. scale effect	β γ	3,810.182	1,537.714	1,134.041	907.815
InCO_2 vs. InSE		715.701	543.851	205.374	137.516
CO_2 emissions vs. technique effect	β γ	2,591.613	1,186.714	968.510	624.637
InCO_2 vs. InTE		918.251	731.872	401.518	215.071
CO_2 emissions vs. technological innovation	β γ	2,261.274	794.163	451.710	281.802
InCO_2 vs. InTECH		714.183	520.614	220.614	163.936
CO_2 emissions vs. energy consumption	β γ	2,802.181	1,037.714	661.845	379.312
InCO_2 vs. InEC		927.706	543.851	205.041	142.631
CO_2 emissions vs. foreign direct investment	β γ	2,505.610	801.706	635.150	274.706
InCO_2 vs. InFDI		798.243	520.742	361.841	132.628
CO_2 emissions vs. trade openness	β γ	2,228.202	794.163	501.053	396.741
InCO_2 vs. InOPEN		1,124.117	720.614	581.030	155.931
CO_2 emissions vs. industrial value-added	β γ	1,110.188	984.718	461.029	263.183
InCO_2 vs. InIGDP		862.703	659.841	301.051	174.803

Source: authors' calculations.

transformation of the country. Healthcare policy, how global change impacts community livelihoods, and how the financial crisis in the "developed world" affects the economy and aid are further areas where domestic technological innovation could have an influence. South Africa has addressed these issues in several ways. First, in order to "help drive South Africa's transformation toward a knowledge-based economy, in which the production and dissemination of knowledge lead to economic benefits and enrich all fields of human endeavor," the Department of Science and Technology came up with the "Ten-Year Innovation Plan of South Africa" in 2008. Second, the government's broad industrialization strategy is outlined in the 2007 National Industrial Policy Framework Industrial Policy Action Plan, which also set the goal of halving unemployment and poverty by 2014 through accelerated growth of at least 6% starting in 2010. This strategy is part of South Africa's Accelerated and Shared Growth Initiative. Lastly, the need to "accelerate economic growth and change the economy to generate decent jobs and improved standards of living" is one of the ten strategic goals included in the Medium-Term Strategic Framework of the Presidency, which was announced in July 2009. The TIA might be seen as a body that facilitates communication between the main knowledge creators and the social and business innovators. As stated in its mission statement, the organization will use various tools to close this gap. These tools include "adequately designed financial intervention strategies, the transformation of human potential, harnessing of domestic and global collaborations, and the establishment of the national dynamic capabilities." Meanwhile, in South Africa, technological innovations and development have significantly led to a reduction in CO_2 emissions in the following ways: 1) the development of end-to-end pipeline technologies that are important in reducing carbon emissions, 2) the use of energy-efficient production technologies, and 2) changes in fuel mixing and transformation of oil mixtures. Technological innovation *via* all these channels increases energy efficiency, which greatly reduces carbon emissions in the country. More importantly, South Africa's significant investment in R&D and technological changes are some of the reasons why technological advances have significantly contributed to improving the country's environmental sustainability. Moreover, as part of a major key to addressing environmental degradation, the country has adopted several policies to develop strong technologies critical to minimizing the intensity of emissions from manufacturing processes and other economic activities that involve high emissions. Due to these features, South Africa is a prime candidate for this study, which examines the asymmetric impact of technological innovation on environmental sustainability.

On the contrary, South Africa is one of the biggest developing markets and a member of the BRICS (Brazil, Russia, India, and China) alliance. The basic and secondary sectors, such as mining, manufacturing, and transportation, continue to provide a sizable contribution to the country's gross domestic product even while its tertiary service industries (e.g., banking, real estate, and business services) have expanded in importance (Statistics South Africa, 2019). Compared to other BRICS nations, South Africa's economy has significantly emphasized coal as a source of energy. Coal accounts for more than 80% of South Africa's power, whereas renewable sources make up barely 7%. (African Development Bank Group, 2019). The replacement of all the coal-fired power plants in South Africa is extremely difficult, although international organizations have mandated the use of renewable energy and a decrease in coal mining. The

TABLE 6 Results of quantile autoregressive distributed lag model (QARDL).

Quantiles (τ)	Constant	ECM	Long-run coefficient estimates						
	$\mu^{*}(\tau)$	$\rho^{*}(\tau)$	$\beta_{InSE}(\tau)$	$\beta_{InTE}(\tau)$	$\beta_{InTECH}(\tau)$	$\beta_{InEC}(\tau)$	$\beta_{InFDI}(\tau)$	$\beta_{InOPEN}(\tau)$	$\beta_{InIGDP}(\tau)$
0.05	2.562	−0.521	0.413	−0.026	−0.203	0.018	0.210***	0.025	0.153
	(0.306)	(0.015)	(0.081)	(0.001)	(0.002)	(0.082)	(0.021)	(0.013)	(0.042)
0.10	3.013**	−0.741**	0.361	−0.034	−0.113	0.046	0.265***	0.021	0.241
	(0.190)	(0.021)	(0.028)	(0.029)	(0.046)	(0.051)	(0.030)	(0.025)	(0.034)
0.20	3.531	−0.751**	0.301	−0.035	−0.216	0.135	0.314***	0.121***	0.317
	(0.274)	(0.019)	(0.038)	(0.035)	(0.031)	(0.279)	(0.031)	(0.018)	(0.043)
0.30	3.962	−0.742***	0.274	−0.036	−0.312*	0.061	0.173***	0.042*	0.218
	(0.277)	(0.001)	(0.073)	(0.071)	(0.163)	(0.271)	(0.002)	(0.162)	(0.072)
0.40	3.571**	−0.231***	0.237**	−0.056*	−0.301***	0.002	0.221**	0.010***	0.210**
	(0.122)	(0.001)	(0.048)	(0.125)	(0.031)	(0.175)	(0.020)	(0.027)	(0.031)
0.50	3.034	−0.201***	0.195**	−0.051***	−0.215***	0.003***	0.173	0.004***	0.182**
	(0.149)	(0.083)	(0.044)	(0.004)	(0.006)	(0.001)	(0.021)	(0.038)	(0.040)
0.60	2.851*	−0.212***	0.132***	−0.050***	−0.159***	0.002**	0.272	0.001***	0.151***
	(0.162)	(0.092)	(0.022)	(0.003)	(0.007)	(0.048)	(0.020)	(0.002)	(0.038)
0.70	2.263	−0.751	0.103***	−0.041***	−0.044***	0.005***	0.118	0.027***	0.128*
	(0.178)	(0.039)	(0.039)	(0.005)	(0.002)	(0.013)	(0.028)	(0.016)	(0.126)
0.80	2.371	−0.761	0.088***	−0.041***	−0.062**	0.006***	0.081	0.048***	0.073**
	(0.278)	(0.052)	(0.022)	(0.001)	(−0.019)	(0.016)	(0.021)	(0.031)	(0.045)
0.90	2.641**	−0.730	0.123***	−0.044***	−0.103***	0.045***	0.110	0.031	0.118***
	(0.191)	(0.001)	(0.003)	(0.018)	(0.006)	(0.019)	(0.004)	(0.013)	(0.004)
0.95	2.416**	−0.641	0.187***	−0.051***	−0.185***	0.013***	0.136	0.048	0.174***
	(0.121)	(0.082)	(0.004)	(0.004)	(0.014)	(0.009)	(0.004)	(0.005)	(0.005)
				Short-runcoefficient estimates					
—	$\omega_1(\tau)$	$\lambda_0^{InSE}(\tau)$	$\sigma_0^{InTE}(\tau)$	$\vartheta_0^{InTECH}(\tau)$	$\varphi_0^{InEC}(\tau)$	$\psi_0^{InFDI}(\tau)$	$\xi_0^{InOPEN}(\tau)$	$\alpha_0^{InIGDP}(\tau)$	—
0.05	0.671***	0.220	−0.017	−0.007	0.024***	0.225***	−0.021	0.120	—
	(0.197)	(0.061)	(0.021)	(0.085)	(0.007)	(0.032)	(0.072)	(0.015)	—
0.10	0.521***	0.631**	−0.028**	−0.025	0.021***	0.221***	−0.031	0.203	
	(0.174)	(0.031)	(0.003)	(0.074)	(0.015)	(0.021)	(0.004)	(0.036)	
0.20	0.529***	0.880*	−0.070***	−0.028	0.120***	0.254***	−0.036	0.301	
	(0.168)	(0.123)	(0.002)	(0.003)	(0.026)	(0.024)	(0.005)	(0.045)	
0.30	0.677***	0.061*	−0.047**	−0.005	0.050***	0.164***	−0.035	0.204	—
	(0.188)	(0.121)	(0.081)	(0.018)	(0.043)	(0.062)	(0.336)	(0.070)	—
0.40	0.671***	0.563***	−0.061*	−0.004	0.003***	0.217**	−0.057	0.203**	—
	(0.204)	(0.026)	(0.118)	(0.003)	(0.001)	(0.021)	(0.124)	(0.026)	—
0.50	0.691***	0.236**	-0.063***	-0.037***	0.005**	0.173**	−0.052***	0.151**	—
	(0.209)	(0.102)	(0.005)	(0.003)	(0.004)	(0.014)	(0.003)	(0.041)	—
0.60	0.705*	0.035***	−0.061***	−0.038***	0.003*	0.218***	−0.051***	0.115***	—
	(0.125)	(0.021)	(0.004)	(0.008)	(0.118)	(0.022)	(0.002)	(0.032)	—
0.70	0.714*	0.037	−0.038	−0.036***	0.006***	0.120	−0.042***	0.114***	—
	(0.164)	(0.338)	(0.061)	(0.004)	(0.025)	(0.021)	(0.004)	(0.036)	—
0.80	0.618**	0.985	−0.027	−0.071**	0.007	0.063	−0.042**	0.072**	—
	(0.021)	(0.062)	(0.034)	(−0.082)	(0.031)	(0.023)	(0.004)	(0.015)	—
0.90	0.719	0.241	−0.042	−0.127***	0.036	0.030	−0.042*	0.125***	—
	(0.023)	(0.004)	(0.032)	(0.003)	(0.042)	(0.005)	(0.124)	(0.006)	—
0.95	0.636	0.074	−0.069***	−0.162***	0.027	0.124	−0.053***	0.162***	—
	(0.027)	(0.071)	(0.005)	(0.027)	(0.006)	(0.007)	(0.005)	(0.003)	—

Source: authors' calculations.
Note: *, ** and *** denote statistical significance at 10%, 5%, and 1% levels, respectively. The standard errors between brackets.

TABLE 7 Results of the Wald test.

Variables	F-statistics [*p*-values]
ρ^*	9.351***
	[0.000]
β_{InSE}	4.513***
	[0.000]
β_{InTE}	5.714***
	[0.000]
β_{InTECH}	2.163**
	[0.023]
β_{InEC}	5.261***
	[0.000]
β_{InFDI}	1.814*
	[0.070]
β_{InOPEN}	1.601*
	[0.085]
β_{InIGDP}	1.20
	[0.27]
ω_1	3.141***
	[0.000]
λ_0	4.250***
	[0.000]
σ_0	5.014***
	[0.000]
ϑ_0	3.748***
	[0.000]
φ_0	1.701*
	[0.072]
ψ_0	1.27
	[0.260]
ξ_0	4.105***
	[0.000]
α_0	0.450
	[0.918]

Source: authors' calculations.
Note: *, ** and *** denote statistical significance at 10%, 5%, and 1% levels, respectively.

assessment of an alternative power source also entails revising energy policy in light of the current political, social, economic, and environmental circumstances (Pathak and Shah, 2019). However, comparing South Africa's greenhouse gas (GHG) emissions globally reveals that it has one of the most carbon-intensive economies in the world. In reality, excluding island nations and based on per capita CO_2 equivalent emissions in 2010, South Africa is the most carbon-intensive developing nation that does not produce any oil (EIA, 2010). Moreover, South Africa alone accounts for 42% of all GHG emissions on the African continent, making it the continent's top emitter. Additionally, South Africa emits more CO_2 than the entirety of the Sub-Saharan African (SSA) region (EIA, 2010). The total estimated GHGs of South Africa in 2000 were 461 million tons CO_2 equivalent, of which 83% were related to energy supply and consumption, 7% were from industrial operations, 8% were related to agriculture, and 2% were related to trash. Therefore, with 380,988 Gg CO_2, the energy sector is by far the greatest contributor to emissions in the country, with fuel combustion accounting for 81% of the industry's emissions and fugitive emissions from fuel accounting for the remaining 19%. The intentional promotion of investment in energy-intensive sectors of the economy, such as aluminum and other non-ferrous metal beneficiation (the so-called "mineral-energy complex," identified by Fine and Rustomjee (1996), by the pre-democratic government prior to 1994, is a factor that has made a significant contribution to South Africa's extremely large energy-related emission levels. The carbon intensity of a largely coal-based electricity generation base, which accounts for 90% of total emissions, is another factor responsible for high emissions in South Africa (Udeagha and Ngepah, 2022a; Udeagha and Ngepah, 2022b). South Africa ranks as the 14th greatest GHG emitter in the world, and most of its CO_2 emissions are caused by a significant reliance on coal. However, a newly unveiled draft power plan suggests a considerable move away from fuel to gas and renewable energy sources. The plan calls for no new plants to be built after 2030 and the closure of four-fifths of the capacity by 2050, even though coal will keep playing a role for decades. Additionally, the nation has committed to peaking its emissions between 2020 and 2025, enabling them to level off for around 10 years before beginning to decline. The US, UK, France, Germany, and the EU offered South Africa $8.5 billion to help the nation lessen its dependence on coal during the Conference of the Parties (COP26) in Glasgow (https://www.bbc.com/news/world-africa-59135169). This is a paradigm-shifting event that can help the nation progressively shut down its coal-fired power plants and make the switch to renewable energy sources, resulting in a decrease in GHGs. Therefore, South Africa presents a compelling case for consideration in a separate study that examines how technological innovation influences pollutant emissions based on the analyses presented above.

Additionally, earlier research on the relationship between technical advancement and CO_2 emissions in a global setting while including trade openness uses the same definition and presentation of trade openness. These publications have employed the trade intensity (TI) or the ratio of trade (exports plus imports) to GDP to measure trade openness. This proxy solely considers a country's status compared to the performance of its internal commerce. This means that the true influence of trade openness on environmental quality is not adequately portrayed and that a country's openness to international commerce is neglected. Because developing nations such as Togo, Nigeria, Ghana, Uganda, Venezuela, Zambia, and Zimbabwe are categorized as open economies due to their low GDP, the use of the TI-based proxy is detrimental to larger economies such as South Africa, Japan,

TABLE 8 Frequency-domain causality test.

Direction of causality	Long-term	Medium-term	Short-term
	$\omega_{i=0.05}$	$\omega_{i=1.50}$	$\omega_{i=2.50}$
InSE → InCO$_2$	<8.31>	<8.50>	<9.96>
	(0.02)**	(0.00)***	(0.00)***
InTE → InCO$_2$	<4.89>	<6.49>	<6.93>
	(0.07)*	(0.03)**	(0.04)**
InOPEN → InCO$_2$	<8.94>	<8.73>	<7.28>
	(0.00)***	(0.00)***	(0.01)**
InEC → InCO$_2$	<5.12>	<6.49>	<6.73>
	(0.08)*	(0.04)**	(0.03)**
InFDI → InCO$_2$	<8.20>	<8.08>	<8.62>
	(0.01)**	(0.03)**	(0.00)***
InTECH → InCO$_2$	<4.84>	<5.14>	<7.83>
	(0.06)*	(0.04)**	(0.02)**
InIGDP → InCO$_2$	<5.46>	<8.82>	<8.89>
	(0.07)*	(0.00)**	(0.00)**

Source: authors' calculations.
Note: *, ** and *** denote statistical significance at 10%, 5%, and 1% levels, respectively.

China, France, the US, and Germany because they are grouped as closed economies due to their higher GDP (Squalli and Wilson, 2011). Different methodological stances and issues with model misspecification are also responsible for the inconsistent findings and lack of empirical agreement in these few works on the effect of technological innovation on CO_2 emissions.

The primary objective of this study is to investigate the asymmetric effect of technological innovation on environmental quality in South Africa. Our investigation in this work is motivated by all the previously mentioned factors, including the lack of scientific consensus on the relationship between technological innovation and CO_2 emissions. The significant contributions of this study are summarized below.

Firstly, by considering the aforementioned statistics, this work is crucial in examining the asymmetric impact of technological innovation on CO_2 emissions in the context of South Africa using the quantile autoregressive distributed lag (QARDL) model developed by Cho et al. (2015). Again, for the aforementioned relationship, one of the most daunting challenges was to provide a dynamic concept for the association's future development that would help policymakers with further planning. In light of contemporary realities, the current research differs from the earlier efforts in terms of the methods used to further assess the composite behavior of technological innovation-CO_2 nexus. The best strategy to avoid challenges or gaps was carefully chosen after thorough scrutiny. Practically, past research emphasized basic correlation or conventional approaches to describe the connection without carefully considering the magnitude (i.e., the quantiles). In order to give a more adaptable econometric framework than the conventional ones to examine the linkages under examination, this investigation employs the QARDL approach to evaluate the long-term stability of the nexus across the quantiles. Furthermore, it was challenging to determine the main characteristics of their changes due to the chaotic and nonlinear behavior of our involved variable. Because the QARDL framework also looks at the asymmetric and nonlinear relationship between technological innovation and CO_2, we used it to further understand the technological innovation-CO_2 nexus.

Secondly, it is important to consider that various levels of policy instruments may have varying impacts on all levels of the target policy parameters when describing the study's policy-level contribution. This relationship must be investigated simultaneously for both short-run and long-run settings, as the results will be used to make policy decisions. The QARDL technique has been used in this endeavor. This strategy offers a variety of advantages. 1) This method allows for examining both long-term associations and short-term dynamics throughout a range of quantiles of the constrained distribution of the target policy parameter. 2) Unlike traditional methods, the novel QARDL model offers an excellent econometric methodology by efficiently and effectively assessing the relationship's long-term stability across quantiles. 3) In order to select the target policy parameter within its constrained distribution, it allows for locational asymmetry among the model parameters. 4) This method also helps us to identify nonlinearity in the relationship between technological advancement and pollutant emissions because the information provided by linear frameworks is insufficient to draw valid conclusions and provide accurate predictions. Consequently, this evidence suggests that the presumed linearity by earlier studies using the simple ARDL model and other cointegration frameworks is severely constrained in various economic manifestations, particularly for the connection between technological innovation and CO_2 emissions. Evidence from the literature suggests the link between technological innovation and CO_2 emissions could be asymmetric and nonlinear. If this happens, the policy implications will differ considerably from when this connection is linear. To the best of our knowledge, previous research on the relationship between technological innovation and CO_2 emissions, particularly in the context of South Africa, has not used this approach. 5) The methodological adaptation now complements the study's policy-level contribution from the perspective of policymaking. Diverse degrees of technological innovation are anticipated to have a range of effects on CO_2 emissions. As a result, the QARDL methodology may address the issue of formulating policies, accordingly contributing to the advancement of environmental economics literature from a methodological standpoint driven by contextual factors.

Thirdly, this study makes a theoretical contribution by revalidating the EKC theory in South Africa. In terms of applications, the findings provide strategies to enhance environmental quality by implementing and conducting effective initiatives. These findings are essential for the South African government and policymakers to implement policies aimed at protecting the environment from the damaging consequences of CO_2 emissions.

Lastly, in order to capture the magnitude of trade compared to global trade and the trade share in GDP, this research also makes a further contribution by using a novel measure of trade openness provided by Squalli and Wilson (2011). As a result, our study significantly differs from prior ones that mostly employed TI-based measures of trade openness by using the Squalli and Wilson proxy of trade openness.

The remainder of the paper is organized as follows: the *literature review and contributions of the study* section reviews the relevant literature on the nexus between technological innovation and CO_2 emissions; the *material and methods* section outlines the material and methods, and the *empirical results and their discussion* section discusses the results. The *Conclusions and policy implications* section concludes with policy implications.

Literature review and contributions of the study

This part is divided into three subsections: the first section discusses the theoretical framework regarding CO_2 emissions and environmental regulations, the second section explores and provides empirical research on the connection between technological innovation and environmental quality, and the last section outlines the gaps in the literature and highlights how the current study adds to the existing knowledge on this topic.

