Social media, artificial intelligence and carbon neutrality

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Social media, artificial intelligence and carbon neutrality

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Editorial: Social media, artificial intelligence and carbon neutrality

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Editorial on the Research Topic
Social media, artificial intelligence and carbon neutrality

1 Introduction

In recent years, more ambitious climate targets have been announced by countries as knowledge of the magnitude and rate of climate change has increased. Terminology like carbon neutrality has become more prevalent (Majava et al., 2022). Carbon neutrality refers to net-zero carbon emission achieved by either raising carbon adsorption or lowering carbon emissions. Many places have set out their road map to achieve the carbon neutrality goal. For example, the European Green Deal, a new growth strategy for the EU, was introduced by the EU Commission in 2019. The fundamental objective of this policy is to make the EU climate neutral by 2050 (Wyrwa et al., 2022). China, the greatest developing nation in the world, has pledged to attain carbon neutrality by 2060 and a peak in carbon dioxide emissions before 2030 to reduce the greenhouse effect (Liu et al., 2022). By 2035, Finland's government intends to be carbon neutral. The creation of low-carbon roadmaps by industry sectors has been one policy tool towards this goal. The government started developing low-carbon roadmaps in 2019, where industry sectors had to state when and how they would achieve carbon neutrality (Majava et al., 2022).

To achieve the goal of carbon neutrality with government policies, problems should be identified. Social media offers effective platforms for disseminating carbon neutrality-related information (Yao et al., 2022) and advancing environmentally friendly living practices. At the same time, AI helps us analyse big data that can be used to make policy recommendations to governments and understand how nations and governments responded to a high-risk event or an environmental disaster by looking at historical data. Given the above, this Research Topic aims to cover carbon neutrality, artificial intelligence and social media.

2 Social media and carbon neutrality

Given that previous research has overlooked social media's potential to exert pressure on corporations to disclose their carbon emissions, Shao and He examined the influence of social media pressure on corporate carbon disclosure based on legitimacy theory, using data from 3,656 Chinese listed businesses between 2009 and 2019. Computer programs classified positive, neutral, and negative sentiments comments. This study employed the Janis-Fadner coefficient (J-F) (legitimacy) to assess the legitimacy pressure on social media. It was found that the legitimacy pressure from social media considerably improved corporate carbon disclosure. Companies should put more effort into effective carbon management strategies and disclosure to achieve consistent carbon management practices.

Zeng et al. analysed Weibo and LinkedIn to learn about the public's and professionals' interest in carbon-neutral cities by comprising 533 postings (3,733 sentences) on LinkedIn and 1908 microposts (14,668 sentences) on Weibo, which is the first of its kind. The research found that organisations and the government Weibo users in the Weibo platform are key opinion leaders in this area, while the co-director of the Alliance for Carbon Neutral Cities was the most influential person on LinkedIn. As for the most popular posts, this study utilised the clustering approach, an artificial intelligence method for analysis. The most influential cluster on Weibo centred on low-carbon city development, while the largest cluster on LinkedIn was related to climate change action. In general, users on Weibo and LinkedIn focused on "energy" and related topics. A slight difference was that Weibo users concerned about green development in the building industry more, whereas LinkedIn users focused more on climate and sustainability.

3 Regulation and carbon neutrality

Because of the importance of carbon-neutral regulations and supervision, this Research Topic consists of three articles about regulations and carbon neutrality.

Gao and Gao (2022)'s study pinpointed waste disposal aids in achieving "double carbon". The most feasible waste treatment is incineration; however, the right choice of location and the legal compensation system are necessary. This project offered a dynamic environmental monitoring system for waste incineration power facilities and addressed the health risk to inhabitants based on a Gaussian model. It computed the pollutants around the waste incineration power plant by considering topography, wind direction, and other effects on pollutants' diffusion. Monitoring stations were installed, and the waste incineration's environmental monitoring system was constructed to study the concentration distribution. This study also designed economic compensation plans to inform future regulation by policymakers by considering the power plant's income, economy, government compensation, and pollution level.

Liu B. et al. suggested that through the use of media, informal environmental control has gradually shown a positive impact on green innovation as information technology has advanced. Using panel data from 285 prefecture-level Chinese cities between 2008 and 2019, this study examined how environmental legislation affected urban green innovation. Using two-way fixed-effect and mediation-effect models, they studied the impact of heterogeneous environmental legislation on urban green innovation. A negative U-shaped relationship existed between market-based and voluntary environmental regulation, whereas an inverted non-linear U-shaped relationship existed between command-based environmental regulation and urban green innovation. Their findings indicated that China's urban green innovation development was sluggish and national policies affected it. This study concluded that China needs to increase environmental regulatory efficiency to meet the country's carbon neutrality target.

Ying et al. investigated the heavy polluting-listed companies' innovation behavioural changes under the tightening environmental regulations following the "smog explosion" event as a "quasi-natural experiment" by using a differences-in-differences approach. By examining the variations in innovation behaviour of firms with varying R&D intensities and varied property rights, this study identifies the contradictory "Porter hypothesis", which proposes that polluting businesses can gain from environmental policies. The quantile regression results demonstrated a U-shaped relationship between enterprise R&D intensity and the haze treatment effect. Compared to privately owned heavy-polluting enterprises, state-owned heavy-polluting firms had a more significant decline in innovation investment.

4 Digital, technology and carbon neutrality

The remaining four articles in this Research Topic are concerned with the influence of the digital economy on carbon emissions. Wu et al. contributed to the existing scholarship by examining the regional variability and threshold effects of the influence of the digital economy on carbon emissions in addition to measuring the spatial impact of carbon emissions. It evidenced that the digital economy could reduce carbon emissions.

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In the second article, Gao et al. reviewed the information in Xinhuanet, a site for Xinhua News Agency's news releases, one prominent media for reporting on China's carbon issues. Using computational algorithm coding, the results found that digital economy transformation in reducing carbon emissions was more effective in China's central area. The effect coefficient of the digital economy was significant when the time lag of carbon emission intensity was included. In addition, local efforts to reduce carbon emissions were severely hampered by those in nearby places. It was challenging for low-tech regions to benefit from the digital economy's emission reduction benefits. Stricter environmental laws in the digital economy accelerated regional carbon emission reductions. To unleash the carbon emission reduction effect of the digital economy, China should enhance its digital infrastructure and encourage reform and innovation (Gao et al.).

Social media has developed into a vital tool for people to learn, work, and live in the era of the mobile internet. In China, there were 832 million consumers of short videos in June 2021 or 85.8% of all internet users. Based on the Stimulus–Organism–Response model, Wang and Yue explored the influence of short science videos on people's environmental willingness *via* stimulus response in the third article. This study found that short videos positively influence people's environmental willingness. This study concluded that we should focus on the emotional resonance of people's thoughts and make better use of sound and pictures to optimise the persuasive effect of short videos (Wang and Yue).

Finally, most studies neglected the impact of reducing carbon emissions on trade while concentrating primarily on the one-way effect of foreign trade on carbon emissions. In the last article, Zhang et al. (2022) examined the dynamic interactions between global business, technological innovation and carbon emissions *via* the panel vector autoregressive model. They demonstrated that whereas international trade and carbon emissions were mutually hindering, technological advancement and improving carbon emissions mutually supported each other. While the Chinese doing business abroad faced challenges in overcoming carbon-related trade obstacles, innovations in low-carbon technologies were essential to this procedure.

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.

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Achieving Carbon Neutrality – The Role of Heterogeneous Environmental Regulations on Urban Green Innovation

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This article examines the impact of heterogeneous environmental regulations on urban green innovation using panel data from 285 prefecture-level cities in mainland China from 2008 to 2019. From the perspective of green patents, this article utilizes a two-way fixed-effect model and the mediation effect model to examine the mechanism of the impact of heterogeneous environmental regulations on urban green innovation in China. Results show that the urban green innovation development in China is relatively slow and can be easily influenced by national policies. More specifically, the relationship between the command-based environmental regulation and urban green innovation presents an inverted non-linear U-shaped model, whereas the relationship between the market-based and voluntary environmental regulation presents a positive U-shaped model. Further investigation of this mechanism concludes that the progression of regional green innovation is primarily accelerated by technological development, effective energy allocation, and industrial structural upgrading. However, the implementation of relevant environmental regulations varies, resulting in various green innovation progression rates. Therefore, in order to achieve the carbon neutrality goal that China proposes, the effectiveness of environmental regulation implementation should be improved. Moreover, the development of various environmental regulation tools should be better coordinated.

Keywords: carbon neutrality, heterogeneous environmental regulation, green innovation, green patent, two-way fixed model, mediation effect

HIGHLIGHTS

- We measure the level of green innovation in Chinese cities from the perspective of green patents.
- We subdivide the types of environmental regulation into three types: command, market, and voluntary.

- We find an inverted U-shaped non-linear relationship between command-based environmental regulations and urban green innovation, while market-based and voluntary environmental regulations have a positive U-shaped non-linear relationship with them.
- We find that environmental regulations promote the level of green innovation in cities mainly by exerting technological progress, energy allocation and structural upgrading effects.
- We find that environmental regulation implementation has a heterogeneous impact on urban green innovation.

INTRODUCTION

Since the economic reform and the 1978 Open Door Policy, China's economy has experienced decades of rapid growth. However, this extensive GDP-based development model has resulted in significant resource waste and environmental damage (Tian et al., 2016). To address the problems caused by the extensive development model with high energy consumption, China's economic development has gradually shifted from high-speed growth to high-quality growth (Fu et al., 2021; Khan et al., 2022). The main challenge of long-term economic development has been balancing environmental regulation and economic benefits during the transformation process (Sun et al., 2021; Llanos et al., 2022). Because of the high externality of environmental problems, the government must use regulation to restrain business pollution behavior in policy evaluation (Su and Jiang, 2021; Cui Y. et al., 2022). According to the "Porter hypothesis," "adequate environmental regulation will stimulate technological innovation (Karmaker et al., 2021; Zhu et al., 2021)." Therefore, in order to achieve coordinated economic growth and environmental protection, it is critical to accelerate the transformation of innovative ways to break through the current development bottleneck (Usman et al., 2022).

To address the environmental pollution problem caused by a resource-intensive economic development model, the Chinese government has enacted a series of policies to strengthen environmental control (Sun and Wang, 2021). However, the impact of environmental control falls short of expectations. At the same time, due to regional differences in development, spatial agglomeration of environmental pollution becomes a pressing issue, making government governance more difficult (Du and Li, 2021; Gan et al., 2021; Hu et al., 2022). Resolving the contradiction between economic development and environmental pollution is critical for the green and high-quality development of regional economies (Shuai and Fan, 2020; Weng et al., 2020; Zhou D. et al., 2022). As an essential component of carbon-neutral development, urban green innovative development has significant theoretical and practical significance (Ley et al., 2016; He, 2019). As a result, strengthening cities' green innovation capabilities has emerged as a key driver of long-term economic growth (Zhao X. et al., 2022). However, there are few market incentives for green innovation due to the externality of the technology and financial markets (Fang et al., 2022; Li Y. et al., 2022; Yuan and Cao, 2022). At the same time, due to the path-dependent effect, a large amount of R&D resources flow to polluting technologies may lead to technology lock, making it difficult to meet social needs (Blackman, 2010; Aghion et al., 2016; Stern and Valero, 2021). To intervene and regulate, the government must implement appropriate policy measures.

Besides, the government's informal environmental regulations actively guide green innovation (Wang and Jiang, 2021; Qiu et al., 2022). With the advancement of information technology, informal environmental regulation has gradually demonstrated a positive impact on green innovation through the use of media (Tziva et al., 2020; Din Dar et al., 2021). Informal and formal environmental regulations led by the government both play important roles in promoting regional green innovation and development (Desheng et al., 2021; Zhao L. et al., 2022). Consequently, based on the development of a carbon-neutral background, we attempt to relate research results at home and abroad based on an analysis of formal and informal environmental regulation's influence on urban green innovation and its mechanism of action (Yasmeen et al., 2020). Looking for the "double win" of economic growth and environmental protection path. has significant practical significance for China's long-term and stable economic growth and sustainable development (Shen et al., 2020).

This manuscript may make the following theoretical contributions to existing research: First, from a micro perspective, this manuscript explains the impact of heterogeneous environmental regulation at the city level on green innovation and identifies the factors influencing the growth of urban green innovation. Second, this manuscript explains the mechanisms of formal and informal environmental regulation on green innovation from a city-level perspective. Finally, this manuscript examines the impact of environmental regulation implementation in the context of geographical and scale heterogeneity. This study's findings may provide theoretical support for promoting carbon neutrality and a carbon peak in China and the rest of the world.

LITERATURE REVIEW

In the extant literature, scholars have focused on three aspects of environmental regulation and regional green development (Wei et al., 2017; Sun et al., 2022; Zhu and Tan, 2022). First, they support the Porter hypothesis, which argues that reasonable environmental regulation policies can stimulate the innovation potential of enterprises and increase their productivity levels (He et al., 2020; Nie et al., 2021). The implementation of environmental regulations has a significant impact on green total factor productivity (Zhang et al., 2011; Tang et al., 2020). Furthermore, scholars have discovered that the stronger the environmental regulation policies introduced by the government, the lower the emissions of pollutants can be observed (Laplante and Rilstone, 1996; Dasgupta et al., 2001). Meanwhile, the external pressure exerted by environmental regulation on firms can effectively overcome firms' organizational inertia, thus creating a mutually reinforcing relationship with the firms' internal governance mechanisms (Ambec and Barla, 2002; Ma and Li, 2021). Secondly, neoclassical economists suggest that environmental regulation exacerbates the level of additional capital investment by firms (Cai and Ye, 2020; Gallen and Winston, 2021), which gradually reduces the funds available for R&D and innovation, thereby inhibiting technological innovation and discouraging productivity and market competitiveness (Fisher and Peterson, 1976; Chen Y.-E. et al., 2021). This is a reflection of the "compliance cost effect" of environmental regulation (Ding et al., 2022). From the perspective of the cost of environmental management, it is argued that the implementation of environmental regulation policies is detrimental to the improvement of environmental quality, and that strict environmental regulation policies have a negative impact on the emission reduction and corporate performance of pollution-intensive firms (Greenstone, 2001; Lanoie et al., 2007). Third, there is uncertainty about the impact of environmental regulation on regional green development, with environmental regulation stimulating environmental R&D but showing a crowding-out effect on non-environmental R&D (Kneller and Manderson, 2012). Meanwhile, there is also significant regional variability in the impact of environmental regulation policy implementation on green total factor productivity in China due to different political attributes of cities (Li and Wu, 2017).

Researchers are divided on the relationship between environmental regulation and regional green development (Kemp and Pontoglio, 2011; Kneller and Manderson, 2012). Some academics fail to recognize the heterogeneity created by various environmental regulation tools, as well as the critical role that heterogeneous environmental regulation tools play (Wei et al., 2017). Some scholars have also studied the impact of heterogeneous environmental regulations on green total factor productivity (Luo et al., 2021), urban environmental pollution (Lu et al., 2021), and corporate green technological innovation (Shen et al., 2019), improving the research on the economic and social impacts of environmental regulations. However, few scholars have explored from the perspective of green patenting to discuss the impact of heterogeneous environmental regulations on urban green innovation in depth (Xie et al., 2017; Guo and Yuan, 2020). Therefore, this manuscript uses panel data from prefecture-level cities in China from 2008 to 2019 to reflect the level of urban green innovation based on green patent information, and analyzes the impact and mechanism of heterogeneous environmental regulation on urban green innovation using a bidirectional fixed effect model and intermediary effect. More discussion of the various impacts of different geographical locations and city scales is required in order to develop reasonable environmental governance policies for the region, promote regional green development, and achieve carbon neutrality goals.

THEORETICAL ANALYSIS AND RESEARCH HYPOTHESIS

Achieving the goal of carbon neutrality requires not only a strong public awareness of environmental protection and resource conservation, but also the introduction of relevant government policies and measures by the government (Wang X. et al., 2022; Yamazaki, 2022). There has been discussion about whether the innovation compensation effect or the cost effect of environmental regulation should be used as an important regulatory tool for limiting businesses' pollution emission behavior (De La Peña et al., 2022; Liu X. et al., 2022). To facilitate an in-depth analysis of the differences in the effects of different types of environmental regulations on urban green innovation, this manuscript further classifies environmental regulations into command-based, market-based, and voluntary environmental regulations (Li and Du, 2021; Wu and Lin, 2022). In the short term, the implementation of these policies may increase the input costs of enterprises and have a negative impact on their economic efficiency and green development (Li et al., 2019). However, from a long-term perspective, this will help enterprises to improve their production processes and advance their green technologies (Wei and Wang, 2021), thus enhancing the overall sustainable development of the region (Wang and Wang, 2021; Lim et al., 2022). The market-based environmental regulation focuses on the emissions trading mechanism and subsidies for energy saving and emission reduction proposed by the government and uses market forces to promote win-win development for both economic efficiency and emission reduction (Yu et al., 2022). Voluntary environmental regulation, on the other hand, emphasizes people's opinions on the supervision and implementation of environmental pollution control (Yang et al., 2020; Liu Z. et al., 2022), and is more of a spontaneous act (Hamamoto, 2006; Hu et al., 2020). Considering the variability in the impact of different types of environmental regulation on regional green development and the fact that improving urban green development requires disruptive technological innovation, this manuscript proposes the following hypothesis.

> *Hypothesis 1: Heterogeneous environments have a significant effect on the level of green innovation in cities, and there may be a non-linear relationship.*

To achieve green and innovative development in a region, we must not only increase investment in technological R&D, but also adjust and optimize the structure of energy production and consumption (Ouyang et al., 2020). During this process, the technology progress effect, energy allocation effect, and structural upgrading effect all play a role in promoting urban green innovation (Kellogg and Reguant, 2021). As a result, this manuscript considers its indirect impact as well.

(1) The technological progress effect. With the introduction and implementation of government policies on environmental regulation, higher requirements are imposed on enterprises' emission standards and equipment (Wang H. et al., 2022; Xiang et al., 2022). Forcing them to carry out technological innovation to fulfill their emission reduction targets and responsibilities, thereby achieving more effective low-carbon development of the regional economy (Chen Z. et al., 2021; Wang and Feng, 2021). On the one hand, environmental regulations may lead to an increase in the cost of treatment and a serious imbalance in the efficiency of inputs and outputs at the early stage of policy implementation, thus aggravating the degree of

resource mismatch (Hao et al., 2020; Peng et al., 2021). On the other hand, environmental regulations can help promote technological innovation, improve production efficiency and environmental protection awareness, fully reflecting the innovative compensation effect of environmental regulation (Cui S. et al., 2022; Zhong and Peng, 2022). It can also be seen that improving the level of technological progress plays an important role in raising the level of green innovation in cities (Fan et al., 2021). In addition, relevant studies have confirmed the positive and significant effect of green technological innovation on environmental performance (Liu Y. et al., 2020; Lv et al., 2021), which further reflects the indispensable status of improving the level of technological progress.

(2) The energy allocation effect. Controlling the use of fossil energy such as coal and increasing the proportion of clean energy is an effective way to achieve green development in the regions (Jie et al., 2021). The energy allocation effect is mainly reflected in the fact that environmental regulations can influence the energy structure of enterprises and encourage enterprises to increase the proportion of the usage of clean energy to reduce carbon emissions (Chen et al., 2022; Li W. et al., 2022). While the use of clean energy mainly involves the power industry, in order to improve the efficiency of energy use in the power industry more effectively (Miniard and Attari, 2021), it is necessary to use energy-saving and emission-reducing technologies and equipment to promote clean and low-carbon development in the regions.

(3) The structural upgrading effect. The main effect of structural upgrading is that environmental regulation can affect the imbalance of inter-industrial structure (Zhang et al., 2019), promote the transformation and upgrade the industrial structure (Yu and Shen, 2020), and then improve the advanced level of industrial structure (Zhou et al., 2020). The implementation of environmental regulation policies can have a positive impact not only on the proportion of different industries, but also on each industry's labor productivity (Zhang et al., 2022a). Furthermore, it can increase the proportion of the tertiary industry, promote green transformation and secondary industry development (Zhou and Tang, 2021), and gradually reduce regional carbon emissions, all of which contribute to the goal of coordinated emission reduction and green development (Zheng et al., 2019; Zhang et al., 2021). To this end, this manuscript puts forward the following hypotheses.

Hypothesis 2: Heterogeneous environmental regulation promotes the improvement of green innovation levels in cities by increasing the level of technological progress.

Hypothesis 3: Heterogeneous environmental regulations promote green innovation in cities by optimizing energy allocation.

Hypothesis 4: Heterogeneous environmental regulation promotes a higher level of green innovation in cities by facilitating the upgrading of industrial structures.

RESEARCH DESIGN

Model Construction

In order to explore the interaction between environmental regulation and urban green innovation, this manuscript builds up a model to study different types of environmental regulation accordingly, and considers the possible linear and non-linear factors of environmental regulation on urban green innovation. The specific model is set up as follows.

$$lngreen_{it} = \alpha_0 + \alpha_1 \sum_{j=1}^{3} En_{jit} + \alpha_2 control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

$$lngreen_{it} = \beta_0 + \beta_1 \sum_{j=1}^{3} En_{jit} + \beta_2 \sum_{j=1}^{3} En_{jit}^2 + \beta_3 control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

Where i and t represent city and year, respectively. $green_{it}$ represents the level of green innovation in the city; En represents the level of environmental regulation and j represents the type of environmental regulation; En^2 represents the quadratic term of environmental regulation; $control_{it}$ represents a set of control variables; $\mu_i$is the individual city fixed effect, i.e., it also reflects the regional fixed effect; γ_t is the time fixed effect; and ε_{it} is the random error term.

Selection and Description of Variables

Explanatory variable: urban green innovation (green). The explained variable in this manuscript is the level of urban green innovation. Previous research has found that the level of patented technology is an important indicator of a region's ability to innovate (Milani and Neumann, 2022). Green innovation focuses on the development of environmental protection and economic growth (Yin and Xu, 2022). Hence, based on previous research, relevant data on green patents in prefecture-level cities is collected as a proxy variable to measure urban green innovation (Zhang et al., 2022b; Zhou G. et al., 2022).

Core explanatory variables: (i) command-based environmental regulation (En_1), the number of environmental agency employees in each region is used to characterize the model; (ii) market-based environmental regulation (En_2), the number of sewage charges levied in each region is chosen as a proxy; (iii) voluntary environmental regulation (En_3), the number of environmental proposals made by the National People's Congress and the Environmental Protection Association in each region is chosen as a proxy.

Control variables: In order to avoid the omission of variables that may produce errors in the model regression results, the following control variables are selected for this study. (1) the level of economic development (*pgdp*), the strength of a region's economic development will have an important impact on the level of regional innovation input, so this manuscript uses each city's current year's GDP and year-end resident population to measure; (2) the urbanization rate (*urban*), using each city's current year's urban population and year-end total resident population to measure; (3) The level of industrial structure (*IS*), characterized by the share of the secondary sector in the total gross industrial product of each prefecture; (4) level of transport infrastructure (*road*), characterized by the area occupied by roads per capita in each prefecture-level city.

Data Sources

This manuscript investigates panel data from Chinese prefecture-level cities. The data came primarily from the China Urban Statistical Yearbook, the China Statistical Yearbook, the China Environmental Statistical Yearbook, prefectural city statistical yearbooks, and official government websites. Some prefecture-level cities have been removed due to significant data gaps, and some missing data has been supplemented using the interpolation method. Finally, this study includes 285 prefecture-level cities' data in China from 2008 to 2019. To avoid the effects of dimensional error, the raw data were logarithmically processed, and all price data was treated as constant price in 2008 as the base period. The results of descriptive statistics for the variables are shown in **Table 1**.

ANALYSIS OF THE EMPIRICAL RESULTS

Direct Effect Test Results

This manuscript conducts regression analysis from both linear and non-linear aspects in order to more effectively analyze the differences in the effects of different types of environmental regulations on urban green innovation. The regression results are shown in **Table 2**.

The results of the direct effects of different types of environmental regulation on urban green innovation in **Table 2** reveal that for the linear regression results of model (1), command-based environmental regulation, being significantly positive at the 5% level, has a more significant contribution to the increase in the level of urban green innovation. Market-based environmental regulation also contributes to the increase of urban green innovation, while voluntary environmental regulation has an inhibitory effect on urban green innovation. From the non-linear regression results in model (2), the relationship between command-based environmental regulation and green innovation shows an inverted U-shape, while the relationship between market-based and voluntary environmental regulation and green innovation shows a positive U-shape (Liu J. et al., 2020). The possible reason is that the government's initial policy intensity will show a downward trend, and market-based environmental regulation measures will gradually stabilize and increase the promotion effect on the level of urban green innovation (Liu Y. et al., 2020). Simultaneously, the popularization and development of Internet technology raise public awareness of environmental protection and supervision, thereby contributing to the region's promotion of green development (Huang and Chen, 2022).

Among the control variables, the level of economic development has a significant positive contribution to urban green innovation, while the urbanization rate, the level of industrial structure and the level of transport infrastructure have a negative relationship with green innovation, which indicates that the long-term innovative development of a region cannot be achieved without the support of economic strength. Meanwhile, it is also necessary to accelerate the optimization of the level of industrial structure upgrading, and reduce the environmental pollution which may be generated in the process of urbanization.

TABLE 1 | Descriptive statistics of the selected variables.

Variables	Sample size	Maximum value	Minimum value	Mean value	Variance
Green	3420	3.657	0	0.149	0.282
En_1	3420	1.236	0.036	0.124	0.092
En_2	3420	2.575	0.923	0.983	0.832
En_3	3420	1.028	0.012	0.234	0.362
pgdp	3420	13.053	4.425	9.082	1.082
Urban	3420	0.952	0.275	0.558	0.091
Us	3420	0.923	0.09	0.326	0.132
Road	3420	8.236	2.634	4.023	2.917

TABLE 2 | Test results for linear and non-linear effects of environmental regulation on urban green innovation.

Variables	(1)	(2)
En_1	0.109** (2.302)	0.085** (2.127)
En_2	1.013** (2.014)	0.054** (2.419)
En_3	−0.089* (−1.851)	0.964** (2.043)
$En_1{}^2$		0.548* (1.916)
$En_2{}^2$		1.254*** (2.724)
$En_3{}^2$		1.228** (2.450)
pgdp	1.528*** (3.125)	0.873** (2.501)
urban	−0.547** (−2.147)	−0.752** (−2.210)
us	−1.128** (−2.051)	−0.642* (−1.953)
road	−0.223** (−2.062)	−0.347** (−2.127)
Cons	3.185** (2.148)	4.042** (2.429)
R^2	0.463	0.628
F-statistic values	5.426	7.253
Sample size	3420	3420

**, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.*

Endogeneity and Robustness Tests of the Model

Endogeneity Discussion

When analyzing the impact of environmental regulation on urban green innovation, endogenous problems should be taken into account during the model-building process. The main reason for this is that there is a reverse causal relationship between the three types of environmental regulation tools in the explanatory variables and the level of green innovation in the explained variables, which causes the model estimation coefficient to be biased or inconsistent, affecting the accuracy of the estimation results. Therefore, this manuscript builds upon the ideas of previous studies and considers the lagged period of the three environmental regulation tools as the instrumental variable for analysis for the first time. Secondly, considering that only using the lagged period of data for regression may not be convincing, this manuscript further adopts the area of rivers in each region as the instrumental variable. This is because areas with more rivers are more likely to discharge wastewater, and other wastes into rivers, and for this reason, the government reduces the discharge of wastes by formulating corresponding policy measures. Furthermore, there are significant differences in the discharge capacity of rivers in areas with different intensities of environmental regulation. At the same time, changes in river area do not have a direct impact on a region's level of green development, and there is no endogeneity problem in choosing the river area as an instrumental variable.

Table 3 shows the regression results for the two-stage least squares test of endogeneity, with IV(1) and IV(2) showing the estimates using the lag and river area of different types of environmental regulation instruments as instrumental variables, respectively, and IV(3) showing the regression results using the lag and river area of environmental regulation instruments together as instrumental variables. As can be seen, the significance of the coefficients on the lagged term of environmental regulation, river area and the interaction term does not differ significantly when the endogeneity of the model is verified, which also indicates the robustness of the regression results.

Robustness Tests

After discussing the possible endogeneity of the model set, there is still a need to consider whether there is any impact on the accuracy of the regression results due to the unreasonable selection of variable indicators and selective errors in the sample. Therefore, the method of replacing the explanatory variables and samples was used to conduct the robustness test analysis.

TABLE 3 | Regression results for the instrumental variables approach.

Variables	IV (1)	IV (2)	IV (3)
En_1	0.205** (2.204)	0.319** (2.413)	0.115*** (2.745)
En_2	0.098** (2.054)	1.425** (1.995)	1.082** (2.253)
En_3	−0.342* (−1.721)	−0.573* (−1.840)	−0.263* (−1.826)
pgdp	1.413** (2.296)	1.208** (2.005)	0.909*** (2.702)
Urban	−0.603** (−2.184)	−1.008** (−2.325)	−0.815**(−2.092)
Us	−1.108* (−1.814)	−0.765** (−2.015)	−1.013** (−2.014)
Road	−0.345* (−1.726)	−0.453* (−1.853)	−0.853* (−1.905)
Cons	2.258** (2.427)	3.109*** (3.048)	1.047*** (2.835)
Phase I *F*-value	15.236***	20.361***	18.013***
Phase I *P*-value	0.000	0.000	0.000
R^2	0.563	0.642	0.758

**, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.*

(1) Substitution of explanatory variables. The size of a region's green innovation level is not only reflected in the output of patents, but also has an important impact in terms of R&D investment. To this end, this manuscript uses the share of R&D investment in total GDP for each region to conduct the analysis. The regression estimation results are shown in columns (1) and (2) in **Table 4**, where (1) is using the fixed effects model and column (2) is the regression analysis result of 2SLS. It can be seen that the regression coefficients of urban green innovation are all significantly positive at the 5% level, confirming the robustness of the regression results.

(2) Analysis of the excluded samples. Since the data sample of municipalities directly under the Central Government has a high strength of economic development, it may have a biased impact on the regression results, as this manuscript further excludes these special samples and conducts the regression again. The regression results are shown in columns (3) and (4) of **Table 4**, and the regression coefficients are still significantly positive, indicating the reasonableness of the regression results.

Testing the Indirect Effect Mechanism

The previous sections have conducted an in-depth study on the impact of different types of environmental regulations on urban green innovation, but the mechanism behind it still needs to be explored further.

$$lngreen_{it} = \delta_0 + \delta_1 \sum_{j=1}^{3} En_{jit} lntec_{it} + \delta_2 \sum_{j=1}^{3} En_{jit} lnes_{it} + \delta_3 \sum_{j=1}^{3} En_{jit} lnsu_{it} + \mu_i + \gamma_t + \varepsilon_{it} + \delta_4 control_{it} \quad (3)$$

Among them, *tec, es,* and *su* are mediating variables. tec represents the effect of technological progress, which is represented by the number of patents granted per capita in each region; es represents the effect of energy allocation, which is represented by the share of coal energy consumption in total energy consumption in each region; *su* represents the effect of structural upgrading, which is represented by the share of industrial value-added in total GDP in each region.

Table 5 shows the regression results of the indirect effects of different types of environmental regulations on urban green innovation. This may be because local enterprises rely more on policy or market-driven actions are lacking a sense of spontaneity. For the energy allocation effect, all three types of environmental regulation tools have positive contributions to the transformation of the regional energy structure. In terms of the energy allocation effect, all three types of environmental regulation tools promote regional energy structure transformation. To achieve green urban development, we must first transform the traditional industrial structure, which is marked by high energy consumption, pollution, and emissions, and

TABLE 4 | Regression results of robustness tests.

Variables	Green		Green	
	FE (1)	2SLS (2)	FE (3)	2SLS (4)
En_1	0.341** (2.214)	0.369** (2.204)	0.418** (1.993)	0.247** (2.218)
En_2	0.142** (2.068)	0.245** (2.342)	0.312** (2.304)	0.328** (2.360)
En_3	−0.478** (−2.061)	−0.617** (−2.247)	−0.327** (−2.259)	−0.365** (−2.107)
pgdp	0.952** (2.201)	0.847** (2.218)	0.642* (1.717)	0.542** (2.305)
Urban	−0.542* (−1.768)	−0.238** (−2.341)	−0.413** (−2.218)	−0.340** (−2.042)
Us	−0.978** (−2.042)	−0.704* (−1.742)	−0.849** (−2.240)	−0.865** (−2.118)
Road	−0.449** (−2.014)	−0.508** (−2.246)	−0.679** (−2.342)	−0.457** (−2.149)
Individual effects	YES	YES	YES	YES
Year effects	YES	YES	YES	YES
N	3420	3420	3372	3372
R^2	0.758	0.769	0.801	0.657

*, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.

TABLE 5 | Examining the mechanisms by which environmental regulation affects urban green innovation.

Variables	Technological progress effect	Energy allocation effect	Structural upgrading effect
En_1	0.425** (2.018)	0.347** (2.452)	0.253 (1.415)
En_2	0.230*** (2.818)	0.249** (2.215)	0.302* (1.746)
En_3	0.302 (1.542)	0.446* (1.813)	0.346** (2.260)
pgdp	0.982*** (3.327)		
Urban	−0.823** (−2.342)		
Us	−1.225** (−2.054)		
Road	−0.354** (−2.304)		
Cons	3.185** (2.058)	2.825*** (3.249)	4.237*** (4.315)
N	3,420	3,420	3,420
R^2	0.768	0.742	0.847

*, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.

then gradually increase the clean energy input and use ratio. As a result, whether through policy formulation and implementation, market competition, or public oversight, it plays a critical role in promoting a region's long-term development. Simultaneously, the correlation coefficient of command environmental regulation on urban green innovation is insignificant in terms of impact on industrial structure upgrading, because policy implementation has a lag, and industrial structure transformation and upgrading also takes time. Market-based environmental regulation and voluntary environmental regulation take changes in the market environment and regional development strategy into account, and optimize industrial upgrading to increase the level of urban green innovation.

Heterogeneity Analysis

(1) Impact of regional heterogeneity on urban green innovation.

Because of China's vast land area, it is necessary to focus on regional differences in economic development strength, resource endowment, and geographic location, which will result in some opposition to environmental regulation policies. Eastern China, for example, has a robust economy and a well-balanced industrial structure, whereas the central and western regions are still in the early stages of development. Based on this, the sample's prefecture-level cities are further subdivided into eastern, middle, and western cities, and regression is run sequentially to investigate differences in regression results.

(2) The impact of city size heterogeneity on urban green innovation.

In addition to regional heterogeneity, the size of cities and changes in population may also have an impact on the effect of environmental regulations in promoting the development of regional green innovation. For this reason, this manuscript refers to previous studies and classifies cities into five types, including medium, large, type II, type I, and megacities, based on their population size, and uses a benchmark regression model to verify the results, which are finally shown in **Table 6**.

Table 6 shows the heterogeneous effects of different types of environmental regulation instruments on regional levels of green innovation. By comparing the differential results across geographical locations and city sizes, it can be seen that there are significant differences in the effects of environmental regulation. Firstly, in terms of the effect of regional heterogeneity, the promotion effect of command-based environmental regulation on urban green innovation is significantly stronger in the western region than in the eastern and central regions, probably because the western region relies more on policy guidance and implementation due to its weaker economic development strength, resource endowment and technological innovation level, while the level of openness to the outside world in the western region is also prone to problems. At the same time, due to the geographical distribution of the western region, the level of openness to the outside world is easily restricted, which also results in stronger command-based environmental regulation than market-based and voluntary environmental regulation. From the perspective of city size heterogeneity, the impact of environmental regulations on the level of green innovation varies significantly between cities of different sizes. From the regression results, the increasing size of cities leads to a diminishing role of command and voluntary environmental regulations, while the effect of market-based environmental regulations tends to increase. This could be due to increased city size resulting in a more pronounced concentration of different factors and resources, but it also

TABLE 6 | Heterogeneity regression results of environmental regulation on urban green innovation.

Variables	Different geographical locations			Different city sizes				
	East	Central	West	Medium	Large	Type II	Type I	Extra large
En_1	0.625*	0.529**	0.436***	1.753***	1.532**	0.872**	0.658**	0.779*
	(1.725)	(2.108)	(2.913)	(3.352)	(2.142)	(2.036)	(1.985)	(1.826)
En_2	0.817***	0.704**	0.532*	1.941**	1.026**	1.172***	0.672***	0.824***
	(2.718)	(2.362)	(1.942)	(2.143)	(2.242)	(2.632)	(2.728)	(3.126)
En_3	−1.248**	−0.935**	−1.462	−1.425**	−0.834**	−0.472**	−0.564*	−0.823*
	(−2.023)	(−2.247)	(−1.515)	(−2.350)	(−2.213)	(−2.032)	(−1.883)	(−1.726)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES
Time effects	YES	YES	YES	YES	YES	YES	YES	YES
Area effects	YES	YES	YES	YES	YES	YES	YES	YES
R^2	0.752	0.814	0.802	0.741	0.653	0.692	0.641	0.608

*, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.

comes with increased difficulties in city management, more prominent environmental pollution emissions, and less apparent technological spillover effects.

CONCLUSION AND POLICY RECOMMENDATIONS

Research Conclusions

Cities are in a pioneering position in achieving the goal of carbon neutrality, and it is important to accelerate the development of green transformation in cities and enhance technological progress to promote high-quality regional economic development. Therefore, this manuscript starts from the perspective of green patent, based on the panel data of 285 prefecture-level cities in mainland China from 2008 to 2019, uses a two-way fixed-effects model and a mediating-effects model to study the changes in the influence of different types of environmental regulation tools on urban green innovation. It also analyses the mechanism of their impacts and draws the following main conclusions: (1) Overall, the development of urban green innovation in China is slow and heavily influenced by national policies. (2) The impact of different types of environmental regulation tools on urban green innovation differs, with command-based environmental regulation promoting the level of urban green innovation and an inverted U-shaped non-linear relationship between the two. Furthermore, market-based environmental regulation can improve the level of urban green innovation and a positive U-shaped non-linear relationship exists. There is a positive U-shaped non-linear relationship between the two; and voluntary environmental regulations have a suppressive effect on urban green innovation, and the suppressive effect gradually decreases as time advances. (3) The analysis of the influence mechanism shows that environmental regulations mainly enhance the level of green innovation in cities through technological progress, energy allocation and structural upgrading. (4) Heterogeneity analysis shows that the impact of environmental regulation on urban green innovation varies significantly across different geographical locations and city sizes, and the effects of different environmental regulation tools are also different.

Policy Recommendations

Based on the above findings, the following recommendations are made: (1) Enhance the implementation of environmental regulation policies and stimulate the potential of regional green development. Relevant government departments should actively formulate corresponding green development strategies, consider the actual local development situation to formulate appropriate environmental regulation policies, deepen institutional reform, and improve cities' overall green development level from a strategic level. (2) When implementing environmental regulation policies, it is critical to fully consider the characteristics of various types of environmental regulation tools as well as the effects of heterogeneous environmental regulation. In order to gradually eliminate the cost effect, subsidies for low-emission and low-pollution businesses should be increased in command-based environmental regulations. Simultaneously, improve the market's driving force for regional innovation by fostering a favorable market competition environment for the development of regional enterprises. Furthermore, for market-based and voluntary environmental regulations to effectively promote regional green innovation, public awareness of environmental protection and oversight should be increased. (3) Further improve technological innovation capabilities, focus on improving the coordination and balance of industrial structures between regions, and adjust the proportion of energy structures. Specifically, the role of heterogeneous environmental regulations for urban green innovation is mainly achieved by raising the level of technological progress, optimizing energy allocation and promoting structural upgrading. Therefore, it is necessary to increase the level of investment and innovation in relevant technological research and development, actively develop green technologies, set reasonable and effective entry thresholds for industries, and vigorously develop green environmental protection and energy-saving industries. At the same time, regions should also actively plan low-carbon energy development strategies, draw on advanced technologies and experiences, and improve the output efficiency of green patents, thereby accelerating regional green transformation and effectively promoting the achievement of carbon neutrality targets.

Shortcomings and Prospects

This manuscript analyzes the impact of heterogeneous environments on urban green innovation and the mechanisms of action, and subsequent research can be conducted at the firm level. Also, the impact of interactions between different types of environmental regulatory instruments can be considered.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: http://www.stats.gov.cn/.