Theoretical framework of CO_2 emissions and environmental regulations

Researchers have been interested in the trending topics of environmental regulation and CO_2 emissions. The green paradox and forced emission reduction are two dominant positions on these topics (Yin et al., 2022). The green paradox contends that CO_2 emissions cannot be successfully reduced by environmental regulation. Energy exploitation quickens as fossil energy producers anticipate that the green legislation may hurt their earning potential. A rise in supply lowers energy prices while raising energy demand. Consequently, environmental control measures have the reverse impact, leading to an increase in CO_2 emissions and pollution (Ngo, 2022). Forced emission reduction is the other viewpoint. This perspective maintains that the fundamental tenet of the green paradox is unrealistic.

The overall amount of fossil fuel reserves is finite and has a finite shelf life. Prices and demand for energy could also not be related, and both might rise simultaneously. Cost increases lead to a decrease in pollution and CO_2 emissions (Hassan et al., 2022). How would environmental regulation affect CO_2 emissions as a result? Will it be favorable or unfavorable? We consider the direct and indirect consequences in order to respond to these two queries.

Environmental regulation has two implications for CO_2 emissions. On the one hand, CO_2 emission is directly impacted by environmental regulation (Figure 2). Environmental regulation is a crucial component of social regulation, which suggests that in order to achieve sustainable economic growth and the atmosphere, the government regulates the manufacturing and operating processes of industry players through governmental actions, carbon pollution authorizations, regulatory fines, and the collection of emission taxes. Although there are many different environmental regulatory mechanisms, they may be loosely grouped into two categories: command control and market incentive (Chen et al., 2022). All parties involved must strictly abide by the required instructions under the command-control environmental regulation, where the state agency establishes the goals and specifications of environmental management in the form of laws or regulations and guidelines (Liu et al., 2022). Command-control environmental regulation is more stringently enforced than the market incentive regulatory style. Carbon emitters can accept the different pollutants' emissions requirements to avoid the environmental protection agency's stiff penalties. By using market-oriented measures such as sanitation surcharges, carbon pollution trading costs, and environmental taxes, the state, through market incentive environmental regulation, supports different market entities to proactively maintain a sustainable environment because of the benefits this has for society as a whole (Xu and Xu, 2022). In general, market-based environmental regulation increases ecological integrity indirectly by employing financial means to increase polluters' financial costs (Wang L. et al., 2022c). As a result, the state creates environmental standards focused on taxing fossil fuel consumption and manufacturing. Consequently, the demand for fossil fuels will be reduced because it will become more expensive to produce energy using fossil fuels. Commercial organizations will conduct research to create green technology and raise their levels of technological innovation as a result. The state also has the power to influence environmental regulation. The state uses administrative measures to limit pollution discharges from industries, such as requiring some high-polluting corporations to shut down and some businesses to adopt low-carbon technologies to effectively reduce CO_2 emissions. These measures are enforced through statutes and rules that maintain industry requirements. The "green paradox" argument, which suggests that stringent environmental regulations will hasten the extraction and sale of fossil fuels and raise CO_2 emissions, may also be considered simultaneously (Gu et al., 2022).

Contrarily, environmental regulation affects CO_2 emissions indirectly through four conductive channels, including FDI, technological innovation, industrial structure, and energy structure (Yin et al., 2022). Environmental regulations have increased the regulatory limit for polluting enterprises and limited their development, as shown in Figure 3 from an examination of the indirect functional route of industrial structure. The cost of conducting energy-intensive enterprises also rises as a result, which encourages upgrading the industrial structure and further cuts CO_2 emissions. An examination of the energy utilization structure reveals that environmental regulation will cause businesses to use less fossil fuel and emit less CO_2. Environmental regulation's impact on energy structure, however, may have a contradictory result (Wang et al., 2022c). According to some researchers, the adoption of environmental regulations will expedite the expansion and deployment of fossil fuels as a source of energy. The "Porter hypothesis" impact and the "following cost" influence are two consequences of environmental regulation on technological innovation, as shown by research. Moderate environmental regulation can encourage companies to employ technological innovation, which will help reduce CO_2 emissions. However, excessively stringent environmental standards would drive up the cost of pollution and limit the capacity for technical R&D (Xie et al., 2022). Therefore, it is difficult to lower CO_2 emissions. A host nation will benefit from FDI's sophisticated managerial and technological capabilities, which will help reduce CO_2 emissions. However, if some nations accept enterprises that produce much pollution by reducing the environmental regulatory requirement, CO_2 emissions will not be reduced. However, the technological spillover effect of FDI and the absorption of cutting-edge technology and knowledge would not be possible if the environmental standards of a host country were significantly tighter than those in other nations (Yirong, 2022). The indirect impact of environmental regulations on CO_2 emissions is the primary goal of this research.

Review of previous literature

Several studies have examined the role technological innovation plays in enhancing environmental quality. However, across a variety of methodological frameworks and nations investigated, the results are often ambiguous and conflicting. Although some studies found that environmental quality is improved by technological innovation through various routes (Rafique et al., 2022), several other works argued that technological advancement exacerbates the state of the environment (Atsu et al., 2021).

For an illustrative sample of 76 Belt and Road economies, Rafique et al. (2022) evaluated the empirical interactions between the consumption of renewable energy, FDI, medium and high-tech industries, economic complexity, human capital, power distance, uncertainty avoidance, and masculinity *versus* femininity. A comprehensive framework for econometric testing was created using a series that covered the years 1996–2019 and included the generalized method of moments and the technique of moment quantile regression. Associated findings supported the authors' initial hypotheses that medium and high-tech industries, as opposed to FDI, caused the diffusion of low-carbon energy across sectors. Changes in human capital have a detrimental impact on the implementation of renewable energy. The authors included several policy recommendations and a methodological comment to incorporate those findings into future energy planning. Likewise, Lin and Ma. (2022) investigated the influence of the urban innovation environment on the effect of technological advances on CO_2 emissions using data on 264 prefecture-level Chinese cities from 2006 to 2017. The empirical findings showed that different types of cities are affected differently by technological advancements. Although the impact is minimal in Chinese cities prior to 2010, technological advancements can help reduce CO_2 emissions after 2010. Second, through improving industrial structure, technical advancements can indirectly lower CO_2 emissions. Thirdly, government spending cannot considerably affect the marginal impact of technical advances when the urban innovation environment is considered. Similarly, Obobisa et al. (2022), who recognized institutional excellence and technical innovation as efficient ways to decrease carbon emissions and advance sustainable development, examined how each contributed to emissions reductions in 25 African nations between 2000 and 2018. The use of renewable energy and technical progress, according to the authors, massively reduces

CO_2 emissions. On the contrary, CO_2 emissions are adversely affected by institutional quality, economic expansion, and the use of fossil fuels as an energy source. The authors suggested that, in order to meet their goals for sustainable development, African nations expand their investment in technical innovation and renewable energy initiatives. Moreover, the analysis of the relationship between technical advancement, renewable energy, and CO_2 emissions from 1990 to 2018 in China by Kuang et al. (2022) using panel data demonstrated that these variables had a long-term, significant negative influence on CO_2 emissions. Additionally, there is no evidence of a short-term relationship between technical innovation and economic development. The authors conclude that putting technological innovation to use has positive externalities. During the 1990–2018 data period, Rahman et al. (2022) investigated the role of contributing factors for CO_2 emissions reduction in the 22 most industrialized countries worldwide. The authors found that reducing CO_2 emissions is aided by export quality and renewable energy. The positive stimuli of technological innovation, as measured by R&D investment and export quality index, reduce these emissions in contradiction to the negative shocks or counter incentives of these variables, which increase CO_2 emissions. Additionally, Habiba et al. (2022) examined the effects of financial development, technological breakthroughs, and the use of renewable energy on carbon emissions for the top twelve emitters using data from 1991 to 2018. In the future, technological developments and the use of renewable energy will be the primary factors in lowering CO_2 emissions, whereas the usage of non-renewable energy will continuously drop. Based on their findings, the authors suggested actions to reduce CO_2 emissions in order to achieve sustainable development. Vitenu-Sackey and Acheampong (2022) examined the impact of economic policy uncertainty (EPU) and technological development on CO_2 emissions in a panel of 18 industrialized countries from 2005 to 2018 using second-generation time-series panel data techniques. The authors used three trustworthy long-run estimators to handle heterogeneity, endogeneity, and simultaneity in the panels: two-stage least squares, panel generalized method of moments (GMM), and generalized least squares (GLS). They discovered that economic growth had a significant and favorable influence on CO_2 emissions, but this benefit peaked at a certain rate of growth and then decreased, demonstrating that the sample had an inverted U-shaped EKC relationship. Second, the impact of EPU on CO_2 emissions varies by country. For example, high levels of EPU have little impact in low-pollution countries while having a considerable impact in high-pollution countries. Thirdly, R&D, FDI, urbanization, and the utilization of renewable energy sources all have varied effects on CO_2 emissions (RE). The authors stressed that there is a heterogeneous relationship between carbon emissions and economic indices, even in advanced economies. This relationship is known as the pollution haven hypothesis (PHH), which is true in high-pollution nations, whereas the pollution halo effect is true for low-pollution ones. This study contends that a one-size-fits-all approach to emission reduction is not the best course of action because not every country's rate of urbanization, FDI inflows, R&D spending, and use of renewable energy directly influence CO_2 emissions in the face of unpredictable economic policies.

Furthermore, Adebayo et al. (2022) used cutting-edge Morlet wavelet analysis to provide a new understanding of the dynamic relationship between CO_2 emission and economic development, the use of renewable energy, trade openness, and technical innovation in the Portuguese economy. The study used a dataset between 1980 and 2019 to apply continuous wavelet transform, wavelet correlation, multiple and partial wavelet coherence, and frequency domain causality (FDC) analysis to the variables under study. The linkage between the markers advances with time and frequency, according to the authors. In addition, they discovered considerable lead and lag linkages and wavelet coherence in the frequency domain but competing interactions between the variables were discovered in the time domain. The wavelet analysis supports the economic position that the use of renewable energy reduces CO_2 emissions whereas trade openness, technical advancement, and economic expansion increase CO_2 emissions. The findings suggested that the usage of renewable energy will reduce CO_2 in Portugal over the long term. Portugal's government ought to encourage investment in renewable energy sources, enact limiting legislation, and promote energy innovation. Chhabra et al. (2022) investigated how trade openness and technical advancement helped middle-income nations reduce their CO_2 emissions to improve the quality of the environment. For a sample of 23 middle-income nations from 1994 to 2018, the generalized method of moments (GMM) approach and the Dumitrescu–Hurlin causality test were used to estimate the long-run relationship between variables and investigate causality, respectively. The inverted u-shape association between innovation and CO_2 emissions was disproved by their research. In terms of commerce, it was discovered that lower middle-income countries experienced environmental deterioration at a more pronounced rate than upper middle-income nations. In contrast, the data also confirmed the existence of the EKC theory for both nation groups; however, the decline in the EKC curve is negligible for low- and middle-income countries suggesting that in order to minimize the steadily growing CO_2 emissions, poor and medium income nations must focus on a higher degree of green innovation than they have in the past. The authors proposed setting a pollution level standard for the industrial and trading sectors, which produce the most polluted waste, and encouraging economic growth through knowledge spillovers. Additionally, according to Li et al. (2022), technological innovation unquestionably contributes significantly to creating job possibilities, enhancing green economic activity, and boosting environmental sustainability. The authors used nonlinear autoregressive distributed lag (NARDL) to examine the impact of technical advancement and energy efficiency on CO_2 emissions in China from 1991 to 2019. Their studies demonstrated how China's CO_2 emissions might be decreased through technical innovation and energy efficiency. Innovation in technology and energy efficiency are significant nonlinear factors of CO_2 emissions. Energy efficiency and technology advancements help reduce CO_2 emissions, but their decline has a long-term negative impact on CO_2 emissions in China.

The high technology (high-tech) industry in China has advanced to a critical strategic position in the Chinese economic objectives, according to Wang et al. (2022a). This posture has led to the rise of FDI and technical innovation as powerful cornerstones of the high-tech sector. Although it is still up for debate, there are rising worries about the industry's carbon emissions. Wang et al. (2022b) examined the impact of FDI and technical advancement on carbon emissions in the high-tech industry from 28 Chinese provinces in this context. China's province statistics from 2000 to 2018 were used in the study. The authors employed quantile regression to estimate long-run correlations among research variables in addition to looking at unit root characteristics, structural breakdowns, and cointegration. The results showed that FDI has a negative effect on carbon emissions. The first three quantiles of technological innovation are favorably impacted, whereas the next six quantiles are negatively impacted. According to the authors, FDI and technical advancement have altered the energy intensity in the high-tech sector, which affects how much CO_2 is emitted over time. Their analysis suggested that policymakers should focus on the diverse effects of FDI and technology-led emissions at different quantiles during the process of CO_2 emission reduction after controlling the effects of urbanization, energy intensity, and economic growth. Based on data from 1990 to 2019, Abid et al. (2022) investigated the effects of technical advancement, financial growth, FDI, energy usage, and urbanization on carbon emissions in G8 member nations. Within the panel nations, their findings showed a substantial cross-sectional reliance. FDI, financial development, and technical innovation in G8 nations have all been found to have a statistically significant long-run and adverse correlation with CO_2 according to the FMLOS estimator. Economic growth, financial development, urbanization, trade openness, CO_2 emissions, and energy usage have been found to have long-term bidirectional causal relationships. In contrast, there is a one-way causal relationship between carbon emissions and FDI. The authors suggested that the current requirement for the growth of industries, technical innovation, and financial development for the G8 nations is a quality FDI. Additionally, urbanization contributes significantly to environmental deterioration, necessitating the need for stronger regulations in these nations.

Moreover, Anser et al. (2021), who investigated the effect of innovation on environmental quality in EU countries using the panel fixed effect and panel quantile regression over the period 2000–2017 found that innovation has contributed immensely to reducing CO_2 emissions. This evidence is supported by Yang et al. (2021) and Erdogan (2021) in the case of BRICS economies. Moreover, Shan et al. (2021) reached a similar conclusion for Turkey using the ARDL framework over the period 1990–2018. Similarly, Guo et al. (2021), who examined the role of technological innovation in improving environmental quality in Asian countries found that innovation is good for the environment and has contributed tremendously to reducing CO_2 emissions in those countries under review.

In contrast, Dauda et al. (2021), who assessed the effect of technological innovation on environmental quality in SSA countries over the period 1990–2018 concluded that innovation increases CO_2 emissions. Using the feasible generalized least square (FGLS) and augmented mean group (AMG) frameworks over the period 1990–2017, Usman and Hammar (2021) found evidence that innovation escalates environmental dilapidation for APEC countries.

Therefore, Table 1 presents a summary of selected literature on the nexus between technological innovation and CO_2 emissions to reflect more comparisons against different regions.

Literature gap and contributions of the study

Based on the literature review, the environmental impact of technological innovation is controversial and has substantially generated more heat than light. Because of its complex nature, we do not precisely know the future effect of technological innovation, and our decision today affects the direction of sustainable development. Therefore, revisiting the role technological innovation plays in fostering environmental quality, especially in the context of South Africa has been an area that requires further analysis. This is because the constant application of technological innovation determines if it could lead to improvement in environmental quality, thus enhancing better lives with good environmental quality in South Africa.

In light of this, we make three contributions to the literature on how technological advancement affects CO_2 emissions. 1) Several studies have looked into how South Africa's CO_2 emissions are impacted by financial development, FDI, trade openness, and energy use. The role of technological innovation in promoting environmental quality in the context of South Africa, however, is less thoroughly examined in empirical research. As a result, this research aims to close this significant vacuum in the body of knowledge on South Africa. 2) The simple ARDL approach suggested by Pesaran et al. (2001) and other cointegration frameworks, which can only estimate and explore the long- and short-run relationships between the variables under review, have been widely used in studies that investigated the relationship between technological innovation and CO_2 emissions in the global context. The newly designed QARDL model presented by Cho et al. (2015), which circumvents the shortcomings of the conventional ARDL technique, is used in this work instead. In contrast to traditional methods, the innovative QARDL model offers a flexible econometric framework by effectively and efficiently assessing the relationship's long-term stability across quantiles. To the best of our knowledge, previous research on the relationship between technological innovation and CO_2 emissions, particularly in the context of South Africa, has not used this approach. 3) There have been criticisms of the definition and measurement of trade openness in a few empirical studies that examined the impact of technical innovation on CO_2 emissions while accounting for trade openness. In order to capture the magnitude of trade compared to global trade and the trade share in GDP, this research also makes a further contribution by using a novel measure of trade openness provided by Squalli and Wilson. (2011). As a result, our study significantly differs from prior ones that mostly employed conventional TI measures of trade openness by using the Squalli and Wilson proxy of trade openness.

Material and methods

This study examines the relationship between technological innovation and CO_2 emissions in South Africa from 1960 to 2020 using the innovative QARDL framework developed by Cho et al. (2015), which circumvents the shortcomings of the straightforward ARDL method. In contrast to traditional methods, the unique QARDL model offers a flexible econometric framework by effectively and efficiently assessing the relationship's long-term stability across quantiles. To the best of our knowledge, previous research on the relationship between technological innovation and CO_2 emissions, particularly in the context of South Africa, has not used this approach. It is crucial to perform a stationarity test on the variables to determine their order of integration before using the innovative QARDL model. As a result, we use the standard Dickey–Fuller GLS (DF-GLS), Phillips–Perron (PP), Augmented Dickey–Fuller (ADF), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) unit root tests. Because structural breaks are persistent and have an impact on many macroeconomic variables, including CO_2 emissions and technological innovation, the Narayan and Popp structural break unit root test is utilized.

Functional form

This study revisits the relationship between technological innovation and CO_2 emissions in South Africa using the standard EKC hypothesis framework, which is a strong empirical technique that has been widely employed in past research. The EKC theory argues that economic expansion significantly worsens environmental quality because, throughout the earlier stages of society's development, reaching greater income levels received more attention than minimizing environmental deterioration. As a result, aggressive efforts were made to achieve faster economic development at the price of reducing carbon emissions, which ineluctably led to the deterioration of the environmental state.

This evidence logically justifies the reason why the scale effect, a stand-in for economic expansion, and environmental quality have a positive association. People grew increasingly ecologically sensitive as society developed, particularly during the advanced industrial era, and governments passed environmental regulations intended to boost environmental quality. As a result, throughout this stage of development, as income rose, the environment got better due to people's propensity for a clean environment and the implementation of stricter environmental norms. The reasoning behind the negative association between the technology impact (square of economic growth) and environmental quality is thus intuitively explained by this argument. The typical EKC hypothesis is thus stated in accordance with Udeagha and Breitenbach (2021), Udeagha and Ngepah. (2019), Cole and Elliott (2003), and Ling et al. (2015) as follows:

$$CO_2 = F(SE, TE), \tag{1}$$

where CO_2 represents CO_2 emissions, an environmental quality measure; SE denotes scale effect, a proxy for economic growth; and TE represents technique effect, which captures the square of economic growth. Log-linearizing Eq. 1 yields the following:

$$\text{In}CO_{2t} = \alpha + \varphi InSE_t + \beta InTE_t + \varepsilon_t. \tag{2}$$

As income rises, the scale effect (economic expansion) causes environmental quality to decline. In contrast, the method effect—following the adoption of environmental regulations and people's propensity for a clean environment—improves environmental quality (Cole and Elliott, 2003; Ling et al., 2015). With this context, the conceptual predictions demand that $\varphi > 0$ and $\beta < 0$ in order for the EKC hypothesis to exist. We mirror the literature and employ FDI, energy consumption, trade openness, and industrial value-added as control variables in the equation relating to technological innovation and CO_2 emissions. Eq. 2 is therefore enhanced to consider these variables and technological advancement as follows:

$$\text{In}CO_{2t} = \alpha + \varphi InSE_t + \beta InTE_t + \rho InTECH_t + \pi InEC_t + \delta InFDI_t + \tau InOPEN_t + \omega InIGDP_t + U_t, \tag{3}$$

where $InTECH_t$ is technological innovation; $InEC_t$ denotes energy consumption; $InFDI_t$ captures FDI; $InOPEN_t$ represents trade openness, and $InIGDP_t$ denotes industrial value-added. All variables are in the natural log.