AUTHOR CONTRIBUTIONS

BL contributed to the conceptualization, methodology, software, and writing–original draft the preparation. JW contributed to the validation and formal analysis. RYML revised, edited, and completed the manuscript. RYML and LP revised and completed the manuscript. LM revised and formatted the manuscript. All authors read and agreed to the published version of the manuscript.

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Study on the synergistic effect of foreign trade, technological progress, and carbon emissions

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A primary development plan for a country is to attain carbon neutrality and high-quality international commerce development. This study uses panel data from 30 provinces in mainland China to analyze the dynamic interplay between international trade, technological innovation, and carbon emissions. The findings show that foreign trade, technological progress, and carbon emissions all have their own "economic inertia" that can be self-motivated and self-reinforcing. Foreign commerce and carbon emissions are mutually inhibiting, but technical progress and carbon emissions are mutually reinforcing. This illustrates that achieving a positive cycle of international trade, technological improvement, and carbon emissions necessitates a significant baseline need. Overcoming carbon trade barriers is currently the most difficult challenge for Chinese enterprises involved in foreign commerce. Low-carbon technology advancements are a critical part in this process. Our research strengthens the positive connections between international trade and carbon emissions as a result of technological improvement and proposes a feasible plan for international trade to achieve carbon peaking and carbon neutrality.

KEYWORDS

foreign trade, technological progress, carbon emission reduction, carbon neutrality, PVAR model

Introduction

As the global greenhouse effect worsens, carbon emissions have become a global issue that affects production, life, and economic development. To actively address climate change, the "double carbon" target of achieving peak carbon by 2030 and carbon neutrality by 2060 was first proposed by China in September 2020 and has been regularly highlighted at important meetings and press conferences. This framework takes green development to a new level. More than 130 countries have set net-zero emission targets in laws, regulations, official documents, and statements (Zhao et al., 2022), but the uncertainty of economic policy makes carbon-trading a bad gamble from the investor's point of view (Li X. et al., 2022), which increases the difficulty in achieving low-cost carbon reductions. Foreign trade, the most basic and important aspect of a country's foreign economic linkages, incurs a large amount of carbon emissions while driving economic development (Wu et al., 2016). From 2010 to 2018, emissions produced the services sector grew at an average rate of +1.34% per year, accounting for nearly 30% of total global trade emissions (Huo et al., 2021). Therefore, there is still a long road of green trade development to go before reaching peak carbon and then realizing carbon neutrality.

The responsibility for carbon emissions is mostly attributed to the production side rather than to consumers, which raises the questions of the flow and measurement of so-called "implied carbon" produced in international trade (Meng et al., 2018). Developed countries have achieved economic leapfrogging through trade activities, which has led to the phenomena of pollution havens and carbon displacement (Lin et al., 2017; Lin and Xu, 2019; Wang et al., 2019; Wen and Wang, 2019; Su et al., 2021). In the context of trade liberalization, countries around the world are also lowering their environmental standards as a sacrifice to maintain their international competitiveness. The "race to the bottom" phenomenon has emerged. The environmental problems caused by trade activities cannot be underestimated. The strong environmental controls imposed by governments have also had a negative impact on foreign trade. On the one hand, environmental regulation has given rise to a new technological innovations and promoted dynamic competition in international technology trade and technology transfer. On the other hand, the potential conflict between unilateral trade measures and multilateral trade rules for a low-carbon economy is increasingly exposed. Carbon labeling (Xu and Lin, 2021; Lohmann et al., 2022) and carbon tariffs (Fang et al., 2020; Zhu et al., 2020) have become new trade barriers and have a huge impact on trade structure. This study attempts to resolve the contradiction between carbon emissions and foreign trade. We will explore the realistic path of the systematic green trade system in China.

Technology is widely recognized as the key to addressing global climate change and achieving carbon emission reduction. Technological progress is essential to reducing carbon emissions (Erdogan, 2021). However, the effect of technological progress is not simple and straightforward to achieve. Sometimes, the siphoning effect of technological progress is accompanied by increased environmental pollution (Liu et al., 2022). Therefore, it is of great practical significance to clarify the role of technological progress in achieving carbon emissions reduction.

Most of the existing literature examining the impact of foreign trade on carbon emissions is based on input–output models (Chen and Chen, 2011; Kim and Tromp, 2021), the general equilibrium model (Guo et al., 2021), the dynamic panel data model (Sharma, 2011), and time series models (Kanjilal and Ghosh, 2013). Most researchers focused only on the unidirectional effect of foreign trade on carbon emissions while neglecting the effect of carbon emission reduction on foreign trade. Few studies in the literature have focused on technological progress in the context of the relationship between foreign trade and carbon emissions. In this paper, the researcher will first review the existing literature to sort out the interactions between foreign trade and carbon emissions and consider the lagged effect of carbon emissions. Second, the researcher will introduce an overall technological progress indicator to better explore the inherent synergy between foreign trade in the process of technological progress and carbon emissions. Third, the researcher will construct a panel vector autoregressive model (PVAR), which can effectively circumvent the overly complicated endogeneity and theoretical discussions between foreign trade and carbon emissions and analyze the two-way causality between them, unlike the unidirectional impact of foreign trade on carbon emissions or the impact of carbon emissions on foreign trade.

Literature review

The study of foreign trade and carbon emissions has been an issue of academic interest in recent years. From an ex-ante perspective, some researchers have modeled the potential impact of international trade policies on carbon emissions. The carbon reduction effect varies with the difference of trade policy. Excessive export tax rebate policies can cause overproduction in highly polluting industries, but biased policy support for low-carbon enterprises will significantly reduce carbon emissions (Song et al., 2015). From an ex-post perspective, the effect of foreign trade on carbon emissions reduction is specifically summarized as three types: positive, negative, and uncertain. Some researchers have argued that foreign trade has shown strong momentum in the development of a low-carbon economy. Renewable energy plays an important role in reducing greenhouse gas emissions (Yuan et al., 2022). Trade liberalization occurs to promote the use of renewable energy in the long or short terms through technological effects rather than scale and structural effects (Zhou and Li, 2022). Carbon emissions trading has a certain promotion effect on carbon emissions reduction (Li and Wang, 2022). Carbon-trading schemes can significantly improve a city's single-factor and total-factor energy efficiency through green innovation and resource allocation channels, which leads to a low-carbon transition to the developing countries (Hong et al., 2022). Although carbon trading can also increase the price of carbon trading through the crowding-out effect on firms' R&D investments, which in turn discourages green technology innovation, it can still significantly reduce carbon emissions and carbon intensity (Zhang et al., 2022). Whether from a city perspective (Yu et al., 2017), a provincial perspective (Zhang et al., 2021), or a national perspective (Wu et al., 2022), the evidence of the decoupling effects of economic growth and environmental issues all further confirms the positive effect of foreign trade on the environment. Pu et al. (2020) argued that total trade is the main factor driving the growth of carbon emissions. Trade openness (Ertugrul et al., 2016) and trade liberalization (Yang, 2001; Lu et al., 2022; Zhou and Li, 2022) have both led to an increase in CO_2 emissions. Especially in the context of growing international trade conflicts, countries are facing greater challenges in how to address environmental issues. Take Sino–United States trade as an example. The Sino–United States trade conflict not only hinders the volume of international trade but also increases the transportation distance of international trade in goods, which will adversely affect the control of carbon emissions of international shipping (Pu et al., 2020). The trade triple effect theory suggests that the impact of foreign trade on the environment depends on the combined effects of scale, structure, and technology effects (Grossman and Krueger, 1995). By comparing import and export data from seven ASEAN countries, the researchers found that higher population correlated with increased carbon emissions but that technological innovation significantly reduced them through increased energy efficiency (Salman et al., 2019). The same conclusion is reached through decomposing the environmental Kuznets curve into size, technology, and composition while incorporating the role of trade openness and foreign direct investment (FDI) effects into the United States carbon emissions function (Shahbaz et al., 2019). Studies on developed and less-developed countries also differ. Some of the literature has suggested that trade openness reduces carbon emissions in high- and upper-middle-income countries, but trade openness increases carbon emissions in low-income countries (Wang and Zhang, 2021). Some researchers have also made opposite arguments by breaking down trade into exports and imports. They argued that imports have a negative effect on the intensity of CO_2 emissions in African countries, whereas exports have the opposite effect (Huang et al., 2022). However, both exports (i.e., production-side emissions) and imports (i.e., consumption-side emissions) are driving the increase in emissions in South Korea (Kim and Tromp, 2021). Carbon transfer in developed countries has been criticized by other countries, but its contribution to carbon reduction seems to be underestimated. The study found that without Germany, global embodied CO2 emissions would increase by an average of 1.53%, its participation in international trade has contributed to carbon reductions in developing countries, particularly China and Russia (Li R. et al., 2022).

The importance of technological progress in alleviating environmental pressures cannot be overstated. The dominant technology progress contributes to the reduction of CO_2 (Leitão et al., 2022). Eco-friendly technologies can mitigate or even eliminate the harmful effects of environmental quality (Erdoğan et al., 2022), especially carbon capture and storage technology (Wilberforce et al., 2021; Vaz et al., 2022). Studies on technology spillover effects also confirmed that technological progress in neighboring regions plays an important role in reducing carbon emissions (Huang et al., 2020). Technological progress does not simply exhibit a facilitating effect on carbon emissions reduction. It also increases carbon emissions, which is the rebound effect of carbon emissions. The rebound effect tends to reduce the marginal effect of carbon emissions reduction. Thus, the impact of technological progress on carbon emission reduction becomes confounded (Zhang et al., 2020). Most of the existing literature has developed a detailed analysis of regional carbon emissions from different technological pathways. Some studies have broken down technological progress into domestic innovation, foreign technology introduction, and regional technology transfer (Lin and Ma, 2022). One study used a panel data model to investigate the carbon reduction effects of technological progress at four levels: energy technology, carbon emission technology, neutral technology, and capital-embodied technology (You and Zhang, 2022). Another study deconstructed technological change into environmental technological change and production technological change and found that the relationship between technological progress and carbon emissions is complex and depends on both environmental technological change and production technological change (Chen et al., 2020). Further studies have considered carbon emissions in agriculture, industry, construction, transportation, wholesale production, and residential building from three technology channels: R&D investments, FDI-related technology spillovers, and technology spillover (Yang et al., 2021).

A large body of literature has examined only the relationship between foreign trade and carbon emissions or only the relationship between technological progress and carbon emissions. However, the literature lacks studies on the synergistic effects of foreign trade, technological progress, and carbon emissions. There is still room to expand its depth and breadth. In this paper, based on the existing literature, the researcher will introduce the overall technological progress index to explore the mechanism of synergistic effect between foreign trade, technological progress, and carbon emissions. The researcher will also explore realistic pathways to low-carbon living alongside economic growth and technological progress.

Empirical design

Model construction

Love and Zicchino (2006) and Lian and Chung (2008) extended the PVAR model after its first creation. It has, since then, become widely adopted. The model combines panel data based on the benefits of the typical VAR model without any pre-existing limits on the relationship between variables.

The lagged value of each explanatory variable is used to read the equation identically and more appropriately reflect the dynamic interactions between endogenous variables. This research develops a PVAR model to investigate the relationship among international trade, technological progress and a low-carbon economy. The model is constructed as follows.

$$G_{i,t} = \Gamma_0 + \sum_{j=1}^{k} \Gamma_j G_{i,t-j} + \varphi_i + \eta_t + \varepsilon_{i,t} \qquad (1)$$

where i is an individual, indicating different provinces; t is time, indicating different years; $G_{i,t}$ is a vector of three observable random variables for individual i at time t (i.e., three different vectors of carbon emissions, foreign trade and technological progress); Γ denotes a matrix of lagged effects of variables; k is the number of lags; φ_i is an individual fixed-effect reflecting individual heterogeneity, η_t is a time-fixed-effect term indicating the trend characteristics of the system variables; ε_{it} denotes a random disturbance term.

Selection of indicators

The two basic international trade indicators are net exports to GDP and external dependency. Foreign trade growth shows that there are different structural characteristics at different stages of economic development. Both foreign trade dependence and net exports as a share of GDP can more appropriately and scientifically depict the degree of international economic development at the appropriate stage of development. In the early days of reform and opening-up, China's economy was primarily boosted by exports. Imports appear to be minor in contrast to exports. The ratio of net exports to GDP accurately reflected international trade at that time. However, as China's economy enters a phase of rapid development, particularly during the current stage of high-quality development, imports of high-quality products, especially high-quality intermediate products, are increasing. Imports and exports are roughly equal in general. As a result, the ratio of net exports to GDP cannot adequately reflect the volume of international trade. Using the ratio of net exports to GDP as a measure of international trade is erroneous. The two indicators used to assess the extent of international trade are exports and imports. Considering the current development of import and export, this paper selects the degree of foreign dependence as the measure of international trade level.

To assess technical progress, there are three commonly used measures: output, input, and total factor productivity. Although the number of issued patents in the output method as an indicator of development has some limitations, the patent output directly reflects the degree of technological innovation. The Patent Office selects the granted patents strictly and objectively according to the criteria, so the statistics are unambiguous. Therefore, using the number of three domestic patent applications in this study as a barometer of technological improvement is well supported.

Carbon emission intensity and carbon emission efficiency are the two most important indicators of low-carbon economy. Carbon intensity refers to the ratio of CO_2 emissions to gross domestic product. It is a more accurate indication of economic health than carbon emission efficiency in the low-carbon economy. Therefore, carbon emission intensity is chosen as a measure indicator to evaluate the relationship between economic growth and carbon emissions in this study. If the province's economy expands when CO_2 emissions decreases, it indicates that the province has successfully implemented a low-carbon development strategy.

Data sources and description

Due to data availability, panel data from 30 mainland Chinese provinces from 2007 to 2019 (excluding Tibet, Hong Kong, Macao, and Taiwan) were chosen for empirical analysis. The import and export of each province, as well as GDPat provincial level, is calculated using the China Statistical Yearbook. The unit of export trade is converted to RMB by using the average exchange rate of the year. The number of three domestic patent applications can be found in the China Statistical Yearbook of Science and Technology. Due to a lack of credible data on CO_2 emissions at provincial level, the IPCC's accounting approach is adopted to calculate CO_2 emissions for each province. In this paper, eight representative energy sources, including coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, and natural gas, were selected. The carbon emissions of each province are calculated from Equation 2 by using the energy consumption of each province in the China Energy Statistics Yearbook and the relevant reference coefficients.

$$TCO_2 = \sum_{i=1}^{8} CO_2 = \sum_{i=1}^{8} E_i \times LCV_i \times CC_i \times COR_i \times (14/12) \qquad (2)$$

Where TCO_2 represents the amount of carbon dioxide released by the consumption of various fossil energy sources; E_i represents the consumption of the i-th energy source in each province; LCV_i refers to the average low level heating value of the i-th energy source; CC_i refers to the carbon content per unit calorific value of the i-th energy source; COR_i refers to the carbon oxidation rate when the i-th energy source is burned; 44/12 refers to the ratio of carbon dioxide to carbon molecular weight.

Because there was a considerable variance in values between each variable's data, the data for all variables were dimensionless. Stata 15.0 software is utilized in the article for the required econometric study. The descriptive statistics for the variables are shown in **Table 1**.

TABLE 1 Descriptive statistics of variables.

Variable	Observations	Mean	Standard error	Min	Max
CO_2	390	0.338	0.219	0.1	1
tra	390	0.299	0.247	0.1	1
tec	390	0.254	0.221	0.1	1

Results of empirical analysis

The panel data should be evaluated for smoothness to ensure the validity of the further study. Following the smoothness test, Granger causality analysis is performed to further filter the interrelationship between variables. The ideal lag order of the PVAR model is then determined. The stability and estimate of PVAR model were then tested. 300 Monte Carlo simulations were finally done to determine the impulse response and variance decomposition of the model. The detailed analysis is as follows.

Smoothness test

The pseudo-regression problem may develop if non-stationary data is directly modeled. The smoothness of the variables is thus the foundation for the following study. Currently, six unit root testing approaches are frequently used: the HT, LLC, Breitung, IPS, Fisher, and HadriLM tests. Except for Breitung, the other five tests only consider perturbation term serial correlation. HT tests can be used for short panel data tests but sample size requirements are strict. Considering the numerous limitations, we use the IPS and Breitung tests of distinct unit root tests in this investigation. The test results are shown in **Table 2**.

The *P*-values for CO_2 and tec were less than 0.05 in the original value test of the variables, indicating that the initial data were stationary. Both the non-stationary IPS and Breitun tests yield *P*-values for *tra* greater than 0.05. Hence, all variables must go through first-order differencing. **Table 2** reveals that the *P*-values after first-order differencing are all less than 0.05, which reject the original hypothesis of non-stationarity of international trade, technological advancement, and carbon emission intensity. Every variable is consistent.

TABLE 2 Unit root test results of panel data.

	Original data		First difference	
	Breitun test	IPS test	Breitun test	IPS test
CO_2	−3.9930***	−2.2651*	−3.9206***	−9.9586***
tra	−0.5010	0.8734	−2.9426***	−4.8858***
tec	−1.8450*	−4.1179***	−3.7798***	−6.8421***

* and *** indicate significance at the significant levels of 0.05, 0.01 and 0.001 respectively.

Determination of the lag order

Before performing PVAR regression, we must determine the optimal lag order. Andrews and Lu's Consistent Moment and Model Selection Criteria (CMMSC) Andrews and Lu's (2001) are employed to determine the lag order of the PVAR model in this work. When the minima are at different lag orders, the order with the most minima is picked as the best lag order. According to **Table 3**, the first lag order is the best lag order since the MBIC, MQIC, and MAIC values are the smallest, although the second lag order has the smallest MAIC value.

Granger causality test

The Granger causality test can determine whether there is a two-way or one-way causal relationship among international trade, carbon emissions intensity, and technological progress in each province. The test results are shown in **Table 4**. The test results reveal a two-way causal link between carbon emissions and technological progress, refuting the null hypothesis. Both test results of international trade and carbon emissions refute the null hypothesis, and confirm a two-way Granger causal link. As the initial hypothesis is accepted, there is no Granger causation between international trade and technical growth.

PVAR model estimation and model stability test

Based on the findings of the panel data smoothness test, the first-order difference series of variables are chosen for PVAR

TABLE 3 Optimal lag order.

Lag	MBIC	MAIC	MQIC
1	−105.7099*	−15.33803	−51.87204*
2	−82.59853	−22.35059*	−46.7066
3	−40.26801	−10.14404	−22.32204

* indicates the optimal lag order selected by this criterion.

TABLE 4 Granger causality test.

Variable	Test item	chi^2	df	p
dCO_2	dtra	3.846	1	0.050
	dtec	6.127	1	0.013
Dtra	dCO_2	4.826	1	0.028
	dtec	1.990	1	0.158
Dtec	dCO_2	7.385	1	0.007
	dtra	0.242	1	0.622

TABLE 5 GMM estimation results of PVAR model.

Explained variable	Explaining variable		
	L1.h_dCO_2	L1.h_dtra	L1.h_dtec
h_dCO_2	0.2096036***	−0.1143221*	0.0401404**
	(0.0297051)	(0.0642055)	(0.0170286)
h_dtra	−0.0214356*	0.1703102	−0.0916079
	(0.0120691)	(0.1116111)	(0.0690461)
h_dtec	−0.0374844***	−0.0991669	0.6124269***
	(0.0135616)	(0.1115857)	(0.1518649)

The value in bracket is standard error; *, ** and *** indicate significance at the significant levels of 1%, 5% and 10% respectively; h_ indicates that the variable has undergone Helmert transformation; L1h_ indicates the first-order lag of the variable.

model estimation in this study. In order to minimize the time fixed effects and individual fixed effects of the sample and avoid biased estimation, we further orthogonalize the variables by using the Helmert method. The variables that have been transformed are, respectively, *h-d*CO_2, *h-dtra*, and *h-dtec*.

Table 5 shows that when *h-d*CO_2 is the explanatory variable, the levels of significance for carbon emission, technical advancement, and international trade are 1%, 5%, and 10%, respectively. Carbon emissions are significant at 10% trade level when *h-dtrade* being the explanatory variable, and the coefficient of the first-order lagged term being negative. It demonstrates that technological progress has no effect on the volume of international trade and that carbon emissions have a detrimental impact on its growth. When *h-dtec* is used as the explanatory variable, carbon emissions are substantial at the 1% level of significance and technological progress also has some self-motivating benefits. The lag period has made a significant and constructive contribution to the technological progress for the current period. However, there is scant evidence that international trade influences technological progress.

The stability of the PVAR model supports the subsequent impulse response analysis and variance decomposition. As seen in Figure 1, all unit roots have eigenvalues smaller than one, and all three estimation sites are within the circle. It implies that both the established PVAR model and the connection between the variables are long-term stable.

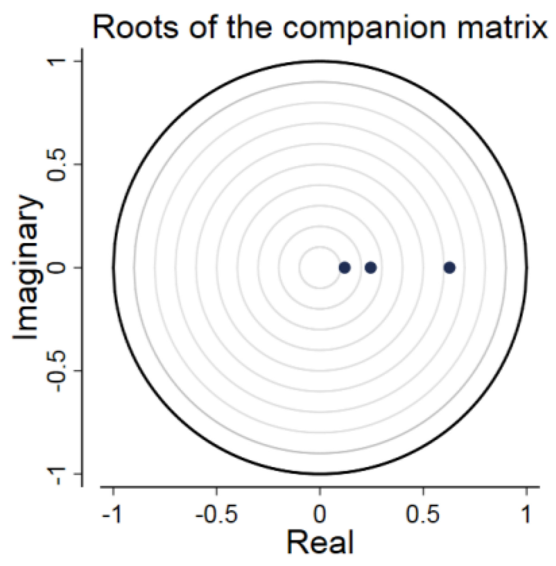

FIGURE 1
Stability test of the model.

Impulse response and variance decomposition

Although PVAR model is a dynamic model, the GMM estimation of PVAR only illustrates the static interaction of variables. Therefore, it is particularly important to perform impulse response analysis between variables. The analysis keeps other variables constant when displaying the dynamic interaction between two variables. The impulse response function is a useful tool to understand the long-run equilibrium relationship between variables. Because not all variables exhibit Granger causality, this work exclusively performs impulse response analysis on endogenous variables with one-way or two-way Granger causality. The impulse response plot in Figure 2 is produced by 300 iterations of Monte Carlo simulation in this work, which intuitively depicts the relationship between carbon emissions, international trade, and technological advancement. The vertical axis depicts how the variables behave to the shocks, while the dashed lines on either side depict the 95 percent confidence intervals. The horizontal axis indicates the number of response periods.

Figure 2 depicts the general patterns of technological progress and carbon emissions. Both have excellent reactions to their own shocks. The reactions to their own informational shocks peak in the present and last longer (especially for technological progress). It is clear that the reactions have some economic "inertia." Both current period carbon emissions and technological progress are anticipated to boost the subsequent carbon emissions and technological progress. They inspire and support one another. However, this reinforcing mechanism lessens as time passes. Consequently, to establish a positive cycle of low carbon and high technology, both carbon emission reduction and technological advancement must have a stable base. This foundation can be built by supporting low-carbon lifestyles, reducing carbon consumption, and usage and boosting investment in technological research and development. When confronted with initial shocks, international trade responds quickly and favorably. This boosting effect quickly goes away to nothing. It demonstrates that foreign trade shocks have relatively mild long-term implications, and the effect on itself is rather short-lived.

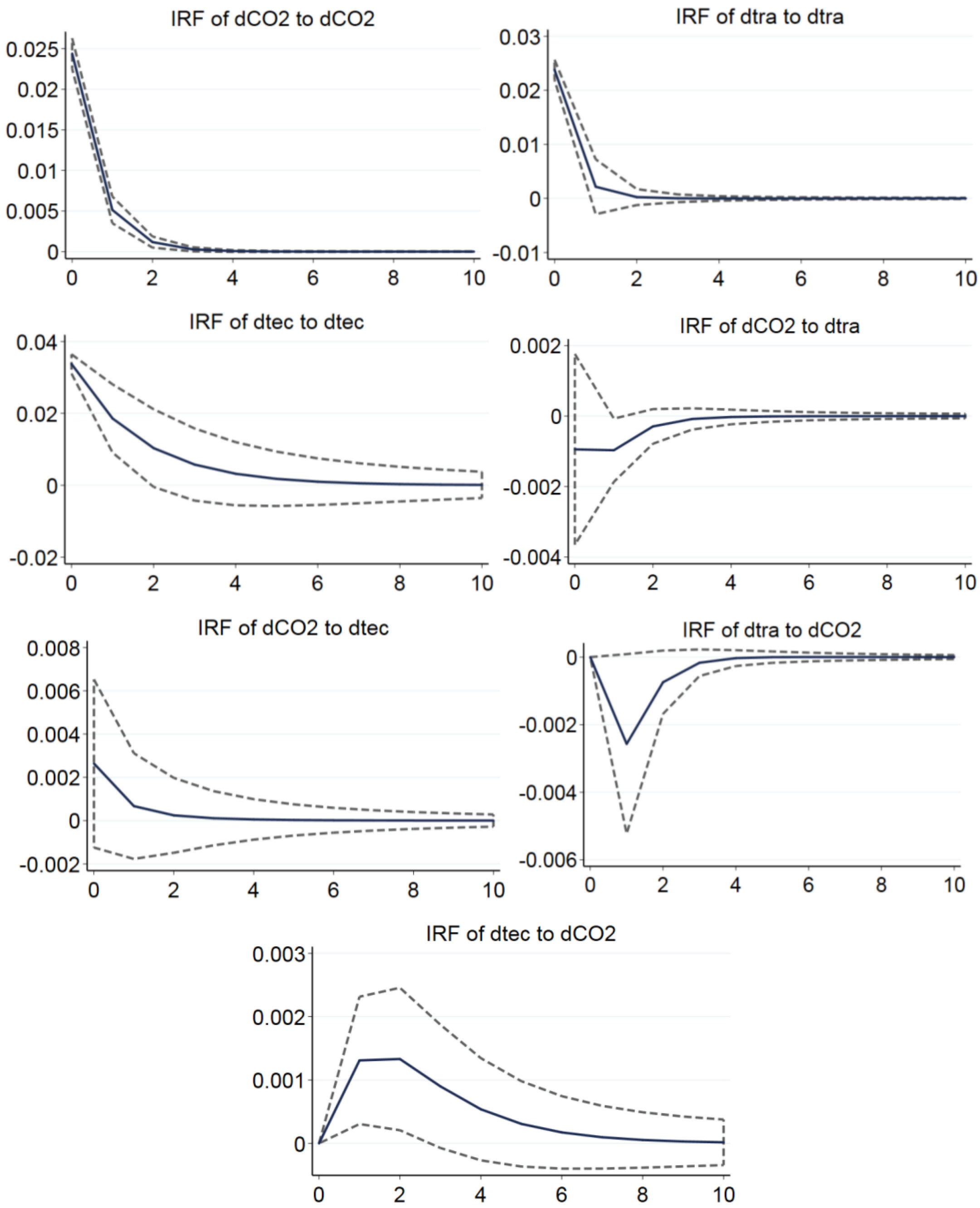

FIGURE 2
Impulse response.

When carbon emissions are used as a shock, foreign trade reacts quickly in an prominent, smooth negative way. After one period, the adverse reaction gradually approaches zero. It demonstrates that the intensity of carbon emissions has a detrimental impact on the expansion of international trade. It could be due to current trade restrictions such as "carbon labeling" and "carbon tariffs," which raise the commercial criterion for carbon-related firms. Technological innovation produces immediate and overwhelming favorable responses. It shows that an increase in carbon emission intensity can stimulate an advance in technological progress. The strengthening of environmental regulations has prompted companies to make significant technological breakthroughs and develop low-carbon technologies to improve energy efficiency.

When foreign trade is deemed a shock, carbon emission intensity does not respond immediately, but rather develops over time until it peaks in period one. Following that, the negative reaction gradually fades. It demonstrates that expanding international trade is an effective method for reducing carbon emissions. It may be due to the learning and imitation effects triggered by the spillover of the technology and environmental effects and the strengthening of environmental controls over a longer time dimension, where foreign trade drives economic growth. It enables a significant increase in productivity and energy usage within the enterprise, thus enhancing energy conservation and emission reduction.

When technological progress is deemed a shock, the intensity of carbon emissions first fails to adjust quickly. Then the favorable response gradually increases to phase I and remains relatively stable until phase II. Eventually, the response fades. It implies that the rise of carbon emissions is accelerated by technological development. On the one hand, it might be due to an expansion of economic scale brought by technological progress in each province, as well as a constrained capacity to advance technology, which leads to increased carbon emissions. On the other hand, it may be due to the long time span and long transmission path of the technology level in the provinces. As a result, there is a certain lag in its impact on carbon emissions.

The variance decomposition can demonstrate each shock variable's relative importance to the explanatory variables' evolution in the PVAR model. It can also look into the interaction between global trade, technological progress, and carbon emissions. The variance contribution of dCO_2 in Table 6 shows that the most significant contribution of carbon emissions is to themselves. It stabilizes at 98.1% after period 5. Foreign trade and technological progress both contribute increasingly. In periods 3 and 4, technological progress stabilizes at 0.7 and 1.1%, respectively. Foreign trade contributes the most to itself in terms of the variance contribution of dtra, which has stabilized at 97% as of period 6. Carbon emissions contribute more in Period 2 and stabilize at 0.3%. In terms of the variance contribution of dtec, technological progress contributes the most to itself. It stabilizes at 98.9% after period 3. The contribution of carbon emissions decreases and it stabilizes at 0.5% in period 2.

TABLE 6 Variable variance decomposition results.

Variable	Lag phase	dCO_2	Dtra	Dtec
dCO_2	1	1	0	0
	2	0.987	0.010	0.003
	3	0.983	0.011	0.006
	4	0.982	0.011	0.007
	5	0.981	0.011	0.007
	6	0.981	0.011	0.007
	7	0.981	0.011	0.007
	8	0.981	0.011	0.007
	9	0.981	0.011	0.007
	10	0.981	0.011	0.007
dtra	1	0.002	0.998	0
	2	0.003	0.981	0.016
	3	0.003	0.974	0.023
	4	0.003	0.971	0.025
	5	0.003	0.971	0.026
	6	0.003	0.970	0.026
	7	0.003	0.970	0.026
	8	0.003	0.970	0.026
	9	0.003	0.970	0.026
	10	0.003	0.970	0.026
dtec	1	0.006	0.009	0.985
	2	0.005	0.007	0.988
	3	0.005	0.006	0.989
	4	0.005	0.006	0.989
	5	0.005	0.006	0.989
	6	0.005	0.006	0.989
	7	0.005	0.006	0.989
	8	0.005	0.006	0.989
	9	0.005	0.006	0.989
	10	0.005	0.006	0.989

Conclusion and discussion

Theoretical significance

In order to achieve the goal of "carbon peaking and carbon neutrality," we must clarify the mechanism and degree of interaction between foreign trade, technological progress, and China's carbon emissions. There is a large body of literature that merely investigates the relationship between foreign trade, technological progress, and carbon emissions. However, there is scant literature that investigates the synergistic relationship among the three indicators and considers the lagged effects of the three. PVAR models combine the advantages of VAR models and panel data, which can circumvent the complex endogeneity problem, and better demonstrate the long-term dynamic relationship between variables. Therefore, this paper will enrich the literature on foreign trade, technological progress, and carbon emissions by constructing a PVAR model, which can provide a relevant theoretical basis for industrial restructuring and development of a low carbon economy in China.

Practical significance

First of all, China must accelerate the process of export tax rebates and improve export tax refunds for low-carbon products. China should concurrently reduce import and export taxes for low-carbon products and implement "tax reduction" and "tax rebate" measures. It is critical to develop new trade patterns and promote the trade structure upgrading. Increasing trade in low-carbon goods and services is also urgent. To stimulate the expansion of high-quality international trade, China must focus on "maintaining growth," "maintaining stability," and "raising quality" at the same time. To effectively implement carbon emission standards, provinces should establish green low-carbon trade standards and certification systems. They should encourage traditional businesses to make the optimal transition to green and environmentally friendly. Provinces should encourage the foreign trade supply chain to move toward green development and develop reasonable environmental management mechanisms.

Besides, China should also increase funding and credit support for equipment upgrades and R&D innovations in traditional businesses to increase the share of low-carbon technologies. China should strengthen subsidies for low-carbon technologies in high-carbon industries and strengthen intellectual property protection for low-carbon technologies. China needs to motivate the technology developers. Furthermore, China should also encourage and facilitate the sharing of technological knowledge and expertise among organizations. It is necessary to eliminate distinctions between national and regional technological capabilities and stress technology's rapid evolution and flexibility. The government should simultaneously establish stricter carbon emission standards and a push-back mechanism supporting R&D to accelerate technological development toward low-carbon development. The government should take into account low carbon requirements while pursuing technological innovation.

At last, the low-carbon economy, international trade, and technology progress all require their own stable foundations because of their intrinsic "economic inertia." Green supply chain development must be accelerated and carbon emissions from the entire industry must be reduced and controlled. Low-carbon laws and regulations must be introduced and improved. Enterprises should act as policy advisors to create a good low-carbon environment. Enterprises should try their best to overcome the fundamental low-carbon core technologies and update the structure of international trade to create a positive social cycle by low carbon for low carbon, technology for technology and commerce for trade. The relationship between international trade and technological progress policies should also be improved, and the "$1 + 1 > 2$" synergistic effect of the two on lowering carbon emissions should be thoroughly utilized.

Limitations and future research directions

There are some limitations to this paper. Firstly, this study bases on panel data for 30 provinces in China from 2007 to 2019. The paper focuses on a relatively short time period of 12 years. Also, from a regional scope perspective, the study is limited to the provincial level in China, which can guide neither other countries nor the prefecture-level cities in China. Secondly, the study introduces an overall technological progress indicator, and the results may not be the same if there is a bias toward low carbon technological progress. Lastly, Currently, there is no Clear Definition and uniform international standard of carbon emissions. In this paper, only CO_2 emissions are chosen as the carbon intensity indicator, without considering other polluting gases.

Therefore, researchers can further lengthen the time span in the future and conduct studies from the perspective of Chinese prefecture-level cities or from the perspective of other countries. Researchers may also focus on biased low-carbon technology progress and consider the carbon emissions of other pollutants to build a better carbon emission system.

Conclusion

This research uses panel data from 30 provinces in mainland China, excluding Tibet, Hong Kong, Macao, and Taiwan, to explore the dynamic interplay between carbon emissions, international trade, and technological progress from 2007 to 2019. The following are the conclusions.

Firstly, the Granger causality test results show that carbon emissions and international trade have a two-way causal link. Furthermore, technological progress and carbon emissions have a bidirectional causal link. The results suggest a direct or indirect link between technological progress, international trade and carbon emissions. However, there is no causal relationship between foreign trade and technological progress.

Secondly, according to the impulse response analysis, international trade, technological progress, and carbon emissions have some "economic inertia" and a particular self-motivating effect. Higher carbon emissions, international trade, and technological progress will be followed by higher carbon emissions, foreign trade, and technological progress in the following period. They can promote themselves better, but the impacts of international trade on self-promotion are minor and fleeting. In the long run, China's foreign trade is taking a high-quality development path. Foreign trade and carbon emissions have a significant mutually inhibiting effect. Foreign trade stimulates economic growth, but technology spillovers and environmental effects greatly increase companies' productivity and energy consumption, promoting energy saving and emission reduction. Some countries are implementing trade barriers such as "carbon labeling" and "carbon tariffs" at the same time. Carbon emissions and technological progress have significant long-term mutually reinforcing consequences. The increased economic scale of technological innovation may contribute to increased carbon emissions. Furthermore, the increase in carbon emissions slows technological progress. The need to reduce carbon emissions is likely to drive further technological progress. The paper takes into account the overall technological progress. The conclusion might be changed if the biased low-carbon technology was chosen as the primary measurement indicator.

Data availability statement

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

Author contributions

GZ: conceptualization, methodology, software, and writing—original draft preparation. HW and LP: data curation and writing—review and editing. XH: validation, formal analysis, investigation, resources, funding acquisition, and supervision. YL: writing—original draft preparation and data collection. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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

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Environmental Regulation and Corporate Innovation Behavior Based on the "Double Carbon" Strategy – Empirical Analysis Based on A-Share Listed Companies of Heavy Pollution Industries on the Shanghai and Shenzhen Stock Exchanges

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Environmental regulations have been intensified across the country under the pressure of the national "double carbon" strategy, the constraints of energy-saving and emission-reduction targets by enterprises, and public opinion. The tightening of environmental regulations is bound to impact the innovation behavior of heavily polluting enterprises; however, it remains uncertain whether the impact is positive or negative. Using a differences-in-differences approach of data from listed companies in China's heavily-polluting industries between 2010 and 2016, this paper examines the changes in their innovation behavior under the tightening environmental regulations after the "smog explosion" event as a "quasi-natural experiment" at the end of 2011. The study found that the "smog event" had a significant net negative effect on the innovation behavior of heavily polluting firms, with a significant decrease in their innovation inputs. The quantile regression results show that the R&D intensity of enterprises is related to the haze treatment effect in a U-shaped curve. Further research found that the decline in innovation investment was more significant for state-owned heavily-polluting firms compared to private heavy polluting firms. Robustness tests indicate that the empirical results of this paper are somewhat robust. This paper aims to identify the contradictory roots of the "Porter hypothesis" debate by analyzing the differences in innovation behavior of enterprises with different R&D intensity and different property rights.

Keywords: smog, environmental regulations, heavily-polluting enterprises, innovative behaviors, differences-in-differences

INTRODUCTION

Since the political reform and opening-up of trade, the Chinese economy developed rapidly to become the second-largest economy in the world. However, with this rapid economic development, industrial pollution, especially air pollution, has become increasingly prominent. Given that the traditional soot pollution has not been effectively controlled, the regional complex air pollution characterized by ozone, smog (PM2.5), and acid rain has grown in prominence. At the end of October 2011, a "PM2.5 explosion"[1] incident resulted in a rise in smog, showcased as a new type of air pollution source to the public. On September 22, 2020, during the general debate of the 75th session of the United Nations General Assembly, President Xi Jinping declared to the world that carbon emissions would peak by 2030 and carbon neutrality would be achieved by 2060. The state increased its environmental regulation and therefore increased the risk of environmental liability for heavy polluters. Reducing $PM_{2.5}$ and carbon sequestration are now included in government reports, and the government has strengthened environmental controls on heavily-polluting industries and introduced several legal policies, resulting in a change in the policy environment for heavily-polluting industries. This has led to a strong 'stress response' from companies in the heavily polluting industries, attracting the attention of many scholars. Liu Yanguo and Liu Mengning examined the impact of political costs on the surplus management of heavy polluters using the "$PM_{2.5}$ explosion" and found that heavy polluters engaged in downward surplus management after the smog (Liu and Liu, 2015). Sheng et al. (2017) examined the impact of the "smog event" on the financing ability of heavily polluting firms and explored the mechanism of this impact. Firms reacted differently to environmental degradation (Sheng et al., 2017). There is no conclusive evidence on the impact of environmental regulation on firm innovation, and neither the "Pollution Paradise Hypothesis" nor the "Porter Hypothesis" has been able to clarify the matter via empirical study. In this study, using the exogenous impact of the "$PM_{2.5}$ explosion," the net effect of the "smog event" on the innovation behavior of heavily-polluting enterprises is analyzed by the differences-in-differences (DID) method. Moreover, using a "quasi-natural experiment," endogenous problems can be avoided, which increases the credibility of our research conclusion. Concurrently, it also enriches the research perspective of the impact of environmental regulation on enterprise innovation behavior.