$\varphi, \beta, \rho, \pi, \delta\, \tau$, and ω are the estimable coefficients capturing different elasticities, whereas U_t captures the stochastic error term with standard properties.

Measuring trade openness

Following Squalli and Wilson (2011), the composite trade intensity (CTI) is employed in this study as a measure of trade openness to adequately account for trade's contribution to GDP and its magnitude in relation to global trade. We can successfully overcome the drawbacks of the conventional TI extensively employed in past research by using this method of measuring trade openness. More crucially, the innovative CTI offers more significant data about a nation's trade contribution to the world economy. Additionally, because it includes both aspects of a nation's relationships with the rest of the world, it reflects the reality of trade outcomes. The CTI is shown as follows:

$$CTI = \frac{(X+M)_i}{\frac{1}{n}\sum_{j=1}^{n}(X+M)_j}\,\frac{(X+M)_i}{GDP_i}, \tag{4}$$

where South Africa is represented by *i* and its trading partners are denoted by *j*. The first part of Eq. 4 signifies the global trade share, and the second part represents the South African trade share.

Variables and data sources

The data used in this study are annual times series data from 1960 to 2020. The dependent variable is CO_2 emissions, which act as a stand-in for environmental quality. To confirm the existence of the EKC hypothesis, economic growth as measured by scale effect and the square of economic growth as measured by technique effect are utilized. Gross domestic investment in R&D is used as a proxy for technological innovation. Following the literature, the additional factors that were considered were as follows: EC, FDI, trade openness (OPEN), and industrial value-added to GDP (IGDP). Therefore, the variable definition and data sources are summarized in Table 2.

Narayan and Popp's structural break unit root test

It is crucial to perform a stationarity test on the variables under consideration in order to determine their order of integration before using the innovative QARDL model. As a result, this study utilizes the unit root tests DF-GLS, PP, ADF, and KPSS. As empirical data demonstrate that structural breaks are persistent in the sense that numerous macroeconomic variables, such as CO_2 emissions and technological innovation, are impacted by structural breaks, the Narayan and Popp structural break unit root test is further applied.

Quantile autoregressive distributed lag framework

The simple ARDL approach put forth by Pesaran et al. (2001) and other cointegration frameworks, which can only estimate and explore the short- and long-run relationships between the variables, have been widely used in previous studies that examined the impact of technological innovation on CO_2 emissions. The recently designed QARDL model established by Cho et al. (2015), which circumvents the shortcomings of the conventional ARDL technique, is used in this work instead. In contrast to traditional methods, the innovative QARDL model offers a flexible econometric framework by effectively and efficiently assessing the relationship's long-term stability across quantiles. This method also helps us identify the nonlinearity in the relationship between technological advancement and CO_2 emissions because the information provided by linear frameworks is insufficient to draw valid conclusions and provide accurate predictions. Consequently, this evidence suggests that the assumed linear relationship by earlier studies using the traditional ARDL model and other cointegration frameworks is severely constrained in a wide range of economic phenomena, especially for the relationship between technological innovation and CO_2 emissions. According to the studies reviewed above, there is cause for concern that the link between technological advancement and CO_2 emissions may be nonlinear and asymmetric. If this were to occur, the policy implications would be considerably different than when this connection is linear. To the best of our knowledge, previous research on the relationship between technological innovation and CO_2 emissions, particularly in the context of South Africa, has not used this approach. The conventional linear ARDL bounds testing approach, following Pesaran et al. (2001), is presented as follows:

$$\begin{aligned} InCO_{2t} &= \gamma_0 + \sum_{i=1}^{m}\gamma_{1i}InCO_{2t-i} + \sum_{i=0}^{n}\gamma_{2i}InSE_{t-i} + \sum_{i=0}^{p}\gamma_{3i}InTE_{t-i} \\ &+ \sum_{i=0}^{q}\gamma_{4i}TECH_{t-i} + \sum_{i=0}^{r}\gamma_{5i}EC_{t-i} + \sum_{i=0}^{s}\gamma_{6i}InFDI_{t-i} \\ &+ \sum_{i=0}^{t}\gamma_{7i}InOPEN_{t-i} + \sum_{i=0}^{u}\gamma_{8i}InIGDP_{t-i} + \varepsilon_t, \end{aligned} \tag{5}$$

where ε_t is the white noise, and *m*, *n*, *p*, *q*, *r*, *s*, *t*, and *u* denote the optimal lags selected by Schwarz's Bayesian Information Criterion (SBIC).

Following the above-mentioned linear ARDL framework, the novel QARDL model is presented as follows:

$$Q_{InCO_{2t}} = \beta_0(\tau) + \sum_{i=1}^{m}\omega_1(\tau)InCO_{2t-i} + \sum_{i=0}^{n}\omega_2(\tau)InSE_{t-i} + \sum_{i=0}^{p}\omega_3(\tau)InTE_{t-1} + \sum_{i=0}^{q}\omega_4(\tau)InTECH_{t-i} + \sum_{i=0}^{r}\omega_5(\tau)InEC_{t-1} + \sum_{i=0}^{s}\omega_6(\tau)InFDI_{t-1} + \sum_{i=0}^{t}\omega_7(\tau)InOPEN_{t-1} + \sum_{i=0}^{u}\omega_8(\tau)InIGDP_{t-1} + \varepsilon_t(\tau), \quad (6)$$

where $\varepsilon_t(\tau) = InCO_{2t} - Q_{InCO_{2t}}(\tau/\cap_{t-1})$ (Kim and White, 2003) and $0 < \tau < 1$ denotes quantile. This study uses a set of quantiles (i.e., 0.05, 0.1, 0.2, 0.3, 0.4, 0.5. 0.6. 0.7, 0.8, 0.9, and 0.95) to conduct the data analysis. Moreover, due to the possible effect of serial correlation in the error term, Eq. 6 is generalized as follows:

$$Q_{\Delta InCO_{2t}} = \beta_0(\tau) + \theta_1 InCO_{2t-i} + \theta_2 InSE_{t-i} + \theta_3 InTE_{t-i} + \theta_4 InTECH_{t-i} + \theta_5 InEC_{t-i} + \theta_6 InFDI_{t-i} + \theta_7 InOPEN_{t-i} + \theta_8 InIGDP_{t-i} + \sum_{i=1}^{m}\omega_1(\tau)InCO_{2t-i} + \sum_{i=0}^{n}\omega_2(\tau)InSE_{t-i} + \sum_{i=0}^{p}\omega_3(\tau)InTE_{t-1} + \sum_{i=0}^{q}\omega_4(\tau)InTECH_{t-i} + \sum_{i=0}^{r}\omega_5(\tau)InEC_{t-1} + \sum_{i=0}^{s}\omega_6(\tau)InFDI_{t-1} + \sum_{i=0}^{t}\omega_7(\tau)InOPEN_{t-1} + \sum_{i=0}^{u}\omega_8(\tau)InIGDP_{t-1} + \varepsilon_t(\tau). \quad (7)$$

Following Cho et al. (2015), the dynamic quantile error correction model of QARDL is presented as follows:

$$Q_{\Delta InCO_{2t}} = \mu(\tau) + \rho(\tau)\big(InCO_{2t-i} - \beta_{InSE}(\tau)InSE_{t-i} - \beta_{InTE}(\tau)InTE_{t-i} - \beta_{InTECH}(\tau)InTECH_{t-i} - \beta_{InEC}(\tau)InEC_{t-i} - \beta_{InFDI}(\tau)InFDI_{t-i} - \beta_{InOPEN}(\tau)InOPEN_{t-i} - \beta_{InIGDP}(\tau)InIGDP_{t-i}\big) + \sum_{i=1}^{m-1}\omega_i(\tau)InCO_{2t-i} + \sum_{i=0}^{n-1}\lambda_i(\tau)InSE_{t-i} + \sum_{i=0}^{p-1}\sigma_i(\tau)InTE_{t-1} + \sum_{i=0}^{q-1}\vartheta_i(\tau)InTECH_{t-i} + \sum_{i=0}^{r-1}\varphi_i(\tau)InEC_{t-1} + \sum_{i=0}^{s-1}\psi_i(\tau)InFDI_{t-1} + \sum_{i=0}^{t-1}\xi_i(\tau)InOPEN_{t-1} + \sum_{i=0}^{u-1}\alpha_i(\tau)InIGDP_{t-1} + \varepsilon_t(\tau). \quad (8)$$

By using the Δ approach, the overall short-term effect of previous carbon emissions on present carbon emissions has been tested through $\omega_i = \sum_{i=1}^{m-1}\omega_i$, whereas the cumulative short-run effects of the initial and present levels of InSE, InTE, InTECH, InEC, InFDI, InOPEN, and InIGDP are determined by $\lambda_i = \sum_{i=1}^{n-1}\lambda_i$, $\sigma_i = \sum_{i=1}^{p-1}\sigma_i$, $\vartheta_i = \sum_{i=1}^{q-1}\vartheta_i$, $\varphi_i = \sum_{i=1}^{r-1}\varphi_i$, $\psi_i = \sum_{i=1}^{s-1}\psi_i$, $\xi_i = \sum_{i=1}^{t-1}\xi_i$, and $\alpha_i = \sum_{i=1}^{u-1}\alpha_i$, respectively. The long-run coefficients of InSE, InTE, InTECH, InEC, InFDI, InOPEN, and InIGDP are, respectively, calculated as β*InSE =−βInSEρ, β*InTE =−βInTEρ, β*InTECH =−βInTECHρ, β*InEC =−βInECρ, β*InFDI =−βInFDIρ, β*InOPEN=−βInOPENρ, and β*InIGDP =−βInIGDPρ. Moreover, ECM parameter ρ in Eq. 9, which captures the speed of adjustment, is expected to be negative and significant..

Frequency domain causality test

Lastly, this study explores the causal connections between the variables under investigation using the FDC technique, a reliable testing procedure recommended by Breitung and Candelon (2006). FDC makes it possible to predict the response variable at a given time-frequency, which is virtually impossible with the traditional Granger causality approach. It also enables capturing permanent causality for medium-, short-, and long-term relationships among the variables being studied. In this study, the robustness of the test is also checked.

Empirical results and their discussion

Summary statistics

Before analyzing the findings, the summary statistics of the variables employed in this work are examined and analyzed. The summary of information in Table 3 shows that the CO_2 emissions average value is 0.264. The square of GDP per capita, the technique effect, has an average mean that is 60.316 times bigger than other variables. FDI, which has 13.203, comes next. Table 2 characterizes the summary statistics and depicts the peak using kurtosis, whereas the Jarque–Bera test statistic is utilized to determine if our data series is normal. The table demonstrates that although the method impact has a negative tendency, scale effect, trade openness, energy consumption, FDI, industrial value-added, and technical innovation all have positive trends. Technique effect (TE) has the largest variation of all of the variables, indicating a significant degree of instability. Because there is less variation in CO_2 emissions than there is in method effect, CO_2 emissions are far steadier. Additionally, there are far higher variances in technical innovation (TECH), scale impact, and trade openness (OPEN). The Jarque–Bera statistics also demonstrates the non-normal distribution of our data series. Our evidence confirms the nonlinearity of the variables in our dataset, and the choice of the QARDL model in this study is supported by this evidence.

Order of integration of the respective variables

All variables that are nonstationary at the level become stationary at I(1) after the first differencing, according to the findings of Table 4' from the DF-GLS, PP, ADF, and KPSS tests. This suggests that none of the series under consideration are I(2) and that all are either I(1) or I(0). The conventional unit root tests mentioned above do not consider structural breaks. Therefore, a testing technique that may consider two structural breakdowns in the variables is used in this work. In the right-hand panel of Table 3, the outcomes of the Narayan and Popp unit root test with two structural breaks are also presented. The empirical data demonstrate that the variables are stationary in the presence of structural breaks. All data series are therefore integrated into order one.

Quantile co-integration test results

To support the cointegration connection between the variables under consideration, this research applies the quantile co-integration technique suggested by Xiao (2009). The fallouts of the quantile co-integration for the variables being studied are shown in Table 5. These findings show the supremum ordinary measures of β and γ coefficients and CV10, CV5, and CV1 of a measurably significant level at 10%, 5%, and 1%, respectively. We reject the null hypothesis because the supremum measures of β and γ values are larger than all the CVs at various significance levels of 10%, 5%, and 1%. Therefore, cointegration between the variables under discussion is supported by our empirical results.

Quantile autoregressive distributed lag model results

Table 6 presents the QARDL model's findings. The speed of adjustment is captured by the parameter ρ^* corresponding to the error correction term (ECT). In quantiles (from 0.10 to 0.60), its calculated coefficient is statistically significant and negative, demonstrating a long-term equilibrium reversal between InSE, InTE, InTECH, InEC, InFDI, InOPEN, InIGDP, and $InCO_2$. For instance, the ECT projected value of −0.741 in the 10th quantile indicates that 74 percent of the disequilibrium is likely to be rectified over time. Table 6 demonstrates how, from the 0.40 to 0.95 quantile, the scale effect (InSE) and technique effect (InTE) have positive and negative effects on CO_2 emissions, respectively. While the technique impact has a mitigating influence on the environment, the scale effect of economic expansion results in a decline in environmental quality. The EKC hypothesis is supported by our empirical data, at least in the instance of South Africa. This empirical evidence agrees with Destek et al. (2020), who used time-varying cointegration and a bootstrap-rolling window estimation approach to re-examine the time-varying effects of economic growth on carbon emissions in the G7 countries over a long history (historical data spanning the period from the 1800s to 2010 as constructed). The investigators found that only pre-1973 data from France, Italy, and the USA support an inverted U-shaped pattern. The authors showed that by analyzing variations in the environmental impact of this expansion from year to year, this empirical evidence gave fresh insights to policymakers on how to enhance environmental quality using economic growth as an economic instrument for the long term. This empirical finding is also supported by Lau et al. (2014) and Shahbaz et al. (2012b).

From quantiles 0.30 to 0.95, the long-run predicted coefficient on technological innovation is statistically significant and negative. Our empirical research demonstrates that, over the long term, a 1% increase in technological innovation results in a 0.31% reduction in CO_2 emissions (from the 0.30th quantile). Technology advancements reduce carbon emissions in South Africa by promoting efficient energy use and producing renewable energy sources at lower costs. Following are some ways that technological innovation benefits South Africa's environment: implementing end-of-pipe technology is essential for reducing carbon emissions, along with using energy-efficient industrial techniques and altering the fuel mix. Through these routes, technological advancements boost energy efficiency, which significantly improves environmental quality. Technology advancements have greatly improved the environmental quality of South Africa, in part due to the country's massive spending on R&D and advances in technology. Additionally, South Africa has implemented several policies aimed at developing strong technologies necessary to minimize the intensity of emissions from production processes and other economic activities linked to high levels of emissions as part of the major key to mitigating the rising levels of carbon emissions. According to Sohag et al. (2015), technical innovation opens up a door for lower energy use, which in turn promotes energy efficiency and significantly lowers carbon emissions. Our conclusion is backed by earlier research, including that of Ahmed et al. (2016) and Yii and Greetha (2017).

From the 0.20th to the 0.80th quantiles, the estimated coefficient over the long run on trade openness (InOPEN) is found to be statistically significant and positive, indicating that a 1% increase in trade openness results in a 0.121% increase in CO_2 emissions (from the 0.20th quantile). The conclusion is backed by Baek et al. (2009), who argued that trade harms developing nations' environments and has significantly worsened them. Our empirical data reveal that long-term access to the global market for commodities does not benefit South Africa's environmental quality. Contrary to the short-term findings, which indicate that trade openness may significantly enhance the nation's environmental quality from the 0.50th to the 0.95th quantiles, unquestionably, the long-term negative impact of openness on South Africa's environmental situation reinforces the opposition to economic liberalization. The majority of a country's exports are made up of certain types of goods, which is one of the potential explanations for why trade openness harms the environment. Because South Africa has a comparative advantage in the export and production of goods that require a lot of natural resources, such as fuelwood, arsenate, canister, base metals, nickel-cobalt mineral deposits, trace elements, molybdenum, valuable minerals, natural gas, chromite, mineral ores, dimes, coal, chromium, gemstones, palladium, and precious metals, an increase in demand for these goods will undoubtedly worsen the country's environmental situation. This is because constant harvesting of them damages the ecology. The empirical results are supported by Shahbaz et al. (2013a), Shahbaz et al. (2013c), Shahbaz et al. (2014a), Shahbaz et al. (2014b), Ngepah and Udeagha (2018), and Ngepah and Udeagha (2019). However, our empirical findings are different from

Destek et al. (2021), who used annual frequency data from 1970 to 2016 and continuously updated fully modified and continuously updated bias-corrected panel estimation techniques that control for cross-section dependence among sampled countries, finding that trade openness reduces both ecological footprint and CO_2 emissions by 0.34–0.55% across the top five biomass energy-consuming countries: Brazil, China, Germany, India, and the US.

In the case of energy consumption (lnEC), the estimated coefficients for the short run (from the 0.05th to 0.70th quantiles) and long run (from the 0.50th to 0.95th quantiles) are statistically significant and positive, indicating that the increasing level of CO_2 emissions in South Africa is significantly exacerbated by the country's energy use. Energy utilization is essential for sustaining output and it promotes economic growth. An increase in energy use results in a rise in CO_2 emissions because producing things requires a significant amount of energy. Ling et al. (2015) and Saboori et al. (2012), who made similar observations using data from Malaysia, bolster our empirical findings.

From the 0.05th to 0.60th quantiles, the short-run estimated coefficient on foreign direct investment (lnFDI) is statistically significant and positive. The calculated long-run coefficient on foreign direct investment, which ranges from quantiles 0.05 to 0.40, is also discovered to be substantial and favorable. Our findings thus imply that an increase in FDI causes environmental deterioration in South Africa. In the case of MENA nations, Abdouli and Hammami (2017) come to the same conclusion that FDI has significantly increased CO_2 emissions and that there is evidence of the pollution haven theory. Similarly, Omri et al. (2014) found that in the case of 54 nations, the level of pollution has increased due to the influx of FDI. However, Destek and Okumus (2019), who examined the pollution haven hypothesis' applicability for the years 1982–2013 in ten newly industrialized nations, observed that the significant signs of the coefficients of FDI and the square of FDI are opposite. As a result, the validity of both the pollution haven hypothesis and the pollution halo hypothesis is thoroughly debunked, and the U-shaped relationship between FDI and ecological footprint is maintained. According to the authors' empirical findings, environmental deterioration decreases up to a certain point with increased FDI, but after that point, environmental degradation grows with increased FDI. In the case of individual country results, the findings revealed that in Brazil, China, Malaysia, Thailand, and Turkey, the sign of the coefficient of FDI is negative and the sign of the coefficient of the square of FDI is positive. Therefore, it is discovered in these nations that there is a U-shaped link between FDI and ecological footprint. Similarly, in the case of BRICS and Next Eleven countries, the Shahbaz et al. (2018) study of the key interactions between foreign capital, financial development, and environmental deterioration over the period 1992–2016 found that economic expansion promotes clean EC, whereas financial development decreases it. On the contrary, it does not seem that foreign capital inflows have a statistically significant impact on renewable energy. The authors made the case that while financial development, economic expansion, and foreign capital inflows all lead to an increase in CO_2 emissions, the BRICS nations' use of sustainable energy prevents environmental damage by reducing carbon emissions. Empirical findings further showed that economic growth and foreign investment had a positive impact on the use of clean energy in the Next Eleven nations. However, CO_2 emissions in the Next Eleven nations rose as a result of economic and financial progress.

The long-run estimated coefficient on industrial value-added (lnIGDP) is statistically significant and positive from quantiles 0.40 to 0.95 showing that industrial sector growth significantly contributes to the deterioration of South Africa's environment in the long run. Our findings are supported by the results of Udeagha and Ngepah (2021) and Sohag et al. (2017). However, Destek (2021), who investigated how structural changes affected environmental deterioration in Turkey from 1970 to 2017, revealed that deindustrialization reduces carbon emissions but has little-to-no effect on ecological footprint. The authors also found that although industrialization and reindustrialization result in a decline in environmental quality, reindustrialization can be less environmentally detrimental due to technological developments.

This study further applies the structural stability evaluation of the model to validate its robustness and its dynamic stability. To this end, this study uses the Wald test to examine the constancy (linearity) of parameters approximated as presented in Table 7. Our results show that the null hypothesis for parameter constancy for the speed of adjustment parameter is rejected at a 1% significance level. Moreover, our empirical results reject the null hypothesis of linearity across different tails of every quantile for long-term parameters lnSE, lnTE, lnTECH, lnEC, lnFDI, and lnOPEN, except for lnIGDP. As a result, this evidence validates the presence of asymmetric long-run relationships between these variables and $lnCO_2$ in South Africa, and the study concludes that long-term parameters are dynamic in various quantiles. Additionally, Table 7 shows that the null of linearity for the short-term cumulative impact of previous levels of lnSE, lnTE, lnTECH, lnEC, and lnOPEN is rejected by the Wald test, except for lnFDI and lnIGDP. This evidence further suggests that there are asymmetric short-run relationships between these variables and $lnCO_2$ in South Africa.

The FDC test developed by Breitung and Candelon (2006) is also used in this study to investigate the relationship between South Africa's lnSE, lnTE, lnTECH, lnEC, lnFDI, lnOPEN, lnIGDP, and $lnCO_2$. According to Table 8, for frequencies $w_i = 0.05$, $w_i = 1.50$ and $w_i = 2.50$, lnSE, lnTE, lnTECH, lnEC, lnFDI, lnOPEN, and lnIGDP Granger-cause $lnCO_2$ in the short, medium, and long term. This suggests that short-, medium-, and long-term CO_2 emissions in South Africa are considerably impacted by lnSE, lnTE, lnTECH, lnEC, lnFDI, lnOPEN, and lnIGDP. Our empirical data agree with those of Udeagha and Ngepah (2019).

Conclusion and policy implications

This study investigated the asymmetric impact of technological innovation on CO_2 emissions in South Africa between 1960 and 2020 using the recently created QARDL framework by Cho et al. (2015). This framework allows us to evaluate the long-term stability across the quantiles and account for the distributional asymmetry based on the position of CO_2 emissions within its own distribution, making it possible to perform an econometric analysis that is more adaptable than that provided by traditional frameworks. Breitung and Candelon's (2006) robust testing technique, the FDC approach, which enables us to capture permanent causation for the medium, short, and long term among variables under consideration, was utilized to assess robustness. By using an innovative measure of trade openness proposed by Squalli and Wilson (2011) that accounts for trade share in GDP and the magnitude of trade relative to global trade for South Africa, this study made an additional contribution to the empirical literature. We employed the unit root tests: KPSS, ADF, PP, and DF-GLS. Additionally, the Narayan and Popp structural break unit root test was employed because empirical data demonstrate that the structural breakdowns are persistent in the sense that they have an impact on several macroeconomic variables, including CO_2 emissions and technological innovation. The data series was integrated into order one, or I(1), according to our empirical evidence from all the tests, and there was no indication of any I(2). In order to determine the ideal lag length, SBIC was used. Our empirical findings for South Africa showed that while an increase in method impact is ecologically beneficial, an increase in scale effect worsens the environmental state. As a result, this evidence supported the EKC theory for South Africa. Environmental quality is harmed by trade openness, FDI, industry value addition, and energy use. Our results confirmed the presence of asymmetric long-run relationships between the scale effect, technique effect, technological innovation, energy consumption, FDI, trade openness, and CO_2 emissions. The FDC results also showed that in the medium, long, and short terms, the scale effect, technique effect, technological innovation, energy consumption, FDI, trade openness, and industrial value-added Granger cause CO_2 emissions, indicating the significance of these variables in influencing CO_2 emissions in South Africa.

Moreover, with regard to the relationship between technological innovation and CO_2 emissions, our empirical results showed that in the short and long term, an upsurge in technological innovation improves environmental quality by reducing CO_2 emissions in South Africa. Our findings are consistent with the results of Sohag et al. (2015), who have shown that technological innovations create a mechanism that helps reduce energy consumption, thus allowing energy efficiency to significantly improve environmental quality. In South Africa, technological innovations and development have significantly led to a reduction in CO_2 emissions in the following ways: 1) the development of end-to-end pipeline technologies that are important in reducing carbon emissions, 2) the use of energy-efficient production technologies, and 3) changes in fuel mixing and transformation of oil mixtures. Technological innovation *via* all these channels increases energy efficiency, which greatly reduces carbon emissions in the country. More importantly, South Africa's significant investment in R&D and technological change are some of the reasons why technological advances have made a significant contribution to improving the country's environment. Moreover, as part of a major key to addressing environmental degradation, the country has adopted several policies to develop strong technologies that are critical to minimizing the intensity of emissions from manufacturing processes and other economic activities that involve high emissions.

On the basis of our findings, the following recommendations for policy are made: first, in order to improve environmental quality, South Africa should support economic policies that encourage innovation and investment in energy-efficient machinery and appliances and capital investment in energy-efficient technologies and the use of hydroelectricity, solar, water, wind, and other clean energy sources (Udeagha and Breitenbach, 2022). South Africa should take steps to limit energy usage and promote renewable energy sources, which would lessen the intensity of fossil fuel-based energy consumption, in order to fully support economic growth.

Second, the government should strengthen its regulations in order to improve the environment. The long-term detrimental impact of trade openness on the nation's environment, however, does not justify ongoing actions to restrict the borders because of certain benefits to South Africa's economy. Instead, proper measures should be made to ensure that international commerce significantly lowers South Africa's growing carbon emissions. In this regard, South Africa's policymakers should step up efforts to adopt cutting-edge, environmentally friendly, and non-polluting technologies that could help the country make the transition from non-renewable to sustainable, consume less carbon-intensive energy sources, and guarantee the competence of its manufacturing processes. Meanwhile, alternative energy sources such as solar power will take the place of non-renewable energy sources, which produce roughly 90% of the nation's energy (Udeagha and Ngepah, 2022c). Furthermore, in order to address the growing transnational environmental degradation as well as other knock-on consequences, international cooperation in climate change mitigation is required. In this sense, the South African government should make efforts to forge significant ties with the rest of the globe, particularly to exchange technology and lessen pollution. In order to promote the transition to environmentally friendly industries and a low-carbon economy, which encourages the creation of sustainable goods and services, South African authorities should, more crucially, include chapters on pollution avoidance in their trade deal policies. To further stimulate long-term value for GHG emission reductions and consistently support the development of innovative technologies that improve South Africa's environmental position and safeguard the global environment, trade policy may be supplemented with additional policies.

Third, South Africa's energy plans should incorporate renewable sources as an attractive alternative to reduce CO_2 emissions. The use of renewable energy has recently received a strong economic promotion in South Africa. However, the nation still does not use enough renewable energy. More than 80% of South Africa's entire primary energy supply comes from fossil fuels (Udeagha and Ngepah, 2022d). Even if the use of fossil fuels is decreasing, this proportion is still substantial. The study's findings showed that a 1% increase in NREC increased environmental degradation by 0.42%, whereas REC decreased emissions by 0.35%. Increased energy usage in South Africa is a result of the growing human effect on the environment. This highlights how crucial it is to switch out NREC with renewable energy sources and promote sustainable energy sources *via* green technology. Despite recent major financial assistance from South Africa for the development of alternative energy sources, total energy use still pollutes the environment. In light of this, the government should enhance its management of natural resources by boosting the proportion of renewable energy in the total energy mix. The nation should also increase tax exemptions for businesses that use clean energy, reinforce incentives for low-carbon energy consumption, and boost energy efficiency and reduce energy intensity. South Africa should provide further assistance to businesses engaged in R&D to reduce the cost of implementing renewable energy sources.

Lastly, as an additional step, South Africa's government could support the expansion of companies that produce energy-saving technology by offering low-interest funding to firms that want to use it in their production processes. The use of tax breaks or other non-price incentives that do not affect the price of fossil fuels can be utilized to promote energy efficiency. Additional incentives, tax breaks, and assistance should be provided to ecologically friendly energy sources in order to move the energy structure away from fossil fuels. In order for alternative energy sources to compete with non-renewable ones, they should receive more attention. Innovations in energy storage technology should be seen as a vital policy tool and managed alongside renewable energy programs. The potential importance of energy technology in reducing GHGs must also be highlighted. To reduce the social costs of utilizing fossil fuels, energy policy should concentrate on energy advancements.

Although the current work has yielded significant useful findings and important policy recommendations in the case of South Africa, one of the major limitations of this work is the use of CO_2 emissions as the only environmental quality. Therefore, further research should examine other environmental quality proxies such as ecological footprint, sulfur dioxide emissions, nitrogen oxide emissions, and organic water pollutants to gain a better understanding of broader coverage.

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

MU and NN conceptualized the study idea, drafted the paper, collected data, analyzed data, wrote the introduction section, organized the literature review, drafted the methodology section, interpreted the results, provided the discussions, concluded the study with policy implications, and organized the reference list.

Conflict of interest

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abdouli, M., and Hammami, S. (2017). Investigating the causality links between environmental quality, foreign direct investment and economic growth in MENA countries. *Int. Bus. Rev.* 26 (2), 264–278. doi:10.1016/j.ibusrev.2016.07.004

Abid, A., Mehmood, U., Tariq, S., and Haq, Z. U. (2022). The effect of technological innovation, FDI, and financial development on CO_2 emission: Evidence from the G8 countries. *Environ. Sci. Pollut. Res.* 29 (8), 11654–11662. doi:10.1007/s11356-021-15993-x

Adebayo, T. S., and Odugbesan, J. A. (2021). Modeling CO_2 emissions in South Africa: Empirical evidence from ARDL based bounds and wavelet coherence techniques. *Environ. Sci. Pollut. Res.* 28 (8), 9377–9389. doi:10.1007/s11356-020-11442-3

Adebayo, T. S., Oladipupo, S. D., Adeshola, I., and Rjoub, H. (2022). Wavelet analysis of impact of renewable energy consumption and technological innovation on CO_2 emissions: Evidence from Portugal. *Environ. Sci. Pollut. Res.* 29 (16), 23887–23904. doi:10.1007/s11356-021-17708-8

African Development Bank Group (2019). South Africa economic outlook. Available at: https://www.afdb.org/en/countries/southern-africa/south-africa/south-africa-econ omic-outlook.

Ahmad, M., and Raza, M. Y. (2020). Role of public-private partnerships investment in energy and technological innovations in driving climate change: Evidence from Brazil. *Environ. Sci. Pollut. Res.* 27 (24), 30638–30648. doi:10.1007/s11356-020-09307-w

Ahmed, A., Uddin, G. S., and Sohag, K. (2016). Biomass energy, technological progress and the environmental Kuznets curve: Evidence from selected European countries. *Biomass Bioenergy* 90, 202–208. doi:10.1016/j.biombioe.2016.04.004

Anser, M. K., Ahmad, M., Khan, M. A., Zaman, K., Nassani, A. A., Askar, S. E., et al. (2021). The role of information and communication technologies in mitigating carbon emissions: Evidence from panel quantile regression. *Environ. Sci. Pollut. Res.* 28 (17), 21065–21084. doi:10.1007/s11356-020-12114-y

Atsu, F., Adams, S., and Adjei, J. (2021). ICT, energy consumption, financial development, and environmental degradation in South Africa. *Heliyon* 7 (7), e07328. doi:10.1016/j.heliyon.2021.e07328

Altinoz, B., Apergis, N., and Aslan, A. (2020). Energy consumption, carbon dioxide emissions and economic growth: Fresh evidence from panel quantile regressions. *Energy Res. Lett.* 1 (3), 17075. doi:10.46557/001c.17075

Álvarez-Herránz, A., Balsalobre, D., Cantos, J. M., and Shahbaz, M. (2017). Energy innovations-GHG emissions nexus: Fresh empirical evidence from OECD countries. *Energy Policy* 101, 90–100. doi:10.1016/j.enpol.2016.11.030

Arshad, Z., Robaina, M., and Botelho, A. (2020). The role of ICT in energy consumption and environment: An empirical investigation of Asian economies with cluster analysis. *Environ. Sci. Pollut. Res.* 27 (26), 32913–32932. doi:10.1007/s11356-020-09229-7

Asongu, S. A. (2018). ICT, openness and CO_2 emissions in Africa. *Environ. Sci. Pollut. Res.* 25 (10), 9351–9359. doi:10.1007/s11356-018-1239-4

Awaworyi Churchill, S. A., Inekwe, J., Smyth, R., and Zhang, X. (2019). R&D intensity and carbon emissions in the G7: 1870–2014. *Energy Econ.* 80, 30–37. doi:10.1016/j.eneco.2018.12.020

Azevedo, V. G., Sartori, S., and Campos, L. M. (2018). CO_2 emissions: A quantitative analysis among the BRICS nations. *Renew. Sustain. Energy Rev.* 81, 107–115. doi:10.1016/j.rser.2017.07.027

Baek, J., Cho, Y., and Koo, W. W. (2009). The environmental consequences of globalization: A country-specific time-series analysis. *Ecol. Econ.* 68 (8-9), 2255–2264. doi:10.1016/j.ecolecon.2009.02.021

Bales, K., and Sovacool, B. K. (2021). From forests to factories: How modern slavery deepens the crisis of climate change. *Energy Res. Soc. Sci.* 77, 102096. doi:10.1016/j.erss.2021.102096

Baloch, M. A., Khan, S. U. D., Ulucak, Z. Ş., and Ahmad, A. (2020). Analyzing the relationship between poverty, income inequality, and CO_2 emission in Sub-Saharan African countries. *Sci. Total Environ.* 740, 139867. doi:10.1016/j.scitotenv.2020.139867

Balsa-Barreiro, J., Li, Y., Morales, A., and Pentland, A. S. (2019). Globalization and the shifting centers of gravity of world's human dynamics: Implications for sustainability. *J. Clean. Prod.* 239, 117923. doi:10.1016/j.jclepro.2019.117923

Bayer, C., and Hanck, C. (2013). Combining non-cointegration tests. *J. Time Ser. analysis* 34 (1), 83–95. doi:10.1111/j.1467-9892.2012.00814.x

Bekun, F. V., Emir, F., and Sarkodie, S. A. (2019). Another look at the relationship between energy consumption, carbon dioxide emissions, and economic growth in South Africa. *Sci. Total Environ.* 655, 759–765. doi:10.1016/j.scitotenv.2018.11.271

Berg, A., and Krueger, A. O. (2003). "Trade, growth, and poverty: A selective survey," in *Annual world bank conference on development economics 2003: The new reform agenda* (Washington, DC: World Bank), 1047.

Brandão Santana, N., Rebelatto, D. A. D. N., Périco, A. E., Moralles, H. F., and Leal Filho, W. (2015). Technological innovation for sustainable development: An analysis of different types of impacts for countries in the BRICS and G7 groups. *Int. J. Sustain. Dev. World Ecol.* 22 (5), 425–436. doi:10.1080/13504509.2015.1069766

Breitung, J., and Candelon, B. (2006). Testing for short-and long-run causality: A frequency-domain approach. *J. Econ.* 132 (2), 363–378. doi:10.1016/j.jeconom.2005.02.004

Chen, Y., Yao, Z., and Zhong, K. (2022). Do environmental regulations of carbon emissions and air pollution foster green technology innovation: Evidence from China's prefecture-level cities. *J. Clean. Prod.* 350, 131537. doi:10.1016/j.jclepro.2022.131537

Chhabra, M., Giri, A. K., and Kumar, A. (2022). Do technological innovations and trade openness reduce CO_2 emissions? Evidence from selected middle-income countries. *Environ. Sci. Pollut. Res.* 29, 65723–65738. doi:10.1007/s11356-022-20434-4

Cho, J. S., Kim, T.-H., and Shin, Y. (2015). Quantile cointegration in the autoregressive distributed-lag modeling framework. *J. Econ.* 188, 281–300. doi:10.1016/j.jeconom.2015.05.003

Cole, M. A., and Elliott, R. J. (2003). Determining the trade–environment composition effect: The role of capital, labor and environmental regulations. *J. Environ. Econ. Manag.* 46 (3), 363–383. doi:10.1016/s0095-0696(03)00021-4

Das, A., and Paul, B. P. (2011). Openness and growth in emerging Asian economies: Evidence from GMM estimations of a dynamic panel. *Econ. Bull.* 31, 2219–2228.

Dauda, L., Long, X., Mensah, C. N., Salman, M., Boamah, K. B., Ampon-Wireko, S., et al. (2021). Innovation, trade openness and CO_2 emissions in selected countries in Africa. *J. Clean. Prod.* 281, 125143. doi:10.1016/j.jclepro.2020.125143

Demir, C., Cergibozan, R., and Ari, A. (2020). Environmental dimension of innovation: Time series evidence from Turkey. *Environ. Dev. Sustain.* 22 (3), 2497–2516. doi:10.1007/s10668-018-00305-0

Destek, M. A. (2021). Deindustrialization, reindustrialization and environmental degradation: Evidence from ecological footprint of Turkey. *J. Clean. Prod.* 296, 126612. doi:10.1016/j.jclepro.2021.126612

Destek, M. A., and Manga, M. (2021). Technological innovation, financialization, and ecological footprint: Evidence from BEM economies. *Environ. Sci. Pollut. Res.* 28 (17), 21991–22001. doi:10.1007/s11356-020-11845-2

Destek, M. A., and Okumus, I. (2019). Does pollution haven hypothesis hold in newly industrialized countries? Evidence from ecological footprint. *Environ. Sci. Pollut. Res.* 26 (23), 23689–23695. doi:10.1007/s11356-019-05614-z

Destek, M. A., Sarkodie, S. A., and Asamoah, E. F. (2021). Does biomass energy drive environmental sustainability? An SDG perspective for top five biomass consuming countries. *Biomass Bioenergy* 149, 106076. doi:10.1016/j.biombioe.2021.106076

Destek, M. A., Shahbaz, M., Okumus, I., Hammoudeh, S., and Sinha, A. (2020). The relationship between economic growth and carbon emissions in G-7 countries: Evidence from time-varying parameters with a long history. *Environ. Sci. Pollut. Res.* 27 (23), 29100–29117. doi:10.1007/s11356-020-09189-y

Dinda, S. (2018). Production technology and carbon emission: Long-run relation with short-run dynamics. *J. Appl. Econ.* 21 (1), 106–121. doi:10.1080/15140326.2018.1526871

Energy Information Administration (EIA) (2010). *Energy statistics for countries*. Washington, DC: U.S. Department of Energy Office of Scientific and Technical Information.

Enevoldsen, M. K., Ryelund, A. V., and Andersen, M. S. (2007). Decoupling of industrial energy consumption and CO_2-emissions in energy-intensive industries in scandinavia. *Energy Econ.* 29 (4), 665–692. doi:10.1016/j.eneco.2007.01.016

Erdogan, S. (2021). Dynamic nexus between technological innovation and building sector carbon emissions in the BRICS countries. *J. Environ. Manag.* 293, 112780. doi:10.1016/j.jenvman.2021.112780

Faisal, S. M., and Idris, S. (2020). Innovation factors influencing the supply chain technology (SCT) adoption: Diffusion of innovation theory. *Int. J. Soc. Sci. Res.* 2 (2), 128–145.

Fine, B., and Rustomjee, Z. (1996). *The political economy of South Africa: From Minerals-energy complex to industrialisation*. London: Hurst.

Fisher-Vanden, K., Jefferson, G. H., Liu, H., and Tao, Q. (2004). What is driving China's decline in energy intensity? *Resour. Energy Econ.* 26 (1), 77–97. doi:10.1016/j.reseneeco.2003.07.002

Godil, D. I., Sharif, A., Rafique, S., and Jermsittiparsert, K. (2020). The asymmetric effect of tourism, financial development, and globalization on ecological footprint in Turkey. *Environ. Sci. Pollut. Res.* 27 (32), 40109–40120. doi:10.1007/s11356-020-09299-7

Grether, J. M., and Mathys, N. (2009). How fast are CO_2 emissions moving to Asia? Vox CEPR policy portal. AvaliableAt: https://voxeu.org/article/global-distribution-carbonemissions (Accessed June 9, 2019).