LITERATURE REVIEW AND RESEARCH HYPOTHESIS

The influence of environmental regulation on enterprise innovation capability has always been a controversial topic. Environmental regulation has both a positive compensation effect and a negative offset effect on enterprise innovation. However, the culminating effect of both can be drenched in uncertainty; hence, research on this issue remains controversial. The traditional view holds that the offset effect of environmental regulation is greater than its compensation effect. Although environmental protection has good positive externalities, environmental regulation will increase the cost of enterprises and reduce the innovation expenditure of enterprises (Barbera and Mcconnell, 1990; Jorgenson and Wilcoxen, 1990; Brännlund et al., 1998; de Miguel and Pazo, 2017). On the contrary, Porter's hypothesis holds that the compensation effect of environmental regulation is greater than the offset effect. Moderate environmental regulation can encourage enterprises to perform technological innovation, improve the production efficiency of enterprises, and reduce the production cost, thus offsetting the increased cost of environmental regulation. Many scholars have verified these two opposing views from an empirical point of view. Amongst others, Gray and Shadbegian (1995); Arduini and Cesaroni (2001), Wagner (2007); Wang et al. (2017) maintain that environmental regulation has a significant offset effect on technological innovation. In response, Berman and Bui (2001); Hamamoto (2006), Lambertini (2017); Fabrizi et al. (2018) and other scholars have verified Porter's hypothesis through empirical tests. Therefore, there is merit to suggest that environmental regulation has a significant compensation effect on technological innovation. On the other hand, Eiadat et al. (2008); Frondel et al. (2008), Lanoie et al. (2008); Stoever and Weche (2018) and other scholars have found that the relationship between environmental regulation and enterprise innovation is uncertain in related industries in Europe and America.

With the increasing strength of environmental protection legislation, Chinese scholars have also started to study the existence and applicability of Porter's Hypothesis in China. Some scholars have made an empirical analysis of the relationship between environmental regulation and productivity in China's manufacturing industry and indirectly proved that environmental regulation can promote technological innovation (Zhao, 2008; Li and Nie, 2010). Multiple theories have been reported as to the exact relationship between environmental regulation and technological innovation in China. For instance, Neng and Feng-chao (2012) found that the "Porter's Hypothesis" only existed in the eastern part of China when they investigated the influence of environmental regulation on technological innovation in different regions. In addition, some scholars have found that the relationship between environmental regulation and technological innovation is not purely linear, but there is a U-shaped relationship or an inverted U-shaped relationship between them. On the other hand, Jiang et al. (2013) and Wang and Liu (2014) found that the relationship between environmental regulation and technological innovation is a polygonal shape, and the influence coefficients between them vary in different stages. However, scholars such as Bing et al. (2008) and Xie (2008) have found an unclear relationship between environmental regulation and technological innovation.

The above-mentioned local and global research examined the relationship between environmental regulation and technological innovation as a whole and did not distinguish the heterogeneity of

[1]In 2011, the United States Embassy's self-testing $PM_{2.5}$ index broke through the threshold of the monitoring instruments. The monitoring threshold of the general instrument was 500, and the $PM_{2.5}$ index initially exceeded 300 to be classified as serious pollution. Then, on the same day, the $PM_{2.5}$ index exceeded 500, which caused great repercussions; hence this day became known as the "$PM_{2.5}$ burst the watch" event.

industries. Factors such as resource endowment, factor structure, and pollution level will cause different relationships between environmental regulation and technological innovation in various industries. Yu and Hu (2016) found that environmental regulation has always had a negative impact on the technological innovation of heavily-polluting industries, whereas it had a significant promoting effect in moderately-polluting industries and a U-shaped relationship in lightly-polluting industries. Liu et al. (2017) also found a U-shaped relationship between the impact of environmental regulation and industrial technological innovation. At present, the intensity of environmental regulation in China is on the left side of the inflection point, and the U-shaped inflection point of pollution-intensive industries appears later than that of clean industries. However, literature analysis reveals that environmental regulation should have a negative effect on the technological innovation of China's heavily-polluting industries. Compared with other industries, heavily-polluting industries produce a lot of pollutants in production, and environmental regulation seriously hinders the normal development of the industry, greatly reduces the profits of the industry, and repurposes investment in the enterprises toward technological innovation. This dilemma is the reality of heavily-polluting industries after the "smog event." Public opinion greatly affects the reputations of enterprises which can intensify the financing constraints of enterprises. Concomitantly, the government has stepped up the control of heavily-polluting industries, and successively introduced a series of targeted control policies. In 2012, the Ambient Air Quality Standard and the Twelfth Five-Year Plan for the Prevention and Control of Air Pollution in Key Areas were issued, and "smog control" was written into the Environmental Protection Law of the People's Republic of China on April 24, 2014. The deterioration of financing constraints, the strengthening of legislation, and the restriction of the nature of industries further weaken the innovation power of heavily-polluting industries which severely handicaps their productivity. Therefore, this paper puts forward the following assumption.

> Hypothesis 1: After the "smog event", the innovation investment of heavily-polluting enterprises will decrease significantly compared with non-polluting enterprises.

In addition, although both state-owned enterprises and private enterprises are the products of the market-oriented reform in China, there remain huge differences between them (Wu and Qian, 2011). State-owned enterprises, as the embodiment of national interests, consider both economic and social goals, while private enterprises take survival and profit as their main goals. Different strategic objectives of enterprises will also lead to different innovative behaviors in enterprises. Xiao-Qing et al. (2014) and other studies have found that the innovation efficiency of state-owned enterprises is generally lower than that of private enterprises. Zhao et al. (2014) and other studies have found that there is a big difference in the innovative spirit between state-owned enterprises and private enterprises—with the innovative power of private enterprises stronger than that of state-owned enterprises. Given these differences, it is worth asking how will environmental regulation affect enterprise innovation? Under the pressure of environmental protection, some large heavily-polluting state-owned enterprises often need higher investment in environmental protection, and environmental regulation weakens the scale and capital advantages of state-owned enterprises, thus affecting the innovation of enterprises (Jiang et al., 2013). In addition, compared with private enterprises, state-owned enterprises often bear huge social responsibilities because of their unique political status. Under strict environmental regulation, state-owned enterprises tend to follow end-of-pipe pollution treatment to create the perception of "environmentally friendly" practices. As a result, pollution control costs increase, corporate profits decrease, and some R&D investments are suspended. As for private enterprises that strive to maximize profit, when faced with strict environmental regulations they tend to improve their production technology and production efficiency to offset the increased environmental costs. After the "smog event", it can be expected that both state-owned and private heavily-polluting enterprises faced more severe environmental pressure. Under the strong pressure of environmental protection, the innovative behavior of state-owned and private heavily-polluting enterprises will inevitably form a great contrast. Based on this, this study puts forward the following assumption:

> Hypothesis 2: After the "smog event," compared with private heavily-polluting enterprises, the innovation investment of state-owned heavily-polluting enterprises decreased more significantly.

MODEL CONSTRUCTION AND DESCRIPTIVE STATISTICS

Sample Selection and Variable Definition

The initial sampling period for this study is between 2009 and 2016. The initial samples include A-share companies in Shanghai and Shenzhen Stock Exchanges as of December 31, 2008. The key point of this paper is to choose the appropriate control group and experimental group, i.e., to reasonably distinguish the heavily-polluting listed companies from the non-heavily-polluting listed companies. According to official documents, such as the "Twelfth Five-Year Plan" on Air Pollution Prevention and Control in Key Regions and the Announcement on the Implementation of Special Emission Limits for Air Pollutants, we manually selected companies belonging to heavily-polluting industries (as defined in the documents) as the experimental group of this study[2]. As for the control group, referring to the matching strategy used by Liu and Liu (2015) and Sheng et al. (2017): Guidelines for the Industry Classification of Listed Companies (2012 Revision), and defined other listed companies

[2]Official documents point out that in key control areas, it is necessary to strictly limit high-pollution projects in coal power, steel, building materials, coking, non-ferrous metals, petrochemicals, chemicals, as well as other industries, and implement special emission limits for atmospheric pollutants for these projects. This article defines listed companies belonging to the above industries as heavily-polluting enterprises.

in the same category of heavily-polluting enterprises as non-heavily-polluting enterprises, i.e., the control group of this study[3]. Then, the sample data were screened as follows: (1) companies with multiple missing values were removed; (2) listed companies in the ST, *ST, and S*ST categories during the sample period with abnormal financial conditions were removed. Among them, there were many missing data concerning the R&D investment of the listed companies. The main reason is that on February 15th, 2006, the Ministry of Finance issued the Accounting Standards for Business Enterprises No. 6-Intangible Assets, which greatly revised the accounting treatment of the original standard stating that the R&D expenses of enterprises should be included in reporting current profits and losses. However, many companies did not disclose R&D investment data in their financial statements from 2008 to 2009. Therefore, the final sample interval of this study was from 2010 to 2016, and the final sample observation value was 3,066. The enterprise R&D data of this study were retrieved from the CCER database, and the financial and property rights data were obtained from the CSMAR and RESSET databases.

As for the measurement of the innovation capability of an enterprise, the research of Wen and Feng (2012) was used as the reference, and the R&D investment intensity of enterprises was used to measure their innovation capability. Among them, R&D investment intensity is equal to the ratio of total R&D expenditure to business income. To improve the accuracy of the model, this study builds on previous studies and adds company characteristic variables that may affect the innovation investment of enterprises (Huihua et al., 2008; Wu, 2012; Wu and Tang, 2016). The control variables of company characteristics include: the asset-liability ratio (*lev*), the *growth* rate of main business income, the net profit rate of total assets (*roa*), intangible asset rate (*int*), company *size*, and company *age*. The specific definitions are shown in **Table 1**.

[3]The Guidelines for the Industry Classification of Listed Companies (2012 Revision) refers to the Classification of National Economic Industries (GBT4754-2011), which divides the economic activities of listed companies into two levels: category and main class. Correspondingly, the category code is represented by a Latin letter, i.e., A, B, C, etc., which represents the different categories; the main class codes are represented by two Arabic numerals, starting from 01 and encoded sequentially.

Model Construction

The main purpose of this study is to investigate the net effect of the exogenous impact of the "smog event" on the innovation behavior of heavily-polluting enterprises. Therefore, we constructed the following DID estimation model:

$$y_{it} = \alpha_1 treat_i + \alpha_2 after_t + \beta(treat \times after)_{it} + \chi control + \varepsilon_{it} \quad (1)$$

Among them, i represents the enterprise, t represents the observation year, $treat_i$ represents whether the sample belongs to the dummy variable of the experimental group, and $after_t$ represents whether the sample is in the period after the "smog event"; y_{it} is the proxy variable of the innovation behavior of the enterprise, which is expressed by the R&D intensity of the enterprise in this study; *control* represents the control variable that affects enterprise innovation; ε_{it} represents the random interference term. The object of concern is the coefficient of interaction β between $treat_i$ and $after_t$. The net effect of the "smog event" on the innovation behavior of heavily-polluting enterprises is measured by β. If its value is negative, the hypothesis of this study is proved, i.e., the innovation investment of heavily-polluting enterprises dropped more obviously than that of non-heavily-polluting enterprises.

Descriptive Statistics

Before DID estimation, the distribution of the experimental group and the control group are first assessed to determine the rationality of sample selection. **Table 2** lists the industrial distribution of 105 heavily-polluting enterprises in the experimental group. As shown in **Table 2**, there was uneven industrial distribution in the experimental group, which closely resembled the actual distribution of listed companies in the heavily-polluting industries of China and could depict the whole to a certain extent. In addition, the sample companies

TABLE 1 | Variable definition.

Variables	Variable description
Explained variable	
R&D	R&D intensity: the ratio of total R&D expenditure to operating income. R&D expenditure includes expensed expenditure and capitalized expenditure.
DID variables	
treat	If the sample belongs to a heavily-polluting enterprise, its value is 1, otherwise, it is 0.
after	If the sample is after 2011, its value is 1, otherwise, it is 0.
treat × *after*	The product of the above *treat* and *after*.
Control variables	
lev	Asset-liability ratio: the ratio of total liabilities to total assets at the end of the period.
growth	The growth rate of main business income: the ratio of the difference between the main business income of this year and the previous year compared to the main business income of the previous period.
roa	A net profit margin of total assets: the ratio of net profit to total assets.
int	Intangible assets ratio: the ratio of net intangible assets to total assets.
size	Company size: the natural logarithm of the total assets of the company at the end of the year.
age	Company age: the establishment period of the company +1 takes the natural logarithm.

TABLE 2 | Sample industry distribution of experimental group.

Industry code	B09	C25	C26	C28	C29	C30	C31	C32	C44
Frequency	4	3	34	5	6	19	12	18	4
Proportion	3.81	2.86	32.38	4.76	5.71	18.10	11.43	17.14	3.81

of the experimental group included nine major industries, accounting for 10% of the 90 major industries classified by the China Securities Regulatory Commission, indicating good representation by the samples.

Table 3 lists the descriptive statistics of the sample data in this study. For financial data, outliers were extremely easy to occur. To prevent the influence of outliers on model estimation, this study truncated all sample data at the 1% level. As seen in **Table 3**, the standard deviation of R&D of the explained variable was the largest, indicating great differences in R&D for each sample, with some of the differences potentially caused by the impact of the "smog event." This also reflects the rationality of the inference drawn in this study.

The common trend assumption is the most critical assumption of the DID method, which requires the experimental group and the control group to have the same change trend before the external impact. The common trend hypothesis sometimes becomes a constant bias hypothesis, i.e., the experimental group and the control group may be dissimilar, allowing them to have certain differences. These differences are mainly caused by unobserved confounding factors that do not change with time. If there is no external impact, the differences between the experimental group and the control group before and after the impact point should be constant. Based on the above analysis, **Table 4** compares and analyzes the differences in innovative behaviors between the experimental group and the control group before and after smog. As seen in **Table 4**, before the "smog event," there was a significant difference in R&D intensity between the experimental group and the control group, whether using the mean or median tests, and the difference was mainly caused by the different nature of the industries. After the "smog event," the difference in the R&D intensity between the experimental group and the control group further widened. This shows that the "smog event" had a certain impact on enterprise innovation, but the specific impact still needs to be follow-up with an empirical test.

TABLE 3 | Descriptive statistics of variables.

Variables	*N*	Mean	Std. dev	Min	Max
R&D	3,066	3.034	2.523	0.040	12.520
lev	3,066	0.475	0.185	0.085	0.927
growth	3,066	0.154	0.369	−0.445	2.330
roa	3,066	0.042	0.059	−0.149	0.232
int	3,066	0.050	0.043	0.000	0.232
size	3,066	22.184	1.107	20.070	25.213
age	3,066	2.817	0.269	2.079	3.497

EMPIRICAL RESULTS AND ANALYSIS

The Overall Regression of the Impact of "Smog" on Enterprise Innovation

Table 5 lists the full sample DID estimation results of the influence of the "smog event" on enterprise innovation. This study used R&D intensity as the proxy variable of enterprise innovation, and mainly investigated the changes in enterprise innovation behavior before and after the "smog event," i.e., the coefficient of *treat* × *after*. If its coefficient is significantly negative, it means that the "smog event" had a significant negative effect on the innovation behavior of heavily-polluting enterprises, and the expected hypothesis of this study is proved. Models (1) and (2) represent benchmark regression, and only examined the relationship between the DID variable and the explained variable. Among them, model (2) controls the influence of the year and industry. To improve the reliability of model estimation, model (3) and model (4) added enterprise characteristic variables at the company level as control variables of the model.

In both models (1) and (2), the coefficient of *treat* × *after* was significantly negative at the 1% level. However, the goodness of fit of model (2) was improved after controlling for the year and industry characteristics. After adding the control variables that reflect the characteristics of the enterprise, the *treat* × *after* coefficients in models (3) and (4) were still significantly negative at the 1% level. The goodness of fit of models (3) and (4) was further improved, and the overall explanatory power of the model was stronger. The regression results of models (1)–(4) show that the "smog event" does have an impact on the innovation behavior of heavily-polluting enterprises. After the "smog event," the innovation investment of heavily-polluting enterprises dropped significantly, which verifies the previous deduction noted in this study. Therefore, hypothesis 1 was proven in this study.

As for other coefficients, the *treat* variable depicts the differences between the experimental group and the control group, and its coefficients are significant in the four models, indicating that there are significant differences in innovation behaviors between heavily-polluting enterprises and non-heavily-polluting enterprises, which is consistent with the results of the mean and median tests mentioned above. After capturing the variables responsible for the possible impact of other events on the innovation behavior of enterprises in the same period after the "smog event", the most likely one was found to be the impact of time. In the model, the coefficient of *after* was significantly positive, indicating that with the passage of events, enterprises are constantly strengthening their R&D investment, which was consistent with the development law of enterprises. In addition, the coefficient symbols of control variables at the enterprise level are also in good agreement with previous literature.

TABLE 4 | Group difference test of enterprise innovation variables.

Variable	Control group			Experimental group			Mean diff.	Median diff.
	N	Mean	Median	*N*	Mean	Median		Chi^2
Before the smog event								
R&D	666	2.250	1.695	210	1.353	0.815	0.897	16.936
After the smog event								
R&D	1,665	3.827	3.360	525	2.24	2.200	1.587	80.274

Quantile Regression of the Impact of the "Smog" on Enterprise Innovation

The results of full sample regression proved that the "smog event" had a negative impact on the innovation behavior of heavily-polluting enterprises. However, for enterprises with different R&D intensities, the impact of the "smog event" on innovation behavior may have varied. Therefore, the difference in the smog treatment effect under different R&D intensities was further estimated by quantile regression.

A total of four quantiles (0.2, 0.4, 0.6, and 0.8) were selected for estimation. **Table 6** lists the estimation results of the treatment effect in each quantile. To improve the explanatory ability of the model, the year and industry characteristics were still controlled in the model, and the control variable reflecting the enterprise characteristics was added. The explained variable of the model remained the R&D intensity. The results of the quantile regression showed that for each quantile, the coefficient of *treat* × *after* was significantly negative at the 1% level, i.e., the "smog event" had a negative effect on the R&D investment of heavily-polluting enterprises. Further analysis showed that the processing effect of the "smog event" was different in each quantile. The treatment effects in the four quartiles were 6.3, 5.9, 5.32, and 11.07%, respectively. As the R&D intensity increased, the treatment effects first decreased and then increased. This indicates that the R&D intensity of the enterprise had a U-shaped curve relationship with the "smog event."

The Return of Sub-Property Rights of the "Smog" on Enterprise Innovation

The unique institutional environment of China determines the environmental differences between state-owned enterprises and private enterprises. For these, the political pressure and environmental pressure caused by the "smog event" were quite different. After the "smog event," the awareness of environmental

TABLE 5 | Full sample DID regression results.

Variables	(1)	(2)	(3)	(4)
treat	−0.913***	−0.911***	−0.678***	−0.657***
	(0.125)	(0.128)	(0.115)	(0.117)
after	1.539***	1.799***	1.869***	2.481***
	(0.106)	(0.173)	(0.104)	(0.173)
treat × *after*	−0.659***	−0.667***	−0.675***	−0.691***
	(0.161)	(0.163)	(0.151)	(0.153)
lev			−2.473***	−2.155***
			(0.283)	(0.286)
growth			0.190*	0.131
			(0.112)	(0.113)
roa			−3.208***	−2.564***
			(0.946)	(0.948)
int			−6.398***	−6.310***
			(0.882)	(0.890)
size			−0.230***	−0.281***
			(0.039)	(0.040)
age			−1.156***	−1.447***
			(0.167)	(0.170)
constant	2.266***	2.216***	11.938***	13.535***
	(0.083)	(0.315)	(0.908)	(0.963)
year and *ind*	Uncontrolled	Controlled	Uncontrolled	Controlled
N	3,066	3,066	3,066	3,066
R^2	0.119	0.127	0.203	0.218

*The numbers in parentheses are standard errors. The superscripted symbols * and *** represent significant levels of 10 and 1%, respectively. The R^2 values represent adjusted R^2 values when mixed regression was used.*

TABLE 6 | Quantile estimates results of corporate R&D intensity.

Variables	Q = 0.2	Q = 0.4	Q = 0.6	Q = 0.8
treat	−0.153	−0.334**	−0.509***	−0.622***
	(0.099)	(0.135)	(0.158)	(0.201)
after	1.559***	2.133***	2.515***	3.144***
	(0.176)	(0.190)	(0.188)	(0.307)
treat × *after*	−0.630***	−0.590***	−0.532***	−1.107***
	(0.132)	(0.128)	(0.194)	(0.253)
lev	−0.997***	−1.514***	−1.939***	−2.844***
	(0.245)	(0.303)	(0.307)	(0.453)
growth	0.185	0.211	0.006	0.208
	(0.101)	(0.119)	(0.142)	(0.151)
roa	0.549	−0.058	−0.921	−4.241***
	(0.773)	(0.851)	(1.082)	(1.262)
int	−3.355***	−5.418***	−7.139***	−8.707***
	(0.591)	(0.863)	(0.904)	(1.186)
size	−0.176***	−0.308***	−0.270***	−0.329***
	(0.035)	(0.044)	(0.047)	(0.070)
age	−6.654***	−1.018***	−1.218***	−1.527***
	(0.138)	(0.148)	(0.187)	(0.228)
constant	6.807***	11.927***	12.336***	16.490***
	(0.932)	(0.938)	(1.063)	(0.151)
year and *ind*	Controlled	Controlled	Controlled	Controlled
N	3,066	3,066	3,066	3,066
R^2	0.099	0.136	0.131	0.157

*The numbers in parentheses are the standard errors. The superscripted symbols ** and *** represent significant levels of 5 and 1%, respectively. The R^2 values represent adjusted R^2 values when mixed regression was used.*

TABLE 7 | Sub-property rights DID regression results.

Variables	(1) State-owned group	(2) Private group	(3) State-owned group	(4) Private group
treat	0.484* (0.279)	1.155*** (0.235)	0.760** (0.310)	1.356*** (0.293)
after	2.122*** (0.192)	1.413*** (0.240)	2.727*** (0.198)	1.862*** (0.258)
treat × *after*	−1.054*** (0.191)	−0.129 (0.235)	−1.122*** (0.178)	−0.099 (0.232)
Control variables	Uncontrolled	Uncontrolled	Controlled	Controlled
tear and *ind*	Controlled	Controlled	Controlled	Controlled
N	1,736	1,330	1,736	1,330
R^2	0.369	0.304	0.411	0.378

*The numbers in parentheses are the standard errors. The superscripted symbols *, **, and *** represent significant levels of 10, 5, and 1%, respectively. The R^2 values represent adjusted R^2 values when mixed regression was used.*

TABLE 8 | Robustness test of smog and enterprise innovation.

Variables	(1)	(2)	(3)	(4)
treat	−0.243*** (0.082)	−0.508*** (0.104)	−0.660** (0.292)	−0.450 (0.279)
after	1.397*** (0.150)	0.614*** (0.124)	1.966*** (0.202)	2.800*** (0.209)
treat × *after*	−0.348*** (0.129)	−0.225* (0.135)	−0.658** (0.309)	−0.592** (0.295)
Control variables	Uncontrolled	Controlled	Uncontrolled	Controlled
year and *ind*	Controlled	Controlled	Controlled	Controlled
N	3,066	3,066	2,696	2,696
R^2	0.055	0.392	0.110	0.215

*The numbers in parentheses are the standard errors. The superscripted symbols *, **, and *** represent significant levels of 10, 5, and 1%, respectively. The R^2 values represent adjusted R^2 values when mixed regression was used.*

protection returned to the people, and the heavily-polluting state-owned enterprises became the "culprits" of pollution. Under the strong pressure of environmental protection, the heavily-polluting state-owned enterprises could only adopt short and quick end-off-pipe treatment methods to reflect so that the government and the public can see their "environmental performance." Private enterprises, after the "smog event" faced stricter environmental regulations. To survive and develop, they had to increase R&D investment to meet the national environmental protection requirements.

Therefore, this study expects that, under the "smog event" and a consequential series of environmental pressures, the innovation behaviors of state-owned and private heavily-polluting enterprises would be different. State-owned enterprises had weak innovation motivation to fulfill their social responsibilities, while private enterprises had strong innovation motivation due to survival pressure. **Table 7** lists the results of the regression of property rights DID grouping. As discussed above, this part is still concerned with the coefficient of *treat* × *after*. For conciseness, the estimation results of control variables are not listed in this study. Models (1) and (2) are the results of property right grouping regression without introducing control variables. The model results show that the coefficient of the state-owned group *treat* × *after* was significantly negative at the 1% level, while the coefficient of the private group *treat* × *after* was not significant. Models (3) and (4) grouped regression results after introducing control variables. The sign and significance of the two groups of the *treat* × *after* coefficients did not change but the values did. The results of sub-property rights DID regression show that after the "smog event," compared with private heavily-polluting enterprises, the innovation investment of the state-owned heavily-polluting enterprises decreased more significantly, whereas the negative effect of the "smog event" on the private heavily-polluting enterprises was not significant. Therefore, hypothesis two is proven from these results. Among them, a possible explanation for the non-significant negative effect of the "smog event" on the heavily-polluting private enterprises is that under the greater pressure of environmental protection, although private enterprises tend to increase R&D investment, the "smog event" caused greater financing constraints (Sheng et al., 2017). The interaction between innovation tendency and financial constraints means the impact of the "smog event" on the technological innovation of heavily-polluting private enterprises is full of uncertainty.

Robustness Test of the Impact of the "Smog" on Enterprise Innovation

The empirical results of this study have verified that the research logic of this study is reasonable to some extent. However, to ensure the robustness of the empirical results, the robustness test of the empirical results is needed. The logic of the robustness test is as follows: First, the explained variable was changed. In our previous article, R&D investment intensity was used as the proxy variable of enterprise innovation. Here, the total R&D expenditure of enterprises was used as the explained variable to test whether the "smog event" had a negative processing effect on enterprise innovation. Second, using the research method of Hou et al. (2015), this study used the method of the placebo test to set a pseudo-smog event as the placebo before the smog event to test the robustness of the model. Theoretically speaking, if there is a causal relationship between the "smog event" and the innovative behavior of heavily-polluting enterprises, then the processing effect of the "smog event" should not be significant if the event does not happen. The specific design of the placebo test was as follows: 2010 was set as the occurrence point of the "smog event," and the research samples were taken from 2009 to 2016. In 2009–2010, the value of the *after* variable was 0, and after 2010, the *after* variable was 1. The *treat* variable was the same as above, with 1 for heavily-polluting enterprises and 0 for non-heavily-polluting enterprises.

Table 8 lists the results of the robustness test. Models (1) and (2) represent the test results of replacing the explained variables, and models (3) and (4) the results of the placebo test. The empirical results of models (1) and (2) showed that after changing the explained variables, the "smog event" still had a negative impact on the innovation behavior of heavily-polluting enterprises. Furthermore, whether the control variables are introduced or not, the *treat* × *after* coefficient remained significantly negative. The conclusion of changing the explanatory variables was consistent with that in **Table 5**. The empirical results of models (3) and (4) showed that whether control variables were introduced or not, the pseudo "smog event" had a negative impact on the innovation behavior of heavily-polluting enterprises. This result was contrary to our expectation of a placebo test and almost overturned the previous research conclusion. However, further analysis showed that the placebo test needed multiple periods of historical data for support. Nevertheless, due to the data limitation, this study could only advance the placebo time by one period, which caused the virtual "smog event" time to be too close to the actual "smog event" time, failing the criteria of the placebo test. The results of the placebo test showed that, although the pseudo "smog event" had a negative impact on the innovation behavior of the enterprises, the significance of the treatment effect was lower and the degree smaller compared with the actual "smog event." This result proved the robustness of this conclusion from the side, because with approaching authenticity, the possibility of a significant *treat* × *after* coefficient is greater, which reveals that the concept of "green development" is a deeply rooted sentiment for people. In this regard, the influence of environmental regulation on enterprise behavior cannot be achieved overnight but requires a process of continuous evolution.

CONCLUSION AND IMPLICATION

In this paper, under the national "double carbon" strategy, using the exogenous shock of "PM2.5 explosion" in many regions of China at the end of 2011 as well as the DID method, it was found that the R&D intensity of heavily-polluting enterprises decreased significantly compared to non-heavily polluting enterprises after the "smog event." The effect of the "smog event" on firms with variable R&D intensities differed significantly, with a U-shaped curve relationship between the two. The regression results of the property grouping showed that the negative effect of the "smog event" on private heavy polluters was not significant, while the decrease in innovation investment of state-owned heavy polluters was more significant. After the variable test and placebo test, the model results were still robust.

This study only discussed the innovation behavior of enterprises from the aspect of R&D investment without discussing the influence of the "smog event" on the innovation output of enterprises. In addition, the innovation behavior of enterprises is only one aspect of many behaviors of enterprises. In this regard, the influence of environmental regulation on enterprise behavior should be discussed from multiple angles concerning the exogenous impact of the "smog event". Mechanisms to enhance the innovation ability of heavily-polluting enterprises via advances in science and technology should also be elucidated to consolidate energy saving and emission reduction. Lastly, the existence and applicability of Porter's Hypothesis in China should be discussed from the micro-enterprise level.

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

NY, LY, XJ, and WD were responsible for designing the framework of the entire manuscript from topic selection to solution to experimental verification. All authors contributed to the article and approved the submitted version.

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How does social media drive corporate carbon disclosure? Evidence from China

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As public concern over global warming increases, there is a growing requirement for companies, as carbon emitters, to disclose (and work to reduce) their carbon emissions. Previous literature has neglected the role of social media as a source of legitimacy pressure to influence corporate carbon disclosure. Based on legitimacy theory, this study analyzed the impact of social media legitimacy pressure on corporate carbon disclosure using data from 3,656 Chinese listed companies from 2009 to 2019. We found that social media legitimacy pressure significantly enhances corporate carbon disclosure. Additionally, this positive relationship is weakened by substantive corporate internal carbon management measures (corporate green innovation and environmental management systems). Accordingly, in order to ensure consistent carbon management practices, companies should focus their efforts on substantive carbon management measures along with carbon disclosure.

KEYWORDS

social media, legitimacy pressure, carbon disclosure, green innovation, environmental management systems

Introduction

Greenhouse gases are the leading cause of global climate change (Depoers et al., 2016), and reducing emissions is the primary way to address global warming and is the consensus of most countries. Either the *Kyoto Protocol* or the *Paris Agreement* encourages countries to reduce greenhouse gas emissions. Generally, businesses are a major source of greenhouse gas emissions, with nearly 90% of carbon dioxide emissions coming from production and operation activities. Therefore, transparent and objective disclosure of carbon information by enterprises is crucial for scientific emission reduction and establishing a carbon trading market. The level of carbon disclosure has improved in recent years; however, companies still have considerable discretion regarding whether, what, and how much carbon information they disclose as corporate carbon disclosure remains voluntary in the majority of countries around the world (He et al., 2022). Numerous researchers have expressed concerns about the quality of corporate carbon disclosure (Stanny, 2018), and some studies have even found no significant improvement in the quality of carbon disclosure (Comyns and Figge, 2015).

How to improve the quality of corporate carbon information disclosure has become an essential stakeholder concern. With the development of internet technology and the advent of the digital economy, the monitoring and pressure facing companies have become more dynamic and complex. The social media created by the mobile internet is likely to become a vital information medium for people to monitor the activities of companies. It reduces the cost of monitoring by stakeholders and helps to establish a practical regulatory framework to improve the transparency of carbon information disclosure.

Existing literature on the determinants and motivations of carbon disclosure can be categorized into external pressures and internal characteristics. External pressures include environmental regulations, regulatory, economic, business, and financial market pressures [see reviews in Borghei (2021) and He et al. (2022)]. Internal characteristics of firms include corporate governance structures (e.g., board characteristics, management shareholding), financial characteristics (e.g., profitability, leverage, opportunities to increase), and managers' attitudes and philosophies toward environmental protection [see reviews in Borghei (2021) and He et al. (2022)]. Regardless of the findings on carbon disclosure, social media has not been adequately discussed as an essential source of information and external pressure. The current research on social media and carbon information has focused on its impact on capital markets. For example, Albarrak et al. (2019) found that posting carbon information on Twitter reduced firms' cost of equity. In contrast, the role of traditional media in corporate carbon disclosure is well understood, similar to that of social media (Guenther et al., 2016; Li L. et al., 2017; Li et al., 2018), but research has been limited to large companies or companies in heavily polluting industries. Contrary to social media, traditional media is "controlled by and for the elite" and may limit or control access to stakeholders. Companies are also adept at using traditional media to shape their reputations and public relations. As a result, stakeholders are limited in conveying their legitimate pressures through traditional media (Lyon and Montgomery, 2013). Social media provide a more accessible platform for stakeholders where content can be fully controlled, stakeholders can communicate, and a network effect of information can be created (Lyon and Montgomery, 2013), thus accelerating the dissemination of information and alleviating information asymmetries (Blankespoor et al., 2014). Given the unique attributes of social media, it is necessary to explore whether social media as an information medium can effectively monitor corporate carbon disclosure.

To address this issue, in this study, we highlighted the monitoring role of social media, arguing that the legitimacy pressure generated by social media comments is a crucial driver of corporate carbon reduction and disclosure. Social media has provided stakeholders with a forum to voice their concerns, which are widely discussed and quickly disseminated on social media platforms (Miller and Skinner, 2015), especially negative comments (Zhang and Yang, 2021). As a result of social media legitimacy pressures, corporate carbon disclosure serves as an effective tool to respond to stakeholders' environmental demands and compensate for legitimacy deficits (Lee et al., 2016).

Furthermore, as carbon disclosure laws, regulations, and regulatory mechanisms are still insufficient, companies may manipulate corporate carbon disclosure (Li L. et al., 2017). Carbon disclosure is more of a symbolic response (Cho and Patten, 2007; Hrasky, 2012) when negative social media comments threaten companies' legitimacy status (most companies' carbon disclosure is insufficient). Therefore, it is necessary for companies to undertake substantial carbon management measures to close the expectation gap between stakeholders and managers and to avoid decoupling in carbon management measures (Herold and Lee, 2019). The implementation of environmental management systems (EMS), as well as the development of green technologies, are effective and substantive carbon management measures for companies. Substantial carbon management measures not only improve carbon performance but also prevent companies from being negatively impacted by social media legitimacy pressure.

To test our hypothesis, we examined the impact of social media legitimacy pressure on corporate carbon disclosure using data from 2009 to 2019 on stock forum comments on the Chinese Eastmoney website. This stock forum is China's most popular and influential financial website for investors. Each listed company has its own forum where investors can post and exchange information as well as offer views on that company (Fan et al., 2021). We find strong evidence that social media legitimacy pressure significantly impacts corporate carbon disclosure. First, it has been shown that social media legitimacy pressures result in companies increasing carbon disclosure, with negative social media comments being the primary source of legitimacy pressures. Second, we observed that the positive relationship between social media legitimacy pressure and corporate carbon disclosure is weakened when firms have excellent green innovation levels and corporate EMS. Third, the legitimacy pressure conveyed by social media also impacts the structure of corporate carbon disclosure, with companies preferring to disclose non-financial carbon information over financial carbon information. In fact, disclosing non-financial carbon information can serve as a symbolic carbon management measure for companies.

There are three main contributions we have tried to make. First, we highlighted the critical role of social media legitimacy pressures in corporate carbon disclosure. It differs from previous studies that have examined the influence of mass media or government regulation on corporate carbon disclosure. Social media, especially in the modern age of intelligence, have a broader stakeholder base and stronger network information effect. Hence, they are superior at conveying legitimacy pressures. Second, we explored the relationship between corporate carbon disclosure and substantive carbon management measures in this study. We found that corporate carbon disclosure is primarily a symbolic carbon management measure for companies, while corporate green innovation and EMS serve as substantive carbon management measures that can reduce corporate social media legitimacy pressure to meet stakeholder regulatory requirements. Third, this study showed that social media could also be a powerful source of legitimacy pressure for businesses, which can affect companies to improve carbon information disclosure. Detailed evidence and insights on carbon information disclosure are provided to policymakers so they can improve the regulatory framework and develop policies or regulations.

Hypothesis development

Theoretical background

Legitimacy has been widely recognized as an essential factor in corporate information disclosure (Li et al., 2018; Zhang and Yang, 2021). In accordance with previous research, we also analyze the impact of legitimacy pressure from social media on corporate carbon disclosure using legitimacy theory. Suchman (1995) defines corporate legitimacy as the general perception that corporate behavior is considered desirable, appropriate and rational within a socially constructed system of norms, values, beliefs and definitions. A "social contract" between business and society is the basis of legitimacy (Deegan and Deegan, 2007), and this contract is dynamic rather than fixed (Deegan and Blomquist, 2006). An organization's legitimacy is the most valuable capital, allowing it to access the resources allocated by its stakeholders, gaining a competitive advantage, and increasing its long-term value. In China, under a regime of authoritarianism, it is even more important. Legitimacy theory suggests that firms should operate within social values; otherwise, they may breach the implicit contract between them and society (Cho and Patten, 2007), undermining their legitimacy (Luo, 2019). Stakeholders are ultimately responsible for determining the legitimacy of a business, and their views are reflected in the legitimization process. There is no doubt that social media plays an indispensable role in the process of public understanding and judging a business, as well as forming an evaluation of its legitimacy. Thus, legitimacy theory provides an appropriate framework for explaining corporate carbon disclosure behavior and carbon management practices when companies are under social media legitimacy pressure.

Social media and corporate legitimacy

The interactive nature of social media provides accessible opportunities for stakeholders to process and disseminate information (Kent and Taylor, 2016), and companies have little control over the content posted by users, who may even exert pressure on management directly. Therefore, the legitimacy and prestige of a company will be undermined when negative comments from social media are widely spread through social media platforms, causing information contagion and influencing the opinions of other stakeholders (Miller and Skinner, 2015). Additionally, negative comments may also increase the possibility of a company being investigated by regulators and revealed to have been acting unethically, which may further undermine the company's legitimacy (Zhang and Yang, 2021). The lack of legitimacy can result in limited resource access, higher financing costs, and regulatory penalties. Accordingly, it is essential for companies to bridge the gap between corporate and social values and move back within the boundaries of social appropriateness in order to minimize the adverse effects of a lack of legitimacy (Gray et al., 1995).

Corporate social responsibility (CSR) is widely regarded as a tool for enhancing and managing corporate legitimacy (Schultz and Wehmeier, 2010; Rankin et al., 2011), which means carbon disclosure, a component of CSR, can also be a powerful tool for companies to manage social media legitimacy pressures (Cho et al., 2006). With governments and the public increasingly concerned about climate change, their awareness of carbon emissions and expectations of companies to address climate change are rising (Li and Ding, 2013). The legitimacy pressure exerted by social media can drive companies to participate in carbon disclosure actively. Carbon disclosure can be an effective communication strategy between companies and the public. It can improve a company's reputation, change social perceptions, and repair legitimacy deficits caused by negative comments. Additionally, legitimacy pressures from competitors may also force companies to provide additional carbon information to gain stakeholders' Satisfaction (Hofer et al., 2012). By doing so, they can differentiate themselves from others who do less well in carbon disclosure. Conversely, if firms are under less pressure to be legitimate, they are subject to relatively little external scrutiny. The only thing they need to do is maintain the social legitimacy already granted to them by society (Ashforth and Gibbs, 1990). Therefore, companies under less legitimacy pressure from social media are likely to disclose less carbon information than companies under high legitimacy pressure. Thus, we propose the following hypothesis:

> ***Hypothesis 1***: There is a positive relationship between the social media legitimacy pressures and the carbon information disclosure.

There is a clear emotional bias in what is discussed or evaluated on social media platforms. According to social psychological research, the public is willing to spend more time thinking or seeking causal information when confronted with negative comments than with positive or neutral comments

(Lange and Washburn, 2012; Kwahk and Kim, 2017). It can be assumed that negative comments on social media will increase the lack of legitimacy of companies to a greater extent, which will ultimately make companies more inclined to disclose carbon information publicly. Furthermore, in the context of enhanced investor protection, negative comments on social media spread more rapidly than positive comments (Lu et al., 2013), bringing more regulatory and public attention to companies and thus increasing the pressure on companies to be legitimate. However, when an organization has more positive than negative comments on social media platforms, it may be less motivated to disclose its carbon footprint since it is seen as more legitimate. Thus, we propose the following hypothesis:

> ***Hypothesis 2a***: There is a positive relationship between the negative comments on social media and the carbon information disclosure.
>
> ***Hypothesis 2b***: Positive comments on social media have no significant impact on corporate carbon disclosure.

Moderating role of substantive carbon management practices

Carbon disclosure often serves as an image management tool for companies when they face legitimate pressures (Cho and Patten, 2007). It should be noted, however, that prolonged symbolic disclosure rather than substantive carbon management activities may increase reputational risks and raise stakeholder concerns about opportunistic corporate behavior. In 2017, China FAW (First Automobile Works) Group disclosed its green factory and green industry chain projects in its CSR report. However, it was subsequently revealed that the company had mishandled pollutants and exceeded carbon emission standards. This opportunistic behavior was not only heavily resisted by the public but also criticized and punished by the regulators (Zhang and Yang, 2021). Likewise, the contradictory behavior of the fast-food giant in promoting its positive stories with farmers while negative events about McDonald's food poisoning and low labor standards appear on social media created a hypocritical image for consumers (Lyon and Montgomery, 2013). The results suggest that when companies face legitimacy pressures, they may use the carbon disclosure tool as a symbolic carbon management tool without engaging in substantive carbon management. As a result, companies may become decoupled from their carbon management practices or suffer adverse economic consequences. Therefore, firms need a mix of substantive and symbolic legitimacy strategies of varying intensities to cope with legitimacy pressures or prevent the decoupling of firm practices (Ashforth and Gibbs, 1990).