Gu, G., Zheng, H., Tong, L., and Dai, Y. (2022). Does carbon financial market as an environmental regulation policy tool promote regional energy conservation and emission reduction? Empirical evidence from China. *Energy Policy* 163, 112826. doi:10.1016/j.enpol.2022.112826

Guo, J., Zhou, Y., Ali, S., Shahzad, U., and Cui, L. (2021). Exploring the role of green innovation and investment in energy for environmental quality: An empirical appraisal from provincial data of China. *J. Environ. Manag.* 292, 112779. doi:10.1016/j.jenvman.2021.112779

Habiba, U. M. M. E., Xinbang, C., and Anwar, A. (2022). Do green technology innovations, financial development, and renewable energy use help to curb carbon emissions? *Renew. Energy* 193, 1082–1093. doi:10.1016/j.renene.2022.05.084

Hang, L., and Tu, M. (2007). The impacts of energy prices on energy intensity: Evidence from China. *Energy policy* 35 (5), 2978–2988. doi:10.1016/j.enpol.2006.10.022

Haseeb, A., Xia, E., Saud, S., Ahmad, A., and Khurshid, H. (2019). Does information and communication technologies improve environmental quality in the era of globalization? An empirical analysis. *Environ. Sci. Pollut. Res.* 26 (9), 8594–8608. doi:10.1007/s11356-019-04296-x

Hassan, T., Khan, Y., He, C., Chen, J., Alsagr, N., Song, H., et al. (2022). Environmental regulations, political risk and consumption-based carbon emissions: Evidence from OECD economies. *J. Environ. Manag.* 320, 115893. doi:10.1016/j.jenvman.2022.115893

Ibrahiem, D. M. (2020). Do technological innovations and financial development improve environmental quality in Egypt? *Environ. Sci. Pollut. Res.* 27 (10), 10869–10881. doi:10.1007/s11356-019-07585-7

Ibrahim, M., and Vo, X. V. (2021). Exploring the relationships among innovation, financial sector development and environmental pollution in selected industrialized countries. *J. Environ. Manag.* 284, 112057. doi:10.1016/j.jenvman.2021.112057

IPCC (2018). "Summary for policymakers," in *Global warming of 1.5 ∘ c. An IPCC special report on the impacts of global warming of 1.5 ∘ c above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Eds. V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, et al. (Geneva, Switzerland: World Meteorological Organization), 32.

IRENA (2021). *Renewable power generation costs in 2020*. Abu Dhabi: International Renewable Energy Agency.

Jiahua, P., Guiyang, Z., Yan, Z., ShouXian, Z., and Qianyi, X. (2010). Clarification of the concept of low-carbon economy and analysis of its core elements [J]. *Int. Econ. Rev.* 4, 88–102.

Jin, P., Peng, C., and Song, M. (2019). Macroeconomic uncertainty, high-level innovation, and urban green development performance in China. *China Econ. Rev.* 55, 1–18. doi:10.1016/j.chieco.2019.02.008

Joshua, U., and Bekun, F. V. (2020). The path to achieving environmental sustainability in South Africa: The role of coal consumption, economic expansion, pollutant emission, and total natural resources rent. *Environ. Sci. Pollut. Res.* 27 (9), 9435–9443. doi:10.1007/s11356-019-07546-0

Khalfaoui, R., Stef, N., Wissal, B. A., and Sami, B. J. (2022). Dynamic spillover effects and connectedness among climate change, technological innovation, and uncertainty: Evidence from a quantile VAR network and wavelet coherence. *Technol. Forecast. Soc. Change* 181, 121743. doi:10.1016/j.techfore.2022.121743

Khan, Z., Ali, M., Kirikkaleli, D., Wahab, S., and Jiao, Z. (2020a). The impact of technological innovation and public-private partnership investment on sustainable environment in China: Consumption-based carbon emissions analysis. *Sustain. Dev.* 28 (5), 1317–1330. doi:10.1002/sd.2086

Khan, Z., Ali, S., Umar, M., Kirikkaleli, D., and Jiao, Z. (2020b). Consumption-based carbon emissions and international trade in G7 countries: The role of environmental innovation and renewable energy. *Sci. Total Environ.* 730, 138945. doi:10.1016/j.scitotenv.2020.138945

Khattak, S. I., Ahmad, M., Khan, Z. U., and Khan, A. (2020). Exploring the impact of innovation, renewable energy consumption, and income on CO_2 emissions: New evidence from the BRICS economies. *Environ. Sci. Pollut. Res.* 27 (12), 13866–13881. doi:10.1007/s11356-020-07876-4

Kim, T. H., and White, H. (2003). "Estimation, inference, and specification testing for possibly misspecified quantile regression," in *Maximum likelihood estimation of misspecified models: Twenty years later* (Bradford, United Kingdom: Emerald Group Publishing Limited).

Kripfganz, S., and Schneider, D. C. (2018). Ardl: Estimating autoregressive distributed lag and equilibrium correction models. Avaliable at: www.stata.com/meeting/uk18/slides/uk18_Kripfganz.pdf.

Kuang, H., Akmal, Z., and Li, F. (2022). Measuring the effects of green technology innovations and renewable energy investment for reducing carbon emissions in China. *Renew. Energy* 197, 1–10. doi:10.1016/j.renene.2022.06.091

Lau, L. S., Choong, C. K., and Eng, Y. K. (2014). Carbon dioxide emission, institutional quality, and economic growth: Empirical evidence in Malaysia. *Renew. Energy* 68, 276–281. doi:10.1016/j.renene.2014.02.013

Li, Y., Zhang, C., Li, S., and Usman, A. (2022). Energy efficiency and green innovation and its asymmetric impact on CO_2 emission in China: A new perspective. *Environ. Sci. Pollut. Res.* 29, 47810–47817. doi:10.1007/s11356-022-19161-7

Lin, B., and Ma, R. (2022). Green technology innovations, urban innovation environment and CO_2 emission reduction in China: Fresh evidence from a partially linear functional-coefficient panel model. *Technol. Forecast. Soc. Change* 176, 121434. doi:10.1016/j.techfore.2021.121434

Ling, C. H., Ahmed, K., Muhamad, R. B., and Shahbaz, M. (2015). Decomposing the trade-environment nexus for Malaysia: What do the technique, scale, composition, and comparative advantage effect indicate? *Environ. Sci. Pollut. Res.* 22 (24), 20131–20142. doi:10.1007/s11356-015-5217-9

Liu, C., Xin, L., and Li, J. (2022). Environmental regulation and manufacturing carbon emissions in China: A new perspective on local government competition. *Environ. Sci. Pollut. Res.* 29 (24), 36351–36375. doi:10.1007/s11356-021-18041-w

Long, X., Chen, Y., Du, J., Oh, K., and Han, I. (2017). Environmental innovation and its impact on economic and environmental performance: Evidence from Korean-owned firms in China. *Energy Policy* 107, 131–137. doi:10.1016/j.enpol.2017.04.044

MacKinnon, J. G. (1996). Numerical distribution functions for unit root and cointegration tests. *J. Appl. Econ. Chichester. Engl.* 11 (6), 601–618. doi:10.1002/(sici)1099-1255(199611)11:6<601::aid-jae417>3.0.co;2-t

Mensah, C. N., Long, X., Boamah, K. B., Bediako, I. A., Dauda, L., and Salman, M. (2018). The effect of innovation on CO_2 emissions of OCED countries from 1990 to 2014. *Environ. Sci. Pollut. Res.* 25 (29), 29678–29698. doi:10.1007/s11356-018-2968-0

Ngepah, N., and Udeagha, M. C. (2018). African regional trade agreements and intra-African trade. *J. Econ. Integration* 33 (1), 1176–1199. doi:10.11130/jei.2018.33.1.1176

Ngepah, N., and Udeagha, M. C. (2019). Supplementary trade benefits of multi-memberships in African regional trade agreements. *J. Afr. Bus.* 20 (4), 505–524. doi:10.1080/15228916.2019.1584719

Ngo, T. Q. (2022). How do environmental regulations affect carbon emission and energy efficiency patterns? A provincial-level analysis of Chinese energy-intensive industries. *Environ. Sci. Pollut. Res.* 29 (3), 3446–3462. doi:10.1007/s11356-021-15843-w

Obobisa, E. S., Chen, H., and Mensah, I. A. (2022). The impact of green technological innovation and institutional quality on CO_2 emissions in African countries. *Technol. Forecast. Soc. Change* 180, 121670. doi:10.1016/j.techfore.2022.121670

OECD (2002). *Indicators to measure decoupling of environmental pressures from economic growth*. Paris: OECD.

Omri, A., Nguyen, D. K., and Rault, C. (2014). Causal interactions between CO_2 emissions, FDI, and economic growth: Evidence from dynamic simultaneous-equation models. *Econ. Model.* 42, 382–389. doi:10.1016/j.econmod.2014.07.026

Ozcan, B., and Apergis, N. (2018). The impact ofinternet use on air pollution: Evidence from emerging countries. *Environ. Sci. Pollut. Res.* 25 (5), 4174–4189. doi:10.1007/s11356-017-0825-1

Pathak, L., and Shah, K. (2019). Renewable energy resources, policies and gaps in BRICS countries and the global impact. *Front. Energy* 13, 506–521. doi:10.1007/s11708-018-0601-z

Pesaran, M. H., Shin, Y., and Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *J. Appl. Econ. Chichester. Engl.* 16 (3), 289–326. doi:10.1002/jae.616

Rafique, M. Z., Schneider, N., Shahzad, U., and Song, M. (2022). *High-tech industries, financial expansion, and low-carbon energy deployment along the Belt and Road Initiative*. New York, United States: John Wiley & Sons, Inc.

Rahman, M. M., Alam, K., and Velayutham, E. (2022). Reduction of CO_2 emissions: The role of renewable energy, technological innovation and export quality. *Energy Rep.* 8, 2793–2805. doi:10.1016/j.egyr.2022.01.200

Razzaq, A., An, H., and Delpachitra, S. (2021). Does technology gap increase FDI spillovers on productivity growth? Evidence from Chinese outward FDI in Belt and Road host countries. *Technol. Forecast. Soc. Change* 172, 121050. doi:10.1016/j.techfore.2021.121050

Roman-Collado, R., Cansino, J. M., and Botia, C. (2018). How far is Colombia from decoupling? Two-level decomposition analysis of energy consumption changes. *Energy* 148, 687–700. doi:10.1016/j.energy.2018.01.141

Saboori, B., Sulaiman, J., and Mohd, S. (2012). Economic growth and CO_2 emissions in Malaysia: A cointegration analysis of the environmental Kuznets curve. *Energy policy* 51, 184–191. doi:10.1016/j.enpol.2012.08.065

Santra, S. (2017). The effect of technological innovation on production-based energy and CO_2 emission productivity: Evidence from BRICS countries. *Afr. J. Sci. Technol. Innovation Dev.* 9 (5), 503–512. doi:10.1080/20421338.2017.1308069

Shahbaz, M., Khan, S., and Tahir, M. I. (2013a). The dynamic links between energy consumption, economic growth, financial development and trade in China: Fresh evidence from multivariate framework analysis. *Energy Econ.* 40, 8–21. doi:10.1016/j.eneco.2013.06.006

Shahbaz, M., Destek, M. A., and Polemis, M. L. (2018). Do foreign capital and financial development affect clean energy consumption and carbon emissions? Evidence from BRICS and next-11 countries. *SPOUDAI-Journal Econ. Bus.* 68 (4), 20–50.

Shahbaz, M., Khraief, N., Uddin, G. S., and Ozturk, I. (2014a). Environmental Kuznets curve in an open economy: A bounds testing and causality analysis for Tunisia. *Renew. Sustain. Energy Rev.* 34, 325–336. doi:10.1016/j.rser.2014.03.022

Shahbaz, M., Lean, H. H., and Shabbir, M. S. (2012b). Environmental Kuznets curve hypothesis in Pakistan: Cointegration and granger causality. *Renew. Sustain. Energy Rev.* 16 (5), 2947–2953. doi:10.1016/j.rser.2012.02.015

Shahbaz, M., Sbia, R., Hamdi, H., and Ozturk, I. (2014b). Economic growth, electricity consumption, urbanization and environmental degradation relationship in United Arab Emirates. *Ecol. Indic.* 45, 622–631. doi:10.1016/j.ecolind.2014.05.022

Shahbaz, M., Tiwari, A. K., and Nasir, M. (2013c). The effects of financial development, economic growth, coal consumption and trade openness on CO_2 emissions in South Africa. *Energy Policy* 61, 1452–1459. doi:10.1016/j.enpol.2013.07.006

Shan, S., Genç, S. Y., Kamran, H. W., and Dinca, G. (2021). Role of green technology innovation and renewable energy in carbon neutrality: A sustainable investigation from Turkey. *J. Environ. Manag.* 294, 113004. doi:10.1016/j.jenvman.2021.113004

Sohag, K., Al Mamun, M., Uddin, G. S., and Ahmed, A. M. (2017). Sectoral output, energy use, and CO_2 emission in middle-income countries. *Environ. Sci. Pollut. Res.* 24 (10), 9754–9764. doi:10.1007/s11356-017-8599-z

Sohag, K., Begum, R. A., Abdullah, S. M. S., and Jaafar, M. (2015). Dynamics of energy use, technological innovation, economic growth and trade openness in Malaysia. *Energy* 90, 1497–1507. doi:10.1016/j.energy.2015.06.101

Sovacool, B. K. (2021). Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation. *Energy Res. Soc. Sci.* 73, 101916. doi:10.1016/j.erss.2021.101916

Squalli, J., and Wilson, K. (2011). A new measure of trade openness. *World Econ.* 34 (10), 1745–1770. doi:10.1111/j.1467-9701.2011.01404.x

Statistics South Africa (2019). Economic growth. Available at: http://www.statssa.gov.za/ ?page_id=735&id=1.

Szigeti, C., Toth, G., and Szabo, D. R. (2017). Decoupling–shifts in ecological footprint intensity of nations in the last decade. *Ecol. Indic.* 72, 111–117. doi:10.1016/j.ecolind.2016.07.034

Tapio, P. (2005). Towards a theory of decoupling: Degrees of decoupling in the EU and the case of Road traffic in Finland between 1970 and 2001. *Transp. Policy* 12 (2), 137–151. doi:10.1016/j.tranpol.2005.01.001

Töbelmann, D., and Wendler, T. (2020). The impact of environmental innovation on carbon dioxide emissions. *J. Clean. Prod.* 244, 118787. doi:10.1016/j.jclepro.2019.118787

Udeagha, M. C., and Breitenbach, M. C. (2021). Estimating the trade-environmental quality relationship in SADC with a dynamic heterogeneous panel model. *Afr. Rev. Econ. Finance* 13 (1), 113–165.

Udeagha, M. C., and Breitenbach, M. C. (2022). Exploring the moderating role of financial development in environmental Kuznets curve for South Africa: Fresh evidence from the novel dynamic ARDL simulations approach. *Financ. Innov.* 2022, 1–38. doi:10.1186/s40854-022-00396-9

Udeagha, M. C., and Muchapondwa, E. (2022). Investigating the moderating role of economic policy uncertainty in environmental Kuznets curve for South Africa: Evidence from the novel dynamic ARDL simulations approach. *Environ. Sci. Pollut. Res.* 29, 77199–77237. doi:10.1007/s11356-022-21107-y

Udeagha, M. C., and Ngepah, N. (2022a). Disaggregating the environmental effects of renewable and non-renewable energy consumption in South Africa: Fresh evidence from the novel dynamic ARDL simulations approach. *Econ. Change Restruct.* 55, 1767–1814. doi:10.1007/s10644-021-09368-y

Udeagha, M. C., and Ngepah, N. (2022b). Does trade openness mitigate the environmental degradation in South Africa? *Environ. Sci. Pollut. Res.* 29 (13), 19352–19377. doi:10.1007/s11356-021-17193-z

Udeagha, M. C., and Ngepah, N. (2022c). Dynamic ARDL simulations effects of fiscal decentralization, green technological innovation, trade openness, and institutional quality on environmental sustainability: Evidence from South Africa. *Sustainability* 14, 10268. doi:10.3390/su141610268

Udeagha, M. C., and Ngepah, N. (2019). Revisiting trade and environment nexus in South Africa: Fresh evidence from new measure. *Environ. Sci. Pollut. Res.* 26, 29283–29306. doi:10.1007/s11356-019-05944-y

Udeagha, M. C., and Ngepah, N. (2022d). Striving towards environmental sustainability in the BRICS economies: The combined influence of fiscal decentralization and environmental innovation. *Int. J. Sustain. Dev. World Ecol.* 1, 15. doi:10.1080/13504509.2022.2123411

Udeagha, M. C., and Ngepah, N. (2021a). The asymmetric effect of trade openness on economic growth in South Africa: A nonlinear ARDL approach. *Econ. Change Restruct.* 54 (2), 491–540. doi:10.1007/s10644-020-09285-6

Udeagha, M. C., and Ngepah, N. (2020). Trade liberalization and the geography of industries in South Africa: Fresh evidence from a new measure. *Int. J. Urban Sci.* 24 (3), 354–396. doi:10.1080/12265934.2019.1695652

Udeagha, M. C., and Ngepah, N. N. (2021b). A step towards environmental mitigation in South Africa: Does trade liberalisation really matter? Fresh evidence from A novel dynamic ARDL simulations approach. *Res. Square*. doi:10.21203/rs.3.rs-419113/v1

Usman, M., and Hammar, N. (2021). Dynamic relationship between technological innovations, financial development, renewable energy, and ecological footprint: Fresh insights based on the STIRPAT model for Asia pacific economic cooperation countries. *Environ. Sci. Pollut. Res.* 28 (12), 15519–15536. doi:10.1007/s11356-020-11640-z

Villanthenkodath, M. A., and Mahalik, M. K. (2022). Technological innovation and environmental quality nexus in India: Does inwardremittance matter? *J. Public Aff.* 22 (1), e2291. doi:10.1002/pa.2291

Vitenu-Sackey, P. A., and Acheampong, T. (2022). Impact of economic policy uncertainty, energy intensity, technological innovation and R&D on CO_2 emissions: Evidence from a panel of 18 developed economies. *Environ. Sci. Pollut. Res. Int.* 1, 20. doi:10.1007/s11356-022-21729-2

Wang, L., Wang, Z., and Ma, Y. (2022b). Does environmental regulation promote the high-quality development of manufacturing? A quasi-natural experiment based on China's carbon emission trading pilot scheme. *Socio-Economic Plan. Sci.* 81, 101216. doi:10.1016/j.seps.2021.101216

Wang, X., Zhang, T., Nathwani, J., Yang, F., and Shao, Q. (2022a). Environmental regulation, technology innovation, and low carbon development: Revisiting the EKC Hypothesis, Porter Hypothesis, and Jevons' Paradox in China's iron & steel industry. *Technol. Forecast. Soc. Change* 176, 121471. doi:10.1016/j.techfore.2022.121471

Wang, Z., Gao, L., Wei, Z., Majeed, A., and Alam, I. (2022c). How FDI and technology innovation mitigate CO_2 emissions in high-tech industries: Evidence from province-level data of China. *Environ. Sci. Pollut. Res.* 29 (3), 4641–4653. doi:10.1007/s11356-021-15946-4

Xia, Y., and Zhong, M. C. (2016). Relationship between EKC hypothesis and the decoupling of environmental pollution from economic development: Based on China prefecture-level cities' decoupling partition. *China Popul. Resour. Environ.* 26 (10), 8–16.

Xiao, Z. (2009). Quantile cointegrating regression. *J. Econ.* 150 (2), 248–260. doi:10.1016/j.jeconom.2008.12.005

Xie, L., Zhou, Z., and Hui, S. (2022). Does environmental regulation improve the structure of power generation technology? Evidence from China's pilot policy on the carbon emissions trading market (CETM). *Technol. Forecast. Soc. Change* 176, 121428. doi:10.1016/j.techfore.2021.121428

Xu, B., and Xu, R. (2022). Assessing the role of environmental regulations in improving energy efficiency and reducing CO_2 emissions: Evidence from the logistics industry. *Environ. Impact Assess. Rev.* 96, 106831. doi:10.1016/j.eiar.2022.106831

Yang, B., Jahanger, A., and Ali, M. (2021). Remittance inflows affect the ecological footprint in BICS countries: Do technological innovation and financial development matter? *Environ. Sci. Pollut. Res.* 28 (18), 23482–23500. doi:10.1007/s11356-021-12400-3

Yang, Y., and Meng, G. F. (2019). The decoupling effect and driving factors of carbon footprint in megacities: The case study of xi'an in western China. *Sustain. Cities Soc.* 44, 783–792. doi:10.1016/j.scs.2018.11.012

Yii, K. J., and Geetha, C. (2017). The nexus between technology innovation and CO_2 emissions in Malaysia: Evidence from granger causality test. *Energy Procedia* 105, 3118–3124. doi:10.1016/j.egypro.2017.03.654

Yin, K., Liu, L., and Gu, H. (2022). Green paradox or forced emission reduction—the dual effects of environmental regulation on carbon emissions. *Int. J. Environ. Res. Public Health* 19 (17), 11058. doi:10.3390/ijerph191711058

Yirong, Q. (2022). Does environmental policy stringency reduce CO_2 emissions? Evidence from high-polluted economies. *J. Clean. Prod.* 341, 130648. doi:10.1016/j.jclepro.2022.130648

Zahonogo, P. (2017). Trade and economic growth in developing countries: Evidence from sub-saharan Africa. *J. Afr. Trade* 3 (1-2), 41–56. doi:10.1016/j.joat.2017.02.001

Zameer, H., Shahbaz, M., and Vo, X. V. (2020). Reinforcing poverty alleviation efficiency through technological innovation, globalization, and financial development. *Technol. Forecast. Soc. Change* 161, 120326. doi:10.1016/j.techfore.2020.120326

Zhang, Q., Zhang, S., Ding, Z., and Hao, Y. (2017a). Does government expenditure affect environmental quality? Empirical evidence using Chinese city-level data. *J. Clean. Prod.* 161, 143–152. doi:10.1016/j.jclepro.2017.05.096

Zhang, Y. J., Peng, Y. L., Ma, C. Q., and Shen, B. (2017b). Can environmental innovation facilitate carbon emissions reduction? Evidence from China. *Energy Policy* 100, 18–28. doi:10.1016/j.enpol.2016.10.005

Zhou, N., Levine, M. D., and Price, L. (2010). Overview of current energy-efficiency policies in China. *Energy policy* 38 (11), 6439–6452. doi:10.1016/j.enpol.2009.08.015

TYPE Original Research
PUBLISHED 12 January 2023
DOI 10.3389/fenvs.2022.953902

OPEN ACCESS

EDITED BY
Yingcheng Li,
Southeast University, China

REVIEWED BY
Yasin Orooji,
Zhejiang Normal University, China
Rita Yi Man Li,
Hong Kong Shue Yan University, Hong Kong SAR, China
Luigi Aldieri,
University of Salerno, Italy
Jose Balsa-Barreiro,
Massachusetts Institute of Technology, United States

*CORRESPONDENCE
Ju'e Guo,
guojue@xjtu.edu.cn

SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal Frontiers in Environmental Science

RECEIVED 26 May 2022
ACCEPTED 02 November 2022
PUBLISHED 12 January 2023

CITATION
Dong H, Guo J, Chen T and Murong R (2023), Configuration research on innovation performance of digital enterprises: Based on an open innovation and knowledge perspective. *Front. Environ. Sci.* 10:953902.
doi: 10.3389/fenvs.2022.953902

Configuration research on innovation performance of digital enterprises: Based on an open innovation and knowledge perspective

Hao Dong[1,2], Ju'e Guo[2]*, Tianqing Chen[1] and Ruiyi Murong[1]

[1]Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi'an, China, [2]School of Management, Xi'an Jiaotong University, Xi'an, China

This paper takes 36 unicorn enterprises in China as a sample case. Based on the perspective of open innovation and knowledge, combined with the background of the transformation and development of China's digital economy, the antecedent conditions such as the three dimensions of knowledge integration ability, the two dimensions of open innovation and knowledge sharing are integrated by using configuration thinking and fuzzy set qualitative comparative analysis (fsQCA) method. The multiple concurrent factors and causal complex mechanisms affecting innovation performance are discussed. The results show that: 1) The different dimensions of knowledge integration capability, open innovation, and knowledge sharing have six configurations to achieve high-level firm performance; 2) Different knowledge integration capabilities can all promote innovation performance; 3) knowledge sharing improves the management and utilization of knowledge, which is an important guarantee for improving innovation performance. The conclusion expands the innovation perspective of the matching of knowledge and open innovation, helps to understand the mechanism of innovation performance, and provides theoretical reference and beneficial enlightenment for enterprises to effectively improve innovation performance.

KEYWORDS
open innovation, innovation performance, knowledge integration capability, knowledge sharing, fsQCA

Introduction

Along with the rapid development of information and communication technologies such as big data, cloud computing, the Internet of Things, artificial intelligence, blockchain, and 5G, the world economy has entered a new era of the digital economy (Autio et al., 2018). By 2020, China's digital economy will account for 38.6% of GDP and is expected to surpass the US as the world's largest digital economy in the future (Jiang, 2020). The digital economy contains two parts: digital industrialization and industrial digitization, corresponding to the digital economic benefits of digital enterprises such as communication technology, and the innovation efficiency of traditional primary, secondary and tertiary industries based on digital technology enhancement (Papadopoulos et al., 2020). Therefore, whether it is digital industrialization or the industrial digitization of digital enterprises and traditional enterprises, the development of the digital economy has become an inevitable trend in the market economy (Teece, 2018). In this process, the vigorous development of the digital economy has formed a new engine of economic development and new momentum, but also to the traditional economy and traditional industrial development has brought the "pain" of fission and the urgent hope of transformation needs, to promote open innovation based on the digital economy driven by the inevitable choice for the future development of enterprises (Cennamo et al., 2020). Compared with the traditional industrial economy environment, the digital economy environment has digital scenarios and new features such as openness, borderlessness, strong interactivity, and uncertainty (Yuan et al., 2021). Open innovation of enterprises in the digital economy environment requires more open knowledge sharing and inclusive knowledge creation mechanism, through which knowledge resources needed for open innovation can be obtained, and through the effective utilization and integration of knowledge, thus promoting the improvement of enterprise innovation capability and innovation performance (Lee et al., 2010; Eftekhari and Bogers, 2015; Sun et al., 2020; Scaliza et al., 2022).

Compared with closed innovation within the enterprise, open innovation breaks through the closed organizational boundaries of the traditional economy. By strategically using inside-out and outside-in paths to acquire knowledge and resources from outside the organization and combine them with the enterprise's original core competencies and organizational strategies, the enterprise can enhance its internal innovation capabilities and spread the innovation results to the external market, to further enhance its dynamic adaptive capabilities and innovation performance (Ahn et al., 2013; Sisodiya et al., 2013; Shu et al., 2016). Although open innovation may profoundly affect innovation performance (Audretsch and Belitski, 2022), existing studies have not clarified the mechanism of the effect of open innovation on innovation performance, so there is a need to further study and explore the relationship between the two (Tang et al., 2021).

Although scholars have studied the relationship between open innovation and innovation performance (Ebersberger et al., 2021; Naseer et al., 2021; Ovuakporie et al., 2021), most of these studies have focused on the independent effect of open innovation on innovation performance, while ignoring that the performance of the role of open innovation can be influenced by other organizational factors (Cheah and Ho, 2021). According to the knowledge base theory, knowledge, as the core element of open innovation, is the foundation of open innovation (Rauter et al., 2019). In the process of promoting the development of open innovation diffusion, knowledge not only needs to be shared but also needs to be integrated efficiently to enhance the degree of knowledge interaction and increase the width and thickness of knowledge, to further enhance the open innovation performance how enterprises carry out specific activities under open innovation (Gkypali et al., 2018). Therefore, knowledge, as an important part of enterprise resources, is bound to influence the role of open innovation in innovation performance (Scaliza et al., 2022). Therefore, this study argues that it is necessary to investigate the preconditions and paths of innovation performance from the perspective of knowledge management, with open innovation-knowledge management as the mainline, to supplement the "new perspective" of innovation performance research (Cuevas-Vargas et al., 2022). In practice, the premise of open innovation is the knowledge sharing among innovation subjects inside and outside the enterprises, and each innovation subject uses knowledge sharing to acquire complementary knowledge and form a knowledge integration mechanism, which eventually becomes innovation performance through systematic evolution and output.

Based on this, this paper integrates the antecedent conditions of open innovation, knowledge integration capability, and knowledge sharing, constructs a model of the driving mechanism of innovation performance of digital enterprises, and mines the role of different groups of antecedent conditions on innovation performance through the fuzzy set qualitative comparative analysis (fsQCA) method. The innovations and theoretical contributions of this paper are 1) Integrating three types of elements, namely, open innovation, knowledge integration capability, and knowledge sharing, into a holistic analysis model and analyzing the influence of the configuration of these elements on innovation performance by applying the fsQCA method, which provides a new research perspective for understanding and explaining the complex causal relationships of the factors influencing innovation performance of digital enterprises. 2) It provides new ideas to explain the contradictions in innovation performance research. Previous studies have argued the relationship between different antecedent conditions and innovation performance, but there is still disagreement on the research findings. In contrast, this paper provides a new explanation for the research disagreement from a histological perspective: innovation performance is the result of matching and linking different antecedent conditions, and the effects of these different antecedent conditions have different characteristics, and exploring the net effect of a single antecedent condition in isolation may lead to contradictory research results.

Theoretical background and hypothesis development

Innovation performance plays a crucial role in the survival and long-term development of digital firms, and understanding and explaining the driving mechanisms of innovation performance has thus become a focal issue for scholars (Yao and Huang, 2022; Li et al., 2022). This paper explores the impact of three types of factors, namely open innovation, knowledge integration capability, and knowledge sharing, on the innovation performance of digital enterprises from the perspectives of open innovation and knowledge management, and constructs a framework for analyzing the driving mechanisms of innovation performance.

Knowledge sharing and innovation performance

The open, borderless, digital resource flow and value co-creation features presented by the digital economy itself contain the basic elements of knowledge flow, exchange, and sharing. Under the digital economy, in the open innovation process promoted by enterprises, knowledge sharing occurs in the innovation activities such as R&D cooperation and co-creation alliance between team members within the organization, between departments, and between the organization and the outside of the organization. This enables the organization's management system to form an inter-temporal and inter-level knowledge-sharing network that spans from consumers to supply chain members/cooperative units and then to the enterprise itself. In practice, the scenarios of knowledge sharing may go far beyond the scope of work in a narrow sense (Swap et al., 2001). These knowledge-sharing scenarios take the knowledge-sharing subject as a knowledge node, while the realization of knowledge-sharing is accomplished by the network transmission between nodes (Tsai, 2001). Tanriverdi (2005) believes that the stronger the absorptive capacity based on knowledge sharing, the more an enterprise can broaden the breadth and depth of knowledge, and the more effectively it can respond to changes in the environment. It is also more capable of screening out knowledge that is valuable for corporate innovation, thus enhancing the innovation performance of the organization (Tanriverdi, 2005). Knowledge sharing will make the sources of enterprise knowledge more diversified, and the higher the degree of diversification of knowledge sources and the higher the frequency of knowledge sharing and exchange, the faster the operation of technology development and other innovation activities of enterprises, thus shortening the product launch cycle. At the same time, when enterprises have better knowledge exchange and sharing mechanisms, they also have a stronger ability to manage new knowledge from other organizations. Successful commercialization of new products can facilitate innovation activities and improve organizational innovation performance. Zahra and George's (2002) empirical study on knowledge sharing, knowledge absorptive capacity, and innovation performance show that knowledge sharing can have an intrinsic effect on innovation performance through the mediating effect of knowledge absorptive capacity, in addition to its direct positive effect on innovation performance (Zahra and George, 2002). Thus, a synergistic evolutionary path of knowledge sharing, knowledge absorption capacity, and innovation performance is formed. Based on this evolutionary path, enterprises continuously increase knowledge stock and enhance knowledge absorption capacity through knowledge sharing, and then internalize each other's knowledge and innovation knowledge system to achieve innovation performance improvement and competitive advantage construction. Tripsas's (1997) empirical study on external knowledge sharing in organizations shows that knowledge is externally shared in the process of cooperation and communication between enterprises (Tripsas, 1997). In turn, this external sharing of knowledge achieves innovation in technology development, production processes, and business models through the creative stimulation of both parties, which in turn has a significant positive impact on innovation performance (Chesbrough and Schwartz, 2007).

Open innovation and innovation performance

Open innovation is based on the strategic goal of innovation development, breaking the traditional organization's closed boundaries, and using the inflow and outflow of knowledge from inside and outside the organization to promote innovation work such as new product development and business model reconstruction (Jin et al., 2022). Roh et al. (2022) believe that open innovation is not only a means but also a strategic business model (Roh et al., 2022). Through inside-out and outside-in open innovation, enterprises benefit from the introduction of new innovative knowledge and technology, and also profit from the export of patented technologies that are not used by enterprises. Baki and Peker (2022) reduce the risk of investment in R&D and enhance innovation performance by supporting new R&D technologies outside the organization through mutual flow or sharing of resources with consumers, suppliers, academic and research institutions, competitors, community teams, and non-profit organizations (Yildirim et al., 2022). The organization and these institutions then form an open-ended value co-creation mechanism, and this value co-creation mechanism can "divide" innovation and ultimately contribute significantly to enhancing the effectiveness of the firm's new product development.

In the digital economy driven by big data, cloud computing and artificial intelligence, open innovation based on internal and external cooperation, intra-enterprise innovation and entrepreneurship and open innovation with the help of public knowledge have become important means for enterprises to adapt to the development of digital transformation and build dynamic competitive advantages (Benitez et al., 2022; Chaithanapat et al., 2022; Kitsios and Kamariotou, 2022). The crowdsourcing model and C2B innovation model around which open innovation is formed constitute important support for the digital development of enterprises. Yang et al. (2022) classify open innovation strategies into two dimensions: "wide external search strategy" and "deep external search strategy" to facilitate the development of new products and improve innovation performance (Yang et al., 2022). At the same time, the external search target of open innovation is divided into two dimensions: "competitors" and "non-competitors". Based on the moderating effect of environmental competitiveness, an empirical study is conducted to investigate the relationship between open innovation strategy and new product innovation performance (Najafi-Tavani et al., 2022; Sanni and Verdolini, 2022; Santos-Vijande et al., 2022). When the external search target is an external organization other than a competitor, the competitive market environment positively moderates the relationship between "depth and width of external search strategy" and "new product innovation performance". When the external search target is a competitor, the competitive market environment negatively adjusts the relationship between "deep external search strategy" and "new product innovation performance".

Knowledge integration capability and innovation performance

Knowledge integration is the connection of formal or informal knowledge between individuals and business organizations that leads to new knowledge sharing and communication and can provide a basis for transforming individual knowledge into organizational knowledge. When an individual's or organization's knowledge is connected with another team's knowledge and discussed, communicated, and exchanged by the individual or organization, it may further develop and integrate up-ward into the organization's knowledge (Inkpen, 1996). Based on knowledge foundation theory and organizational learning theory, when the internal knowledge accumulation of an organization is not enough to support the development of an enterprise, seeking knowledge from outside becomes one of the important channels for the innovation and development of an enterprise. In the era of a knowledge-driven digital economy, cross-organizational cooperation enables enterprises to acquire more knowledge. However, how can the new knowledge acquired be effectively converted into useful value for the organization and make the organization more innovation-driven? Only by integrating relevant knowledge and resources more rapidly and flexibly, and coordinating the allocation of internal and external knowledge of the organization, can such effective conversion of new knowledge be successful in the open digital competitive environment.

McDonough et al. (2001) believe that enterprises create new knowledge through knowledge integration, and apply it to the business activities of the enterprise. Therefore, by the knowledge integration ability, the knowledge advantage created by the knowledge exchange and combination will be reflected in the related activities of the organization's value creation, thus contributing to the organization's innovation performance. Ritala et al. (2017) believe that knowledge integration is the integration of professional knowledge among members to meet the organization's adaptation to a specific business environment. Because integrated knowledge enables organizations to efficiently plan products and markets in uncertain environments, promote new product innovation and evolution, and lay the foundation for business operations to achieve expected execution results. Therefore, the stronger the knowledge integration capability of the organization, the more knowledge will be available. The more solidly these organizations can establish their core competencies, the higher their innovation performance.

Zobel et al. (2017) empirical research based on organizational learning theory shows that if an enterprise can acquire new knowledge and integrate existing knowledge in the organization in different ways, the enterprise will have a good performance in innovation matters such as products and processes. Therefore, the stronger the organizational knowledge integration capability, the higher the level of enterprise innovation. Based on the perspective of dynamic capability theory and the empirical data of 261 enterprises participating in the Standard Alliance, Zhang et al. (2022) conducts an empirical study on the relationship between knowledge integration capabilities, partnership quality, and alliance innovation performance. The knowledge integration ability of the enterprise has a positive effect on improving the performance of the technical standards alliance, and the improvement of the quality of the partnership in the technical standards alliance will also help the knowledge integration ability and the alliance management ability to jointly play a positive role in the performance of the technical standards alliance (Qin et al., 2021; Sousa-Ginel et al., 2021; Junaid et al., 2022; Sultana et al., 2022).

The linkage of knowledge integration capability, open innovation, and knowledge sharing

Open innovation guides the direction and behavioral choices of digital enterprises and has a supportive role in their innovation performance. To achieve the goal of open innovation-oriented innovation performance, enterprises must have sufficient

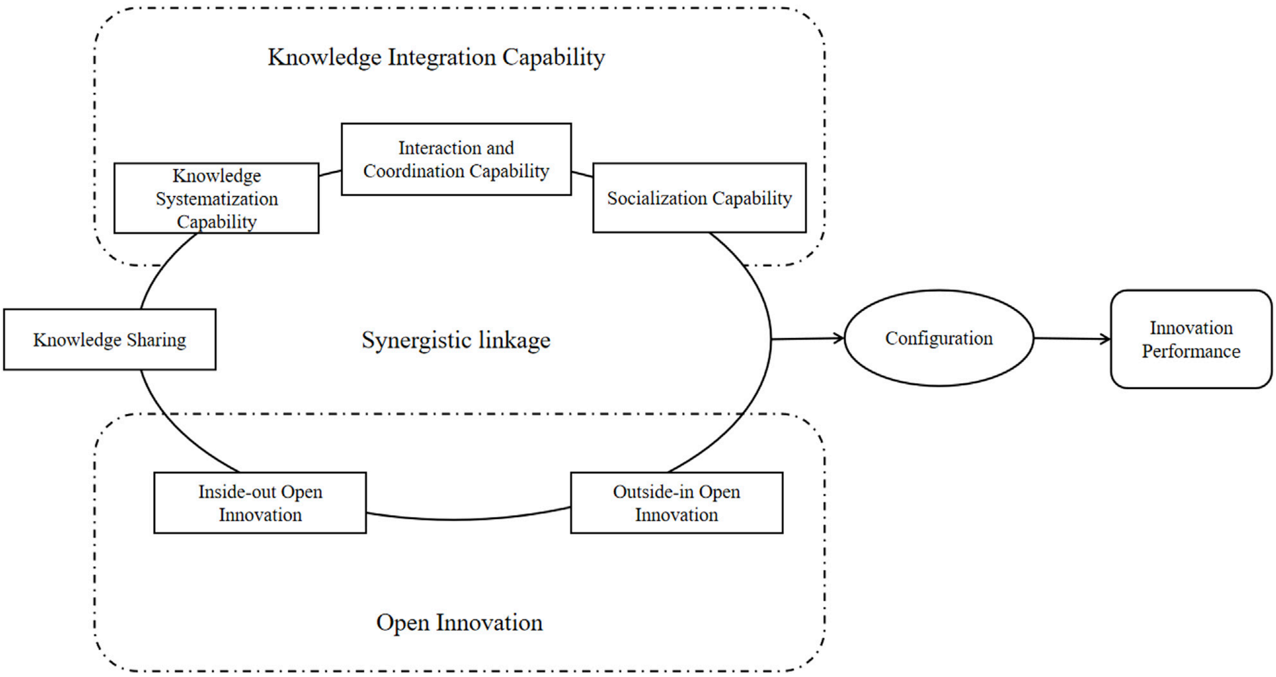

FIGURE 1
Research model.

organizational resources to promote innovation actions (Acharya et al., 2022). For enterprises, the knowledge integration capability accumulated in the long-term production and operation process becomes a valuable capability. Knowledge integration capability can provide support for the realization of enterprise innovation performance (Ahlfänger et al., 2022). When the knowledge integration ability is difficult to be directly utilized, the enterprise will realize the improvement of its innovation performance by sharing knowledge with other enterprises and complementing them through knowledge sharing (Bao and Wang, 2022). Compared with enterprises with strong knowledge integration ability, enterprises with weak knowledge integration ability need to play the role of knowledge sharing more and fully release knowledge value through knowledge-sharing processes such as constructing a knowledge portfolio, improving knowledge management ability, and using knowledge to leverage opportunities (Kong et al., 2021). Meanwhile, knowledge sharing improves the open innovation environment of enterprises through optimal knowledge management, which is conducive to better innovation performance (Sheng and Hartmann, 2019; Qin et al., 2021). Therefore, the innovation performance of digital enterprises may be influenced by the linkage and complementarity of open innovation, knowledge integration capability, and knowledge sharing, which include six factors: inside-out open innovation, outside-in open innovation, knowledge systematization capability, interaction and coordination capability, socialization capability and knowledge sharing. The research framework of this paper is shown in Figure 1.