The effectiveness of social media legitimacy pressure, which works as an informal external mechanism, depends on the substantive response from within the firm. It does not directly contribute to improving the carbon performance of firms (Li et al., 2018). In this study, we examined two substantive carbon measures, corporate green innovation and EMS, both of which are internal formal responses to legitimacy pressures within firms (Tachizawa and Wong, 2015).

Green innovation is characterized by the notion of sustainability and the reduction of environmental burdens. It is defined as innovation related to conserving resources and energy and improving technologies or processes to reduce environmental pollution (Saunila et al., 2018). Green innovation is essential for firms to achieve economic growth and environmental sustainability (Shao et al., 2021). It is a critical factor in maintaining firm competitiveness and improving the quality of life in society (Dangelico and Pujari, 2010). Specifically, for the firm itself, green innovation effectively improves resource efficiency and optimizes environmental performance during the product life cycle (Chen et al., 2006). It also helps ensure that the company complies with environmental requirements and avoids regulatory penalties (Chang, 2011). For society and external firms, green innovation has a "double externality": in addition to benefiting firms that do not invest in green innovation by spreading knowledge (Berrone et al., 2013), green innovation can also be a quasi-public good that contributes to resource conservation, environmental protection, and reducing waste emissions, thus benefitting society (Li L. et al., 2017). Furthermore, green innovation sends a positive signal that a company is practicing carbon management, thus setting itself apart from competitor companies and enhancing its image and reputation (Barnett and Salomon, 2012). As a result, corporate green innovation can enhance corporate legitimacy from several perspectives.

When companies face social media legitimacy pressures, their ability to innovate green can cushion the impact of legitimacy pressures and thus minimize carbon-related risks. As public and government interest in corporate carbon disclosures increases and social media become more widely used, companies are subject to increased regulatory pressures. The sustainable nature of green innovation and its "double externality" not only satisfy the dynamically changing expectations of social legitimacy but also serve to bridge the gap between corporate and social values. Furthermore, as a substantive carbon management practice, green innovation is an effective strategy for repairing the legitimacy deficit caused by negative comments and easing regulatory pressure when the legitimacy status is under threat. Thus, we propose the following hypothesis:

> ***Hypothesis 3:*** The positive relationship between the social media legitimacy pressures and corporate carbon disclosure is weaker for firms with a higher level of green innovation.

Similarly, corporate EMS are substantive carbon management practices that assist companies in organizing their internal processes, improving their environmental performance, as well as gaining legitimacy by meeting their environmental commitments to external stakeholders (Aravind and Christmann, 2011). Corporate EMS provide guidelines for corporate production, systematize and standardize a range of internal organizational procedures, and require managers to document production activities and processes, making a company's environmental impact more transparent and manageable (King and Lenox, 2001). Corporate EMS also contribute to reducing the preparation costs of carbon information disclosure, including human resources, time, and financial costs (Ott et al., 2017). External stakeholders consider the establishment of EMS as a signal of the company's environmental commitment to society, which helps to improve the company's image and gain trust and support among stakeholders, thus increasing the company's level of legitimacy (Boiral, 2007). External stakeholders view a company with an EMS as more credible and trustworthy than those without (Jiang and Bansal, 2003).

When companies face legitimacy pressures from social media, an environmental management system not only responds to increased regulatory demands and legitimacy expectations from stakeholders, but also sends a positive signal about a company's carbon management practices. An environmental management system means that companies have standardized production processes, efficient production technologies and stringent emission standards, all of which effectively improve the relationship between companies and the public and alleviate social media legitimacy pressures. Based on the above discussion, we develop our third hypothesis:

> ***Hypothesis 4:*** The positive relationship between the social media legitimacy pressures and corporate carbon disclosure is weaker for firms with the establishment of EMS.

Methodology

Sample and data source

For our research, we examined the impact of social media on corporate carbon information disclosure by using all Chinese companies listed on the Shanghai and Shenzhen Stock Exchanges between 2009 and 2019. Listed companies are the main subject of carbon information disclosure and are the main target of public discussion on social media platforms. In terms of the disclosure of corporate carbon information, we mainly gathered it manually

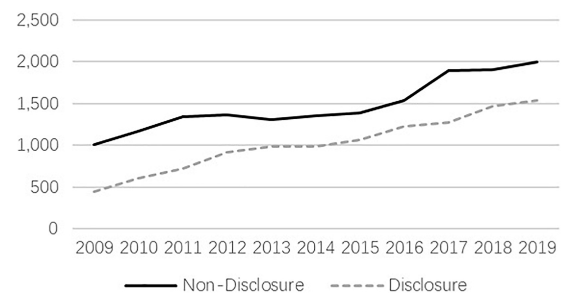

FIGURE 1
Number of companies disclosing carbon information versus those not disclosing carbon information.

from corporate social responsibility reports and corporate sustainability reports. The social media sentiment tendency data was obtained from the CNRDS database Eastmoney stock forum comment data, which had already collected and classified stock forum comments data daily, and we consolidate daily stock forum commentary data into annual data. In the Chinese securities market, which is dominated by small and medium-sized investors, the Eastmoney stock forum is the largest exchange platform in China. Obtaining data from this platform makes our data source more general. The rest of our data comes from the CSMAR database, which is one of the largest sources of data on listed companies in China.

Using the data extracted from the above sources, we have collected an initial dataset of 35,532 observations from all listed companies. Then, we selected the sample by the following criteria (Liu et al., 2021). (a) Excluding all foreign capital shares (listed in the Shanghai and Shenzhen B-share markets); (b) Dropping observations that were specially treated (ST); and (c) Deleting all observations with missing variables. A total of 27,520 firm-year observations corresponding to 3,656 different companies were collected. **Figure 1** shows the annual trend of corporate carbon disclosure. As shown in the graph, there has been a progressive increase in corporate carbon disclosure, with 448 companies disclosing carbon information in 2009 and 1,542 firms disclosing carbon information in 2019. A possible explanation for this graph might be that as government and public concern about climate change increases, companies face increasing regulatory pressure.

Measures of dependent variable

We used the corporate carbon information disclosure score (*CID*) as the dependent variable in this study (Li L. et al., 2017; Li et al., 2018). Following Aerts and Cormier (2009), we used content analysis to assess the level of disclosure of carbon information by corporations. Specifically, we assessed the level of corporate carbon information disclosure in nine items (Table 1) by referring to the *Carbon Disclosure Project China Report* and the characteristics of carbon disclosure in companies' CSR and sustainability reports. The level of corporate carbon disclosure consists of the sum of the scores of the nine items. In addition, for robustness checking, two alternative measures of corporate carbon disclosure are applied. The *CIDlogit* dummy variable is coded 1 if the firm disclosed relevant carbon information in a specific year, 0 otherwise. The *LnCID* is the logarithm of the $CID + 1$.

Measures of independent variable

Our independent variable is social media legitimacy pressure, and we collected data on the sentiment tendency of stock forum comments for each day of the Eastmoney website from 2009 to 2019. The sentiment of the comments is categorized as positive, neutral and negative. We used the Janis-Fadner coefficient (J-F) to measure social media legitimacy pressure (Legitimacy). This is a metric proposed by Janis and Fadner for content analysis methods, followed by Aerts and Cormier (2009), Li L. et al. (2017), Li et al. (2018), and others have used this coefficient to quantify legitimacy pressure. It is calculated as follows.

$$J-F=\begin{cases}\frac{(e^2-ec)}{t^2} & if\ e>c\\ \frac{(ec-c^2)}{t^2} & if\ e<c\\ 0 & if\ e=c\end{cases} \tag{1}$$

Where: e represents the number of positive comments, c represents the number of negative comments, and t is the sum of e and c. *J-F* coefficients have values ranging from -1 to 1. The more negative comments about a company, the closer the *J-F* coefficient is to -1 and the more legitimacy pressure the company faces. Moreover, in order to test hypotheses H2a and H2b, we consider the logarithm of the number of negative media posts as well as the number of positive comments (*NLegitimacy*/*PLegitimacy*) as independent variables.

In order to test hypotheses 3 and 4, we used the logarithm of the sum of green utility patents and green invention patents as a measure of green innovation (*GreenInv*). Further, we selected whether the company had implemented the IS014001 environmental management system and whether it had established a "three simultaneous" system to capture its environmental management system (*EMS*). The *EMS* is a dummy variable that is coded as 1 if the company has adopted the IS014001 environmental management system or set up the "three simultaneous" system, and 0 otherwise. Comparatively to the international standard environmental management system of IS014001, the "three simultaneous" system is a unique environmental management system in China. It is emphasized that environmental protection measures must be implemented simultaneously with the project, from

TABLE 2 Descriptive statistics.

Variable	Number	Mean	SD	Min.	Max.
CID	27,520	0.690	1.068	0	8
Legitimacy	27,520	0.083	0.081	−0.040	0.274
GreenInv	27,520	0.435	0.881	0	7.342
EMS	27,520	0.249	0.433	0	1
Indep	27,520	0.374	0.055	0.091	0.800
Dual	27,520	0.270	0.444	0	1
Size	27,520	22.064	1.319	19.199	27.048
ROA	27,520	0.043	0.065	−0.285	0.228
Lev	27,520	0.427	0.215	0.050	1
Growth	27,520	0.177	0.500	−0.662	3.894
Cashflow	27,520	0.044	0.073	−0.201	0.248
TobinQ	27,520	2.084	1.399	0.868	9.884
Top1	27,520	0.349	0.149	0.085	0.743
SOE	27,520	0.377	0.485	0	1
Heavy_polluting	27,520	0.279	0.448	0	1

TABLE 1 Specifications of carbon information disclosure.

Disclosure items	Score	Instructions
Low-carbon development goals or plans	0, 1	Undisclosed is 0, disclosed is 1
Low-carbon advocacy and training	0, 1	Undisclosed is 0, disclosed is 1
Government subsidies or incentives for carbon reduction	0, 1	Undisclosed is 0, disclosed is 1
Response to national low carbon policies	0, 1	Undisclosed is 0, disclosed is 1
Investment in carbon reduction technology, funding	0, 1, 2	Undisclosed is 0, qualitative disclosure is 1, quantitative disclosure is 2
Government recognition of carbon reduction	0, 1	Undisclosed is 0, disclosed is 1
Carbon emission reductions	0, 1, 2	Undisclosed is 0, qualitative disclosure is 1, quantitative disclosure is 2
Greenhouse gas emissions	0, 1, 2	Undisclosed is 0, qualitative disclosure is 1, quantitative disclosure is 2
IS014001 environmental management system certification	0, 1	Undisclosed is 0, disclosed is 1

design to construction through completion to commissioning (Li D. et al., 2017).

Measures of control variable

In order to control for the potential impacts of corporate carbon disclosure, we selected control variables at the level of the top management team (TMT), as well as at the firm and industry levels. At the TMT level, corporate governance plays a significant role in influencing corporate carbon disclosure (Choi et al., 2013). Liao et al. (2015) also find that independent directors are likely to favor more transparent carbon disclosure since they have different backgrounds and have no financial interest in the company. Therefore, we controlled the independent directors' ratio (*Indep*) and whether the chairman and CEO were the same people (*Dual*). We measured *Indep* by the number of independent directors as a proportion of the total. In addition, *Dual* was coded as 1 if the chairman and CEO were the same people and 0 otherwise.

In addition, we have considered a set of firm characteristics that may influence firms' disclosure of carbon information. *Firmsize* was measured as the natural logarithm of total assets, because larger firms may experience more pressure from stakeholders (Berrone and Gomez-Mejia, 2009). *ROA* was measured by the ratio of total net profit to total assets, and *Lev* was measured by the ratio of total liabilities to total assets. *Growth* was measured as the growth rate of a firm's operating income. Because these factors are closely related to corporate profitability, higher profitability increases the financial resources available to companies to invest in carbon reduction and disclosure (Ott et al., 2017). *Cashflow* was measured as the ratio of net cash flow from operating activities to total assets. *TobinQ* was measured by the ratio of the sum of the market value of equity and the book value of liabilities to total assets (Liu et al., 2022). *Top1* was measured by the proportion of shares held by the first largest shareholder. *SOE* was measured by whether the ultimate ownership of the firm is owned by the state (Li L. et al., 2017; Li et al., 2018). At the industry level, we measured *Heavy_polluting* by whether a firm belongs to the heavy pollution industry (Luo, 2019). Finally, we controlled for year, industry, and province effects to capture changes in *CID* over time, industry, and province. A detailed definition for each variable used in this study is provided in **Appendix A**.

Estimation model

To test our Hypothesis 1, Hypothesis 2a, and Hypothesis 2b, we constructed the following test models. The models

TABLE 3 Pearson correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
CID	1										
Legitimacy	−0.012**	1									
GreenInv	0.201***	0.069***	1								
EMS	0.510***	−0.00300	0.157***	1							
Indep	−0.015***	0.017***	0.012**	−0.010*	1						
Dual	−0.088***	0.014***	0.00800	−0.012**	0.109***	1					
Size	0.323***	0.067***	0.218***	0.082***	0.00500	−0.184***	1				
ROA	0.00600	0.170***	0.052***	0.047***	−0.023***	0.059***	−0.022***	1			
Lev	0.119***	−0.070***	0.056***	−0.023***	−0.012**	−0.161***	0.460***	−0.393***	1		
Growth	−0.052***	0.069***	−0.018***	−0.040***	0.00700	0.021***	−0.102***	−0.00100	−0.003	1	
Cashflow	0.090***	0.060***	0.036***	0.066***	−0.014**	−0.00800	0.046***	0.341***	−0.165***	−0.062***	1
TobinQ	−0.142***	0.056***	−0.086***	−0.080***	0.041***	0.058***	−0.427***	0.074***	−0.180***	0.161***	0.060***
Top1	0.069***	0.037***	0.027***	0.025***	0.043***	−0.043***	0.178***	0.138***	0.017***	−0.026***	0.096***
SOE	0.159***	−0.00200	0.012**	0.012**	−0.061***	−0.301***	0.339***	−0.099***	0.279***	−0.043***	0.00400
Heavy_polluting	0.181***	0.00400	−0.033***	0.131***	−0.046***	−0.051***	0.027***	−0.016***	0.015***	−0.022***	0.084***
	(12)	**(13)**	**(14)**	**(15)**							
TobinQ	1										
Top1	−0.132***	1									
SOE	−0.126***	0.213***	1								
Heavy_polluting	−0.066***	0.058***	0.074***	1							

N = 27,520; ***p < 0.01, **p < 0.05, *p < 0.1.

were estimated using least squares regression (OLS), controlling for year, industry, and province fixed effects (Li L. et al., 2017).

$$CID_{it} = \beta_0 + \beta_1 \times Legitimacy_{it}/NLegitimacy_{it}/PLegitimacy_{it} + \sum \beta_i \times Controls_{it} + \varepsilon_{it} \quad (2)$$

Where CID is the dependent variable and CID_{it} refers to firm i's carbon disclosure score in year t. Legitimacy, NLegitimacy, and PLegitimacy are independent variables. $Legitimacy_{it}$ describes the social media legitimacy pressure faced by firm i in year t. Controls are a set of control variables.

To test for moderating effects Hypothesis 3 and Hypothesis 4, we estimated the following regression

TABLE 4 Estimates for carbon information disclosure.

Variables	DV: CID						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Legitimacy		−0.174** (0.071)			−0.250*** (0.077)	−0.258*** (0.080)	−0.313*** (0.084)
NLegitimacy			0.017** (0.007)				
PLegitimacy				0.013 (0.008)			
Legitimacy × GreenInv					0.170** (0.070)		0.150** (0.071)
Legitimacy × EMS						0.326** (0.143)	0.280* (0.145)
GreenInv	0.072*** (0.006)	0.073*** (0.006)	0.072*** (0.006)	0.072*** (0.006)	0.056*** (0.009)	0.072*** (0.006)	0.058*** (0.009)
EMS	1.151*** (0.012)	1.151*** (0.012)	1.151*** (0.012)	1.151*** (0.012)	1.150*** (0.012)	1.124*** (0.017)	1.127*** (0.017)
Indep	−0.123 (0.094)	−0.119 (0.094)	−0.126 (0.094)	−0.127 (0.094)	−0.119 (0.094)	−0.119 (0.094)	−0.119 (0.094)
Dual	−0.041*** (0.012)	−0.041*** (0.012)	−0.041*** (0.012)	−0.041*** (0.012)	−0.041*** (0.012)	−0.041*** (0.012)	−0.041*** (0.012)
Size	0.208*** (0.006)	0.209*** (0.006)	0.203*** (0.006)	0.204*** (0.006)	0.209*** (0.006)	0.209*** (0.006)	0.209*** (0.006)
ROA	−0.328*** (0.093)	−0.298*** (0.094)	−0.301*** (0.094)	−0.316*** (0.094)	−0.298*** (0.094)	−0.297*** (0.094)	−0.297*** (0.094)
Lev	0.010 (0.032)	0.007 (0.032)	0.011 (0.032)	0.012 (0.032)	0.005 (0.032)	0.006 (0.032)	0.005 (0.032)
Growth	−0.019* (0.010)	−0.018* (0.010)	−0.019* (0.010)	−0.019* (0.010)	−0.018* (0.010)	−0.018* (0.010)	−0.018* (0.010)
Cashflow	0.438*** (0.077)	0.436*** (0.077)	0.440*** (0.077)	0.440*** (0.077)	0.434*** (0.077)	0.433*** (0.077)	0.432*** (0.077)
TobinQ	0.015*** (0.004)	0.015*** (0.004)	0.013*** (0.004)	0.014*** (0.005)	0.015*** (0.004)	0.015*** (0.004)	0.015*** (0.004)
Top1	−0.109*** (0.036)	−0.109*** (0.036)	−0.098*** (0.037)	−0.101*** (0.037)	−0.109*** (0.036)	−0.109*** (0.036)	−0.110*** (0.036)
SOE	0.130*** (0.013)	0.130*** (0.013)	0.128*** (0.013)	0.129*** (0.013)	0.130*** (0.013)	0.129*** (0.013)	0.130*** (0.013)
Heavy_polluting	0.201*** (0.014)	0.203*** (0.014)	0.201*** (0.014)	0.200*** (0.014)	0.204*** (0.014)	0.203*** (0.014)	0.203*** (0.014)
Constant	−4.350*** (0.133)	−4.357*** (0.133)	−4.379*** (0.134)	−4.371*** (0.134)	−4.352*** (0.133)	−4.351*** (0.133)	−4.347*** (0.133)
Year effect	YES	YES	YES	YES	YES	YES	YES
Industry effect	YES	YES	YES	YES	YES	YES	YES
Province effect	YES	YES	YES	YES	YES	YES	YES
Observations	27,453	27,453	27,453	27,453	27,453	27,453	27,453
R^2	0.392	0.392	0.392	0.392	0.393	0.393	0.393

Standard errors are in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

models, including the moderating variables and their interaction terms.

$$CID_{it} = \beta_0 + \beta_1 \times Legitimacy_{it} + \beta_2 \times Legitimacy_{it} \times GreenInv_{it} + \beta_3 \times Legitimacy_{it} \times EMS_{it} + \sum \beta_i \times controls_{it} + \varepsilon_{it} \quad (3)$$

Results

Descriptive statistics and correlation matrix

Table 2 summarizes the results of descriptive statistics for all variables. Accordingly, the mean value of the dependent variable carbon information disclosure (*CID*) is 0.69, indicating that the corporate carbon information disclosure level is not high. The results are similar to other relevant studies on corporate carbon information disclosure (Li L. et al., 2017). The mean values of *GreenInv* and *EMS* are 0.435 and 0.249, respectively, suggesting that most companies do not have substantial carbon management practices.

The Pearson correlation coefficient between variables is shown in Table 3. In line with expectations, social media legitimacy pressure (*Legitimacy*), reflected by the J-F coefficient, is positively correlated with corporate carbon information disclosure (CID). The higher the J-F coefficient, the lower the legitimacy pressure faced by the firm. The correlation coefficients between CID and the other variables are low. Additionally, we calculated the variance inflation factor (VIF) for each variable. We found that the maximum value was 1.88 and the mean value was 1.23, which is much smaller than the acceptable level, indicating that multicollinearity is not a serious issue.

Multivariate regression tests

According to the research hypotheses, a multiple regression analysis of the relationship between social media legitimacy pressures and corporate carbon disclosure was performed. These results are presented in Table 4. Model 1 is the baseline model with control variables only. *Legitimacy*, a measure of social media legitimacy pressure, has been added to Model 2 to test Hypothesis 1. The results show that social media legitimacy pressure (the lower the *Legitimacy*, the higher the legitimacy pressure) has a positive and significant effect on corporate carbon disclosure at the 5% level ($\beta = -0.174$, $\rho < 0.05$). This strongly supports Hypothesis 1 and confirms that social

TABLE 5 Estimates for FCID and NFCID.

Variables	DV: FCID Model 1	DV: NFCID Model 2	DV: FCID Model 3	DV: NFCID Model 4
Legitimacy	0.003 (0.033)	−0.171*** (0.065)		
NLegitimacy			−0.004 (0.003)	0.021*** (0.007)
GreenInv	0.004 (0.003)	0.071*** (0.006)	0.004 (0.003)	0.070*** (0.006)
EMS	0.025*** (0.006)	1.942*** (0.011)	0.025*** (0.006)	1.943*** (0.011)
Indep	−0.151*** (0.043)	0.011 (0.087)	−0.150*** (0.043)	0.003 (0.087)
Dual	−0.028*** (0.006)	−0.018 (0.011)	−0.028*** (0.006)	−0.018 (0.011)
Size	0.020*** (0.003)	0.169*** (0.005)	0.021*** (0.003)	0.162*** (0.006)
ROA	−0.114*** (0.044)	−0.173** (0.087)	−0.120*** (0.044)	−0.170* (0.087)
Lev	0.089*** (0.015)	−0.074** (0.030)	0.089*** (0.015)	−0.069** (0.030)
Growth	−0.007 (0.005)	−0.013 (0.010)	−0.007 (0.005)	−0.014 (0.010)
Cashflow	0.152*** (0.036)	0.292*** (0.071)	0.151*** (0.036)	0.296*** (0.071)
TobinQ	−0.016*** (0.002)	0.027*** (0.004)	−0.016*** (0.002)	0.024*** (0.004)
Top1	−0.087*** (0.017)	−0.014 (0.034)	−0.090*** (0.017)	−0.001 (0.034)
SOE	0.021*** (0.006)	0.101*** (0.012)	0.021*** (0.006)	0.100*** (0.012)
Heavy_polluting	0.098*** (0.007)	0.094*** (0.013)	0.098*** (0.007)	0.092*** (0.013)
Constant	−0.287*** (0.062)	−3.599*** (0.123)	−0.280*** (0.062)	−3.628*** (0.124)
Year effect	YES	YES	YES	YES
Industry effect	YES	YES	YES	YES
Province effect	YES	YES	YES	YES
Observations	27,465	27,453	27,465	27,453
R^2	0.080	0.589	0.081	0.589

Standard errors are in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

media can effectively monitor corporate carbon information disclosures. The results in **Table 4** allow us to calculate the economic significance of social media legitimacy pressure on corporate carbon disclosure, with a 100% increase in legitimacy pressure on companies increasing their carbon disclosure score by approximately 17.4%.

Models 3 and 4 examined the impact of negative and positive social media comments on corporate carbon disclosure, respectively. In model 3, *NLegitimacy* is positive and significant ($\beta = -0.017$, $\rho < 0.05$), but *PLegitimacy* is not significant ($\rho > 0.1$). This suggests that negative social media comments are the primary reason for the lack of corporate legitimacy and that companies are more likely to disclose carbon data under pressure from negative comments. However, positive evaluations do not encourage companies to disclose carbon information actively, thus confirming our expectation in Hypothesis 2a and Hypothesis 2b.

The results of the moderating effects are reported in Models 5 and 6. In Model 5, we added the interaction terms of *Legitimacy* and *GreenInv* to test the moderating effect of corporate green innovation. There is a positive and significant coefficient ($\beta = 0.326$, $\rho < 0.05$), which indicates that corporate green innovation (*GreenInv*) negatively moderates the relationship between social media legitimacy pressure and carbon disclosure, thus providing support for Hypothesis 3. Similarly, the coefficient of the interaction term between *Legitimacy* and *EMS* is positive and significant in Model 6 ($\beta = 0.280$, $\rho < 0.1$), suggesting that *EMS* also

TABLE 6 Robustness check using alternative dependent variables.

Variables	**DV: LnCID**			**DV: CIDlogit**			**DV: NFCID**	
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
Legitimacy	−0.076** (0.032)	−0.115*** (0.035)	−0.114*** (0.036)	−0.067** (0.032)	−0.098*** (0.035)	−0.084** (0.036)	−0.222*** (0.072)	−0.283*** (0.074)
Legitimacy × GreenInv		0.086*** (0.032)			0.069** (0.032)		0.112* (0.065)	
Legitimacy × EMS			0.144** (0.064)			0.065 (0.064)		0.433*** (0.132)
GreenInv	0.026*** (0.003)	0.018*** (0.004)	0.026*** (0.003)	0.012*** (0.003)	0.005 (0.004)	0.012*** (0.003)	0.060*** (0.009)	0.071*** (0.006)
EMS	0.608*** (0.006)	0.608*** (0.006)	0.596*** (0.008)	0.625*** (0.006)	0.625*** (0.006)	0.620*** (0.008)	1.942*** (0.011)	1.906*** (0.016)
Indep	−0.035 (0.042)	−0.035 (0.042)	−0.035 (0.042)	−0.013 (0.042)	−0.013 (0.042)	−0.013 (0.042)	0.011 (0.087)	0.011 (0.087)
Dual	−0.022*** (0.005)	−0.022*** (0.005)	−0.022*** (0.005)	−0.021*** (0.005)	−0.021*** (0.005)	−0.021*** (0.005)	−0.018 (0.011)	−0.017 (0.011)
Size	0.087*** (0.003)	0.087*** (0.003)	0.087*** (0.003)	0.056*** (0.003)	0.056*** (0.003)	0.056*** (0.003)	0.169*** (0.005)	0.169*** (0.005)
ROA	−0.120*** (0.042)	−0.120*** (0.042)	−0.119*** (0.042)	−0.038 (0.042)	−0.037 (0.042)	−0.037 (0.042)	−0.173** (0.087)	−0.171** (0.087)
Lev	0.009 (0.014)	0.008 (0.014)	0.009 (0.014)	0.020 (0.014)	0.019 (0.014)	0.019 (0.014)	−0.075** (0.030)	−0.076** (0.030)
Growth	−0.009* (0.005)	−0.009* (0.005)	−0.009* (0.005)	−0.007 (0.005)	−0.007 (0.005)	−0.007 (0.005)	−0.013 (0.010)	−0.013 (0.010)
Cashflow	0.186*** (0.035)	0.185*** (0.035)	0.185*** (0.035)	0.118*** (0.035)	0.117*** (0.035)	0.118*** (0.035)	0.290*** (0.071)	0.288*** (0.071)
TobinQ	0.003 (0.002)	0.003 (0.002)	0.003 (0.002)	−0.005*** (0.002)	−0.005*** (0.002)	−0.005*** (0.002)	0.026*** (0.004)	0.026*** (0.004)
Top1	−0.038** (0.016)	−0.038** (0.016)	−0.038** (0.016)	−0.015 (0.016)	−0.015 (0.016)	−0.015 (0.016)	−0.015 (0.034)	−0.015 (0.034)
SOE	0.062*** (0.006)	0.062*** (0.006)	0.062*** (0.006)	0.050*** (0.006)	0.050*** (0.006)	0.050*** (0.006)	0.101*** (0.012)	0.101*** (0.012)
Heavy_polluting	0.091*** (0.006)	0.091*** (0.006)	0.090*** (0.006)	0.069*** (0.006)	0.069*** (0.006)	0.069*** (0.006)	0.095*** (0.013)	0.094*** (0.013)
Constant	−1.767*** (0.060)	−1.764*** (0.060)	−1.764*** (0.060)	−1.038*** (0.060)	−1.036*** (0.060)	−1.037*** (0.060)	−3.596*** (0.123)	−3.591*** (0.123)
Year effect	YES	YES	YES	YES	YES	YES	YES	YES
Industry effect	YES	YES	YES	YES	YES	YES	YES	YES
Province effect	YES	YES	YES	YES	YES	YES	YES	YES
Observations	27,453	27,453	27,453	27,453	27,453	27,453	27,453	27,453
R^2	0.441	0.441	0.441	0.417	0.417	0.417	0.589	0.589

Standard errors are in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 7 Robustness check using alternative independent variables.

Variables	DV: CID			
	Model 1	Model 2	Model 3	Model 4
NLegitimacy	0.017** (0.007)	−0.006 (0.008)	−0.001 (0.008)	−0.018** (0.008)
NLegitimacy × GreenInv		−0.051*** (0.006)		−0.047*** (0.007)
NLegitimacy × EMS			−0.073*** (0.014)	−0.057*** (0.014)
GreenInv	0.072*** (0.006)	−0.311*** (0.048)	0.071*** (0.006)	−0.282*** (0.049)
EMS	1.151*** (0.012)	1.150*** (0.012)	0.624*** (0.103)	0.740*** (0.104)
Indep	−0.126 (0.094)	−0.149 (0.094)	−0.132 (0.094)	−0.151 (0.094)
Dual	−0.041*** (0.012)	−0.043*** (0.012)	−0.041*** (0.012)	−0.042*** (0.012)
Size	0.203*** (0.006)	0.199*** (0.006)	0.202*** (0.006)	0.199*** (0.006)
ROA	−0.301*** (0.094)	−0.290*** (0.094)	−0.304*** (0.094)	−0.293*** (0.094)
Lev	0.011 (0.032)	0.021 (0.032)	0.014 (0.032)	0.023 (0.032)
Growth	−0.019* (0.010)	−0.019* (0.010)	−0.019* (0.010)	−0.019* (0.010)
Cashflow	0.440*** (0.077)	0.433*** (0.077)	0.438*** (0.077)	0.432*** (0.077)
TobinQ	0.013*** (0.004)	0.013*** (0.004)	0.013*** (0.004)	0.013*** (0.004)
Top1	−0.098*** (0.037)	−0.093** (0.037)	−0.098*** (0.037)	−0.094** (0.037)
SOE	0.128*** (0.013)	0.127*** (0.013)	0.129*** (0.013)	0.127*** (0.013)
Heavy_polluting	0.201*** (0.014)	0.200*** (0.014)	0.201*** (0.014)	0.200*** (0.014)
Constant	−4.379*** (0.134)	−4.120*** (0.138)	−4.228*** (0.137)	−4.022*** (0.140)
Year effect	YES	YES	YES	YES
Industry effect	YES	YES	YES	YES
Province effect	YES	YES	YES	YES
Observations	27,453	27,453	27,453	27,453
R^2	0.392	0.394	0.393	0.394

Standard errors are in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

negatively moderates the relationship between legitimacy pressure and carbon disclosure. Collectively, these results suggest that substantive carbon management practices within firms (green innovation or EMS) can increase the level of legitimacy of firms and alleviate legitimacy pressures due to negative social media comments.

Supplementary analyses

Corporate carbon information disclosure can be divided into two categories: financial carbon information disclosure (*FCID*) and non-financial carbon information disclosure (*NFCID*) (Li L. et al., 2017). The main difference between them is whether they are measured in monetary terms. Following Li L. et al. (2017), the scores of "government subsidies or incentives for carbon emission reduction" as well as "investments in carbon emission reduction technologies and funds" are utilized to assess the *FCID* of enterprises. The remaining seven items were used as *NFCID*.

To test the structural impact of social media legitimacy pressure on corporate carbon information disclosure, we further examined the relationship between social media legitimacy pressure (*Legitimacy/NLegitimacy*) and financial or non-financial carbon information (*FCID/NFCID*). **Table 5** reports the regression results. Models 1 and 3 report the impact of social media legitimacy pressures on corporate *FCID*, whereas Models 2 and 4 report the impact of social media legitimacy pressures on corporate *NFCID*. Both *Legitimacy* and *NLegitimacy* are insignificant in Model 1 and Model 3, but both *Legitimacy* and *NLegitimacy* in Model 2 and Model 4 are significant at the 1% level ($\beta = -0.172$, $\rho < 0.01$; $\beta = 0.021$, $\rho < 0.01$). This suggests that under the pressure of social media legitimacy, firms are more inclined to disclose non-financial carbon information rather than financial carbon information. This finding is in line with the study by Li L. et al. (2017).

Robustness check

We tested the robustness of our results through a set of robustness checks. First, we adopted an alternative measure of the dependent variable. Referring to Li et al. (2018), we used the natural logarithm of a firm's carbon disclosure score (*LnCID*), whether or not carbon information is disclosed (*CIDlogit*), and *NFCID* as dependent variables for robustness tests. All results are reported in **Table 6**. For the dependent variable *LnCID*, Model 1–Model 3 show that the coefficients on *Legitimacy*, *Legitimacy* × *GreenInv* and *Legitimacy* × *EMS* are significant ($\beta = -0.076$, $\rho < 0.05$; $\beta = 0.086$, $\rho < 0.01$ and $\beta = 0.144$, $\rho < 0.05$). Similarly, in Model 4–Model 8, the results are similar to those of previous analyses, except for the non-significant

TABLE 8 Robustness check using Tobit model.

Variables	DV: CID			
	Model 1	Model 2	Model 3	Model 4
Legitimacy	−0.174** (0.071)	−0.250*** (0.077)	−0.258*** (0.080)	−0.313*** (0.084)
Legitimacy × GreenInv		0.170** (0.070)		0.150** (0.071)
Legitimacy × EMS			0.326** (0.143)	0.280* (0.144)
GreenInv	0.073*** (0.006)	0.056*** (0.009)	0.072*** (0.006)	0.058*** (0.009)
EMS	1.151*** (0.012)	1.150*** (0.012)	1.124*** (0.017)	1.127*** (0.017)
Indep	−0.119 (0.094)	−0.119 (0.094)	−0.119 (0.094)	−0.119 (0.094)
Dual	−0.041*** (0.012)	−0.041*** (0.012)	−0.041*** (0.012)	−0.041*** (0.012)
Size	0.209*** (0.006)	0.209*** (0.006)	0.209*** (0.006)	0.209*** (0.006)
ROA	−0.298*** (0.094)	−0.298*** (0.094)	−0.297*** (0.094)	−0.297*** (0.094)
Lev	0.007 (0.032)	0.005 (0.032)	0.006 (0.032)	0.005 (0.032)
Growth	−0.018* (0.010)	−0.018* (0.010)	−0.018* (0.010)	−0.018* (0.010)
Cashflow	0.436*** (0.077)	0.434*** (0.077)	0.433*** (0.077)	0.432*** (0.077)
TobinQ	0.015*** (0.004)	0.015*** (0.004)	0.015*** (0.004)	0.015*** (0.004)
Top1	−0.109*** (0.036)	−0.109*** (0.036)	−0.109*** (0.036)	−0.110*** (0.036)
SOE	0.130*** (0.013)	0.130*** (0.013)	0.129*** (0.013)	0.130*** (0.013)
Heavy_polluting	0.203*** (0.014)	0.204*** (0.014)	0.203*** (0.014)	0.203*** (0.014)
Constant	−4.357*** (0.133)	−4.352*** (0.133)	−4.351*** (0.133)	−4.347*** (0.133)
Year effect	YES	YES	YES	YES
Industry effect	YES	YES	YES	YES
Province effect	YES	YES	YES	YES
Observations	27,453	27,453	27,453	27,453
Pseudo R^2	0.168	0.168	0.168	0.168

Standard errors are in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

moderating effect of corporate *EMS* in Model 5. These results are consistent with the main findings in **Table 4**, suggesting the robustness of our results.

Second, we used an alternative measure of the independent variable. Previously, we discovered that social media legitimacy pressures are primarily a result of negative comments on social media platforms. Therefore, we try to examine the moderating effect of corporate green innovation (*GreenInv*) and *EMS* by utilizing *NLegitimacy* as an independent variable. All results are reported in **Table 7**. In model 1, the coefficient on *NLegitimacy* is positive and significant ($\beta = 0.017$, $\rho < 0.05$). In models 2 and 3, the coefficients for *GreenInv* × *NLegitimacy* and *GreenInv* × *EMS* are negative and significant ($\beta = -0.051$, $\rho < 0.01$; and $\beta = -0.073$, $\rho < 0.01$). These results are consistent with our previous, suggesting that our results are robust.

Third, most Chinese companies do not disclose their carbon emissions; that is, they have a carbon information disclosure score of 0 (CID = 0). Thus, the dependent variable is truncated at 0. In our study, they account for 59.17%. We, therefore, considered a robustness test using the Tobit model. All the results are reported in **Table 8**. From the reported results, all the findings remain consistent with the previous analysis, which further indicates the robustness of our results.

Discussion and conclusion

As countries in the world continually implement measures to address climate and environmental change, corporate carbon information disclosure is becoming increasingly important to stakeholders. Social media offers the public a convenient and effective platform to voice their concerns about climate change. As a result, we examined the impact of social media legitimacy pressure on corporate carbon disclosures, using the largest listed Chinese stock exchange platform as a data source. We provide strong evidence that social media legitimacy pressure has a significant positive impact on corporate carbon disclosures. Furthermore, we find that substantive carbon management measures have a moderating effect on corporate legitimacy pressure, and corporate green innovation and EMS alleviate the legitimacy pressure faced by enterprises.

Theoretical contributions

This study makes two main contributions to the existing literature. First, using social media as a means of generating corporate legitimacy pressure, we validated the effectiveness of social media monitoring of corporate carbon disclosure, which contributes to the application of legitimacy theory to information disclosure. Earlier literature has concentrated on institutional pressure from the government (Luo, 2019), mass media (Li L. et al., 2017; Li et al., 2018), and most studies have focused on heavily polluting industries or large companies. However, our study sample includes a significant number of small and medium-sized enterprises as well as businesses located in non-heavy polluting industries. Using a more comprehensive sample, we found that legitimacy pressure not only enhanced corporate disclosure but also impacted the structure of corporate disclosure. Second, we contribute to the carbon management literature by considering corporate carbon disclosure as a symbolic carbon management measure and emphasizing the interaction between symbolic and substantive carbon management measures. We find that both symbolic and substantive carbon management measures alleviate the legitimacy pressure on companies.

Practical implications

More practically, in the context of the carbon-neutral, carbon-cycling era, this study provides evidence and insights for policymakers to formulate regulatory policies better. First, corporate carbon disclosure is a response strategy to threats to corporate legitimacy. However, it is likely to be a symbolic management measure. Governments need to establish appropriate regulations to make it mandatory that companies disclose substantive carbon management practices in order to prevent companies from trying to "bleach" themselves by using such low-cost measures. Second, our research has proved the appropriateness of social media as a strong regulator of corporate carbon disclosure. Social media is a potent regulator of corporate carbon disclosure. In other words, when companies disclose additional carbon information on their social media platforms voluntarily, this will increase their credibility and differentiate them from companies in the same industry that make low-quality disclosures. Consequently, it is crucial that companies use substantive carbon management practices to improve their carbon performance. Third, although both substantive and symbolic carbon management measures can effectively alleviate the legitimacy pressure of social media, if companies engage in only symbolic carbon management behaviors rather than substantive carbon management behaviors for a long time. This will inevitably lead to decoupling companies' carbon management practices and consequent stakeholder penalties. Therefore, it is necessary for companies to maintain consistency between carbon disclosure and carbon management activities.

Limitations and directions for future research

Our study has several limitations. Firstly, due to data availability, only nine carbon information disclosure items were selected in this article to calculate enterprises' carbon information disclosure score, and this measurement method may not be authoritative. When the quality of corporate carbon information disclosures is further enhanced, additional carbon information disclosure items will have to be selected to calculate the corporate carbon information disclosure scores. Second, although the stock forum has the characteristics of social media, it is still different from popular social media such as Facebook and Twitter. A further investigation needs to be conducted into whether stakeholders expressing their legitimacy expectations on social media platforms such as Facebook and Twitter enhance corporate carbon disclosure.