Research design

Method

The main reasons for adopting fsQCA in this paper are as follows: 1) Traditional statistical analysis methods, such as regression analysis, can only analyze the “net effect” of individual conditions on innovation performance, which cannot solve the problem of causal complexity in innovation performance research (Ragin, 2014; Xie and Wang, 2020). The QCA method can reveal the impact of complex relationships among multiple antecedent conditions on the results based on the pooling theory (Fiss, 2011). 2) Although the group states relationships among the antecedents of innovation performance can be tested by typical correlation analysis and discriminant analysis. However, these methods are difficult to identify the interdependence and asymmetric causality among the antecedent conditions (Ragin, 2006). 3) The causal conditions in this paper are mostly continuous variables, and fsQCA can ensure the accuracy of the data after variable processing, which

TABLE 1 Basic information of sample enterprises.

Number	Enterprise	Industry segment	Number	Enterprise	Industry segment
N1	ZGSH	Manufacturing	N19	CBC	Finance and insurance
N2	BGJT	Manufacturing	N20	CMSB	Finance and insurance
N3	HFJ	Manufacturing	N21	CIB	Finance and insurance
N4	DFQC	Manufacturing	N22	HW	Technology
N5	SAJT	Manufacturing	N23	XM	Technology
N6	SHBL	Wholesale/retail	N24	JD	Consumer business/goods
N7	DLSC	Wholesale/retail	N25	TB	Consumer business/goods
N8	BJHL	Wholesale/retail	N26	SXDJ	Industrials (construction and industrial goods)
N9	GMDQ	Wholesale/retail	N27	SXJZ	Industrials (construction and industrial goods)
N10	JLF	Wholesale/retail	N28	AMM	Agriculture
N11	SNPC	Energy and utilities	N29	APB	Agriculture
N12	CNPC	Energy and utilities	N30	PBB	Health care
N13	CPCS	Energy and utilities	N31	HCR	Health care
N14	CT	Telecommunications	N32	XJT	Consulting services
N15	CM	Telecommunication	N33	ZLZP	Consulting services
N16	CU	Telecommunication	N34	YYQ	Oil and gas
N17	PBC	Finance and insurance	N35	SM	Oil and gas
N18	BOB	Finance and insurance	N36	BJZY	Pharmaceutical

can fully reflect the subtle effects produced by changes in different degrees or levels of innovation performance influencing factors.

Sample selection and data collection

Regarding existing studies and the normative requirements of fsQCA methods (Fiss, 2011; Ragin, 2014). When there are 6 pre-elements in the configuration path model, more than 25 research samples are required to ensure the reliability and validity of the research results. This study combines industry planning and thinks tank research reports such as "the 2020 China Unicorn Enterprise Research Report" and "the 2020 Hurun List of China's Top 500 Private Enterprises". A total of 36 digital enterprises (including five provinces: Shaanxi, Henan, Jiangsu, Zhejiang, and Liaoning) provided by MBA students of Xi'an Jiaotong University are selected as research samples. The information of sample enterprises is shown in Table 1. The sample selection in this paper follows the theoretical sampling principle (Fiss, 2007), which satisfies the following three criteria: 1) the sample enterprises should be listed enterprises or industry-leading enterprises among digital enterprises to ensure the adequacy of the information. 2) The enterprises have experienced a complete innovation performance process to ensure the typicality of the sample. 3) The enterprises are involved in different industries to ensure the diversity of the sample. Meanwhile, according to the requirements of the QCA method on sample size, when the number of conditions is n, the number of samples should not be less than 2^{n-1}. Based on this, 36 digital enterprises are finally selected as samples in this paper, and the basic information of some sample enterprises is shown in Table 1.

The research data in this paper were mainly collected through secondary sources. The reasons are as follows: first, the relevant public information data are abundant and have high authenticity and reliability; second, to avoid subjective influence on the collection and analysis of information when researchers conduct interviews; third, the number of sample enterprises and their scattered locations make it more difficult to conduct field research and interviews. At the same time, to try to avoid the limitations of the research caused by secondary data, this paper selects high-quality information such as annual reports of enterprises, authoritative research reports, and well-known media reports when collecting data; when processing data, members of the research team conducted several data collations and discussions and conducted coding reliability tests to ensure the validity and reliability of secondary information. The sources of information in this paper include 1) official websites of enterprises, annual reports, internal speeches, and public interviews of senior leaders; 2) industry research reports and related books; and 3) information such as mainstream media reports and comments of self-publishers. In collecting and organizing the information, the main focus is on enterprises' innovation performance experience, open innovation, knowledge integration capability, and corresponding knowledge-sharing activities, which eventually results in a sample database of more than 900,000 words.

TABLE 2 Questionnaire.

Variable	ID	Measurement item	Sources
Innovation performance	IP1	The speed of new product development.	Zobel et al. (2017)
	IP2	The number of new products introduced to the market.	
	IP3	The number of new products that are first-to-market	
	IP4	The variable share of incremental innovation	
	IP5	The number of new technologies that are first-to-market	
	IP6	The number of new technologies introduced to the market	
	IP7	With self-developed patents	
Inside-out open innovation	IOI1	Our enterprise often sells its technology to outside organizations	Chesbrough and Schwartz (2007)
	IOI2	Our enterprise often sells its patents to outside organizations	
	IOI3	Our enterprise often licenses its patents or technologies to outside organizations	
	IOI4	Our enterprise often promotes our industry presence by disclosing new knowledge and technologies	
Outside-in open innovation	OOI1	Our enterprise often collaborates with outside organizations to develop new technologies	Chesbrough and Schwartz (2007)
	OOI2	Our enterprise often receives knowledge support from external organizations	
	OOI3	Our enterprise often collaborates with external organizations to develop new technologies	
	OOI4	Our enterprise sells the intellectual property for commercial value	
Knowledge sharing	KS1	Our enterprise can acquire new knowledge quickly according to the market	Daniel Sherman et al. (2005)
	KS2	Our enterprise can quickly acquire new knowledge from universities or academic research	
	KS3	Our enterprise can quickly acquire new knowledge from other companies	
	KS4	Our companies can acquire new knowledge to implement new business models	
	KS5	Our enterprise can acquire new knowledge to generate new products	
	KS6	Our enterprises can acquire new knowledge to generate new technologies	
Knowledge systematization capability	KSC1	Priori procedures	De Boer et al. (1999)
	KSC2	formal language and codes	
	KSC3	Policies and working manuals	
	KSC4	information systems	
Interaction and coordination capability	ICC1	Our enterprise has a good cooperative relationship with other companies	De Boer et al. (1999)
	ICC2	Our enterprise has a good cooperative relationship with other companies	
	ICC3	Our enterprise has many professionals	
	ICC4	Our enterprise has a very good licensing environment.	
	ICC5	Our enterprise uses a flat management model	
Socialization capability	SC1	Our enterprise has a common ideology (culture)	De Boer et al. (1999)
	SC2	Our enterprise produces a distinct identity for its participants	
	SC3	Our employees have a strong sense of identity with the corporate values	
	SC4	Our enterprise has a very good and authoritative training system	

The coding basis for the QCA approach is derived from a holistic reflection of quantitative and qualitative data. This paper mainly draws on the concept of anchoring variables and looks for statements about open innovation, knowledge integration capability, knowledge sharing, and innovation performance from the case materials as the basis for the assignment. Referring to Fiss's (2011) approach (Fiss, 2011), this paper adopts a quadratic assignment method, which is based on four anchors of 0 (completely unaffiliated), 0.33 (biased unaffiliated), and 0.67 (biased affiliated), and 1 (completely affiliated). The specific coding assignment process includes three steps: constructing a coding table (see Table 2), coding the information, and testing the coding reliability. Taking the coding of knowledge-sharing factors of ZGSH as an example: this paper first draws on 's study to construct a coding table and determines six indicators in two dimensions of knowledge-sharing channels and knowledge-sharing degree as coding criteria (Daniel Sherman et al., 2005). Then two coders from the research team independently coded the sample enterprises based on the information collected from them. The coders assigned a value of 1 to the market orientation factor when they judged that the enterprise met 5 or more of the 6 indicators,

TABLE 3 Analysis of necessary conditions.

Conditional variable	Consistency	Coverage
IOI	0.811	0.829
~IOI	0.189	0.850
OOI	0.622	0.812
~OOI	0.378	0.872
KSC	0.834	0.824
~KSC	0.166	0.882
ICC	0.556	0.833
~ICC	0.444	0.833
SC	0.590	0.828
~SC	0.410	0.841
KS	0.856	0.846
~KS	0.144	0.765

Notes: IOI, interaction and coordination capability; OOI, outside-in open innovation; KSC, knowledge systematization capability; ICC, interaction and coordination capability; SC, socialization capability; KS, knowledge sharing; "~", the negation of the condition.

and a value of 0.67 if it met 3–4 of the 6 indicators, 0.33 if it met 1–2 of the 6 indicators, and 0 if it met less than 1. Finally, the coding reliability test was conducted based on the aggregated results of the coders to ensure the reliability of the coding results.

Coding reliability test

Coding reliability refers to the degree of consistency in the coders' assignment of factors. The higher the degree of consistency, the higher the coding reliability. Drawing on the studies of Bhatt et al. (2010) and Greckhamer et al. (2018) (Bhatt et al., 2010), this paper uses the average mutual agreement reliability index to measure coding reliability. This paper contains 252-factor coding assignments (36 enterprises, 7-factor coding assignments per enterprise), and a total of 43-factor coding assignments were initially inconsistent between the two coders in the coding process, so the value of the mutual agreement index (MAI) obtained using the Holsti formula is 82.94%, which is calculated as follows:

$$MAI = \frac{2M}{N_1 + N_2} = \frac{2 \times (252 - 43)}{252 + 252} \times 100\% = 82.94\% \qquad (1)$$

where M is the number of factors assigned identically by both coders, N_1 is the number of factors assigned by the first coder, and N_2 is the number of factors assigned by the second coder.

Since this paper is assigned by two coders, the mutual agreement is the average mutual agreement, and the reliability coefficient is calculated as follows:

$$\text{reliability} = \frac{n \times MAI}{1 + (n-1) \times MAI} = \frac{2 \times 0.8294}{1 + (2-1) \times 0.8294} \times 100\% = 90.67\% \qquad (2)$$

From the above calculation results, it can be seen that this paper has good coding confidence. In addition, for the different results appearing in the process of coding assignment, the members of the group discuss together and finalize the corresponding assignment results.

Data analysis and results

Analysis of the necessity of individual conditions

The necessity of the antecedent conditions was first analyzed to test whether any single antecedent condition constitutes a necessary condition for innovation performance. fsQCA3.0 test results are shown in Table 3. It can be seen that the consistency values of the influence of each antecedent condition on innovation performance are below 0.9, indicating that there is no single antecedent condition that has a dominant influence on innovation performance, and a configuration analysis of each antecedent condition is required.

Analysis of sufficient conditions

The adequacy of conditional configuration is measured using conformance, but its calculation method and minimum acceptance criteria differ from necessity analysis. According to Schneider and Wagemann, the frequency threshold should be set according to the size of the research sample, and the frequency threshold for small and medium-sized studies is usually set to 1 (Schneider et al., 2010). Since the number of samples in this paper is 36, the frequency threshold is set to 1 in the adequacy analysis. Meanwhile, according to the suggestion of Ragin and Fiss, this paper sets the original consistency threshold to 0.8 and the PRI consistency threshold to 0.75. In subsequent normalization operations, complex, parsimonious, and intermediate solutions are obtained. Following the existing research practice, this paper selects the intermediate solution as the main reference for the explanatory sufficiency analysis and distinguishes the core and auxiliary elements of the group state based on the parsimonious solution and the intermediate solution. If the antecedent condition appears in both the parsimonious solution and the intermediate solution, the condition is the core condition; if the antecedent condition appears only in the intermediate solution, the condition is the auxiliary condition, and the results are shown in Table 4.

TABLE 4 Sufficiency analysis of conditional configuration.

Conditional configuration	Path					
	A balanced drive model of "knowledge integration capability-open innovation-knowledge sharing"		A dual drive model of "knowledge integration capability-open innovation"		A dual drive model of "knowledge integration capability-knowledge sharing"	
	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 5	Configuration 6
KSC	●	●		●	●	●
ICC		●	●	⊗	●	⊗
SC			●	⊗		●
IOI	●		●	●	●	
OOI		●	⊗	⊗	●	⊗
KS	●	●	●			●
Raw coverage	0.589	0.366	0.222	0.199	0.321	0.177
Unique coverage	0.178	0.090	0.023	0.022	0.045	0.011
Consistency	0.841	0.846	0.869	0.900	0.879	0.941
Solution coverage	0.780					
Solution consistency	0.844					

Notes: IOI, interaction and coordination capability; OOI, outside-in open innovation; KSC, knowledge systematization capability; ICC, interaction and coordination capability; SC, socialization capability; KS, knowledge sharing; ●, core casual condition (present); ● = peripheral casual condition (present); ⊗, core casual condition (absent); ⊗, peripheral casual condition (absent). Blank spaces indicate "do not care."

As can be seen from Table 4, the consistency level of both individual solutions (configuration) and the overall solution is above the minimum acceptable standard of 0.75, where the consistency of the overall solution is 0.844 and the coverage of the overall solution is 0.780. The six configurations in Table 4 can be considered a sufficient combination of conditions for digital firms to achieve innovative performance.

Configuration 1 (KSC*IOI*KS→IP): This configuration is a sufficient condition for innovation performance consisting of high knowledge systematization capability, high inside-out open innovation, and high knowledge sharing capability. When the knowledge systematization capability is strong, to meet market demand, achieve competitive advantage in the market and achieve high innovation performance, enterprises need knowledge sharing and knowledge systematization capability to break organizational boundaries. At the same time, enterprises can further improve the effectiveness of knowledge utilization through knowledge sharing, creatively integrate and allocate knowledge to market innovation activities, and improve the ability of enterprises to launch new products and develop new technologies, thus promoting innovation performance.

Configuration 2 (KSC*ICC*OOI*KS→IP): This configuration is a sufficient condition for innovation performance consisting of high knowledge systematization capability, high interaction and coordination capability, high outside-in open innovation, and high knowledge sharing capability. Unlike configuration 5, although the knowledge systematization capability and interaction and coordination capability are high in configuration 2, it only has high outward-inward open innovation. In this case, knowledge sharing becomes a key factor to ensure the successful development and use of new products and technologies.

Configuration 3 (ICC*SC*IOI*~OOI*KS→IP): This configuration is a sufficient condition configuration for innovation performance consisting of high interactive co-ordination capability, high socialization capability, high inside-out open innovation, low outside-in open innovation, and high knowledge sharing capability. The results of this configuration show that firms with high interaction and coordination capabilities and high socialization capabilities are willing to invest in knowledge acquisition actions inside and outside the organization and influence innovation performance by exploring new technologies, products, and business markets. In contrast, more inside-out open innovation and strong knowledge-sharing capabilities provide firms with the knowledge and capabilities to undertake technological innovation and new product development, which in turn leads to innovation performance.

Configuration 1, Configuration 2, and Configuration 3 are all manifested by the combined effect of open innovation, knowledge integration capability, and knowledge sharing, so this paper names them as the balanced driving model of "knowledge integration capability-open innovation-knowledge sharing".

Configuration 4 (KSC*~ICC*~SC*IOI*~OOI→IP): This configuration is a sufficient condition for innovation performance consisting of high knowledge systematization capability, low interaction, and coordination capability, low socialization capability, high inside-out open innovation, low outside-in open innovation. In configuration 2, the firm has high knowledge systematization capability as the main knowledge integration capability, and high inward-looking open innovation provides a suitable environment for the firm's innovation and innovation performance. At the same time, the low external-inward open innovation environment reduces the external coordination pressure on innovation and allows firms to focus on improving their innovation performance in technology innovation and new product development due to the low number of collaborators and the difficulty of transforming existing knowledge and technology into market-compatible value innovation.

Configuration 5 (KSC*ICC*IOI*OOI→IP): This configuration is composed of high knowledge systemization ability, high interaction, and coordination ability, high in-side-out open innovation, and high outside-in open innovation configuration of sufficient conditions for innovation performance. Enterprises with dual capabilities of high knowledge systemization ability and high interaction and coordination ability need to improve their innovation performance in the case of a highly open innovation environment. Because enterprises need an open innovation environment, to achieve breakthroughs in both market development and technological innovation. The inside-out open innovation guarantees the internal environment that enterprises need to carry out risk-taking activities and free innovation, while the outside-in open innovation promotes enterprises to improve their innovation performance based on external knowledge.

Both Configuration 4 and Configuration 5 show that the innovation performance of digital enterprises is driven by knowledge integration capability and open innovation, so this paper names them as a dual drive model of "knowledge integration capability-open innovation".

Configuration 6 (KSC*~ICC*SC*~OOI*KS→IP): This configuration is a sufficient condition for innovation performance consisting of high knowledge systematization capability, low interaction and coordination capability, and high socialization capability, low outside-in open innovation, and high knowledge sharing. This configuration reflects the tendency of enterprises to develop the knowledge integration capability of internalizing knowledge systematization and turning knowledge into value. Under this knowledge integration capability, enterprises are good at seizing opportunities and being brave in innovation, and continuously integrating and developing existing knowledge, which can significantly affect innovation performance. However, due to the limited innovation environment within the enterprise, it is necessary to promote the cultivation of open innovation culture through knowledge sharing, reduce the cost of market development and innovation actions, and then ensure that corporate activities can be supported by innovation culture.

Configuration 6 shows the linkage effect of knowledge integration capability and knowledge sharing on innovation performance, so this paper names it a dual drive model of "knowledge integration capability-knowledge sharing".

Robustness test

We used standard methods to conduct a robust analysis of QCA results. The commonly used methods are: Adjusting the calibration threshold, changing the consistency threshold, adding or deleting the shell, changing the frequency threshold, and adding other conditions. This paper draws on Greckhamer's practice and increases the PRI consistency threshold from 0.75 to 0.80 to carry out an adequacy analysis (Greckhamer et al., 2018), and finds that the test results are almost completely consistent with the original research results (see Table 4). In addition, in this paper, the original consistency threshold is increased from 0.80 to 0.85, the robustness test is performed again, and the obtained results are consistent with the original consistency threshold of 0.80.

Discussion and implications

Research implication

From the perspective of configuration matching, this paper uses fuzzy set qualitative comparative analysis (fsQCA) to explore the configuration effects of antecedent conditions, such as knowledge systematization ability, interaction coordination ability, socialization ability, open innovation from inside out, open innovation from outside in and knowledge sharing, on innovation performance of digital firms. Three models to improve innovation performance are summarized: the balanced driving mode of "knowledge integration ability-open innovation-knowledge sharing", the dual driving mode of "knowledge integration ability-open innovation" and the dual driving mode of "knowledge integration ability-knowledge sharing".

Firstly, innovation performance has the characteristics of "multiple concurrent" and "all paths lead to the same destination". The innovation performance of digital enterprises is the result of the interaction of multiple antecedents, that is, multiple concurrencies. In addition, the interaction between antecedent conditions will form different configurations, that is, all paths lead to the same destination. The results show that there are six different configurations of innovation performance, and each configuration is composed of multiple antecedent conditions. In this paper, the fsOCA method is adopted to reveal the matching effect of the above antecedent conditions on innovation performance, explain the influencing mechanism of innovation performance from a holistic perspective, and enrich and supplement the previous research on innovation performance based on the contingency perspective.

Secondly, knowledge integration ability is an important foundation for digital enterprises to improve innovation performance. It can be seen from the configuration results that among the six configurations to improve innovation performance, any configuration has the condition of knowledge integration ability, that is, innovation performance can be improved under the guidance of knowledge systematization ability, interaction coordination ability, or socialization ability. Under different knowledge integration capabilities, enterprises will present different choices for their organizational knowledge management and utilization methods. No matter what kind of knowledge integration capability is based on, enterprises' innovation actions are formulated and implemented according to the internal and external conditions of enterprises (Sun et al., 2022). Therefore, different knowledge integration capabilities can promote innovation performance to a certain extent.

Thirdly, knowledge sharing is important for enterprises to improve innovation performance. According to the configuration results of innovation performance, knowledge sharing plays a core role in multiple configurations. This indicates that no matter whether there is a good open innovation environment or not (Fan et al., 2021), enterprises need to integrate and utilize knowledge effectively. When the enterprise has a good open innovation environment, only by using an effective knowledge-sharing strategy can the open innovation environment be converted into real performance gains. In the conservative open innovation environment, enterprises can fully cultivate the open innovation environment by using knowledge sharing, excavating the innovation value of the environment, and avoiding the low innovation performance caused by the environment.

Management implications

This paper provides the following management implications for digital enterprise innovation performance.

Firstly, the environment in which digital enterprises are located is characterized by uncertainty, interactivity, and borderlessness. It is increasingly difficult for enterprises to improve innovation performance in the actual development process. Therefore, enterprises should pay attention to the guiding role of knowledge integration ability in innovation performance (Hu et al., 2020). Based on selecting knowledge integration ability suitable for their development, enterprises should make corresponding adjustments to innovation activities according to knowledge integration ability, and promote the formation of technology or product innovation matching knowledge integration ability.

Open innovation can improve the risk tolerance of enterprises in pursuing innovation performance and provide them with necessary environmental support. This internal policy for the enterprise offers a new way to improve innovation performance: according to the needs of innovation performance, enterprises in the process of production and management necessary to have a good open innovation environment, namely through the analysis of the unfavorable situation of innovation may face and the deep understanding of the effect on different types of open innovation. Enterprises can achieve a dynamic balance between innovation performance and knowledge sharing to avoid hindering high innovation performance due to too high or too low open innovation levels.

The findings of this paper can inspire digital firms to consider and improve innovation performance from a knowledge-sharing perspective. The purpose of knowledge sharing is to manage the knowledge owned by an enterprise and to generate "new knowledge or capabilities". The improvement of innovation performance depends, to a certain extent, on acquiring and using knowledge. Therefore, enterprises should explore and create new uses for their existing knowledge through knowledge sharing, try to construct new knowledge combinations, and apply the new combinations to innovation performance practices.

Limitations and further research

This paper has the following shortcomings, and also provides a direction for future research: Firstly, this paper only considers antecedent conditions such as knowledge integration ability, open innovation, and knowledge sharing, but many factors affect innovation performance. Future research can include factors such as strategic orientation, resources, and senior management team, to study the influencing factors of innovation performance more comprehensively and improve the explanatory power of research results. Secondly, 36 enterprises were selected as the analysis samples in this paper. Limited by the number of samples, the results of qualitative comparative analysis are limited in the universality of application. In the future, more data on industries and enterprises can be collected for further analysis.

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

JG made significant contributions to the conception or design of the work, and made major adjustments to the theoretical framework in the process of repair. TC and RM critically drafted or modified important knowledge contents, and made major adjustments and modifications to research hypotheses in the revision stage to sort out the structure of the full text.

Funding

This research was funded by the Humanities and Social Sciences Project of the Ministry of Education in 2019: A comparative research on Sino-German vocational education integration of industry and education and inheritance of craftsman spirit (19YJC880010, Ministry of Education, China). Research on intelligent technology consultation service system driven by big data (2020ZDLGY09-05)

Conflict of interest

HD, TC ,and RM were employed by Shaanxi Provincial Land Engineering Construction Group Co., Ltd.

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

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Acharya, C., Ojha, D., Gokhale, R., and Patel, P. C. (2022). Managing information for innovation using knowledge integration capability: The role of boundary spanning objects. *Int. J. Inf. Manag.* 62, 102438. doi:10.1016/j.ijinfomgt.2021.102438

Ahlfänger, M., Gemünden, H. G., and Leker, J. (2022). Balancing knowledge sharing with protecting: The efficacy of formal control in open innovation projects. *Int. J. Proj. Manag.* 40, 105–119. doi:10.1016/j.ijproman.2021.09.007

Ahn, J. M., Mortara, L., and Minshall, T. (2013). The effects of open innovation on firm performance: A capacity approach. *STI Policy Rev.* 4, 79–93.

Audretsch, B. D., and Belitski, M. (2022). The limits to open innovation and its impact on innovation performance. *Technovation* 152, 245–259. doi:10.1016/j.technovation.2022.102519

Autio, E., Nambisan, S., Thomas, L. D. W., and Wright, M. (2018). Digital affordances, spatial affordances, and the Genesis of entrepreneurial ecosystems: AUTIO et al. *Strategic Entrepreneursh. J.* 12, 72–95. doi:10.1002/sej.1266

Bao, Z., and Wang, C. (2022). A multi-agent knowledge integration process for enterprise management innovation from the perspective of neural network. *Inf. Process. Manag.* 59, 102873. doi:10.1016/j.ipm.2022.102873

Benitez, J., Arenas, A., Castillo, A., and Esteves, J. (2022). Impact of digital leadership capability on innovation performance: The role of platform digitization capability. *Inf. Manag.* 59, 103590. doi:10.1016/j.im.2022.103590

Bhatt, G., Emdad, A., Roberts, N., and Grover, V. (2010). Building and leveraging information in dynamic environments: The role of IT infrastructure flexibility as enabler of organizational responsiveness and competitive advantage. *Inf. Manag.* 47, 341–349. doi:10.1016/j.im.2010.08.001

Cennamo, C., Dagnino, G. B., Di Minin, A., and Lanzolla, G. (2020). Managing digital transformation: Scope of transformation and modalities of value Co-generation and delivery. *Calif. Manag. Rev.* 62, 5–16. doi:10.1177/0008125620942136

Chaithanapat, P., Punnakitikashem, P., Khin Khin Oo, N. C., and Rakthin, S. (2022). Relationships among knowledge-oriented leadership, customer knowledge management, innovation quality and firm performance in SMEs. *J. Innovation Knowl.* 7, 100162. doi:10.1016/j.jik.2022.100162

Cheah, S. L.-Y., and Ho, Y.-P. (2021). Commercialization performance of outbound open innovation projects in public research organizations: The roles of innovation potential and organizational capabilities. *Ind. Mark. Manag.* 94, 229–241. doi:10.1016/j.indmarman.2021.02.012

Chesbrough, H., and Schwartz, K. (2007). Innovating business models with Co-development partnerships. *Research-Technology Manag.* 50, 55–59. doi:10.1080/08956308.2007.11657419

Cuevas-Vargas, H., Aguirre, J., and Parga-Montoya, N. (2022). Impact of ICT adoption on absorptive capacity and open innovation for greater firm performance. The mediating role of ACAP. *J. Bus. Res.* 140, 11–24. doi:10.1016/j.jbusres.2021.11.058

Daniel Sherman, J., Berkowitz, D., and Souder, W. E. (2005). New product development performance and the interaction of cross-functional integration and knowledge management. *J. Prod. Innov. Manage.* 22, 399–411. doi:10.1111/j.1540-5885.2005.00137.x

De Boer, M., Van Den Bosch, F. A. J., and Volberda, H. W. (1999). Managing organizational knowledge integration in the emerging multimedia complex. *J. Manag. Studs.* 36, 379–398. doi:10.1111/1467-6486.00141

Ebersberger, B., Galia, F., Laursen, K., and Salter, A. (2021). Inbound open innovation and innovation performance: A robustness study. *Res. Policy* 50, 104271. doi:10.1016/j.respol.2021.104271

Eftekhari, N., and Bogers, M. (2015). Open for entrepreneurship: How open innovation can foster new venture creation: Open innovation and new venture creation. *Creativity Innovation Manag.* 24, 574–584. doi:10.1111/caim.12136

Fan, Y.-J., Liu, S.-F., Luh, D.-B., and Teng, P.-S. (2021). Corporate sustainability: Impact factors on organizational innovation in the industrial area. *Sustainability* 13, 1979. doi:10.3390/su13041979

Fiss, P. C. (2007). A set-theoretic approach to organizational configurations. *Acad. Manage. Rev.* 32, 1180–1198. doi:10.5465/amr.2007.26586092

Fiss, P. C. (2011). Building better causal theories: A fuzzy set approach to typologies in organization research. *Acad. Manage. J.* 54, 393–420. doi:10.5465/amj.2011.60263120

Gkypali, A., Arvanitis, S., and Tsekouras, K. (2018). Absorptive capacity, exporting activities, innovation openness and innovation performance: A sem approach towards a unifying framework. *Technol. Forecast. Soc. Change* 132, 143–155. doi:10.1016/j.techfore.2018.01.025

Greckhamer, T., Furnari, S., Fiss, P. C., and Aguilera, R. V. (2018). Studying configurations with qualitative comparative analysis: Best practices in strategy and organization research. *Strateg. Organ.* 16, 482–495. doi:10.1177/1476127018786487

Hu, X., Danso, B. A., Mensah, I. A., and Addai, M. (2020). Does innovation type influence firm performance? A dilemma of star-rated hotels in Ghana. *Sustainability* 12, 9912. doi:10.3390/su12239912

Inkpen, A. C. (1996). Creating knowledge through collaboration. *Calif. Manag. Rev.* 39, 123–140. doi:10.2307/41165879

Jiang, X. (2020). Digital economy in the post-pandemic era. *J. Chin. Econ. Bus. Stud.* 18, 333–339. doi:10.1080/14765284.2020.1855066

Jin, C., Liu, A., Liu, H., Gu, J., and Shao, M. (2022). How business model design drives innovation performance: The roles of product innovation capabilities and technological turbulence. *Technol. Forecast. Soc. Change* 178, 121591. doi:10.1016/j.techfore.2022.121591

Junaid, M., Zhang, Q., and Syed, M. W. (2022). Effects of sustainable supply chain integration on green innovation and firm performance. *Sustain. Prod. Consum.* 30, 145–157. doi:10.1016/j.spc.2021.11.031

Kitsios, F., and Kamariotou, M. (2022). Digital innovation and entrepreneurship transformation through open data hackathons: Design strategies for successful start-up settings. *Int. J. Inf. Manag.*, 102472. doi:10.1016/j.ijinfomgt.2022.102472

Kong, Q., Li, R., Peng, D., and Wong, Z. (2021). High-technology development zones and innovation in knowledge-intensive service firms: Evidence from Chinese A-share listed firms. *Int. Rev. Financial Analysis* 78, 101883. doi:10.1016/j.irfa.2021.101883

Lee, S., Park, G., Yoon, B., and Park, J. (2010). Open innovation in SMEs—an intermediated network model. *Res. Policy* 39, 290–300. doi:10.1016/j.respol.2009.12.009

Li, L., Li, M., Ma, S., Zheng, Y., and Pan, C. (2022). Does the construction of innovative cities promote urban green innovation?. *J. Environ. Qual.* 318, 115605. doi:10.1016/j.jenvman.2022.115605

McDonough, E. F., Kahnb, K. B., and Barczaka, G. (2001). An investigation of the use of global, virtual, and colocated new product development teams. *J. Prod. Innovation Manag.* 18, 110–120. doi:10.1111/1540-5885.1820110

Najafi-Tavani, S., Zaefarian, G., Robson, M. J., Naudé, P., and Abbasi, F. (2022). When customer involvement hinders/promotes product innovation performance: The concurrent effect of relationship quality and role ambiguity. *J. Bus. Res.* 145, 130–143. doi:10.1016/j.jbusres.2022.03.001

Naseer, S., Khawaja, K. F., Qazi, S., Syed, F., and Shamim, F. (2021). How and when information proactiveness leads to operational firm performance in the banking sector of Pakistan? The roles of open innovation, creative cognitive style, and climate for innovation. *Int. J. Inf. Manag.* 56, 102260. doi:10.1016/j.ijinfomgt.2020.102260

Ovuakporie, O. D., Pillai, K. G., Wang, C., and Wei, Y. (2021). Differential moderating effects of strategic and operational reconfiguration on the relationship between open innovation practices and innovation performance. *Res. Policy* 50, 104146. doi:10.1016/j.respol.2020.104146

Papadopoulos, T., Baltas, K. N., and Balta, M. E. (2020). The use of digital technologies by small and medium enterprises during COVID-19: Implications for theory and practice. *Int. J. Inf. Manag.* 55, 102192. doi:10.1016/j.ijinfomgt.2020.102192

Qin, J., van der Rhee, B., Venkataraman, V., and Ahmadi, T. (2021). The impact of IT infrastructure capability on NPD performance: The roles of market knowledge and innovation process formality. *J. Bus. Res.* 133, 252–264. doi:10.1016/j.jbusres.2021.04.072

Ragin, C. C. (2006). Set relations in social research: Evaluating their consistency and coverage. *Polit. Anal.* 14, 291–310. doi:10.1093/pan/mpj019

Ragin, C. C. (2014). *The comparative method: Moving beyond qualitative and quantitative strategies*. La Jolla, CA: University of California Press. doi:10.1525/9780520957350

Rauter, R., Globocnik, D., Perl-Vorbach, E., and Baumgartner, R. J. (2019). Open innovation and its effects on economic and sustainability innovation performance. *J. Innovation Knowl.* 4, 226–233. doi:10.1016/j.jik.2018.03.004

Ritala, P., Huizingh, E., Almpanopoulou, A., and Wijbenga, P. (2017). Tensions in R&D networks: Implications for knowledge search and integration. *Technol. Forecast. Soc. Change* 120, 311–322. doi:10.1016/j.techfore.2016.12.020

Roh, T., Noh, J., Oh, Y., and Park, K.-S. (2022). Structural relationships of a firm's green strategies for environmental performance: The roles of green supply chain management and green marketing innovation. *J. Clean. Prod.* 356, 131877. doi:10.1016/j.jclepro.2022.131877

Sanni, M., and Verdolini, E. (2022). Eco-innovation and openness: Mapping the growth trajectories and the knowledge structure of open eco-innovation. *Sustain. Futur.* 4, 100067. doi:10.1016/j.sftr.2022.100067

Santos-Vijande, M. L., López-Sánchez, J. Á., Loredo, E., Rudd, J., and López-Mielgo, N. (2022). Role of innovation and architectural marketing capabilities in channelling entrepreneurship into performance. *J. Innovation Knowl.* 7, 100174. doi:10.1016/j.jik.2022.100174

Scaliza, J. A. A., Jugend, D., Chiappetta Jabbour, C. J., Latan, H., Armellini, F., Twigg, D., et al. (2022). Relationships among organizational culture, open innovation, innovative ecosystems, and performance of firms: Evidence from an emerging economy context. *J. Bus. Res.* 140, 264–279. doi:10.1016/j.jbusres.2021.10.065

Schneider, M. R., Schulze-Bentrop, C., and Paunescu, M. (2010). Mapping the institutional capital of high-tech firms: A fuzzy-set analysis of capitalist variety and export performance. *J. Int. Bus. Stud.* 41, 246–266. doi:10.1057/jibs.2009.36

Sheng, M. L., and Hartmann, N. N. (2019). Impact of subsidiaries' cross-border knowledge tacitness shared and social capital on MNCs' explorative and exploitative innovation capability. *J. Int. Manag.* 25, 100705. doi:10.1016/j.intman.2019.100705

Shu, C., Zhou, K. Z., Xiao, Y., and Gao, S. (2016). How green management influences product innovation in China: The role of institutional benefits. *J. Bus. Ethics* 133, 471–485. doi:10.1007/s10551-014-2401-7

Sisodiya, S. R., Johnson, J. L., and Grégoire, Y. (2013). Inbound open innovation for enhanced performance: Enablers and opportunities. *Ind. Mark. Manag.* 42, 836–849. doi:10.1016/j.indmarman.2013.02.018

Sousa-Ginel, E., Franco-Leal, N., and Camelo-Ordaz, C. (2021). Knowledge conversion capability and networks as drivers of innovation in Academic Spin-Offs. *J. Eng. Technol. Manag.* 59, 101615. doi:10.1016/j.jengtecman.2021.101615

Sultana, S., Akter, S., and Kyriazis, E. (2022). How data-driven innovation capability is shaping the future of market agility and competitive performance? *Technol. Forecast. Soc. Change* 174, 121260. doi:10.1016/j.techfore.2021.121260

Sun, Y., Liu, J., and Ding, Y. (2020). Analysis of the relationship between open innovation, knowledge management capability and dual innovation. *Technol. Anal. Strateg. Manag.* 32, 15–28. doi:10.1080/09537325.2019.1632431

Sun, Y., Sun, Y., and Liu, J. (2022). Does strategic alliance knowledge heterogeneity truly promote innovation performance? *Sustainability* 14, 3443. doi:10.3390/su14063443

Swap, W., Leonard, D., Shields, M., and Abrams, L. (2001). Using mentoring and storytelling to transfer knowledge in the workplace. *J. Manag. Inf. Syst.* 18, 95–114. doi:10.1080/07421222.2001.11045668

Tang, T., Fisher, G. J., and Qualls, W. J. (2021). The effects of inbound open innovation, outbound open innovation, and team role diversity on open source software project performance. *Ind. Mark. Manag.* 94, 216–228. doi:10.1016/j.indmarman.2021.02.013

Tanriverdi, H. (2005). Information technology relatedness, knowledge management capability, and performance of multibusiness firms. *MIS Q.* 29, 311–334. doi:10.2307/25148681

Teece, D. J. (2018). Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world. *Res. Policy* 47, 1367–1387. doi:10.1016/j.respol.2017.01.015

Tripsas, M. (1997). Surviving radical technological change through dynamic capability: Evidence from the typesetter industry. *Industrial Corp. Change* 6, 341–377. doi:10.1093/icc/6.2.341

Tsai, W. (2001). Knowledge transfer in intraorganizational networks: Effects of network position and absorptive capacity on business unit innovation and performance. *Acad. Manage. J.* 44, 996–1004. doi:10.5465/3069443

Xie, X., and Wang, H. (2020). How can open innovation ecosystem modes push product innovation forward? An fsQCA analysis. *J. Bus. Res.* 108, 29–41. doi:10.1016/j.jbusres.2019.10.011

Yao, H., and Huang, W. (2022). Effect of R&D Subsidies on External Collaborative Networks and the Sustainable Innovation Performance of Strategic Emerging Enterprises: Evidence from China. *Sustainability* 14 (8). doi:10.3390/su14084722

Yang, H., Li, L., and Liu, Y. (2022). The effect of manufacturing intelligence on green innovation performance in China. *Technol. Forecast. Soc. Change* 178, 121569. doi:10.1016/j.techfore.2022.121569

Yildirim, E., Ar, I. M., Dabić, M., Baki, B., and Peker, I. (2022). A multi-stage decision making model for determining a suitable innovation structure using an open innovation approach. *J. Bus. Res.* 147, 379–391. doi:10.1016/j.jbusres.2022.03.063

Yuan, S., Musibau, H. O., Genç, S. Y., Shaheen, R., Ameen, A., and Tan, Z. (2021). Digitalization of economy is the key factor behind fourth industrial revolution: How G7 countries are overcoming with the financing issues? *Technol. Forecast. Soc. Change* 165, 120533. doi:10.1016/j.techfore.2020.120533

Zahra, S. A., and George, G. (2002). Absorptive capacity: A review, reconceptualization, and extension. *Acad. Manage. Rev.* 27, 185–203. doi:10.5465/amr.2002.6587995

Zhang, L., Yang, W., Yang, L., and Gao, L. (2022). How does the value co-creation of e-commerce platform and manufacturers affect channel performance? The moderating role of innovation capability and market turbulence. *Electron. Commer. Res. Appl.* 52, 101120. doi:10.1016/j.elerap.2022.101120

Zobel, A.-K., Lokshin, B., and Hagedoorn, J. (2017). Formal and informal appropriation mechanisms: The role of openness and innovativeness. *Technovation* 59, 44–54. doi:10.1016/j.technovation.2016.10.001