Data availability statement

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

Author contributions

JS completed the logical structure of the study as well as the data collection. ZH completed the empirical research in the study. Both authors contributed to the article and approved the submitted version.

Conflict of interest

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

Publisher's note

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APPENDIX A Variable definition.

Variable	Definition	Data source
CID	The total score of firm carbon disclosure items	CSR report
Legitimacy	The Janis-Fadner coefficient calculated by the social media comments (Eq. 1)	CNRDS database
GreenInv	The natural logarithm of the amount of one firm's green utility patents and green invention patents	CNRDS database
EMS	A dummy variable equals 1 if the firm adopted the IS014001 environmental management system or set up the "three simultaneous" system and 0 otherwise	CSMAR database
Indep	The percentage of independent directors to the total number of directors	CSMAR database
Dual	A dummy variable equals 1 if the chairman and CEO were the same people and 0 otherwise	CSMAR database
Size	The natural logarithm of total assets	CSMAR database
ROA	The ratio of total net profit to total assets	CSMAR database
Lev	The ratio of total debt to total assets	CSMAR database
Growth	The growth rate of a firm's operating income	CSMAR database
Cashflow	The ratio of net cash flow from operating activities to total assets	CSMAR database
TobinQ	The ratio of the sum of the market value of equity and the book value of liabilities to total assets	CSMAR database
Top1	The percentage of shares held by the first largest shareholder	CSMAR database
SOE	A dummy variable equals 1 if the ultimate ownership of the firm is owned by the state and 0 otherwise	CSMAR database
Heavy_polluting	A dummy variable equals 1 if the firm belongs to the heavy pollution industry and 0 otherwise	CSMAR database

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Using media reports to analyze the spatio-temporal evolution of carbon dioxide management development in China

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Over the past few decades, the carbon dioxide (CO_2) emissions management problem has attracted global attention. China is transitioning to carbon neutrality and experienced rapid development in low-carbon management. However, current studies have limited understanding of the evolutionary process and development issues at a macro-level, which may hinder the structural reformation of stepwise carbon-neutral development. This study used the content analysis method to process and code reports from China's most prominent news media, Xinhua News Agency, to identify China's low-carbon evolution and development issues. The results depict a trend of gradually increasing carbon management within China and highlight the staged development features. Years 2010 and 2021 are the critical nodes of carbon emissions management in China, representing the two primary actions of low-carbon pilot city projects and the carbon-neutral construction. However, the results also reveal the uneven development problem of China's carbon management behind the rapid transition. The government is the primary participant in carbon management, but the participation of firms and the public is relatively low. The power industry implements the highest amount of carbon management actions, but less attention is paid to other sectors with high carbon emissions. Report tones on environmental protection and green technology have gradually declined, while the tone on economic and social development has increased. There are evident differences in the number of carbon management measures implemented between regions. The southeast coastal regions report more management numbers than China's central and western regions. The top three provinces (or municipalities) are Beijing (131), Shanghai (93), and Guangdong (78). From an industry perspective, more-reported regions have implemented carbon management measures in more industries than less-reported regions. This study provides a distinctive contribution to the theoretical work on China's carbon emissions regulation and the emerging planning and management mechanisms.

KEYWORDS

news media report, carbon neutrality, content analysis, evolution, uneven policy implementation

Introduction

Over the past few decades, the carbon dioxide (CO_2) emissions problem has attracted the attention worldwide. CO_2 contributes to air pollution and is responsible for the energy imbalance in the atmosphere, causing the greenhouse effect and secondary issues such as natural disasters and severe weather (Nawaz et al., 2020; Umar et al., 2020). Therefore, reducing CO_2 emissions has become a common target globally to alleviate the greenhouse effect and realize humankind's sustainable development in the future. Countries worldwide have introduced carbon management policies and measures such as carbon emission reduction, new energy development, and carbon fixation technologies to reduce carbon emissions (Ducat and Silver, 2012; Zheng et al., 2021). Alternatively, some economists proposed to use economic tools, such as establishing carbon markets to limit and manage carbon emissions through carbon trading (Perdan and Azapagic, 2011; Weng and Xu, 2018). China is at the rapid development stage with increasing emerging markets and industries (Gao et al., 2022) and has a high carbon emission level. Hence, carbon management issues have received increasing attention in China, and theChinese Government set a clear commitment to reach the carbon peak in 2030 and achieve carbon neutrality by 2060 (Zhao et al., 2022). In this transition period, the Chinese Government has introduced and implemented diverse practices and trails to control carbon and issued a series of policies and actions to transit into a low-carbon society. These emerging practices include carbon emission reduction, low-carbon urban construction, green energy development, green transportation, carbon market, and carbon trading, and their practicability and effectiveness were also well studied (Zhang et al., 2016; Yang and Cheng, 2017; Hu et al., 2019; Umar et al., 2020; Wang K.-H. et al., 2021).

However, for such public policy development issues, little is known about the evolution process and potential development issues of China's carbon management issues from a macro perspective. As China enters a new phase of carbon-neutral construction, the exploration from the macro perspective is necessaryto help analyze an issue's temporal and spatial characteristics and changes and overcome conflicts between long-term goals and short-term concerns (Rotmans et al., 2001; Herold et al., 2003). Hence, understanding the evolutionary process of carbon management is urgently needed to spur sustainable development. For the societal study, media datasets are critical data sources that cannot be ignored. The news media, a precise source for recording time-definite information, helps provide necessary data for societal and evolutionary studies (Wei et al., 2017). The news media is one of the central explanatory systems in modern society, representing the views and attitudes of different groups, and has the power to create common knowledge and enhance public coordination (Potter, 2011). The media can reflect the Government's values, attitudes, and opinions and official public opinion on environmental management issues (Kavanaugh et al., 2012), thereby reflecting the objective status, trends, and development characteristics of the issue. At the administrative level, China's top-down regulation mechanism enables the Government to play a more dominant role in managing social and environmental public issues (Saravade et al., 2022). Therefore, the content expression of the mainstream media in China is likely to be very different from that of Western democracies. The state-owned nature of China's mainstream media makes it a guidance for mainstream values and policies in mainland China (Wei et al., 2017), which reflects the implementation of local policies and their impact on the public. Such disparities pose opportunities for research on understanding China's official responses to carbon issues and the potential problems within the development.

In this context, this study attempts to analyze the coverage of carbon issues by major Chinese news media through content analysis, providing new perspectives for understanding the evolution and potential development issues of carbon management in China. Through big data screening and analysis, the results reflect the long-term status of China's carbon management development. In theory, this study provides a distinctive contribution to the studyof China's carbon emissions regulation, emerging planning, and management mechanisms. Specifically, the objectives are screening and coding the primary variables of news reports and analyzing these variables temporally and spatially to identify the development trends and the unfairness within the management. The findings conclude the progress and deficiency of carbon management in China and assist carbon policymakers in improving management strategies to achieve carbon neutrality goals in the future. In addition, the findings from public news media reveal lessons on the carbon issue in China that might not emerge from other data sources.

The remaining content of the paper is structures as follows. Section "Background" provides a relevant background of China's carbon management development and summarizes the milestones.Section "Materials and methods" presents the methodology for this study; Section "Results" demonstrates the results and interpretation. Section "Discussion" presents the discussion and the implication of the findings and sums up to conclude the paper.

Background

Development of the carbon emissions management in China

China is one of the largest carbon emitters, accounting for 28% of global carbon emission (Friedlingstein et al., 2020). Within these industries, manufacturing and industrial production contributes the largest proportion of CO_2 emissions in China (50%), then follows the power industry contributes

40%. The transport industry occupied 8%, and the other industrial and economic sectors, including commercial, residential, agricultural, and building and construction, shared the rest (Sandalow, 2019).

As early as 2000, the Chinese Government decided to implement the Natural Forest Protection Program (NFPP) to enhance and protect the stability of the economy and the population's livelihood (Qiao et al., 2021) and it has become one of the primary measures for carbon fixation after the carbon emission reduction target is proposed. In 2005, the Chinese Government launched the National Circular Economy pilot work to explore the valid mode of carbon emission reduction in critical areas and industries (Geng et al., 2013). Then, the Chinese Government first proposed energy conservation and emission reduction targets during the 11th 5-year plan (FYP) in 2006 to support the development of the Circular Economy (Yang et al., 2019). In addition, the Chinese Government is constantly improving carbon management laws. The National Development and Reform Commission (NDRC) issued China's first global warming policy, China's National Climate Change Program, in 2007. This program focuses on carbon emission governance and energy intensity in energy production and use, agriculture, forestry, and waste industries (Marks, 2010). In the following years, the Chinese government has successively introduced national policies related to carbon.

Meanwhile, the Chinese Government realized cities' profound impact on CO_2 emissions. Given China's fast urbanization process and higher energy consumption than the rural areas, the NDRC initiated a low-carbon pilot city and province program in July of 2010 (also known as LCCP) to lead the transition of cities to a low-carbon development model (Khanna et al., 2014). The first five pilot provinces include Yunnan, Guangdong, Hubei, Shaanxi, and Liaoning provinces and the eight pilot cities include Tianjin, Baoding, Hangzhou, Chongqing, Nanchang, Guiyang, Xiamen, and Shenzhen (Wang et al., 2015). However, research assessments suggest that while pilot cities have made progress in carbon management planning, the complexity and confusion caused by multiple parallel plans and the lack of supportive policies and market support may hinder the realization of low-carbon cities (Khanna et al., 2014). Correspondingly, China's Ministry of Transport launched a green transportation pilot project in 2011 to complement the construction of low-carbon cities. The project aims to promote the application of low-carbon transportation equipment by constructing low-carbon transportation infrastructures (Qu and Liu, 2016) and integrating the low-carbon concept into people's lives. In addition, the Chinese government started to rely on market surveillance tools to achieve policy goals. For example, drawing on the experience of foreign carbon market construction, China's National Development and Reform Commission implemented an Emissions Trading Scheme (ETS) in seven pilot regions in 2013, and all of them started operation in 2014 (Munnings et al., 2016). Although the carbon trading outcomes are suboptimal due to the inadequate scheme design, the experience of establishing and operating the pilot systems is valuable. The empirical study showed that China's carbon intensity declined by 33% from 2000 to 2015, which is mainly attributed to the progress made by these carbon management projects, especially the improvement of industrial energy efficiency contributed the most to the reduction of emissions (Liu et al., 2019).

Internationally, the Chinese Government has actively participated in global carbon reduction conferences and activities in recent years. In 2016, China signed the Paris Agreement with 180 countries worldwide, aiming to limit the global average temperature rise to 2 or 1.5°C by the end of this century. To achieve a low-carbon society earlier, China committed to achieving peak CO_2 emissions around 2030 and enlarging carbon intensity reduction by 65% from the 2005 level (Zhou et al., 2021). Based on the peak carbon emission target, China proposed a new goal in 2020: to achieve carbon neutrality by 2060 (Mallapaty, 2020). This goal reflects the determination of China to tackle climate change, and it also poses challenges to China's development. In summary, China's major carbon management actions are listed in the timeline below (**Figure 1**).

Existing challenges in carbon emissions management in china

However, China still faces many challenges from peak carbon to carbon neutrality in the transition period. (1) China's carbon emission continues to increase, while its carbon emission may not reach its peak in the short term; (2) China relies heavily on fossil energy (up to 85%) to maintain its rapid development, with significant energy consumption and low efficiency; (3) China's economic development level is relatively lower than developed countries, making it weak to resist economic risks; (4) low-carbon and renewable energy technologies are immature; (5) promoting regional low-carbon emissions and a national "green market" remains an important challenge in realizing a comprehensive low-carbon society (Musa et al., 2018; Liu et al., 2021; Zhao et al., 2022). Therefore, to address these issues, China's low-carbon policies and actions must ensure that top-down socio-economic development measures coincide with bottom-up economic incentives and technological development.

Materials and methods

This study applies content analysis to examine media coverage of carbon issues in China. Content analysis is a systematic and replicable technique that compresses texts into content categories by explicit coding rules (Stemler, 2001). This method has been applied in diverse fields and multidisciplinary

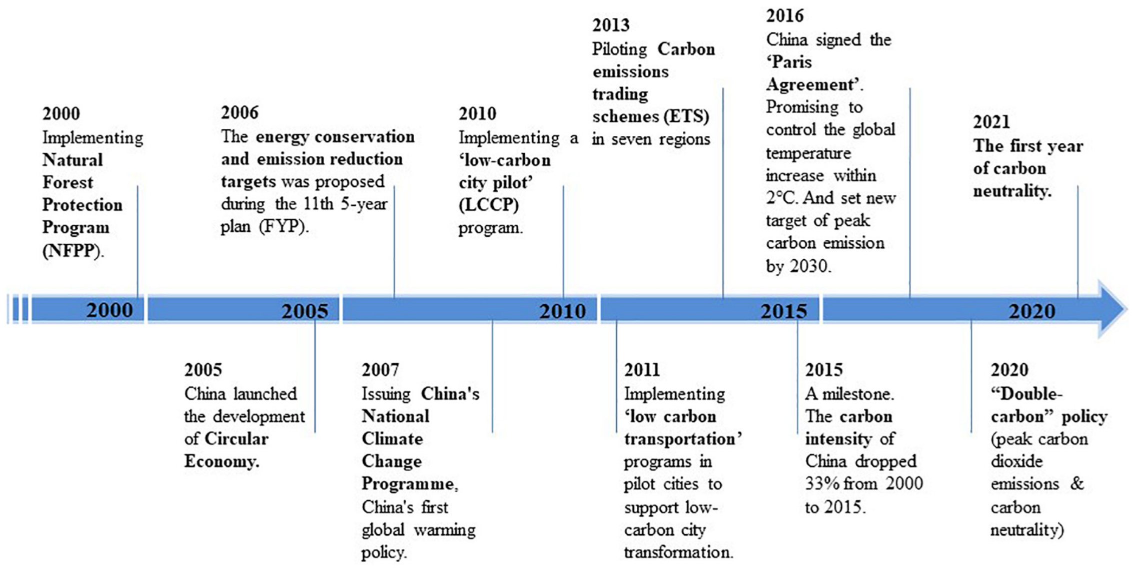

FIGURE 1
The timeline of China's major carbon management events.

studies for mining large, unstructured, and fuzzy textual data, discovering unintuitive information other than numeric data in the text to determine the public attitudes, relevance, and public tones of media reports on issues (Xiong et al., 2016; Hickman et al., 2022). Besides, these steps include media source selection, sampling method selection, coding strategies, and result interpretation.

Media selection

News media website was selected as the media source for carbon issue reports in China. The news media, also known as mass media, includes print media (newspapers), electronic media (radio, television), and online media that have emerged with the rise of the Internet. The news media is an essential and high-quality source of information on public issues, providing readers with continuous and in-depth information and maintaining timeliness, accuracy, and authenticity (Van der Wurff, 2008). Online news media is a new platform for news, and many print and electronic media established their corresponding online platforms. Online news is simple and easy for readers to obtain, without losing the accuracy and authority of the information. In addition, online news and print media can provide readers with a historical perspective on issues. By reviewing past reports, one can draw results with a historical empirical value that cannot be provided by channels such as radio and television (Ghersetti, 2014).

Xinhua News Agency, established in November 1931, is the official state news agency of the People's Republic of China (China). Xinhua News Agency is the largest and most influential media organization in China. It has established a News Information Collection network covering the whole world, has more than 100 branches worldwide, and formed a multilingual, multimedia, multi-channel, multi-level, and multi-functional news release system (Hong, 2011). As the direct and authoritative information channel for the Chinese Government to the outside world, Xinhua News Agency has substantial and far-reaching influences on public opinion. Especially for major events and issues, the internal norms it published play a leading role in the Chinese media while setting the tone of coverage that other Chinese media must follow (Xin, 2006). This study used Xinhua News Agency's news release platform Xinhuanet[1] as the source of news reports on China's carbon issues. Due to the leading role of Xinhuanet's news in the domestic media of China, its content is sufficient to cover carbon-related news from other media. In previous studies, using a single mainstream media was recognized as a viable approach (Wei et al., 2015, 2017, 2021; Xiong et al., 2016).

Sampling

Two approaches were used for social media analysis. The first is a computational approach that uses algorithms to code. However, algorithms analysis may not accurately identify the sensitivity of the conceptual boundaries of topics and the sampling frames of the large-scale data, which increases the

1 http://www.xinhuanet.com/

difficulty in categorizing complex variables and nuanced texts (Zamith and Lewis, 2015). The second is the big data approach, which collects and analyzes existing content of target issues (Russell Neuman et al., 2014). This approach does not include the traditional sampling process as it relies on keyword-based content selection. The reports were assembled for a 20-year study period (2002–2021) using the Factiva database, with 15,648 news reports. This study combined two methodological approaches for analysis processing: collecting and encoding all the reports. Following previous studies, analyses reported in this study were enforceable to the relatively small sample size (Kim et al., 2018).

Reports retrieval and review

We used "carbon" (Chinese) as the keyword to search for reports in the online database. The total number of reports retrieved was 15,768. The reports were downloaded and stored as a "raw database," and their relevance was manually reviewed and checked by four researchers over a two-month period using the criteria in **Table 1**. The reports mentioned the word "carbon" occasionally and did not involve issues such as carbon emissions, carbon finance, carbon sink, carbon trading, low-carbon technologies, dual carbon (carbon neutrality, carbon peaking), carbon management, etc., were deleted. The final number of the reports that directly related to carbon issues for analysis was 2101.

Report coding

The researchers preliminarily determined the relevance of the reports to carbon issues, and the relevance judgment criteria are listed in **Table 1**. Then, the filtered high-relevance reports were analyzed according to the coding table (**Table 2**).This paper designs a set of variables based on the ideas and methods proposed by previous studies; it analyzed and codes each report according to the media framing theory and agenda-setting theory (Joshi et al., 2011; Xiong et al., 2016). These two theories provide a solid theoretical foundation for this study. The media frame theory refers to the news media setting a fixed frame, situation, and viewpoint for news reports to guide the audiences attitude and cognitive judgment of facts, thereby influencing public opinion on specific issues. News framework formulation's objectivity and rationality directly affect whether public opinion can be correctly and effectively guided. Agenda-setting theory demonstrates that the media guide people's attention to specific events by providing information and prioritizing related issues. This theory builds on the assumption that the more emphasis the media puts on an event, the higher the public's attention to the issue (Mccombs and Shaw, 1972; De Vreese, 2005). The study's framework established by these two theories will help explore the evolution of mainstream society's views on specific issues, as detailed in **Table 2**.

TABLE 1 Relevance criteria.

Criteria for including reports	• Reports on carbon-related actions that have been or will be introduced and implemented • Reports on carbon-related policies and regimes that have been or will be published • Meetings and conferences to discuss carbon management issues (carbon management must be the main content of the meeting) • Develop guidelines and policies for carbon management
Criteria for excluding reports	• Reports did not address carbon emissions management issues (e.g., carbon mining; carbon materials; carbon fibers; carbon isotope in dating studies) • Reports mentioned carbon management issues, which were not the main content (e.g., meetings mentioned carbon emission management but did not discuss practical actions, policies, regimes, or goals) • Reports covering the same carbon-related actions, conferences, or regimes were counted as only one item during the coding process

Coding variables were divided into two categories. The first category summarized the essential context information of the news reports. Include the time of the news reports; the location or area of concern; organizations involved in the reports (i.e., government agencies, non-governmental organizations, firms; industries, and economic sectors); and policies and initiatives (i.e., carbon management-related laws and policies formulated by national and local governments). The second category contains the thematic information of the reports, including the theme and the tone of the event. The report themes covered major carbon issue categories, such as carbon sequestration, carbon neutrality, carbon finance, and other hot topics (Hua et al., 2011; Hu et al., 2019; Umar et al., 2020; Wang K.-H. et al., 2021); the tones were coded as environmental, social, economic, technical, and not mentioned. For example, a report on environmental development is considered "environmental"; if a report addressed the development of green economies, its tone is assessed as "economic." These tones reflected views on different dimensions of China's carbon issue.

This study applied an interpretive approach to the content analysis of reports, and the encoding process was done manually. Rather than just recording and counting instances of keywords, the coding team scrutinized the occurrence of specific keywords and obscure content throughout the text. This approach enanbled one to understand and examine what is and isn't present in the text, capture latent meaning, as well as discover changes and nuances in encoded categories over time (Bransford et al., 1972; Wei et al., 2017). The two coders were trained at first to ensure coding was checked for reliability and develop a common understanding of the meaning of the codes. Then, to assess the consistency of coding results, the two coders

TABLE 2 Description of coded variables.

Category	Variables	Description
	Relevance	Based on the criteria identified in Table 1, we used a dummy variable (1 = relevant reports, 0 = irrelevant reports) to determine whether the news reports were relevant
I: Context Information of the reports	Year	Publication year of the reports
	Administrative location (regional or national)	Provinces and cities that have implemented carbon management measures. Further, if the action is a cooperative action with another country, only the province is recorded
	Organizations	Which organizations were mentioned in the reports? Government, non-governmental organizations, or firms
	Policy	The policy was mentioned in the reports. The type of policy was divided into three levels: regional, national, and international
	Industry and economic sectors for carbon emissions management	Industry or economic sector in the reports. Disaggregates global greenhouse gas emissions by different industries and economic sectors, including: "Electricity and heat production (energy)"; "Manufacturing industry"; "Transportation"; "Agriculture and forestry and other land use; "Commercial and residential"; "Building and construction" (EPA, 2020)
II: Thematic Information of the reports	Themes	Carbon issues were divided into multiple themes, covering major issues of carbon management "Carbon market"; "CO_2 emissions goal setups"; "Carbon neutrality and carbon peaks"; "CO_2 reduction technology"; "Green energy development"; "Low-carbon ecology development"; "Investments in the low-carbon industry"; "Low-carbon footprint and low-carbon life"; "Corporate carbon information disclosure"; and "Low-carbon building and construction"
	Report tones	The tones of the report were divided into four aspects: "Environmental," "Social," "Economic," and "Technical"

randomly selected 10% of reports from each year for double coding and used Cohen's kappa (O'Connor and Joffe, 2020) to test the agreement. The agreement was 0.86, which was higher than the excellent agreement level of 0.8 recommended in the past study (McHugh, 2012).

Statistical and trend analysis

After reporting coding, descriptive statistics were used to present temporal trends of the main coding variables. The regression analysis was used to describe the change in different types of policies. The spatial distribution of the variables was processed using ArcGIS software to present the spatial differences between regions. The descriptive analysis used for the two thematic variables, theme, and tone of news reports, aimed to describe and explain transitions of carbon issues and reflect the changes in governmental attitudes, options, and guiding principles on carbon management in news coverage.

Results

The temporal development status of carbon emission management in China

This section concluded the temporal changes and characteristics of carbon emissions management in China. This study's total number of reports directly related to carbon emission management was 2101. The number of these reports is diverse (**Figure 2**) and showed an increasing trend in reporting numbers. 2002 to 2004 had the least number of carbon-related reports. The first milestone occurred in 2010, then the reports of the following years retained a relatively high level compared to the previous period (2002–2009). Then in 2021, this number reached the highest among the others, reflecting the enhancing attention on carbon neutrality construction in China.

In **Figure 3A**, "green energy development" was the most reported theme in the news reports (20.69%), followed by "CO_2 emission goal setup" (19.25%). The carbon market and constructions in low-carbon ecology and industries were also the topics that attracted a high proportion of attention. These themes contributed to more than 75% of the overall news reports. On the contrary, the coverage on low-carbon building construction, corporations' carbon emission information disclosure, and CO_2 reduction technologies were small. **Figure 3B** demonstrates the themes of the news reports in the time scale; the diversity of themes was low in the first seven years (2002–2008). The "goal setup" theme occupied the most considerable portion in the first three years, and then "green energy development" exceeded it in 2005. Still, these two themes were dominantly reported throughout the study period. More reporting themes on carbon issues emerged after 2008, assigning dominance to the themes of "goal setup" and "green energy," reflecting the continued diversification of China's carbon governance issues The theme "carbon neutrality and carbon peaks" first occurred in 2008 but had a low-level proportion; it became a dominant theme in 2019 and reached its peak in 2020. The theme "CO_2 reduction technology" was one of the primaries

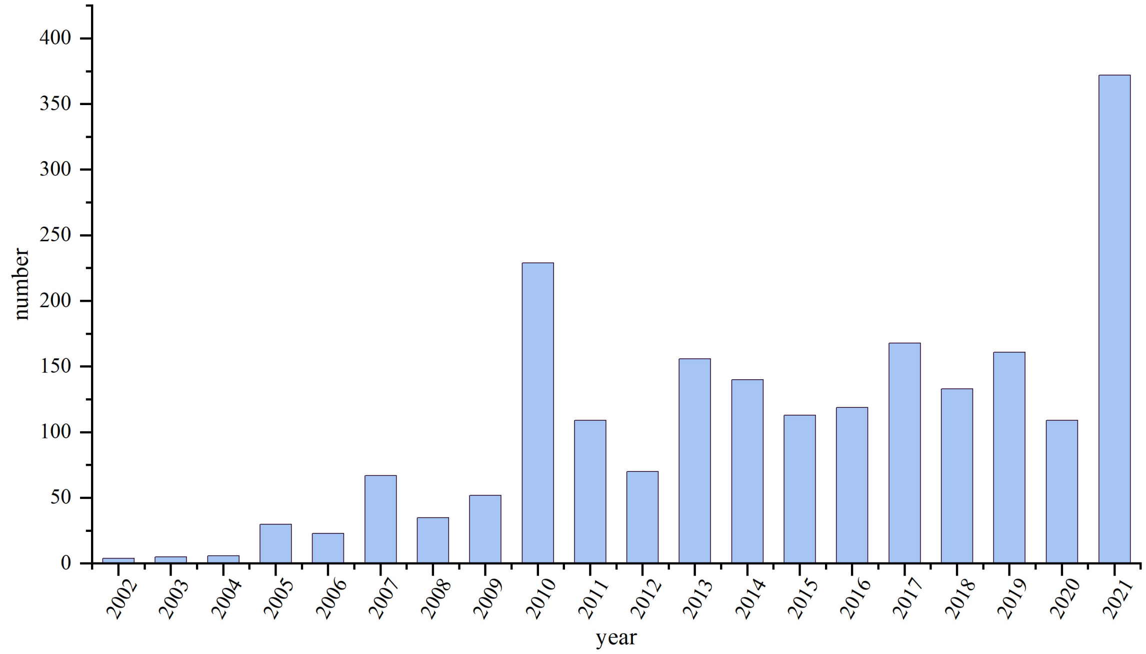

FIGURE 2
The number of carbon emission management reports from 2002 to 2021.

at the initial stage of development but was less discussed in the later stage.

Figure 4 shows the nature of major organizations participating in carbon management actions. Government agencies have been the prominent participants and had more than 50% participation in most of the years. These governmental agencies include government units and departments at all levels and regions. No firm or non-governmental organization (NGO) or public participated in carbon emissions management at the beginning stage (2002). Starting from 2003, the participation of firms and NGOs occupied an evident proportion of the management action, though it did not exceed the Government. In 2021, there was a rapid increase in firms' participation and shared the same proportion with the Government, reflecting the growing importance of firms in participating the carbon emissions management.

Figure 5 demonstrates changes in the proportion of different carbon-related policies and treaties mentioned in the news reports. A regression analysis was performed to determine the trend of change. The results showed that the evolution change follows a sigmoid function, with an adjusted R^2 of 0.91 for the international policy, 0.743 for the national policy, and 0.71 for the regional policy. The international policies were dominant at the earliest stage from 2002 to 2006. After 2006, the coverage of international policies in the news reports began to decline and stayed at a low level after 2010 (around 15%). Meanwhile, the proportion of national policies increased with the decrease of the international policies proportion and occupied the dominant part in the following ten years. The regional policy had a continuous growth trend. In 2021, national and regional carbon emission management policies were mostly mentioned in the news reports.

The tone of the reports reflects the government's attitudes and views on carbon management issues (Figure 6). Obviously, the expression of environmental tones dropped continuously, then stabled at a constant dynamic level after 2010. On the other hand, the tones of economic, social, and technical have risen, but with different trends. The proportion of economic-tone reports increased harshly from 2002 to 2006 then remained fluctuating in a range of 25–40%. The proportion of technical-tone reports was the lowest of the others; it increased sharply after 2002 and reached its peak in 2003. The increase in social tone reports was later than the economic and technical tone reports. The evident increase of proportion was after 2007 and reached the peak of 53% in 2013, and then the proportion dropped and retained a state of great fluctuation (20–45%).

Figure 7 demonstrates the proportion of the carbon emission management actions introduced in each industrial and economic sector. The management behavior of the power (power generation) industry accounted for the largest proportion at that time, reaching 40%, followed by the emission management of "commercial and residential operations." The "agriculture, forestry and other land-use," "transportation," and "manufacturing and industrial production" emission management had a similar proportion. The "Construction and

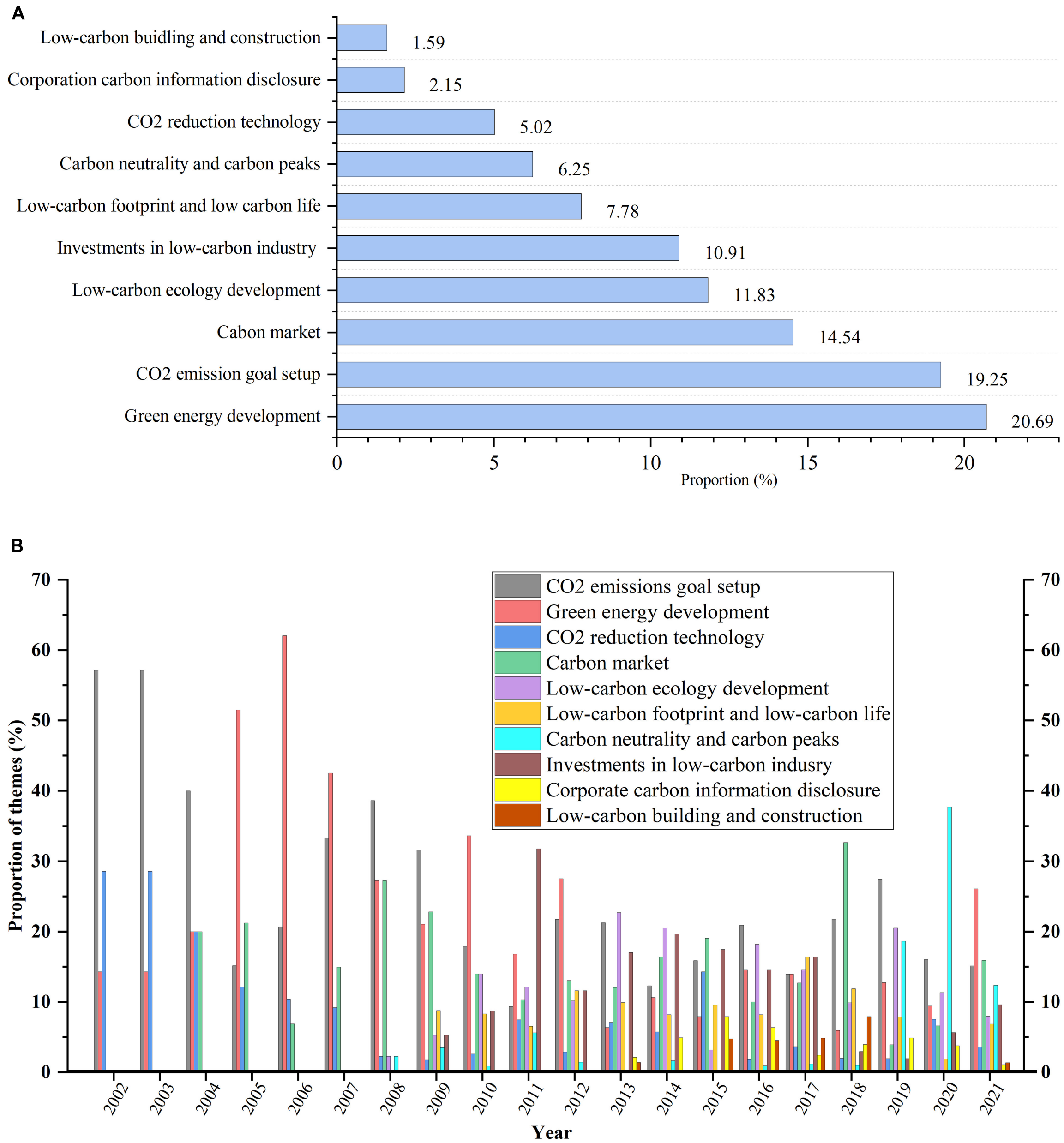

FIGURE 3
(A) The proportion of theme topics identified as key topics in newspapers from 2002 to 2021. **(B)** The themes of carbon emission management in the news reports 2002-2021.

Building" sector was the least concerned, occupying only 3.7% of the total introduced actions.

The spatial differences in carbon emission management in China

The number of carbon emission management actions implemented by provinces (or municipalities) in China is uneven (**Figure 8**). Beijing, Shanghai, and Guangdong reported the highest number of actions and are also the economic centers and the most developed regions in China. First, Beijing was at the top (more than 100), then followed by Shanghai (≥90). Guangdong had the third-largest number of actions (78). The fourth tier (40–59) includes Jiangsu and Zhejiang, Inner Mongolia, Shanxi, Sichuan, and Tianjin. Then the rest provinces (or municipalities) were in tier five (20–39) and tier six (0-19), of which Guangxi province reported the least number of carbon-related actions. The details are listed in **Table 3**.

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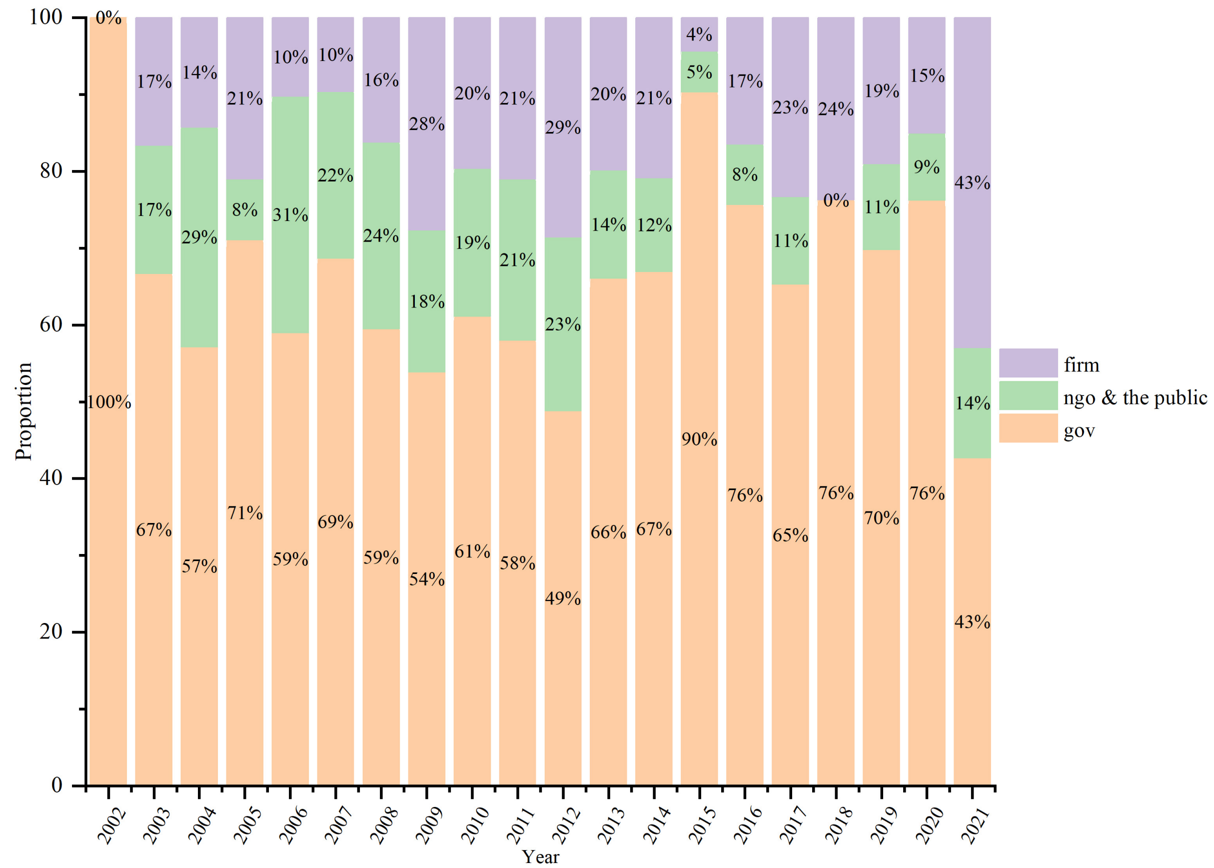

FIGURE 4
The proportion of different types of organizations and agencies that participate in the carbon emissions management.

Specifically, Figure 9 demonstrates the proportion of the carbon-related economic section in each province (or municipality), reflecting the uniqueness and the unevenness of carbon management actions applied in each place. Evidently, carbon management in the power industry was dominant, especially in Shanxi and Liaoning provinces. Ningxia, Gansu, Xinjiang, and Jilin provinces (>50%) also regarded carbon management in the power industry as a primary action. In the second-largest economic section (Figure 7), commercial operations and residential activity did not account for the same proportions across provinces. Though some provinces have reached a ratio of more than 20% (the highest in Shanghai for 32 there were also some provinces below 10% or even no relevant reports, such as Guangxi, Yunnan, Jilin, Shandong, and Shanxi. In contrast, agricultural and forestry carbon emission management existed in all provinces; it was highly significant in some provinces and exceeded the proportion of the power industry (i.e., Heilongjiang, Tibet, and Inner Mongolia). Carbon management actions in transportation and manufacturing industries were not as dominant as in the power and agriculture sectors, but they occupied a significant proportion in some provinces. In most provinces, carbon emissions management in the construction and building industry was least focused on and had no relative reports. It was reported in only a few provinces but occupied a low proportion (<10%). Tianjin was the only city with a large (32%) share of carbon management in the construction sector.

Discussion

It is important to understand the evolution of China's carbon management-related regimes and actions toward carbon neutrality to be able to explore the strengths and weaknesses in carbon emissions reduction development. This paper develops a new perspective on understanding China's carbon emissions management regimes using longitudinal empirical study and content analysis of *Xinhua News Agency*, China's major official news media The main research results theoretically help regulate the uneven development of China's emerging carbon-related institutional planning and carbon emission management. The findings and their implication for practices and future research are as follows.

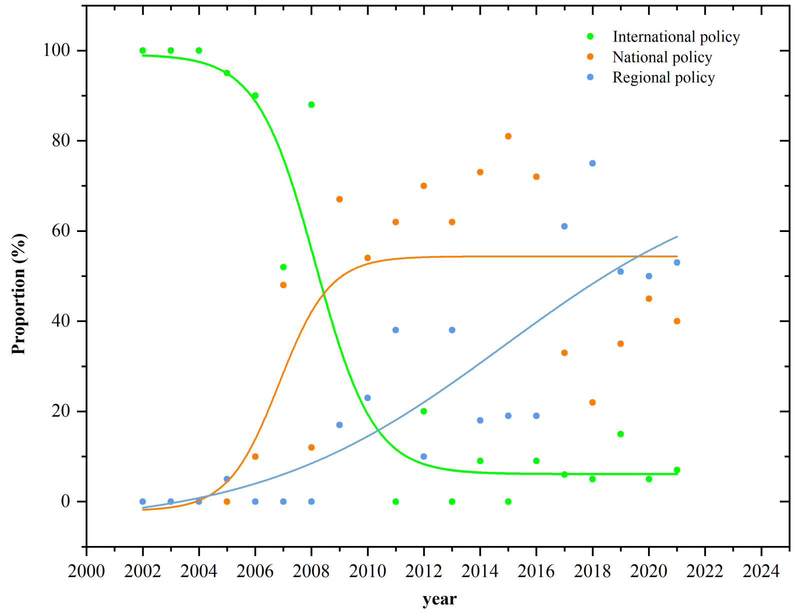

FIGURE 5
The proportion of the policy types mentioned in the news reports.

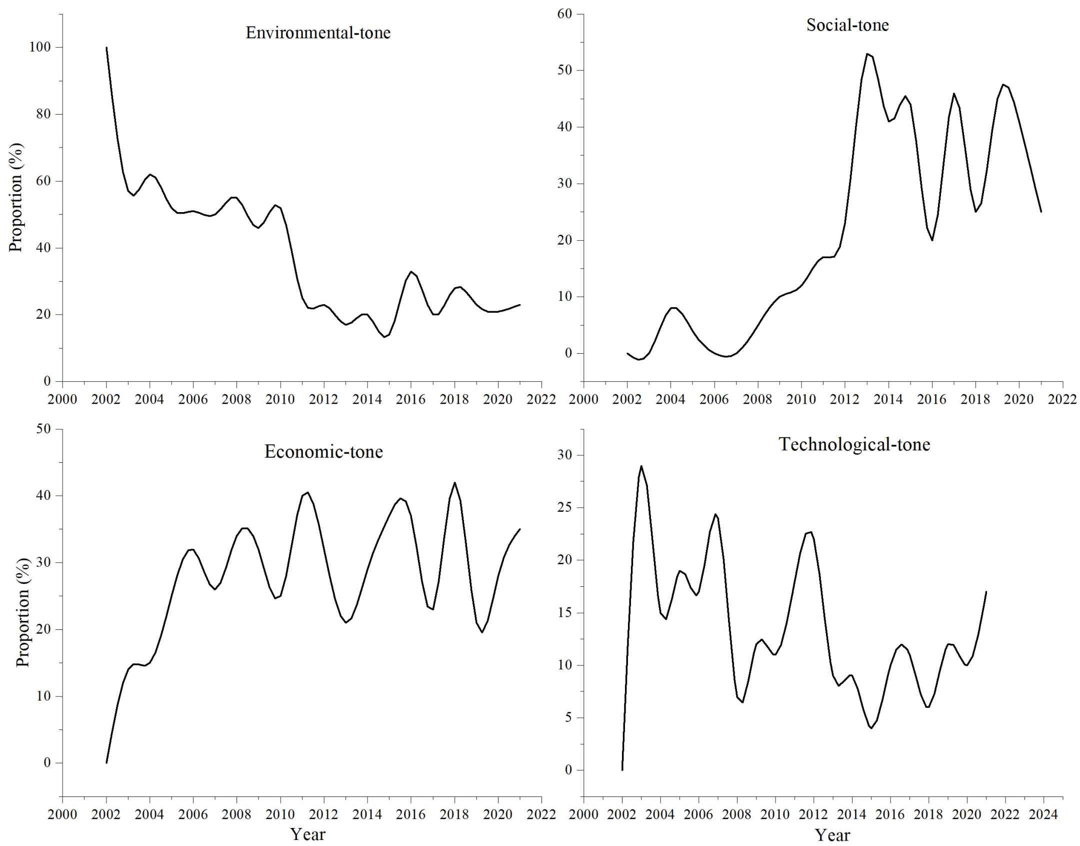

FIGURE 6
The time changes in the tones of news reports.

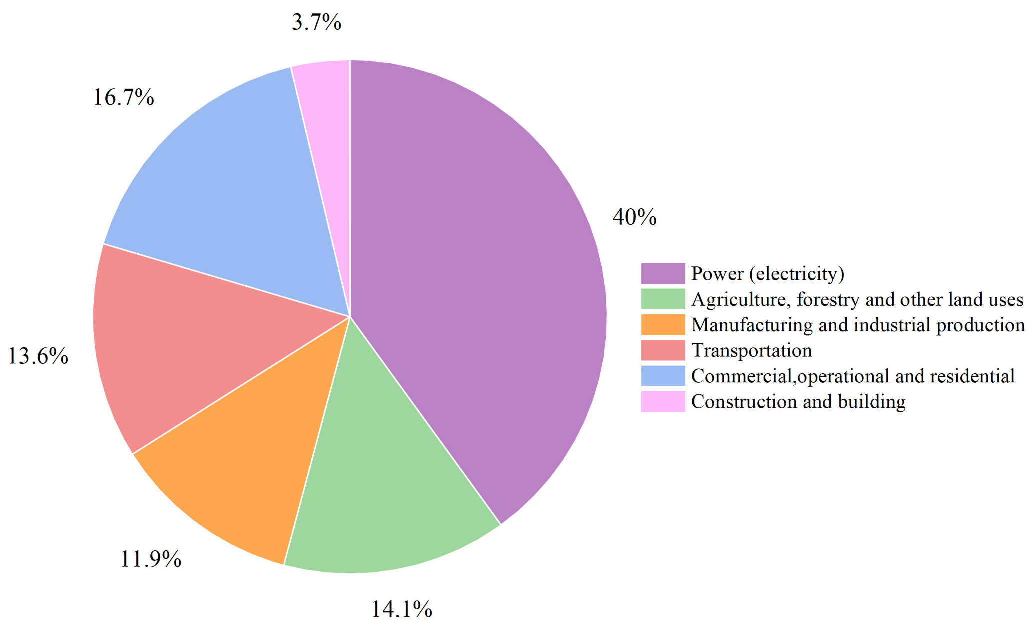

FIGURE 7
The proportion of each industrial and economic sector covered in the news reports.

Carbon emissions management issues are relatively prominent in Chinese news media coverage, and the number has generally increased over time. The results show the periodic growth characteristics of the report. The two most prominent years, 2010 and 2021, were milestones in carbon management, corresponding to low-carbon city pilots and carbon-neutral construction, respectively. Since the Chinese Government began implementing concrete carbon management actions in 2010, the number of carbon-related news reports has increased and remained higher than the previous years. In addition, the key findings also show that the theme of the news reports has become diverse since around 2010 (**Figure 3B**), evolving from low-diversity themes to more diverse and comprehensive themes involving the construction of a low-carbon society Low-carbon economic development, and low-carbon ecology. Thus, 2010 can be regarded as an important time node for carbon emissions management in China. From this node, China introduced concrete actions of national low-carbon construction pilot projects, such as low-carbon transportation and carbon market pilot programs (Khanna et al., 2014; Qu and Liu, 2016). In addition, 2021, as the first year of carbon neutrality in China, will become a new node in the development of carbon management. The increased news reports indicate that carbon management in China has entered a new stage, from pilot city projects to nationwide low-carbon constructions, meaning that more concrete regimes and actions will be implemented in the future.

Furthermore, looking at the composition of policies covered in the report, the number of international policies declined significantly after 2010, replaced by an increasing number of national and regional policies. From passivity to proactivity, domestic actions and policies were intensified, leading to a leadership role on the national stage in 2010 (Garnaut et al., 2018). After 2017, regional policy overtook national policy, maintaining its dominance in 2021. China's carbon management has transitioned from international learning to national leadership and local implementation. With the advancement of carbon neutrality and national low-carbon plans, it is estimated that the number of local policies will continue to remain at a high level in the future, which is of positive significance for achieving carbon peaking and carbon neutrality goals.

However, the results show that during the decades of China's low-carbon transition, there are serious development imbalances that are prevalent in different management studies elsewhere (Gobel, 2011; Xin-gang et al., 2014; Lo, 2020; Xiong et al., 2020). First, in terms of the participation of different types of institutions, the Government had higher participation than that of firms, the public, and other non-governmental organizations. This reflects that the carbon management in China is primarily governmental driven and has top-down management characteristics. Previous studies illustrate that firms must emphasize green process innovation and participate in activity implementation to achieve carbon neutrality (Lee, 2021; Zameer et al., 2021). In addition, although the Government plays a role in leading structural change in a stepwise manner, the transition is ultimately chosen and determined by society (Rotmans et al., 2001). Therefore, a

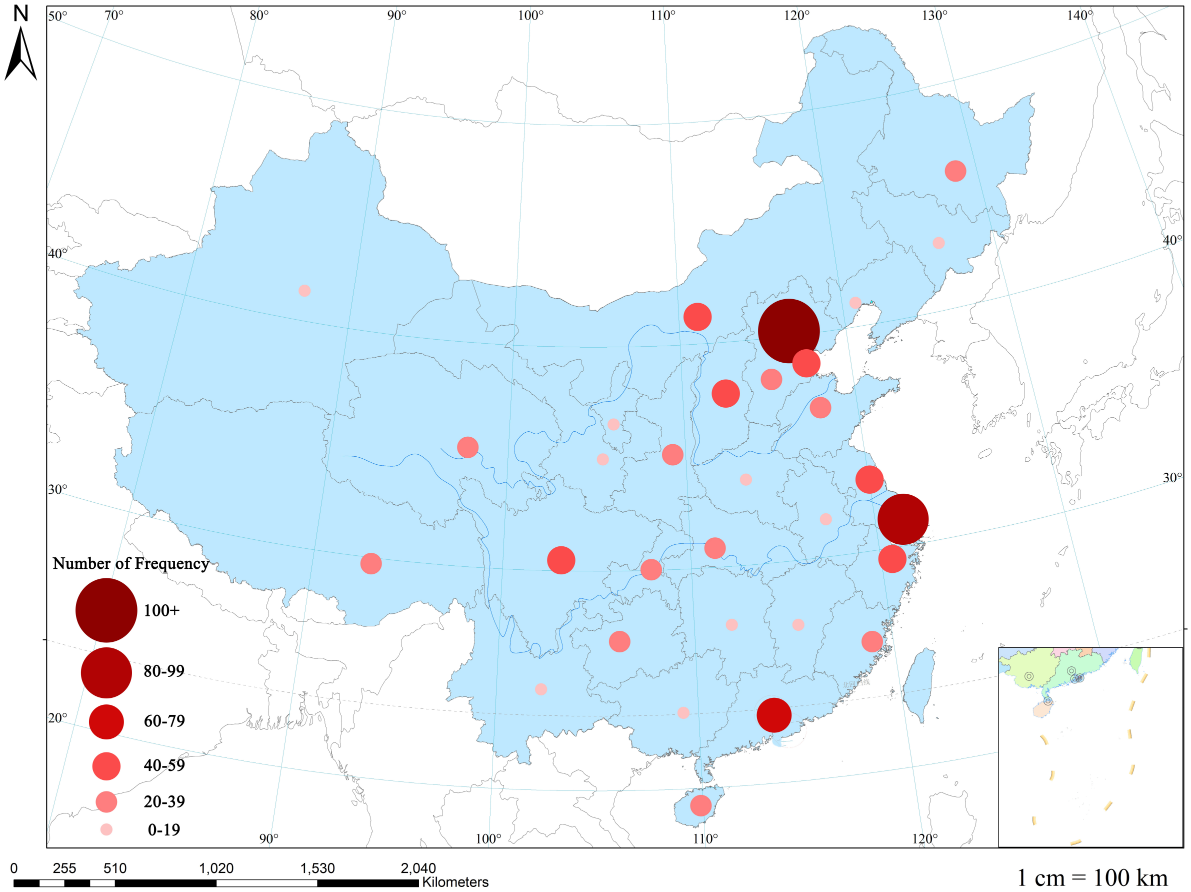

FIGURE 8
The geographic location in mainland China of carbon emissions management regimes and actions reported in the reports.

high participation and cooperation of firms and the public are necessary. It is remarkable to notice that firms' participation evidently increased in 2021, which signifies the deepening of cooperation and collaboration between the Government and firms. Nevertheless, this ongoing government-business collaboration needs to be maintained to achieve future carbon peaking and neutrality goals across industry sectors.

Second, there are distinctive differences in carbon management themes and industries. The news reports continue to decline the focus on low-carbon technologies. Achieving carbon neutrality requires technological innovation in sectors of all aspects, such as reforming the current energy and production system and enhancing atmospheric CO_2 capture (Wang F. et al., 2021). The results show that the Chinese Government attaches utmost attention to green energy development, for instance, increasing investments in relative industries and implementing more power industry management activities in each province (**Figure 9**). Since the green energy industry promotes the development of the economy and investment (Naqvi et al., 2022), strengthening green energy development to achieve economic growth and carbon neutrality goals become a top-down consensus among Chinese governments.. Judging from the proportion of other carbon abatement technologies such as carbon fixation, carbon sequestration, and carbon capture, the publicity of these low-carbon technologies did not receive sufficient attention from the Government. This asymmetric reporting of news theme and tone preferences explains that current carbon emission management strategies in most regions of China are biased toward achieving economic and social goals, while partially ignoring technological and environment-related improvements and advocacy (**Figure 6**). Although the role of renewable energy in promoting carbon emission reduction is more obvious than that of technological innovation, improving green technological innovation cannot be ignored from the perspective of long-term development (Shao et al., 2021b; Su et al., 2022). Therefore, the diversity of carbon reduction technologies should be improved.

Furthermore, the implementation of low-carbon management is uneven across industries and economic sectors (**Figure 7**). Comparing the results with the sectoral contribution of CO_2 emissions in China (Sandalow, 2019), the proportion of low-carbon management in the industrial sector

TABLE 3 The number of carbon-related actions of each province/municipality.

Province/ Municipality	No.	Province/ Municipality	No.	Province/ Municipality	No.
Tier 1					
Beijing	131	Shanghai	93	Guangdong	78
Tier 2					
Sichuan	52	Shanxi	50	Jiangsu	48
Inner Mongolia	43	Zhejiang	44	Tianjin	40
Tier 3					
Fujian	38	Hebei	38	Qinghai	36
Shandong	29	Hubei	28	Heilongjiang	26
Guizhou	26	Shaanxi	25	Tibet	22
Hainan	22	Chongqing	20		
Tier 4					
Xinjiang	19	Jiangxi	19	Jilin	18
Hunan	18	Ningxia	18	Henan	16
Liaoning	16	Anhwei	16	Gansu	14
Guangxi	12				

(11.9%) is much lower than its CO_2 emissions (50% of total industries). Although it is worth affirming that, the Chinese government implement management actions in major carbon emission sectors, but the uneven allocation of management resources and the lagging low-carbon development in some sectors will hinder the rapid realization of carbon-neutral goals.

Third, regarding geographical distribution, carbon management reporting systems and actions are highly concentrated in the core provinces and cities with the most developed economic and social development in mainland China. Among all the 31 provinces and municipalities, Beijing (131), Shanghai (93), and Guangdong (78) reported a higher number of actions than other provinces. Although this result showed the news coverage of the *Xinhua News Agency* is nationwide, the asymmetry in the amount of news across provinces illustrates the clear geographic differences and uneven development of carbon emissions management. Specifically, the intensity of carbon management in the eastern and coastal regions of China is higher than in most inland provinces. Moreover, each province's industry sector proportion is highly different due to each region's industrial structure characteristics, which may be driven by the regional industrial clustering effect (Zhong et al., 2022). For instance, major energy provinces such as Shanxi and those with abundant ecological resources like Inner Mongolia and Tibet invested more in comparable carbon management actions. However, some provinces did not invest in all the industry sectors, such as the construction and building industries. Therefore, the key conclusion is that the development and implementation of carbon management actions are uneven in quantity and type of industry across regions.

According to these deficiencies, the practical implications of this study are as follows. Initially, cultural construction should be strengthened to promote carbon neutrality. Empirical results of previous studies show that fostering green values and spreading green culture at the micro-level significantly affects carbon neutrality. Specific measures can include creating green hotspots at the macro-level such as promoting the concept of green life, building green cities, creating low-carbon cultural

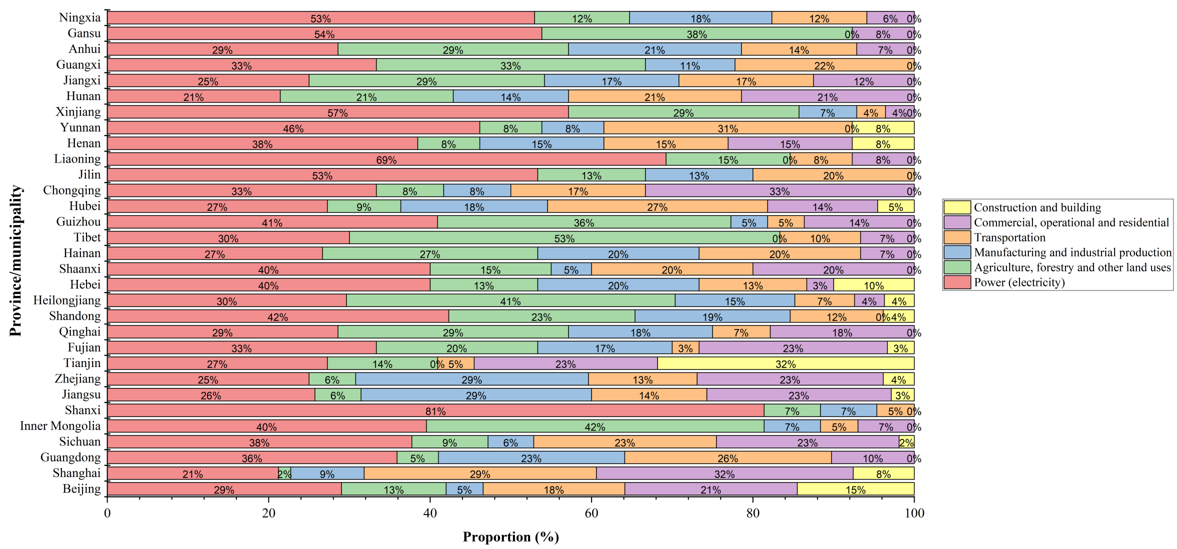

FIGURE 9
The proportion of carbon emissions management activities and actions in different industry sectors mentioned in the news reports of each province and municipality.

industries, and building green cultural and technological centers and museums (Xiao et al., 2021; Wang et al., 2022). These measures could help establish a top-down green communication system to enhance people's awareness of green development, advocate green ideas, and increase public participation in constructing a low-carbon society. The Government could fully use the official media's propaganda capabilities to achieve this goal. Second, the Government should increase low-carbon investment in more industries and fields, including emerging industries such as green tourism (Yue et al., 2021) and neglected and undervalued industrial and economic sectors such as environment-related research and development (R&D) and consumption-based carbon-emitting activities (Su et al., 2020; Shao et al., 2021a). Thirdly, increase investments in low-carbon actions in provinces and municipalities with relative backward carbon management development to reduce the uneven distribution of management resources among regions. These proposals are the adjustments to sensitivities to dynamics and goals of China's staged low-carbon development. They ensure the coherence and consistency of public policies and help promote the gradual realization of structural changes in China's carbon management.

The limitations of this study are as follows. Firstly, this study used the primary data from news media, which may not be comprehensive enough to cover all the unevenness and asymmetry factors within the carbon management development in China, such as the specific economic and environmental data. In addition, similar studies could be extended by considering the city/county-level data. Hence, future studies could consider combining relative data sets for quantitative and in-depth analysis of specific uneven issues in China's carbon management. Moreover, the coding framework could evolve according to the development of carbon management as more carbon-related themes, and emerging industries might be proposed in the future. In conclusion, carbon emissions management in China has developed rapidly and made landmark trials and practices. However, our study indicates that the actions, policies, and regimes implemented throughout the development exist uneven issues in the management themes and preferences, industrial and economic sectors, and between regions. Therefore, it strongly suggests that policymakers could actively use China's top-down management characteristics and the official media to promote improving relevant laws and measures to formulate the public's low-carbon concepts, thereby stimulating the achievement of carbon-neutral goals.

Data availability statement

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

Author contributions

RG and KY: writing—original draft, methodology, formal analysis, and research design. CQ: formal analysis and review and editing. YW: formal analysis and review and editing. All authors contributed to the article and approved the submitted version.

Conflict of interest

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

Publisher's note

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Nonlinear Effect of Digital Economy on Carbon Emission Intensity—Based on Dynamic Panel Threshold Model

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Under the background of carbon peak and carbon neutralization, it is vital to study the impact of digital economy on carbon emission reduction. Based on a provincial panel data from 2013 to 2019, this paper establishes a dynamic panel model, a dynamic spatial autoregressive model, and a dynamic threshold model to study the impact of digital economy on carbon emission intensity. Our findings show that digital economy has a significant inhibitory effect on carbon emission intensity. Results of regional heterogeneity show that the central region can transform the impact of digital economy on carbon emission reduction more efficiently. After adding the time lag term of carbon emission intensity, the impact coefficient of digital economy is still significant. Carbon emission intensity has obvious spatial effect, and the carbon emission of adjacent areas will significantly inhibit local carbon emission reduction activities. Under the threshold of innovation and environmental regulation, the emission reduction effect of digital economy is different. For regions with low technological level, digital economy is difficult to give full scope to its emission reduction advantages. At the same time, stricter environmental regulations can cooperate with digital economy to accelerate regional carbon emission reduction. Therefore, China should continue to improve the construction of digital infrastructure and promote the reform and innovation of enterprise digital technology in order to release the carbon emission reduction effect of digital economy.

Keywords: digital economy, carbon emission reduction, threshold model, dynamic panel model, spatial autoregressive model

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1 INTRODUCTION AND LITERATURE REVIEW

The spread of COVID-19 has caused economic losses such as global supply chain interruption (Nikolopoulos et al., 2021) and the slowdown of the aviation industry and other transportation industries (Liu et al., 2022). At the same time, the substantial decrease of economic activity has reduced global carbon dioxide emissions. However, with the gradual economic recovery in various countries, carbon dioxide emissions from local production and living activities have shown a retaliatory growth trend (Wang et al., 2020). As the first economy to recover from COVID-19, China has continually faced environmental pollution problems (Yang et al., 2021). As the world's largest carbon emitter, China has not only acted responsibly as an advocate in addressing climate change but is also committed to finding a new path of carbon emission reduction. At the General Assembly of the United Nations in 2020, the Chinese government proposed the goal of achieving carbon peak in 2030 and carbon neutralization in 2060, demonstrating China's determined resolution to reduce carbon emission. In recent years, China has responded to climate change by upgrading carbon emission reduction technologies and adopting various carbon emission reduction measures. In 2021, the Chinese scientific research team released the global carbon flux data set based on China's first carbon satellite, marking that China has the ability to quantitatively monitor the global carbon budget. In July 2021, China's first carbon emission market officially began trading. In October of the same year, The State Council issued the Action Plan for Peaking Carbon Emissions by 2030, proposing that by 2030, carbon emission intensity would be reduced by over 65% compared with 2005. In November 2021, The People's Bank of China has set up carbon emission reduction support tools to help enterprises with large space for carbon emission reduction from a financial perspective. The high energy consumption oriented by resource consumption needs to be transformed (Irfan et al., 2021), and the problem of economic slowdown caused by COVID-19 needs to be solved urgently. Sustainable development and high-quality economic development are the inevitable choices to deal with the above problems (Yang et al., 2022).

Meanwhile, the digital economy has become the backbone of the new round of industrial reform in China. COVID-19 has accelerated the application of digital technology (Amankwah-Amoah et al., 2021). The combination of the digital revolution and technological innovation has paved the way for the fourth industrial revolution (Wang ang Wang, 2020). Meanwhile, digital platforms provide many employment opportunities, and those with advanced technological skills are accelerating the digitization process (Zaman and Sarker, 2021). In recent years, the digital economy has developed rapidly and the digitization process is steadily advancing in most emerging economies, especially in Asian countries. Digital government affairs such as electronic identity authentication have facilitated convenience in daily life and solved the problem of information asymmetry between the government and other enterprises (Yang et al., 2014; Liu et al., 2021). The gradual improvement of digital infrastructure has laid the foundation for the rise of e-commerce in various countries. Consumers are able to read detailed descriptions, view photos of goods, and even compare prices with intelligent software, which reduces not only the time and cost of shopping but also the information asymmetry between consumers and goods (Li et al., 2020). The digital economy has contributed to cross-border business development (Autio, 2017), business opportunities (Smith et al., 2017; Von Briel et al., 2018), an intelligent transportation network (Ablyazov and Asaul, 2021), and a shared economy (Sutherland and Jarrahi, 2018; Pouri and Hilty, 2021).

In addition, the digital economy also has the potential to prevent and control pollution. The application of digital technologies shortens the distance between upstream and downstream industries, realizes the optimal allocation of inventory, improves the efficiency of supply chain distribution, and reduces unnecessary losses in transportation (Watanabe et al., 2018). Furthermore, the digital economy can break the boundaries of time and space (Richardson, 2020), simplify steps of information flow, reduce unnecessary waste of resources, eventually improve carbon performance (Zhang et al., 2022), and help economically underdeveloped areas solve energy-related problems (Xu et al., 2022). Due to the continuous advancement of digital processes in the energy field, improved carbon efficiency will reduce the growth rate of digital emissions (Zhou et al., 2022). The improvement of digital production structures will make energy use safer and more efficient, improve green total factor productivity (Zhang et al., 2021), and realize the sustainable development of resources and environment (Hosan et al., 2022). Digital production can also reduce power generation (Wang J. et al., 2022), improve resource utilization (Shao et al., 2021) and green innovation output, and make positive contributions to the development of green and circular economies (Kristoffersen et al., 2020; Uçar, 2020; Kivimaa et al., 2021; Yue et al., 2021).

Most of the existing literature separates the digital economy from carbon emissions; very few articles discuss the impact of the digital economy on carbon emissions. From the existing limited literature, some researchers focus on implicit carbon emissions and carbon emission performance (Wang P. et al., 2022; Zhang et al., 2022), or pay attention to the spatial effect and intermediary factors of digital economy on carbon emissions (Li and Wang, 2022). From the perspective of existing research, there is a long-term cointegration relationship between digital economy and carbon emissions (Ma et al., 2022). From the perspective of digital industry, its direct structural effect reduces the implied carbon emissions, but its indirect structural effect has the opposite effect (Wang J. et al., 2022). Firstly, based on the existing literature, the researcher will sort out the path of the impact of digital economy on carbon emissions in this paper. Secondly, the researcher will focus on carbon emission intensity, which is the target index of reaching carbon peak; the time-lag term of carbon emission intensity will be incorporated into the empirical model to establish a dynamic spatial panel model. Thirdly, the researcher will establish a threshold regression model to study whether the impact of the digital economy on carbon emission intensity will change under different levels of scientific and technological innovation and environmental regulation and to study the threshold effect of digital economy decomposition indicators, respectively.

2 THEORETICAL ANALYSIS AND RESEARCH HYPOTHESES

The impact mechanism of the digital economy on carbon emission reduction can be summarized in five ways. The first is the effect on industrial structure optimization. Digital inclusion can drive the digital transformation of traditional enterprises, and the continuous penetration of digital technology can eliminate information asymmetry among enterprises. The emergence of data, a new factor of production, can reduce the excessive dependence of enterprises on resources (Ren et al., 2021), optimize the allocation of resources, weaken the boundaries of economic activities (Eapen, 2012), and promote transformation of enterprises to green and low-energy consumption. The second is the effect on technological innovation (Weina et al., 2016). The application of digital technologies such as cloud computing reshapes enterprise production, management, and sale, and further allocates the use of resources, such as to plan pollution treatment strategies through digitization to build a new platform for safe, green, low-carbon resource utilization. The third way is the effect on resource utilization. Digital economy can improve total factor productivity (Diaz-Ramos et al., 2019; Pan et al., 2022), minimize loss of energy allocation, and gradually drive consumers to develop digital habits such as using a paperless office, attending online conferences, and reading e-books (Bai, 2021). Big data and other digital technologies can provide personalized service experiences and optimization schemes intelligently by collecting exclusive energy consumption habits of enterprises and individual users. The fourth is the effect on international competitiveness. Digital technology can solve problems in the process of exporting original products, such as complicated procedures and long customs clearance times, which improves the efficiency and success rate of commodity trading and reshapes the international industrial chain and regional trade model (Li et al., 2020). The fifth is the intelligent effect of supervision platforms. The establishment of carbon emission trading markets is inseparable from the application of digital technology, which has curbed the carbon emission violations of a small number of enterprises. Intelligent carbon emission supervision platforms realize the power of energy-saving planning in advance, real-time supervision in the process, and prevention management after the event. Enterprises can reduce the information asymmetry of pollution behavior in supervision by realizing accurate and efficient management of carbon emissions.

Hypothesis 1: The digital economy can reduce the intensity of regional carbon emissions.

Judging from the current development of China's digital economy, there has been unbalanced development in both the manufacturing industry and the intelligence industry. Most enterprises have stagnated in the "internet +" stage and have not stepped into the "artificial intelligence" field. Because carbon emission is the unexpected output from enterprises' economic activities, the production activities of enterprises located in different spaces are bound to be affected by the overall local technical level. Digital technology can help enterprises realize real-time tracking of supply chains (Centobelli et al., 2020), simplify production processes, and improve supply chain efficiency by using cloud technology and carry out dynamic monitoring and early warning of pollutant emission at the same time. Use of digital technology will fundamentally change the production and life efficiency of enterprises (Ranta et al., 2021). Some enterprises in high-tech areas will use digital technology more actively to maximize expected output and minimize carbon emissions. In addition, the popularity of digital facilities affects consumers' consumption behavior. Consumers in areas with adequate digital support facilities will have a variety of digital consumption choices. In the long run, digital consumption choices will have a positive impact on regional carbon emission reduction. Judging from the current development of China's digital economy, there is a trend of deep digitization in the eastern region and sluggish digitization in the western region. Therefore, the digital technologies that enterprises can master vary among different regions, which may lead to the heterogeneity of the impact of digital economy on carbon emission intensity.

Hypothesis 2: There may be regional heterogeneity in the impact of the digital economy on carbon emission intensity.

5G and other digital technologies have set off a huge wave of change in the intelligence, manufacturing, and service industries, with infinite scalability (Attaran, 2021). As a highly permeable and leading economic form, it can enable all links of enterprise production comprehensively and boost the transformation of energy structure (Lyu and Liu, 2021). Digital technology needs to cooperate with digital infrastructure and digital talent to make full use of its advantages. Therefore, in the early stages of the development of the digital economy, if digital support facilities in a region are not complete, the system construction will be outdated, the technical tools will not be fully mastered by firms, and the cumulative effect of the digital economy may be hidden. In addition, environmental regulations are an important factor that affect the green development of enterprises (Meng et al., 2020), like the renewable energy structure affect enterprises (Polzin et al., 2015). Appropriate environmental regulations can establish comparative advantages for green enterprises, whereas regulations that are too strict will be a heavy burden to enterprises. Low-carbon technology can play a role in emission reduction only when environmental regulation reaches a certain level. In areas with stricter environmental regulations, enterprises are more inclined to choose green processing technology to achieve emission reduction. Digital technology is favored by enterprises because of its low cost, high return and replicable characteristics.

Hypothesis 3: The threshold effect of scientific and technological innovation and environmental regulation may exist in the impact of the digital economy on carbon emission intensity.

3 VARIABLE SELECTION AND MODEL CONSTRUCTION

3.1 Variable Selection

Due to the lack of data in Tibet, Hong Kong, Macao and Taiwan, this paper uses the data of 30 provinces in China as research sample. The data comes from China energy statistical yearbook, China Statistical Yearbook, China Science and technology statistical yearbook and statistical yearbooks of provinces and cities.

Carbon emission intensity (TCO2) is the explained variable, which measures the amount of carbon dioxide consumed per unit of GDP. Eight kinds of main consumption energy are selected, we refer to IPCC to calculate carbon emission as follows:

$$CO_2 = \sum_{i=1}^{8} CO_{2,i} = \sum_{i=1}^{8} E_i \times NCV_i \times CEF_i \times COF_i \times \frac{44}{12} \quad (1)$$

The level of digital economy (DGC) is the core explanatory variable. Based on the measurement standard introduced by Li et al. (2021), this paper constructs the measurement of digital economy index, determines the weight of each index through entropy weight method, and calculates the digital economy index.

The threshold variables are scientific and technological innovation (IN) and environmental regulation (ER). Scientific and technological innovation (IN) is measured by the proportion of scientific and technological expenditure in local financial expenditure, while environmental regulation (ER) is measured by the ratio of industrial pollution investment to GDP.

In this paper, the control variables are: Industrial structure (ISU), which is measured by the ratio of the added value of the tertiary industry to the added value of the secondary industry. Economic development level (PGDP) is measured by the ratio of regional GDP to resident population at the end of the year. Foreign direct investment (FDI) is measured by the total investment of foreign-invested enterprises. Income of residents (INCOME) is measured by per capita disposable income of residents. Government expenditure (EXP) is measured by the ratio of regional general public service expenditure to public budget expenditure. Energy consumption is measured by total regional energy consumption. Green coverage rate (GREEN) is measured by the green coverage rate of built-up areas. In order to alleviate the influence of heteroscedasticity, control variables are all logarithmicized.

3.2 Model Establishment

Based on the STIRPAT model of population, economy and Technology (York et al., 2002), this paper establishes the basic model formula (2) to verify hypothesis 1, in which i and t represent specific cities and years, respectively. $tco2_{it}$ represent carbon emission intensity, DGC_{it} measure the level of digital economy, X_{it} expressed as control variables, μ_i and φ_t expressed as individual and time fixed effects respectively, and ε_{it} expressed as random disturbance terms.

$$tco2_{it} = \beta_0 + \beta_1 DGC_{it} + \Sigma\beta_c X_{it} + \mu_i + \varphi_t + \varepsilon_{it} \quad (2)$$

The first-order carbon emission intensity ($L.tco2_{it}$) is added as the explanatory variable, and establish the dynamic panel model formula (2) of the time lag term of carbon emission intensity:

$$tco2_{it} = \gamma_0 + \gamma_1 DGC_{it} + \gamma_2 L.\, tco2_{it} + \Sigma\gamma_c X_{it} + \mu_i + \varphi_t + \varepsilon_{it} \quad (3)$$

3.2.1 Dynamic Panel Space Measurement Model

Considering that carbon emissions may have spillover effect, this paper uses anti geographic matrix to construct spatial econometric model. Before model construction, Moran's I index, LM test and LR test shall be calculated. Firstly, the Moran's I index of carbon emission intensity of each year is calculated. From the results in **Supplementary Appendix Table S2**, it can be seen that the Moran's I value of each year from 2013 to 2019 is significantly positive, which represents the aggregation of regions with similar carbon emission intensity, but this impact shows a gradual decreasing trend. Secondly, the LM Test is conducted to determine the types of spatial econometric models. The *p*-value in LM SEM test and robust LM SEM test are all greater than 0.10, which means, it is considered that the spatial error term does not exist. And the *p*-value in LM SAR test and robust LM SAR test is less than 0.10. Therefore, it is considered that the spatial autoregressive (SAR) model should be established. After LR test, the results in rows 8-9 of **Supplementary Appendix Table S3** show that SDM model can be degraded into SEM or SAR model. Combined with LM test results, this paper believes that the SAR model is more robust. Lastly, combined with the results of Hausman test and LR test of fixed effect, this paper adopts the spatial autoregressive model of individual fixed effect (4):

$$tco2_{it} = \alpha_0 + \rho W tco2_{it} + \alpha_1 DGC_{it} + \alpha_2 L.tco2_{it} + \Sigma\alpha_c X_{it} + \mu_i + \varepsilon_{it} \quad (4)$$

ρ is the spatial coefficient, W is the spatial weight matrix, α_2 is the lag term coefficient of carbon emission intensity, and the interpretation of other variables is the same as that of the benchmark model (2).

3.2.2 Dynamic Panel Threshold Model

Before establishing the threshold model, we test whether there is a threshold effect on the impact of digital economy on carbon emissions first. Then, we set the threshold variable as scientific and technological innovation (IN) and environmental regulation (ER), and conduct self-sampling for 300 times. The results are shown in **Supplementary Appendix Table S4**. When scientific and technological innovation is used as the threshold variable, the digital economy index and decomposition index have significantly passed the first threshold test. At the same time, when environmental regulation is used as the threshold variable, the digital economy index and decomposition index also significantly pass the double threshold test. γ_1 and γ_2 are first threshold of innovation and first threshold of environmental regulation, while ζ_1 and ξ_1 are the lag coefficient of carbon emission intensity. Therefore, dynamic threshold models (10) 11) are established:

$$tco2_{it} = \zeta_0 + \theta_1 DGC_{it}(IN < \gamma_1) + \theta_2 DGC_{it}(IN \geq \gamma_1) + \zeta_1 L.tco2_{it} + \Sigma\zeta_c X_{it} + \varepsilon_{it} \quad (5)$$

$$tco2_{it} = \xi_0 + \lambda_1 DGC_{it}(ER < \gamma_2) + \lambda_2 DGC_{it}(ER \geq \gamma_2) + \xi_1 L.tco2_{it}\Sigma\xi_c X_{it} + \varepsilon_{it} \quad (6)$$

4 EMPIRICAL ANALYSIS

4.1 Distribution of Carbon Emission Intensity and Digital Economy Index in 2013 and 2019

Figures 1, **2** draw the distribution map of carbon emission intensity of provinces and cities in 2013 and 2019 through

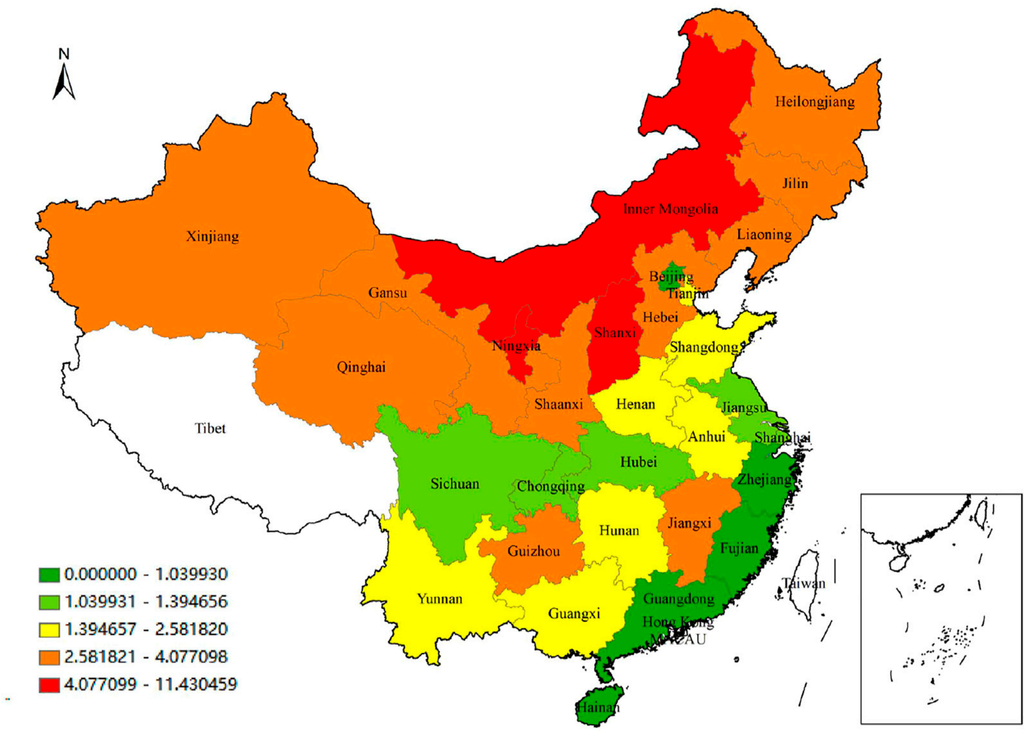

FIGURE 1 | Distribution map of carbon emission intensity in 2013.

ArcGIS 10.7, and **Figures 3**, **4** draw the distribution map of digital economy index of provinces and cities in 2013 and 2019, respectively. Horizontally, the carbon emission intensity of Qinghai, Guizhou, Henan and other places has decreased significantly, while Guangdong, Zhejiang, Fujian and other places have always maintained a low level of carbon emission intensity, but the carbon emission intensity of Inner Mongolia and Shanxi is still high. However, from the original data, the carbon emission intensity of these two places has decreased. It can be said that the overall carbon emission intensity across China has a significant downward trend. At the same time, **Figure 1** and **Figure 2** have a certain difference in carbon emission intensity between the north and the south, which may be due to the fact that the north still adopts the heating method of burning coal, and the fossil energy consumed has caused higher carbon emissions. In terms of digital economy index, Beijing has always been in the first echelon of digital economy development. Sichuan, Guangdong, Zhejiang and other places have strong digital economy strength, and the digital economy level of other provinces and cities has been improved. This is inseparable from the Chinese government's attention to the development of digital economy, the great breakthrough of digital technology and the improvement of digital infrastructure in recent years. From the perspective of regional heterogeneity, the level of digital economy shows an upward trend from the West to the East. The development of digital economy in the western region is generally deficient, the development of digital economy in the central region is average, and the level of digital economy in the eastern region is ahead the other regions.

From the vertical perspective, the carbon emission intensity of Beijing, Zhejiang, Guangdong, Jiangsu and other places with high digital economy level in 2013 is low, and that of Xinjiang, Qinghai, Heilongjiang, Gansu and other areas with poor digital economy development is high. In 2019, the carbon emission intensity of Sichuan, Jiangsu, Tianjin, Henan and other places with rapid development of digital economy decreased significantly, and the further development of digital economy in Qinghai, Liaoning, Shaanxi and other places also reduced the carbon emission intensity.

4.2 Benchmark Regression

Model (1) in **Supplementary Appendix Table S5** is the benchmark regression result. From a national perspective, the digital economy significantly inhibits the carbon emission intensity. Specifically, for every unit of digital economy development, the carbon emission intensity decreases by 27.15 units. This conclusion verifies *hypothesis 1*. Digital economy has penetrated into various regions at a lower cost. The application of digital technology can improve the production efficiency and resource utilization of enterprises. The rational allocation of resources can help regional carbon emission reduction by coordinating and balancing the energy structure. In terms of control variables, under the 1% confidence level the upgrading of industrial structure and energy consumption have increased the carbon emission intensity. The flow of industrial structure towards rationalization and upgrading can adjust the energy structure, but the carbon emission released in its

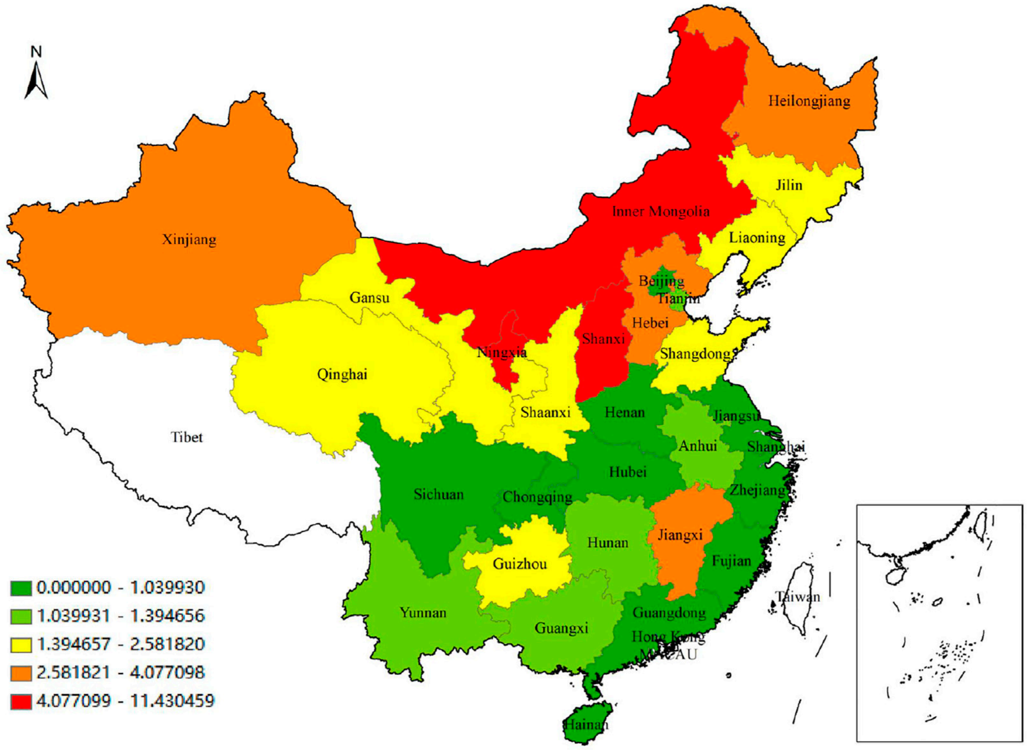

FIGURE 2 | Distribution map of carbon emission intensity in 2019.

transformation and upgrading is more than that of emission reduction. Therefore, to a certain extent, the upgrading of industrial structure interferes with carbon emission reduction. In addition, China is still in the stage of massive consumption of fossil energy, with fossil energy consumption exceeding 80%. The problem of carbon emission caused by the combustion of non-renewable energy has not been completely solved, which has restricted the realization of peaking carbon dioxide emissions and achieving carbon neutrality. At the same time, the level of economic development, residents' income and governmental investment have significantly reduced the intensity of carbon emissions. In areas with high level of economic development and residents' income, residents will have a strong desire to pursue green life and put the concept of green life into action and generally adopt an environmentally friendly lifestyle, which is more conducive to regional carbon emission reduction. Government investment provides a strong backing for the completion and application of infrastructure such as digitization. At the same time, regional governments put forward targeted carbon emission reduction suggestions, encourage and support more enterprises and residents to join the team of carbon emission reduction, accelerate the transformation of enterprises to the direction of low energy consumption and high efficiency, and provide conditions for carbon emission reduction.

Models (2)–(4) in **Supplementary Appendix Table S5** are the heterogeneity test of the impact of digital economy. The impact coefficient of digital economy on carbon emission reduction in the eastern region is −11.1239, while the absolute value of the impact coefficient of digital economy in the central region is the largest. Compared with the eastern region benefiting from digital economy for a long time, the development of digital economy in the central region is in the stage of rapid development. The application of digital technology, an emerging technology, provides cleaner and greener production technology for the industrially developed the central region and helps enterprises optimize production, operation, and sales processes. Therefore, compared with other regions, this influence coefficient is the largest. The impact coefficient of the western region failed to pass the significance test. Although the development of digital economy in the western region has improved to a certain extent from **Figure 3** and **Figure 4**, the level of digital economy in the western region is still poor from the original data. At the same time, the market development level is limited, and the emission reduction effect of digital empowerment cannot be maximized, which may cause the situation that the emission reduction effect is offset by the resources consumed by the application of digital technology. Therefore, the role of digital economy in emission reduction in the western region is not significant.

4.3 Dynamic Panel Model

The first-order lag term of carbon emission intensity ($L.tco2_{it}$) is added to the model (1) in **Supplementary Appendix Table S6**, and the lag term is significantly positive. The carbon emission

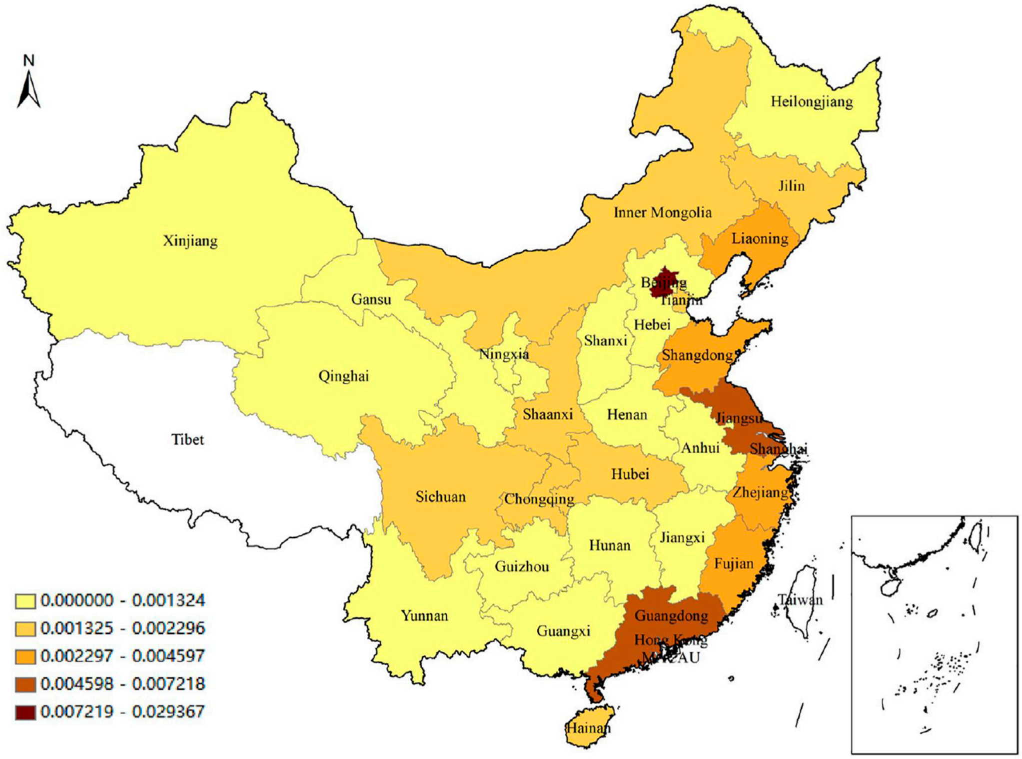

FIGURE 3 | Distribution map of digital economy index in 2013.

intensity has time lag, that means the carbon emission intensity will improve its own carbon emission in the next period. The core explanatory variable digital economy is significantly negative, which is consistent with the conclusions in **Supplementary Appendix Table S5**. In models (2)–(4) in **Supplementary Appendix Table S6**, the three decomposition indicators of the digital economy index are taken as explanatory variables, and they all significantly inhibit carbon emissions, indicating that the digital economy can contribute to carbon emission reduction through three directions: digital infrastructure, digital inclusive and digital transaction. In models (2)–(4), the lag term of carbon emission intensity is significant under 1% confidence, and the three decomposition indexes are significant under 5% confidence. In terms of the control variables, the transformation of industrial structure and energy consumption still improve the intensity of regional carbon emissions, and the improvement of economic development level and residents' income has a significant inhibitory effect on carbon emissions. On the impact of the level of digital infrastructure on carbon emission intensity, the government investment is significantly negative. The government's capital investment is conducive to the construction of digital platform and provides financial support for the improvement of digital infrastructure, which can help the digital economy display its advantages and is beneficial to carbon emission reduction. In the impact of digital trading level on carbon emission intensity, the increase of residents' income can significantly reduce carbon emissions.

4.4 Dynamic SAR Model

Supplementary Appendix Table S7 shows the results of spatial autoregressive model. The coefficient rho is significantly positive, indicating that the regions close to each other will affect the local carbon emission intensity, which is not conducive to the local carbon emission reduction. The coefficient of digital economy is −11.4161, and the time lag term is significantly positive. In terms of control variables, industrial structure and energy consumption are significantly positive, and economic level and residents' income are significantly negative, which is also consistent with the results of benchmark regression. Columns 3–5 of **Supplementary Appendix Table S7** decompose the spatial effects. From the results, digital economy, time lag term of carbon emission intensity, industrial structure, economic level, resident's income and energy consumption have significant direct and indirect effects on carbon emission intensity, and the direct effects are greater than the indirect effects.

4.5 Dynamic Panel Threshold Model

The threshold regression results of scientific and technological innovation as threshold variables are shown

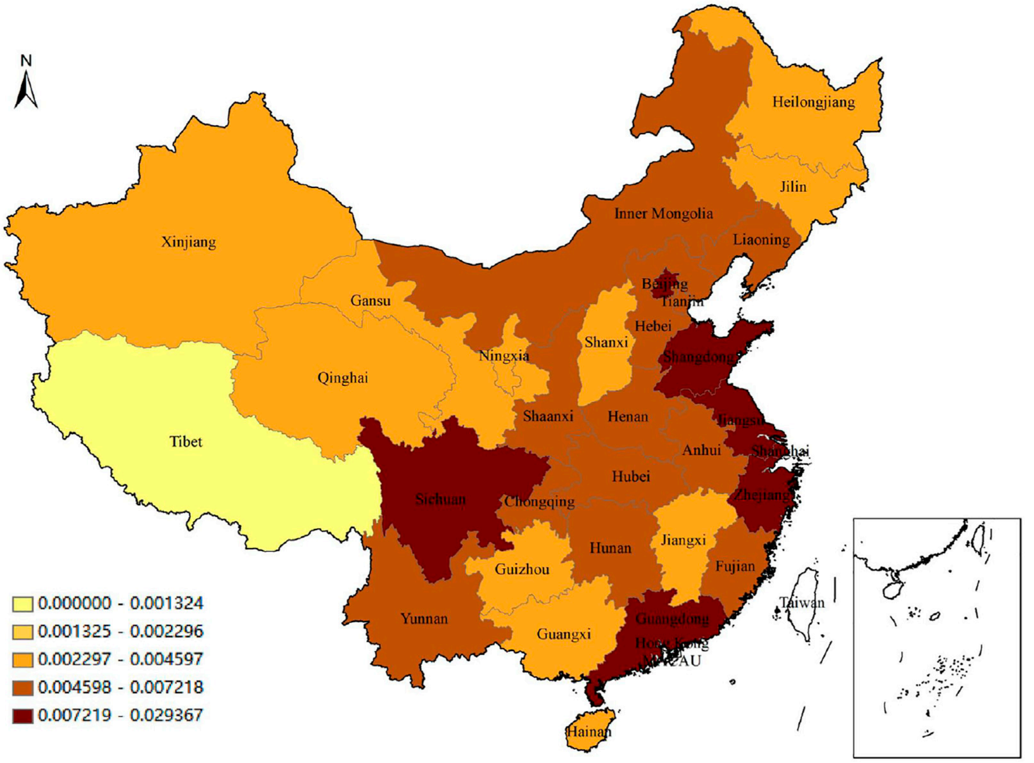

FIGURE 4 | Distribution map of digital economy index in 2019.

in **Supplementary Appendix Table S8** models (1)–(4). When scientific and technological innovation is lower than 0.0120, the digital economy index is not significant. While scientific and technological innovation is higher than 0.0120, the digital economy coefficient is −12.5949, indicating that for each unit of digital economy, the carbon emission intensity will be reduced by 12.5949 units. From the perspective of decomposition indicators, the digital infrastructure coefficient is significantly −28.1199 when the scientific and technological innovation is greater than 0.0120, and the digital transaction coefficient is significantly −20.5690 when the scientific and technological innovation is greater than 0.0120. The digital inclusive coefficient is not significant before and after threshold IN. From the specific value, the provinces with scientific and technological innovation less than 0.0120 are mainly distributed in western regions such as Qinghai and Gansu. The scientific and technological level is limited, which restricts the role of digital economy. It is urgent for these regions to actively introduce scientific and technological means from other regions to promote the matching of regional scientific and technological level with digital economy, so as to use digital advantages fully.

The threshold regression results of environmental regulation as a threshold variable are shown in **Supplementary Appendix Table S8** models (5)–(8). When the environmental regulation is lower than 0.0115, the digital economy coefficient is significantly −12.2024. When the environmental regulation is higher than 0.0115, the digital economy is significantly −23.4579. The bias effect before and after the threshold value has increased. More stringent environmental regulation policies need to cooperate with green production methods to achieve the purpose of environmental protection, and the digital economy meets this requirement well. Under the relevant regulatory policies of the government, the digital economy leverages its own advantages and uses technologies such as Big Data and Blockchain to achieve high utilization of enterprise resources, save the cost of management and sales, escort the building of smart enterprises, and then contribute to regional carbon emission reduction. From the perspective of decomposition indicators, the partial effects of digital infrastructure and digital transactions before and after the threshold have increased and have always been significant. For digital inclusive level, the coefficient is significantly −5.3119 after crossing the environmental regulation threshold of 0.0115. After enterprises are burdened with more stringent environmental regulation policies, they either actively or passively choose digital technology and use digital platforms to realize business processes such as negotiation and transaction. Office workers are used to digital office imperceptibly, realizing a virtuous cycle of emission reduction. However, it is worth noting that the threshold value in model (8) is 0.0133, which is greater than the threshold value in models (5)–(7), indicating that digital transactions can play a full role only under higher-level environmental regulation measures.

5 DISCUSSION

5.1 Theoretical Significance

Starting from the background of the carbon peak and carbon neutralization goals, and based on the samples of 30 provincial panel data from 2013 to 2019, this paper focuses on exploring the theoretical mechanism of digital economy, a new way of carbon emission reduction. Overall, previous studies paid less attention to the relationship between digital economy and carbon emissions. Most of the existing literature focused on the current situation and impact of digital economy (Chen et al., 2022; Xue et al., 2022) and the driving factors of carbon emissions. In the past two years, a few pieces of literature have begun to study the carbon emission reduction effect of digital economy (Ma et al., 2022). However, it is worth noting that the existing research focuses on the intermediary effect and spatial effect. Based on existing literature, this paper not only measures the spatial effect of carbon emissions, but also focuses on the regional heterogeneity and threshold effect of the impact of digital economy on carbon emissions.

5.2 Practical Significance

First of all, China should continue to improve the construction of digital infrastructure and create a green production and living system. China should accelerate the construction of 5G base stations comprehensively, promote the carbon emission monitoring platform nationwide, and realize the "cloud prevention and control" of carbon emission through intelligent means such as UAV patrol. China should publicize the concept of green consumption by using digital platform, customize personalized green services by using VR and Big Data technology, improve customers' green service experience and build a green smart city. Secondly, enterprises should continue to promote the reform and innovation of digital technology and achieve breakthroughs in low-carbon technology and new energy technology. Enterprises should take the initiative to carry out digital technology reform. At present, enterprises have obtained the ability to use the Internet for production and marketing activities; however, very few enterprises can use artificial intelligence such as Machine Learning to realize product production and marketing analysis. Besides, enterprises should continue to explore carbon emission reduction technologies, formulate carbon sequestration measures according to local conditions through data analysis, and use 3S technology to find renewable energy that can replace fossil energy, so as to curb carbon emissions from the source of energy utilization. Thirdly, based on regional heterogeneity, the government reasonably formulates relevant policies and exerts to the government's regulatory role through a series of policy combinations (Rogge and Schleich, 2018). The government should use digital technology to accurately identify and actively help high pollution enterprises. In addition, the government can take the lead in introducing experts and scholars to carry out seminars and courses on digital emission reduction technology, so as to promote the implementation of digital technology in the production process of enterprises. The government should formulate targeted emission reduction targets and policies. While monitoring carbon emissions in real-time, the government should take the initiative to coordinate carbon emission transactions between enterprises that have excess emission and enterprises that fail to meet the quota, so as to achieve the overall carbon emission standard of enterprises.

5.3 Limitations and Future Research Directions

This study has some potential limitations. Firstly, this paper is based on China's provincial panel data and we acknowledge that there are some limitations in sample size. And this study may ignore the reduction effect of the digital economy carbon emission in prefecture-level cities and even county-level cities. Future research should pay more attention to the data of prefecture level cities and county-level cities.

Secondly, the progress of the digital economy in various countries is different. Therefore, it is difficult to generalize the carbon emission reduction effect of the digital economy. Thus, scholars should focus on survey data under different regions and aim to broaden regional coverage in the future research.

Lastly, there is no unified standard to measure the level of digital economy from the current literature. In future research, scholars can focus on formulating recognized measurement standards to accurately describe the development of digital economy.

6 CONCLUSION

Firstly, the overall carbon emission reduction across the country has continued to improve in recent years. There may be a north-south difference in carbon emission intensity due to the fact that the north still uses coal-burning heating. In terms of the digital economy, the digital economy level of all provinces in China has steadily improved by 2019, and the digital economy level from west to east in China has gradually increased. Secondly, the digital economy has a significant inhibitory effect on the carbon emission intensity. The improvement of residents' income, governmental investment, and economic development can reduce the regional carbon emission intensity. Given the regional heterogeneity, digital economy can play a more critical role in reducing carbon emission in the middle and eastern regions. Thirdly, after adding the time lag term of carbon emission intensity, the impact coefficient of the digital economy is still significant. At the same time, the decomposition items of the digital economy: digital infrastructure level, digital inclusive level, and digital transaction level are all conducive to carbon emission reduction. Fourthly, carbon emission intensity has an obvious spatial effect. Carbon emission in adjacent areas will significantly inhibit local carbon emission reduction activities, and the digital economy and control variables such as industrial structure mainly affect carbon emission through direct effect. Lastly, under the threshold of scientific and technological innovation and environmental regulation, the impact of digital economy on emission reduction is different. For regions with low levels of scientific and technological development, it is challenging for the digital economy to utilize its emission reduction advantages, and stricter environmental regulations can cooperate with the digital economy to reduce regional carbon emission.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

RW: Conceptualization, methodology, software, writing—original draft preparation; XH: Validation, formal analysis, investigation, resources, funding acquisition, supervision; LP: Data curation, writing—review and editing; visuali-zation. YL: Writing—original draft preparation, data collection; YY: Writing—review and editing, data curation. All authors have read and agreed to the published version of the manuscript.

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Research and analysis of environmental legal compensation mechanisms related to waste incineration in the context of "double carbon"

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In the context of "double carbon," waste disposal has become a critical issue so far, and how to deal with it is the key to ensuring compliance with the double carbon target, the most practical treatment is still incineration, and how to establish the site selection and legal compensation mechanism is crucial. This paper establishes an environmental dynamic monitoring system for waste incineration power plants based on the Gaussian model and successfully solves the health risk of surrounding residents. Regarding the economic compensation issues, we first applied the AHP to analyze the pollutants comprehensively, constructed the judgment matrix, and conducted a consistency test, determined the weight of each index, and integrated various emissions into one pollutant, which is convenient for the concentration of pollutants. Then, by taking into account the effects of wind direction, rainfall, topography, and other factors on the diffusion of pollutants, we calculated the pollutants around the waste incineration power plant site based on the "elevated continuous point source" "diffusion model." To obtain the concentration distribution, monitoring points were set up at representative locations, and the environmental monitoring system of the waste incineration power plant was established. Finally, Matlab software was used to draw the contour map of pollutant concentration, and the concentration level of pollutants was divided according to waste incineration. Given the income of the power plant, the economic level of the surrounding residents, the amount of compensation from the local government, and the pollution level, economic compensation plans for the surrounding residents were developed. Through analyzing the proposed compensation scheme, it can be known that the compensation scheme can satisfy the surrounding residents. The highlights of this paper can be described as follows: First, the analytic hierarchy process is used to comprehensively consider the pollutants, simplifying the establishment process of the model. Second, the pollutant concentration is graded, and the concentration equivalent map is drawn to make the monitoring point layout more representative. The economic compensation plan is more reasonable and more convincing to the public.

KEYWORDS

environmental monitoring, compensation scheme, analytic hierarchy process, elevated continuous point source diffusion model, carbon neutrality, double carbon

Introduction

On September 22, 2020, President Xi Jinping announced at the 75th General Assembly General Debate that China will increase its national contribution, adopt more robust policies and measures, and strive to peak its carbon dioxide (CO_2) emissions by 2030 to achieve carbon neutrality by 2060. Carbon neutrality is a comprehensive goal that involves all sectors of the national economy and the whole process of social reproduction. Strong measures are needed to achieve peak and carbon neutrality, including source reduction, energy substitution, energy saving and efficiency improvement, recycling, process transformation, carbon capture and utilization, and other means. Achieving carbon peaking and carbon neutrality is a dynamic process that involves all aspects of society, including the transformation of energy technologies and production methods, the transformation of economic development methods, and the transformation of lifestyles. Compared with traditional sanitary landfills, waste incineration reduces the amount of CH_4 and CO_2 generated during landfill degradation, while incineration serves as an alternative to fossil fuels through resource utilization. In a region where incineration replaces landfills, it can be said that domestic waste disposal has achieved carbon peaking (Dongyue and Guangwei, 2021; Yanqing et al., 2021; Liu et al., 2022; Naqvi et al., 2022).

The "garbage siege" is a global problem, particularly prominent in today's China. In 2012, the national municipal solid waste transportation volume reached 171 million tons, an increase of 13 million tons over 2010. The data shows that more than two-thirds of the cities in the country are facing the problem of a "garbage siege," and the landfill has accumulated a total of 750,000 mu of land. Therefore, waste incineration has gradually become one of China's primary means of garbage disposal. Municipal wastes are sorted and treated, the recyclable and harmful garbage is removed, and the remaining garbage is incinerated in an incinerator, which can avoid encroachment on a large amount of land and generate electricity and obtain a considerable economy *via* waste incineration. Benefit, However, due to various reasons such as poor government supervision and short-sighted investors, the waste incineration power plants built in various places have experienced increasing environmental pollution problems over the past few years, which significantly inhibits the promotion of waste incineration technology in China. The location selection of new waste incineration plants in the city has been increasingly difficult due to opposition from residents (Fan, 2018; Pu and Li, 2018; Wang, 2018; Yang et al., 2018; Yu et al., 2018).

The risk of environmental pollution caused by waste incineration plants is directly related to the scale of construction investment and the intensity of operational supervision. Due to the lack of scale effect, pollution control will also affect small-scale waste incineration plants, resulting in severe pollutant discharges, difficulty meeting new national emission standards, and a more significant environmental hazard. With the increase in urbanization level, land resources are becoming increasingly tense, and residents' living standards are gradually increasing, and their environmental awareness is becoming stronger. Many public waste incineration projects have been publicly investigated during the EIA phase. The location selection of incineration plants is also becoming more and more difficult. Some of the completed waste incineration plants have sufficient environmental protection distance before the urban area planning. However, as the surrounding residents and factories are gradually approaching the waste incineration plant, some of the built incineration plants exert a particular impact on the surrounding environment. Residents around the incineration plants are accumulating and expressing their dissatisfaction. This phenomenon has seriously damaged the image of the waste incineration industry and even concealed its environmental benefits of waste reduction and resource utilization. Therefore, the location selection of existing urban waste treatment facilities is becoming more and more difficult. Currently, major cities in China are now tempted to replace small-scale incinerators with new large incinerators. However, large incineration plants have problems such as the high cost of garbage transportation and road construction. Therefore, studying the scale of construction of large incineration plants in different cities is worthwhile. In the operation supervision of waste incineration plants, measurement and monitoring are mainly carried out in waste incineration plants, and there is a lack of peripheral dynamic monitoring from the perspective of the surrounding environment. Therefore, forming an effective

TABLE 1 Daily rainfall (unit: mm) in Baoan district (G3531) from 2011-04 to 2012-03.

Year day	11.4	11.5	11.6	11.7	11.8	11.9	11.1	11.11	11.12	12.1	12.2	12.3
1	0	0	0	0.3	0	0.6	5.7	0	0	0	0	0
2	0	0	0	0	0	28.3	1.5	0	0	0	0	0
3	0	30.3	0	0	0	9.5	0.9	0	0	0	0.2	0
4	0	7.7	0	0	0	1	0.3	0.5	0	0	0	0
5	0	0.6	0	0	0	1.8	0	0	0	2.9	0	0

TABLE 2 EXCEL processing data results.

Wind direction frequency at the site of incineration plant								
Wind direction season	***N***	**NE**	**e**	**SE**	**S**	**SW**	**W**	**NW**
Spring	0.08	0.05	0.00	0.04	0.08	0.26	0.36	0.14
Summer	0.17	0.22	0.11	0.10	0.05	0.06	0.15	0.14
Autumn	0.01	0.00	0.01	0.02	0.03	0.65	0.24	0.02
Winter	0.00	0.00	0.00	0.00	0.17	0.59	0.21	0.03
The annual average	0.07	0.07	0.03	0.04	0.08	0.38	0.24	0.08
The average wind speed of each wind direction at the site of the incineration plant (unit:m/s)								
Spring	1.08	1.5	0	2.07	3.05	2.41	3.05	2.29
Summer	2.36	1.92	1.62	1.52	1.6	2.32	2.28	3.18
Autumn	0	0	0.4	1.35	1.9	2.78	3.26	1.1
Winter	0	0	0	0	3.94	3.42	3.79	2.85
The annual average	2	1.85	1.51	1.61	3.13	2.03	3.01	2.64

The data given is not the year-round wind direction data, and some of the data is missing, resulting in slight error in wind speed statistics.

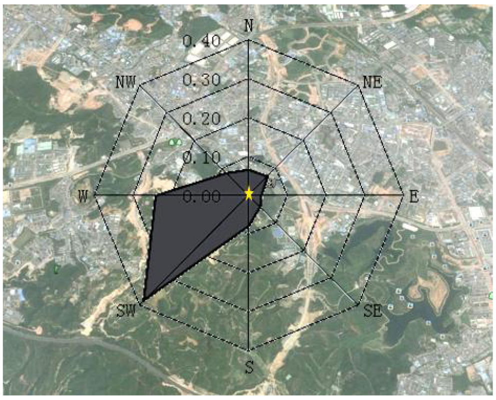

FIGURE 1
The dominant wind direction frequency map at the site of the waste incineration plant.

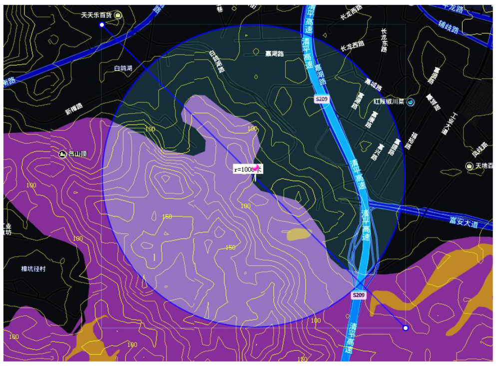

FIGURE 2
Contour map.

environmental monitoring system for all waste incineration plants is difficult (Cao and Zhang, 2017; Chen, 2017; Song and Gao, 2017; Wei, 2017; Wei and Wen, 2018; Zhang et al., 2021).

Environmental compensation is an essential manifestation of social equity. The location of urban waste treatment facilities in the provision of garbage disposal services for the entire city will inevitably impact the local environmental quality. The essence of this problem is the damaged areas in the urban development process, while other areas transport the garbage out of the local area and protect it. At the same time, the land is used for economic development to obtain income, and its essence is that the beneficiary is in the process of urban development. The environmental compensation mechanism can improve social equity to a certain extent, not only

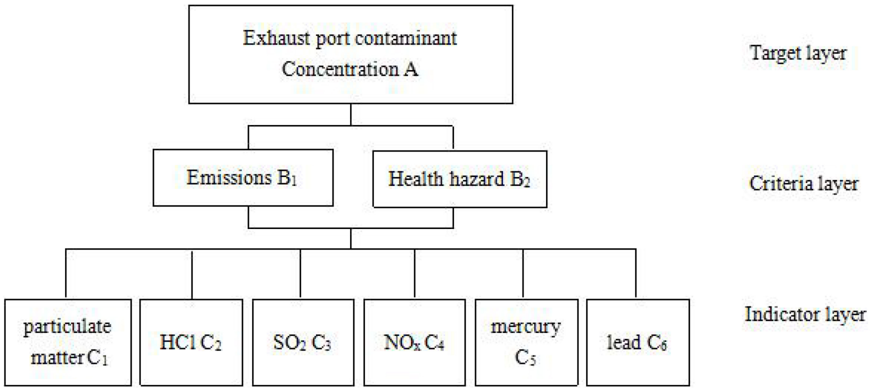

FIGURE 3
Hierarchical analysis structure.

to compensate for the psychological damage caused by the construction of sanitation facilities in the local area but also to compensate the residents for their reduction in economic income due to the use of land for sanitation facilities. Generally, the degree of opposition to the construction of sanitation facilities will naturally also decrease, so it is essential to establish an environmental compensation mechanism (Han, 2017; Li et al., 2017; Lu, 2017; Ma and Tsai, 2017; Qian et al., 2017; Zhao and Ren, 2017; Zhao et al., 2017; Ma et al., 2018).

Analysis of issues

Shenzhen plans to build a medium-sized waste incineration plant with a planned waste disposal capacity of 1,950 tons per day (including three incinerators capable of handling 650 tons of waste per day, with a smoke outlet height of 80 m, operating 24 h a day). To meet the need to build a dynamic monitoring system for the environment and make reasonable economic compensation for the surrounding residents based on potential pollution risks, relevant departments hope to comprehensively consider various factors that cause environmental pollution as well as hazards to the surrounding waste incineration plants (for example, incinerators). With consideration of the discharge amount of pollutants, the distance from the residential zone to the waste incineration plant, the wind direction, the weather conditions such as rainfall, the topography and the occlusion of the building, etc., a feasible dynamic monitoring and evaluation method is established based on scientific quantitative analysis to investigate the environmental impacts of waste incineration plants. A reasonable economic compensation plan is developed for potential environmental risks.

It is assumed that the emission of incinerators meets the national new pollutant discharge standards, and an environmental indicator monitoring method is designed according to the surrounding environment of the waste incineration plant to realize the reasonable emission of flue gas from the waste incineration plant. Based on the actual monitoring results of the designed environmental

TABLE 3 Judgment matrix scale.

Serial number	Importance level	C_{ij} assignment
1	*i*, *j* two elements are equally important	1
2	*i* element ratio *j* element is slightly important	3
3	*i* element ratio *j* element is obviously important	5
4	*i* element ratio *j* element is strongly important	7
5	*i* element ratio *j* element is extremely important	9
6	*i* element ratio *j* element is slightly less important	1/3
7	*i* element ratio *j* element is obviously not important	1/5
8	*i* element ratio *j* element is strongly unimportant	1/7
9	*i* element ratio *j* element is extremely unimportant	1/9

TABLE 4 Judgment matrix of emissions versus emissions.

B_1	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	1/3	1/5	1/9	9	7
C_2	3	1	1/3	1/7	9	7
	5	3	1	1/5	9	7
C_4	9	7	5	1	9	7
C_5	1/9	1/9	1/9	1/9	1	1/3
C_6	1/7	1/7	1/7	1/7	3	1

TABLE 5 Judgment matrix of emissions to human hazards.

B_2	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	3	1/3	3	5	5
C_2	1/3	1	1/3	1	3	3
C_3	3	3	1	5	7	7
C_4	1/3	1	1/5	1	3	3
C_5	1/5	1/3	1/7	1/3	1	1
C_6	1/3	1/3	1/7	1/3	1	1

TABLE 6 Indicators of maximum eigenvalue and deviation consistency.

	B_1	B_2
λ	7.1256	6.1598
CI	0.02093	0.03196

dynamic monitoring system, a rational risk-bearing economic compensation scheme for surrounding residents' is designed.

In the question, the emission of the incinerator is assumed to meet the national new pollutant discharge standards. Under this premise, it is necessary to comprehensively consider factors such as pollutant discharge amount, the distance from the residential area to the waste incineration plant, the wind direction, the rainfall, the topography, and the occlusion of the building. A feasible environmental monitoring system is established to determine the degree of building occlusion on the air's concentration and spread of pollutants. An economic compensation plan is developed for the surrounding affected residents. First, each influencing factor should be analyzed according to the data given.

Since the environmental indicators are detected as atmospheric pollutants, and there are many kinds of incinerator emissions, this paper intends to integrate multiple pollutants into one kind of emission to facilitate the calculation of emission concentration and the establishment of the evaluation system. Then, comprehensively considering the above factors, the model is built according to the site selection of waste incineration power, and the distribution of pollutant concentration around the waste incineration power plant is obtained. Monitoring points are set up at representative locations, and waste incineration power generation is under monitoring is realized. An economic compensation plan is developed for the surrounding residents by grading the pollutant diffusion concentration. Finally, the environmental monitoring system is evaluated in terms of its effectiveness, pertinence, and accuracy.

Model assumptions and symbolic descriptions

Model assumptions

(1) Hypothesis 1: According to the hypothesis SPD, the average wind speed in 10 min is the average wind speed per day and is the average wind speed at the exhaust port;

(2) Hypothesis 2: According to the topography and geomorphology around the site, the atmospheric stability is assumed to beClevel;

(3) Hypothesis 3: Assume that the contaminant concentration is y, z, and the direction distribution is a normal distribution;

(4) Hypothesis 4: It is assumed that the contaminants are conserved during the diffusion process.

Model preparation

Before solving the problem, we first searched the website of the Shenzhen Meteorological Bureau. We obtained the wind direction and rainfall data at the waste incineration power plant site from 2011 to 2012. Then, EXCEL software was used to process the data. Finally, Google Earth software was applied to obtain information on topography, settlements, and buildings within a range of 1,000 m around the location of the waste incineration power plant.

Meteorological data of Shenzhen City in 2011–2012

In addition to the data on wind speed and wind direction shown in Annex 4, we also searched from the website of the Shenzhen Meteorological Bureau and found the average annual rainfall from 2011 to 2012. Some data are shown in Table 1.

TABLE 7 Average random consistency indicator of the judgment matrix.

Order	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Data after EXCEL processing

The annual wind speed was statistically compiled by EXCEL, and the wind direction frequency and average anemometer of each season and year were obtained. The detailed results are shown in Table 2.

Dominant wind direction frequency map at the site of waste incineration plant

Using Google Earth software, the topographic map around the site of the waste incineration power plant was obtained. Then by integrating the annual average wind frequency rose diagram (Figure 1) into the topographic map, the dominant wind direction frequency map at the site of the waste incineration plant was obtained (see Figure 1).

Contour map around the site of the waste incineration plant

Using the Orvieto interactive map software, a contour map (see Figure 2) within a range of 1,000 m around the waste incineration power plant was drawn. The lower purple area in the figure refers to the mountain area, and the upper black area refers to the residential area.

Model establishment and solution

To solve the problem, a feasible dynamic monitoring and evaluation method was constructed to investigate the environmental impact of waste incineration plants, and a reasonable economic compensation plan was developed to offset potential environmental risks. According to the data in the question, many kinds of incinerator emissions exist. In order to facilitate the calculation of emission concentration, first, AHP is used to determine the weights of pollutants. Then the total emissions are converted into a "comprehensive" emission. Second, the atmospheric pollutant diffusion model is reused to determine the distribution of pollutant ground concentration. Since the waste incineration plant is located in the low hilly coastal area, the back mountain bay is distanced from the pollution source center, with terrain height lower than the height of the smoke outlet so that the surrounding terrain can be regarded as a simple terrain. The long-term atmospheric pollution model of the elevated continuous point source is used to make the contour map of the equal concentration, and the location of the maximum concentration drop is calculated. Considering the monitoring point layout scheme and the monitoring period, the dynamic monitoring system is constructed around the waste incineration power plant. Then actual and modeled data are combined into the environmental dynamic monitoring system. Finally, the pollution level is divided based on the pollutant concentration, the compensation area is divided based on the pollution level, and the economic compensation for the surrounding residents is determined based on the pollution concentration level and the number of contaminated days.

Determine the comprehensive concentration of pollutants in the exhaust vent

(1) Construction of emission assessment system for waste incineration power plants

According to the country's new pollutant discharge standards, there are six main types of pollutants: particulate matter, mercury, and lead. Meanwhile, considering the pollutant emissions and harm to the human body, a pollutant index evaluation system is established, as shown in Figure 3.

(2) Use AHP to determine the weight of each indicator

(1) Structure level analysis chart

Regarding the concentration index of the exhaust outlet, the analytic model is divided into three layers. The target layer is to determine the pollutant concentration, the criterion layer is to determine the pollutant discharge index, and the plan layer is to determine the pollutant type. The specific structure of the evaluation index system is shown in Figure 3.

(2) Construction of judgment matrix and consistency check

The relative importance of each factor in the criterion and indicator layers is given by consulting the data, and the judgment matrix is constructed. The two factors in the criterion layer can be regarded as equally crucial concerning the target layer. The relative importance of the two indicators in the

TABLE 8 CR analog value.

	B_2
CR	0.02577

TABLE 9 Hierarchical single sorting and total sorting weights.

Guidelines index	B_1	B_2	Total sort$_W$
	0.5	**0.5**	
C_1	0.0872	0.2465	0.16685
C_2	0.1302	0.1174	0.1238
C_3	0.2156	0.4382	0.3269
C_4	0.5166	0.1080	0.3123
C_5	0.0189	0.0450	0.03195
C_6	0.0314	0.0450	0.0382

TABLE 10 Average wind speed of each wind direction throughout the year.

Direction	N	NE	e	SE	S	SW	W	NW
u_x (m/s)	2	1.85	1.51	1.61	3.13	2.03	3.01	2.64

criterion layer is 1–9 scaled (see Table 3), with appropriate scale values being introduced, as shown in Tables 4, 5.

Note:$C_{ij} = \{2, 4, 6, 8, \frac{1}{2}, \frac{1}{4}, \frac{1}{6}, \frac{1}{8}\}$ indicates that the importance level is between $C_{ij} = \{1, 3, 5, 7, 9, \frac{1}{3}, \frac{1}{5}, \frac{1}{7}, \frac{1}{9}\}$. These numbers are based on the intuition and judgment of people conducting qualitative analysis.

In the above process, a judgment matrix is established, which makes the judgment thinking mathematical, simplifies the problem analysis, and quantifies the pollutant index evaluation process. In addition, this decision-making method also helps to maintain consistency in judgment.

In the analytic hierarchy process, the negative mean of the remaining eigenvalues other than the largest eigenvalue of the judgment matrix is introduced, which is used as an indicator to measure the deviation of the judgment matrix.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

The larger the value of CI *is*, the greater the degree to which the judgment matrix deviates from complete consistency; The smaller the value of CI *is* (closer to 0), the better the consistency of the judgment matrix is.

The judgment matrix of Tables 5, 6 is calculated by MATLAB software, and the maximum eigenvalue of the judgment matrix and the deviation consistency index are obtained. The results are shown in Table 6.

It is agreed that for different levels of judgment matrices, the consistency error is different and the requirements for the value of CI are also different. To measure whether the judgment matrices of different orders have satisfactory consistency, it is necessary to use the average random consistency index of the judgment matrix. For the judgment matrix of 1∼9 order, the values of RI are listed in Table 7.

When the order of matrix is 1 or 2, the judgment matrix always has complete consistency; when the order of matrix is greater than 2, the random consistency ratio CR is calculated:

$$CR = \frac{CI}{RI} \tag{2}$$

When CR < 0.1, the judgment matrix is considered to have satisfactory consistency, otherwise the judgment matrix needs to be adjusted. According to the results in Table 7, take RI $= 1.24$, the random consistency ratio of the two matrices in Tables 5, 6 can be obtained, as shown in Table 8.

Obviously, $CR(B_1) < 0.1$, $CR(B_2) < 0.1$, so both matrices have satisfactory consistency.

(3) Determine the weight of each indicator

The hierarchical single sorting problem can be converted to be the maximum eigenvalue and eigenvector problem of the computational judgment matrix. By normalizing the eigenvectors, the hierarchical ranking result can be obtained:

$$w_1 = \begin{bmatrix} 0.0872 \\ 0.1302 \\ 0.2156 \\ 0.5166 \\ 0.0189 \\ 0.0314 \end{bmatrix}, w_2 = \begin{bmatrix} 0.2465 \\ 0.1174 \\ 0.4382 \\ 0.1080 \\ 0.0450 \\ 0.0450 \end{bmatrix}$$

The sorting method and result of the hierarchical order are shown in Table 9. The index level and the criterion layer are, respectively, multiplied by the following formula to obtain the total hierarchical ordering W:

$$w_i = \sum_{j-1}^{2} B_j C_{ij} \qquad (i = 1, 2, 3, 4, 5, 6) \tag{3}$$

3) Determine the comprehensive concentration of pollutants in the exhaust vent

By summation of the weights obtained above and the emission concentration of each pollutant C_F, the "comprehensive" concentration of the overall pollutant discharge C_Z can be obtained, as shown in formula (4):

$$C_Z = \sum_{i=1}^{6} W_i C_F (i = 1, 2, 3, 4, 5, 6) \tag{4}$$

By substituting the data given in the question into (4), the C_Z is calculated to be 113.795395 mg/m^3 .

Establishment of pollutant diffusion model

Since the site of waste incineration plant has a simple terrain, the influence of surrounding hills on the spread of atmospheric

TABLE 11 Distances at which maximum landing concentration and maximum concentration in each direction occur.

Direction	N	NE	e	SE	S	SW	W	NW
Maximum landing concentration	0.1637	0.1770	0.2168	0.2033	0.1046	0.1613	0.1088	0.1240
Maximum concentration occurrence distance	928.4540							

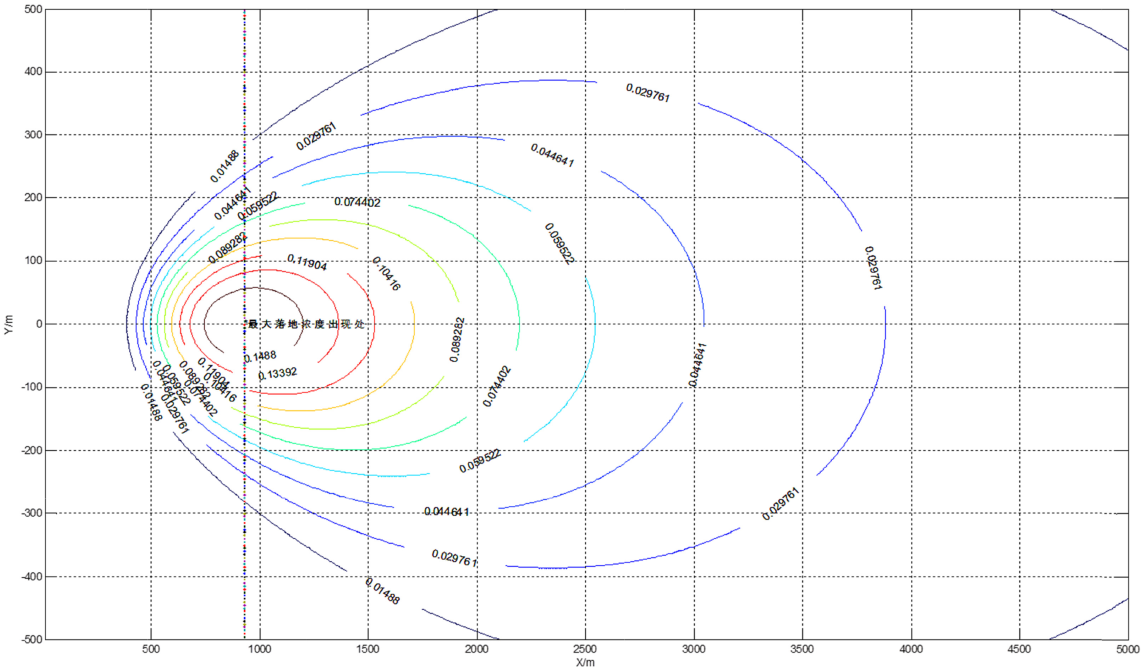

FIGURE 4
Contour map in N direction.

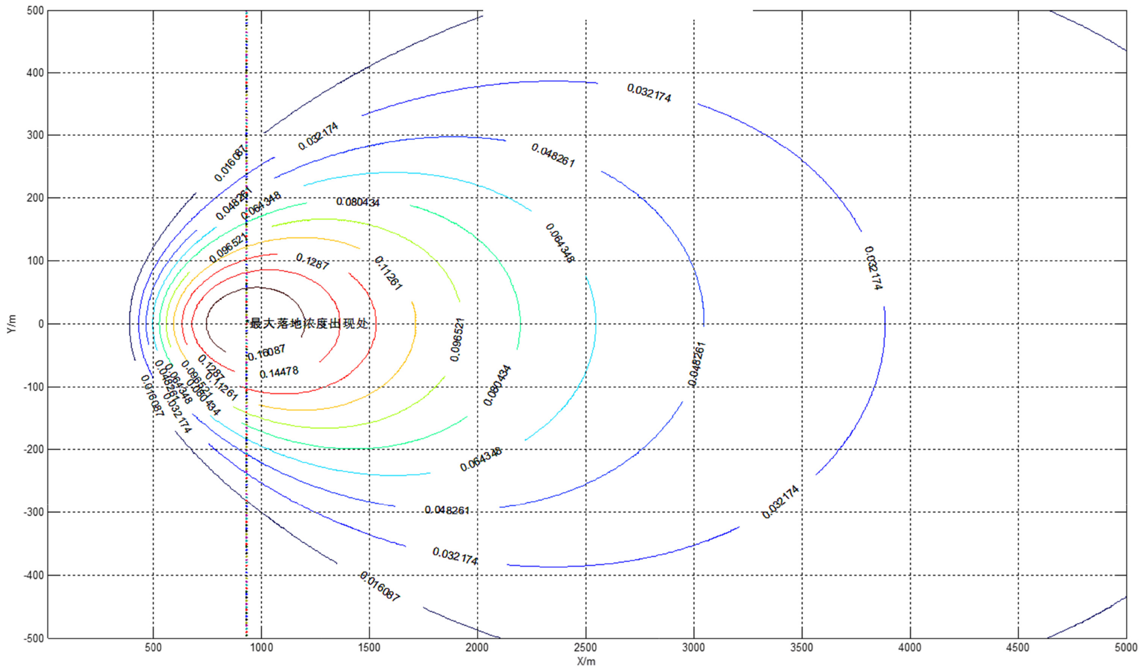

FIGURE 5
Contour map in NE direction.

pollutants can be ignored. An elevated continuous point source diffusion model is adopted, with the projection point of the exhaust outlet on the ground as the coordinate origin, and the height is z.The flue gas diffuses downward in the wind direction after leaving the exhaust vent, and the ground concentration of the pollutant satisfies the diffusion formula of Gaussian mode:

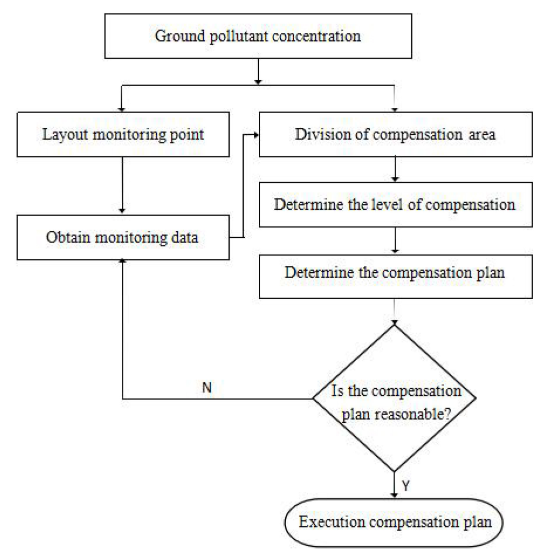

FIGURE 6
Flow chart for developing an economic compensation plan.

$$C(x, y, z, H_e) = \frac{Q}{2\pi u_x \sigma_y \sigma_z}. \{\exp[-\frac{1}{2}(\frac{y^2}{\sigma_y^2} + \frac{(z-H_e)^2}{\sigma_z^2})] + \exp[-\frac{1}{2}(\frac{y^2}{\sigma_y^2} + \frac{(z+H_e)^2}{\sigma_z^2})]\} \quad (5)$$

$z = 0$, the concentration of pollutants at any point on the ground can be expressed as the ground concentration model of the elevated continuous point source:

$$C(x, y, 0, H_e) = \frac{Q}{\pi u_x \sigma_y \sigma_z}. \exp(-\frac{y^2}{2\sigma_y^2} - \frac{H_e^2}{2\sigma_z^2}) \quad (6)$$

The maximum landing concentration occurs in the direction of the wind from the origin of the chimney, and then $y = 0$, and the ground concentration on the axis is:

$$C(x, 0, 0, H_e) = \frac{Q}{\pi u_x \sigma_y \sigma_z}. \exp(-\frac{H_e^2}{2\sigma_z^2}) \quad (7)$$

$$By\sigma_y^2 = 2E_{t,y}t = \frac{2E_{t,y}x}{u_x}., \sigma_z^2 = 2E_{t,y}t = \frac{2E_{t,z}x}{u_x}$$

and (3) are available:

$$C(x, 0, 0, H_e) = \frac{Q}{2\pi x\sqrt{E_{t,y}E_{t,z}}}. \exp(-\frac{u_x H_e^2}{4E_{t,z}x}) \quad (8)$$

Deriving x,

$$\frac{dc}{dx} = \frac{Q}{2\pi x^2\sqrt{E_{t,y}E_{t,z}}}. \exp(-\frac{u_x H_e^2}{4E_{t,z}x}) + \frac{Q}{2\pi x^2\sqrt{E_{t,y}E_{t,z}}}. \exp(-\frac{u_x H_e^2}{4E_{t,z}x}).(-\frac{u_x H_e^2}{4E_{t,z}x^2}) \quad (9)$$

FIGURE 7
Location of monitoring point.

Let $\frac{dc}{dx} = 0$, the distance at which the maximum landing concentration occurs is obtained:

$$x_m = \frac{u_x H_e^2}{4E_{t,z}} = \frac{xH_e^2}{2\sigma_z^2} \tag{10}$$

The maximum landing concentration is:

$$C_m = C(x_m, 0, 0, H_e) = \frac{2Q\sqrt{E_{t,z}}}{\pi e u_x H_e^2 \sqrt{E_{t,y}}} = \frac{2Q\sigma_z}{\pi e u_x H_e^2 \sigma_y} \tag{11}$$

For Equation (10), when $x = x_m$, there are:

$$\sigma_z \left|_{x=x_m}\right. = \frac{H_e}{\sqrt{2}} \tag{12}$$

Due to $\sigma_z = (\frac{H_e}{2x}\sigma_z = \frac{H_e}{2x_m})^{1/2} x^{1/2}$ and the diffusion of pollutants in the lateral direction is similar to the diffusion in the vertical direction, so σ_y with σ_z can be written as x.Function, i.e.:

$$\sigma_y = \gamma_1 x^{\alpha_1} \tag{13}$$

$$\sigma_z = \gamma_2 x^{\alpha_2} \tag{14}$$

Where σ_y, σ_z represent the diffusion coefficient; γ_1 and α_1 represent the horizontally regression coefficient and regression index of the diffusion (y); γ_2 and α_2 represent vertically regression coefficient and regression index of the diffusion parameter of the direction; γ_1, α_1, γ_2, α_2 can be obtained by looking up the table according to different levels of atmospheric stability.

If substituting Equations (13) and (14) into Equation (7), we get:

$$\begin{aligned} C(x, 0, 0, H_e) &= \frac{Q}{\pi u_x \sigma_y \sigma_z} . \exp(-\frac{H_e^2}{2\sigma_z^2}) \\ &= \frac{Q}{\pi u_x \gamma_1 \gamma_2 x^{(\alpha_1+\alpha_2)}} . \exp(-\frac{H_e^2}{2\gamma_2^2 x^{2\alpha_2}}) \end{aligned} \tag{15}$$

Pair (15) to x find the partial guide, it can be found the model that can accurately calculate the maximum landing concentration of the elevated continuous point source:

$$C_m(x_m) = C(x_m, 0, 0, H_e) = \frac{2Q}{e\pi u_x H_e^2 P_1} \tag{16}$$

$$Where\ P_1 = \frac{2\gamma_1 \gamma_2^{-\alpha_1/\alpha_2}}{(1+\frac{\alpha_1}{\alpha_2})^{\frac{1}{2}(1+\frac{\alpha_1}{\alpha_2})} . H_e^{(1-\frac{\alpha_1}{\alpha_2})} . e^{\frac{1}{2}(1-\frac{\alpha_1}{\alpha_2})}}$$

The distance at which the maximum landing concentration occurs is:

$$x_m = (\frac{H_e}{\gamma_2})^{1/\alpha_2}(1+\frac{\alpha_1}{\alpha_2})^{-(1/2\alpha_2)} \tag{17}$$

Table 10 shows the average wind speed of each wind direction throughout the year u_x

Pollutant emission Qequals to the smoke outlet concentration $C_{总}$ the product of the daily smoke flow, the daily handling flow rate of waste incineration plant can be given according to the item given in Annex 2. The daily processing capacity of the incineration plant is calculated on a proportional basis;

$$Q = \frac{113.795395 \times (832.05 \times \frac{650}{350} \times 10000)}{24 \times 60 \times 60} = 20352\, m^3/s$$

The effective height of the elevated point source is the sum of the chimney height and the smoke lift height. Since the diameter of the exhaust port is not given in the question, the smoke lift height cannot be accurately calculated. Moreover, as the chimney itself has a high height, the smoke life height can be ignored;

Then $H_e = H = 80\ m$

For the distance from the waste incineration plant along the wind direction, the value range is $10 \sim 5000\ m$;

For the distance from the waste incineration plant along the vertical wind direction, the range is $-500 \sim 500\ m$;

The model is solved by MATLAB software, and the distance between the maximum landing concentration and the maximum concentration in each direction is solved. The solution results are shown in **Table 11**. The concentration contour map of the direction N and NE, is shown in **Figures 4, 5**:

In **Table 11**, it can be seen from the established model (17) that the maximum concentration occurrence distance is the effective emission height H_e, and the regression coefficient of the diffusion parameter is only related to the regression index, so the maximum concentration in each direction is 928.4540.

It can be seen from the calculation results that the maximum drop distance is independent of the wind speed of 928 m. At the point where the concentration determined by the model is the short-term average concentration, it is necessary to understand the long-term law of the change of pollutants with time and space from the perspective of long-term environmental monitoring. Due to the unique climate at the site, sudden heavy rain often occurs. Every time rainwater pollutants fall to the ground with rainwater, the pollution and concentration distribution caused by it are equal. Therefore, the influence of acid deposition is consistent with the impact level of air pollution. Moreover, due to the rain, the concentration of pollutants in the air is almost zero, and the short-term concentration is calculated again so that the model can achieve our goal.

In order to obtain a feasible dynamic monitoring and evaluation method for the environmental impacts of waste incineration plants, the elevated continuous point source diffusion model is adopted to discuss the problem of pollutant diffusion and its impact on surrounding residents to construct

TABLE 12 Division of compensation regions in the *N* direction.

First level compensation area		Second level compensation area		Third level compensation area	
The inside diameter of	Outer diameter	The inside diameter of	Outer diameter	The inside diameter of	Outer diameter
590	1,700	480	2,760	430	3,860

TABLE 13 Compensation area division in the NE direction.

First level compensation area		Second level compensation area		Third level compensation area	
The inside diameter of	Outer diameter	The inside diameter of	Outer diameter	The inside diameter of	Outer diameter
570	1,810	470	2,900	420	4,040

TABLE 14 Division of compensation area in E direction.

First level compensation area		Second level compensation area		Third level compensation area	
The inside diameter of	Outer diameter	The inside diameter of	Outer diameter	The inside diameter of	Outer diameter
530	2,100	450	3,280	410	4,540

TABLE 15 Compensation area division in the SE direction.

First level compensation area		Second level compensation area		Third level compensation area	
The inside diameter of	Outer diameter	The inside diameter of	Outer diameter	The inside diameter of	Outer diameter
540	2,010	450	3,150	410	4,380

TABLE 16 Division of compensation regions in the S direction.

First level compensation area		Second level compensation area		Third level compensation area	
The inside diameter of	Outer diameter	The inside diameter of	Outer diameter	The inside diameter of	Outer diameter
928	928	540	2,050	460	2,950

TABLE 17 Compensation area division in the SW direction.

First level compensation area		Second level compensation area		Third level compensation area	
The inside diameter of	Outer diameter	The inside diameter of	Outer diameter	The inside diameter of	Outer diameter
590	1,680	480	2,730	430	3,830

a monitoring system and develop an economic compensation plan for surrounding residents. The specific process of developing an economic compensation plan is shown in **Figure 6**.

(1) Layout of monitoring points

According to the maximum concentration drop location, the maximum concentration position in eight directions is obtained to be 928 m. Monitoring points are placed to achieve the best monitoring results. It can be obtained from the wind frequency map that the dominant wind direction (southwesterly

TABLE 18 Compensation area division in the W direction.

First level compensation area		Second level compensation area		Third level compensation area	
The inside diameter of	Outer diameter	The inside diameter of	Outer diameter	The inside diameter of	Outer diameter
800	1,080	530	2,110	460	3,020

TABLE 19 Compensation area division in the NW direction.

First level compensation area		Second level compensation area		Third level compensation area	
The inside diameter of	Outer diameter	The inside diameter of	Outer diameter	The inside diameter of	Outer diameter
690	1,310	510	2,300	450	3,270

FIGURE 8
Area division map.

wind) is significant throughout the year. Therefore, it is encrypted in the downwind direction and comprehensively considers the topographical factors, so that each monitoring point coincides with the monitoring environment air sensitive area, and is installed at the foothills and the top of the mountain. The essence of environmental monitoring is to study the impact of pollutants on people, the height of the sampling point should be set at the ground $1.5 \sim 2.0m$.The monitoring point should be updated every hour, or at 2:00, 5:00, 8:00, 11:00, 14:00, 17:00, 20:00, 23:00. The location of the monitoring point is shown in Figure 7.

(2) Division of compensation area

According to the theoretical data, the maximum concentration values in all wind directions are not equal. Due to the ambiguity and uncertainty of wind speed and wind direction, the minimum floor concentration value of

0.1046 in eight directions is used as the lower limit of the concentration for the first level compensation area. As the concentration difference is increasingly less significant, 0.0523 is taken as the lower limit of the concentration of the second level compensation region. Finally by looking up the data, the concentration value of 0.025 is used as the lower limit of the concentration of the third level compensation area. MATLAB is applied to solve the range in the eight wind directions, as shown in the following table (**Tables 12–19**).

In the tables above, the distances of the three concentration levels are marked out. If there is no data, the distance is out of range. Using the distance points of the eight wind directions, the compensation level curve is fitted, and the residents near the garbage incineration plant are considered to be subjected to other pollution. Therefore, the first level of compensation is also applied to the residents within the range of 1,000 m, thereby realizing the division of the economic compensation area.

The area division map is shown in **Figure 8**.

The economic compensation plan for the surrounding residents is approved by the local government (street or community). The compensation target is, in principle, the original resident who was not registered in the previous year as the standard.

(1) Compensation method:

According to the level of local economic development, the minimum wage standard, and the relevant provisions of the state, the amount of compensation per person is determined.

During the operation period of the sanitation facilities, the income from the operating unit (mainly the garbage disposal fee) or the government's finances shall be paid to the affected communities in the local area. At the same time, the community shall decide the distribution method of compensation under the supervision of the relevant department. The amount of compensation per person can be adjusted according to price changes.

Set up medical insurance compensation to protect the health of the surrounding residents.

Under the supplementation by some indirect compensation schemes, material benefits are brought to the surrounding people, such as waste treatment by-product feedback (including ash, scrap iron, electricity, steam, heat); public facilities sharing; contracting projects, procurement, employment priority; partial tax relief; compensation for falling operating income and other indirect compensation methods.

The annual satisfaction survey and market analysis change the compensation plan dynamically and promptly.

(2) Compensation standard:

According to different economic compensation areas, different economic compensation weights are set up, and the degree of pollution is proportional to the amount of compensation. The garbage incineration plant targets the minimum compensation fund and the highest satisfaction of residents. 10% of the annual profit of the incineration plant plus government financial subsidies are pooled as the total funds for economic compensation. For the residents of different regions, the compensation plan is formulated according to the local development situation, and the total compensation amount for each level of compensation area is 5:3:2.

Conclusion

By taking a medium-sized waste incineration plant in Shenzhen as an example, in this paper, mathematical models are constructed to improve the integrity and scientificity of the environmental compensation mechanism and solve the economic compensation problem for the surrounding residents. Through analysis, it can be seen that the proposed compensation scheme can satisfy the requirements of the surrounding residents.

Data availability statement

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

Author contributions

YG and RG were responsible for designing the framework of the entire manuscript from topic selection to solution to experimental verification.

Conflict of interest

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

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Publisher's note

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A study on the mechanism of the influence of short science video features on people's environmental willingness in social media—Based on the SOR model

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Based on the SOR (Stimulus−Organism−Response) model, the influence of short science videos on people's environmental willingness is explored from the perspective of stimulus response, and their intrinsic mechanisms of action are explored. The study finds that the content features of short videos (usefulness, ease of use, and entertainment) can positively influence people's environmental willingness through two paths: emotional evocation and perceptual fit. In addition, we should focus on the emotional resonance of people's hearts and bring into play the advantages of sound and picture so as to enhance and optimize the persuasive effect of short science videos on people.

KEYWORDS

social media, short science video, environmental willingness, SOR model, environment

Introduction

In September 2020, China announced to the world at the United Nations General Assembly the goal of achieving carbon peaking by 2030 and carbon neutrality by 2060 (Wang et al., 2022a). In response to environmental protection issues, although China has enacted laws and regulations to conserve resources and protect the environment and has promoted scientific guidance, the reality of environmental problems has not yet been effectively addressed (Wei et al., 2021). The general public lacks awareness of environmental protection and simply understands it as sanitation, greening, etc., (Zhang and Hanaoka, 2021). They believe that environmental protection is the responsibility of the government and do not consider the impact of their own activities on the environment, their participation in environmental protection is low, and the culture of universal participation in environmental protection is far from being formed (Wu, 2021).

In the age of mobile internet, social media has become an important tool for people to learn, work, and live (Song et al., 2021). By June 2021, the number of short video users in China reached 832 million, accounting for 85.8% of all internet users (Li and Wang, 2021).

With the increase in number of short-form video users and the promotion of new technologies and applications, short-form video content will further shift from general entertainment to vertical content and become a powerful tool for public education (Yang and C Treadway, 2018). Compared to traditional methods of environmental protection publicity, the use of short videos to organize and carry out environmental protection publicity can further improve efficiency and quality (Risselada et al., 2018). However, the effect of environmental protection propaganda on social media is not ideal, so it is a matter of concern of how to improve people's environmental behavior through social media short videos (Pike and Lubell, 2018).

With the advent of short video platforms, the role of short videos on science topics in enhancing people's knowledge base has been widely received by the academic community (Lin et al., 2019; Liu et al., 2019). However, most of the current results focus on what kind of marketing effect science knowledge-based short videos has on users and how to produce good marketing effects from the perspective of communicators, but there is a lack of in-depth research on the psychological mechanisms between science knowledge-based short videos and people's environmental willingness (Zheng et al., 2022a). In order to better investigate the factors that influence people's environmental willingness in science knowledge-based short videos (Wang et al., 2022b), this study explored the intrinsic mechanism between the stimulus–response perspective of short videos and the public's environmental willingness using the SOR model of "stimulus–organization–response" theory and analyzed the factors influencing the public's environmental awareness of short video platforms in order to provide a reference for environmental protection work (Zheng et al., 2022b).

In this study, we verified through questionnaire data that the three features of short science videos (entertainment, usefulness, and ease of use) affect viewers' attitudes toward the videos (enhancing environmental intention). In addition, we found through further investigation that the three features of the videos mainly influence viewers' willingness to protect the environment through two psychological mechanisms (perceived fit and emotional arousal). This plays a key role in the design of future public service announcements and the promotion of environmental knowledge by environmental authorities. This study first introduces the background of the study, followed by a literature review and formulation of the research hypothesis, and finally validates the research hypothesis through data and draws conclusions that point to the management implications of this study.

Literature review and research hypothesis

The SOR theoretical model suggests that the stimulus of the external environment influences individuals' behavioral decisions by affecting their emotions (Zheng et al., 2022c). Stimulus refers to the factors that motivate and cause people to behave. Organism refers to an individual's internal psychological state, response refers to the various ways in which individuals exhibit stimulus, and organism based on response refers to the various behaviors or behavioral intentions that individuals display on the basis of stimulus and organism (Cai et al., 2021). In the SOR framework, the stimulus is generally used as the independent variable, organism as the mediating variable, and response as the dependent variable. In the process of users learning about environmental protection through the short video platform, the individual's organism, i.e., (Baltas et al., 2017) psychological state is generated by the content stimulus of the short video and in the process of interaction with other users (Gong and Li, 2017). The usefulness, ease of use, and entertainment of the short video will directly affect user experience and emotional evocation, which in turn affects people's environmental willingness and environmental behavior (Bergkvist et al., 2016).

The impact of short video features on the users' psychological state

According to research findings, entertainment, usefulness, and ease of use are the most important factors that attract users to view short videos (Treem and Leonardi, 2012; Chen et al., 2017). According to research reports, the desire for "fun" content ranks first in both Snack Video and Tik Tok, with skill demonstrations in second place and tutorials also very attractive to the public. According to the Short Video User Value Study 2020–2021 (INVALID CITATION), "humorous short video content is the most popular", and fun and entertainment are still the main factors that attract people to engage heavily (Davis et al., 2020). Bekalu M A (2018) found that people's judgment of the usefulness, ease of use, and entertainment of APPs will directly influence their behavioral intentions and usage behavior (Bekalu et al., 2018). Baltas. G (2017) confirmed that usefulness and ease of use, such as product-related descriptions and website navigation design, positively influence users' emotional evocation (Jiang et al., 2019). Lin J (2019) confirmed that the quality of the marketing platform entertainment has a positive effect on people's emotional evocation (Lin et al., 2019). Jiang C (2019) found that system quality and service level can significantly and positively influence perceptual fit (Mallapaty, 2020).

Therefore, the following hypotheses are proposed.

H1a: Entertainment positively influences individuals' emotional evocation.

H1b: Entertainment positively influences individuals' perceptual fit.

H2a: Usefulness positively influences emotional evocation.

H2b: Usefulness positively influences individuals' perceptual fit.

H3a: Ease of use positively influences individual emotional evocation; H3a: ease of use positively influences individual emotional evocation.

H3b: Ease of use positively influences individuals' perceptual fit.

The influence of the user's mental state on environmental willingness

Organism is an internal cognitive process in response to an external stimulus, in which the valid information generated by the organism due to the stimulus, such as feelings, perceptions and emotions, will become the basis for subsequent behavioral intentions and behaviors (Du et al., 2021). The emotions generated by an individual's exposure to the external environmental stimulus will cause the individual to engage in approaching or avoiding behaviors toward the environment and produce a mediating effect between the environment and behavior (Wei et al., 2020). Zhang R (2021) study shows that the quality of information on websites evokes people's inner emotions, which in turn triggers the production of environmental willingness (Zhang and Hanaoka, 2021); Wei W(2020) pointed out that information on green products provided by websites can positively cause people's emotional arousal, which in turn positively influences people's environmental willingness (Jimenez-Navarro et al., 2020).

Davis L S (2020) points out that algorithmic recommendation is an important indicator of good user experience (Davis et al., 2020). Jimenez-Navarro J P(2020) and others point out that perceptual fit has a significant positive impact on people's purchase of products or services (He et al., 2020). He J K (2020) found that perceptual fit significantly and positively influenced people's attitudes toward using social networking sites to obtain information about green products (Chen et al., 2020).

Therefore, the following hypotheses are proposed:

H4: Emotional evocation positively influences individuals' environmental willingness.

H5: Perceptual fit positively influences individuals' environmental willingness.

The mediating role of the user's psychological state

Zhang R (2021) found that external stimulus positively influenced people's environmental behavior by affecting factors such as emotional evocation, and Chen A (2020) found that emotional evocation positively influenced information choice and information dissemination in the process of information usefulness, content value, and information novelty (Zhou et al., 2019; Zhang and Hanaoka, 2021). Song G J (2021) found that emotional evocation plays a mediating effect in the process of information usefulness, content value, and information novelty, positively influencing information choice and information dissemination (Li and Wang, 2021; Song et al., 2021). Zhou Y (2019) concluded that perceptual fit affects the intention to continue using information by influencing satisfaction (Xiao et al., 2019; He et al., 2020).

Therefore, the following hypotheses are proposed:

H6a: Perceptual fit has a mediating role in entertainment's influence on individuals' environmental willingness.

H6b: Emotional evocation mediates the process by which entertainment influences individuals' environmental willingness.

H7a: Perceptual fit mediates the process by which usefulness affects individuals' environmental willingness.

H7b: Emotional evocation mediates the process by which usefulness affects an individual's environmental willingness.

H8a: Perceptual fit mediates the process by which ease of use influences individuals' environmental willingness.

H8b: Emotional evocation mediates the process by which ease of use affects an individual's environmental willingness.

Research model

In summary, using the SOR theory as the research framework and entertainment, usefulness, and ease of use as the antecedent variables of perceptual fit, emotional evocation, and people's environmental willingness, we constructed a model of the effect of science knowledge-based short videos on people's environmental willingness (Murphy et al., 2013). The research model of the influence of science knowledge-based short videos on people's environmental willingness was constructed (Figure 1).

Data collection

The content of the questionnaire was divided into two themes: first, the demographic characteristics of the sample, including gender, age, literacy, occupation, and income (Treem and Leonardi, 2012); second, the main variables of interest for this study, including usefulness, ease of use,

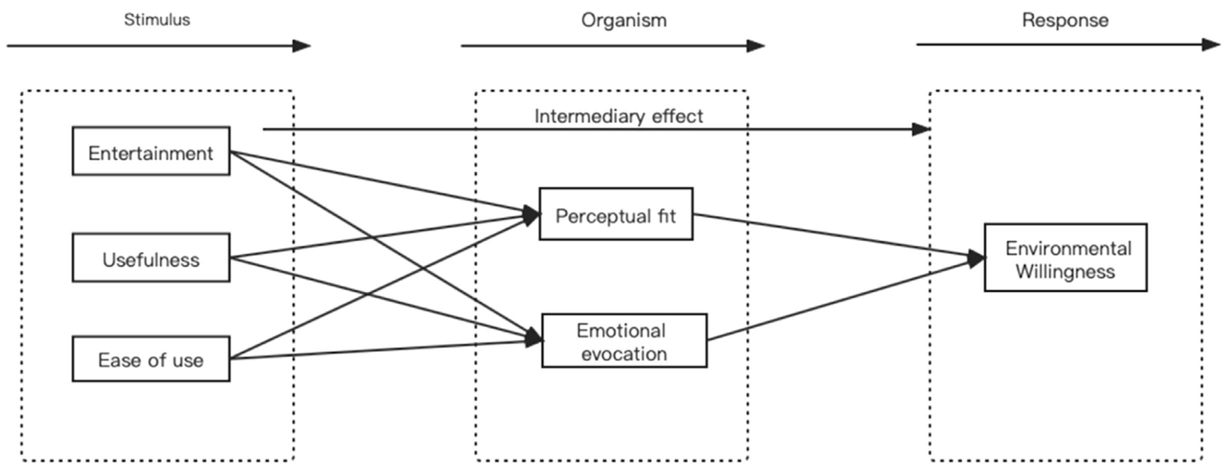

FIGURE 1
Framework of this study.

TABLE 1 Variable measurement terms and sources.

Variable	Measurement topic	Reference
Usefulness	1. Short science videos help me better understand information related to the environment	Jiang et al. (2019)
	2. Short science videos help me better choose green products that meet my needs	
	3. The videos help me make better decisions about environmental behavior	
	4. The information provided in the videos is useful to me	
Entertainment	1. I find the content of the short science videos interesting	Ben Yahia et al. (2018)
	2. I find the content of the videos relaxing	
	3. I found the user comments on the science videos interesting	
	4. In general, I think the content of the short science videos is interesting	
Ease of use	1. The total length of the short science video is reasonable and complete	Han et al. (2018)
	2. The screen of the short science video is clear and neat	
	3. The content of the short science video is clear and easy to understand	
	4. The short science video is played smoothly and at an appropriate pace	
Perceptual fit	1. The short science videos sent to me by the platform match my needs	Yang et al. (2015)
	2. The short science videos sent to me by the platform match my interests	
	3. The short science videos delivered to me by the platform match my expectations	
	4. I feel that the short science videos sent to me by the platform are highly relevant to my needs	
Emotional evocation	1. Short science videos can give me a clear understanding of the current state of the environment	Chen et al. (2013)
	2. Short science videos can make me feel anxious about environmental issues	
	3. The short science video can raise my concern about environmental issues	
	4. Short science videos can make me empathize with them	
Environmental willingness	1. I am willing to participate in environmental protection activities	Treem and Leonardi, (2012)
	2. I prefer to choose environmentally friendly products and services	
	3. I am willing to share environmental protection ideas with my friends	

entertainment, perceptual fit, emotional evocation, and environmental willingness (Dunlop et al., 2010). A 5-point Likert scale was used for this study, and the scales for most of the variables were derived from established scales in the authoritative literature to ensure reliability of the scales (Marku and Silver, 2008). The initial scale contained six constructs and 23 questions (Table 1) (Boyd and Ellison, 2007). A combination of convenience sampling and snowball sampling was used to select the respondents for this study (Rimal and Real, 2005). A total of 372 questionnaires were collected, and 294 valid questionnaires were returned after eliminating the questionnaires with problems (short response time, contradictory options, etc.) and invalid questionnaires (not having followed the popular science video) (Ben Yahia et al., 2018). The characteristics of the sample were as follows: by gender, 30.9% were male and 69.1% were female; by age, 4.0% were aged 18 or below, 50.0% were aged 19–24, 18.1% were aged 25–30, 22.1% were aged 31–48, and 5.8% were aged 48 or above; by education level, 46.2% had a college degree or below, 38.1% had a bachelor's degree or equivalent, and 38.1% had a master's degree or above. In terms of educational attainment, 46.2% had a college degree or less, 38.1% had a bachelor's degree or equivalent, and 15.7% had a master's degree or above.

Data analysis

Reliability and validity tests

In this study, the intrinsic reliability of the scale was tested using Cronbach's Alpha and Composite Reliability, CR. The 294 sets of data collected were tested by SPSS 19.0, and the reliability of the latent variables' usefulness, ease of use, entertainment, perceptual fit, emotional evocation, and environmental willingness Cronbach's Alpha values, which are 0.875, 0.845, 0.812, 0.898, 0.875, and 0.901, respectively, indicate that the data obtained in this study have high reliability. In terms of content validity, most of the questions in this study were based on research scales designed by domestic and international scholars, and these research scales have been proven to be valid by some scholars through empirical studies, so the content validity of this study is valid and reasonable.

Model Fit Test

The model fit of the 294 questionnaires was found to be within the reference value through the AMOS 17.0 operational analysis, indicating that the model fit was good and acceptable (Table 2).

As seen in Figure 2, the model hypotheses of this study were all supported ($p = 0.000$ or $p < 0.01$). Entertainment, usefulness, and ease of use positively affect perceptual fit and emotional evocation. The study also showed that usefulness not only positively influenced environmental willingness through emotional evocation and perceptual fit but could also directly and significantly influence H1a, H1b, H2a, H2b, H3a, H3b, H4, and H5, which were verified.

Table 3 shows the direct and indirect effect values of the standardized regression coefficients for the structural equation model. As can be seen from Table 4, of the stimulus variables, usefulness had the greatest effect on users' environmental willingness, with a total effect of 0.512; followed by entertainment, with a total effect of 0.181; and ease of use, with a total effect of 0.142. Among the organism variables, emotional evocation had the largest effect on users' environmental willingness, with a total effect of 0.423, which was much higher than the perceptual fit's value 0.178.

Mediating effect test

As can be seen from Table 4, usefulness, ease of use, and entertainment have a significant positive effect on environmental willingness, and the coefficients become smaller after the introduction of the mediating variable perceptual fit or emotional evocation. Specifically, usefulness not only significantly and positively affects environmental willingness through emotional evocation but also can directly, significantly, and positively affect environmental willingness so that emotional evocation plays a partial mediating effect. In contrast, usefulness, ease of use, and entertainment can only significantly and positively influence environmental willingness through perceptual fit so that perceptual fit has a full mediating effect. Therefore, emotional evocation and perceptual fit can partially or fully mediate the effects of usefulness, ease of use, and entertainment on users' environmental willingness. Hypotheses H6a, H6b, H7a, H7b, H8a, and H8b hold true.

Discussion

Through model testing and mediating effect testing, we found that usefulness, ease of use, and entertainment can all significantly and positively affect perceptual fit and emotional evocation. This suggests that when short science videos are presented with usefulness, ease of use, and entertainment, these "Perceptual fit and Emotional evocation had a positive effect on environmental willingness. This suggests that positive 'organism' processes can trigger positive 'responses' from users.

Usefulness, ease of use, and entertainment differed in the extent to which they significantly positively influenced perceptual fit and emotional evocation. Among the factors that significantly and positively influenced perceptual fit, entertainment had the greatest influence, and among the factors that significantly and positively influenced emotional evocation, usefulness had the greatest influence.

From the model, it can be seen that when perceptual fit exerts a mediating effect, it is a full mediating effect, while when emotional evocation exerts a mediating effect, usefulness can still directly and positively influence environmental willingness, indicating that emotional evocation has a partial mediating effect [44]. In this study, usefulness refers to the fact that the information provided in the short videos helps users understand environmental policies and benefits and motivates individual users to make environmental behavioral decisions,

TABLE 2 Structural equation model fit results.

Fitting metric	Indicator value	References value	Model fit judgement
Absolute fit parameter cardinality × 2	325.432		
Degrees of freedom df	217		
	1.500	<3.00 (common) < 2.00 (good)	Good
×2/df	0.041	<0.08	Good
Square root of error of approximation RMSEA	0.892	>0.90	Accept
AGFI	0.915	>0.90	Good
GFI	0.027	<0.05	Yes
RMR	0.0369	<0.08	Yes
SRMR	0.973	>0.90	Good
Value Added Fit Index TLI	0.933	>0.90	Good
Value Added Fit Index NFI	0.977	>0.90	Good
Value Added Fit Index IFI	0.977	>0.90	Good
Value Added Fit Index CFI	0.715	>0.50	Yes
Parsimonious Fit Index PGFI	0.838	>0.50	Yes
Parsimonious Fit Index PCFI	0.801	>0.50	Yes
CN	242	>200	Yes

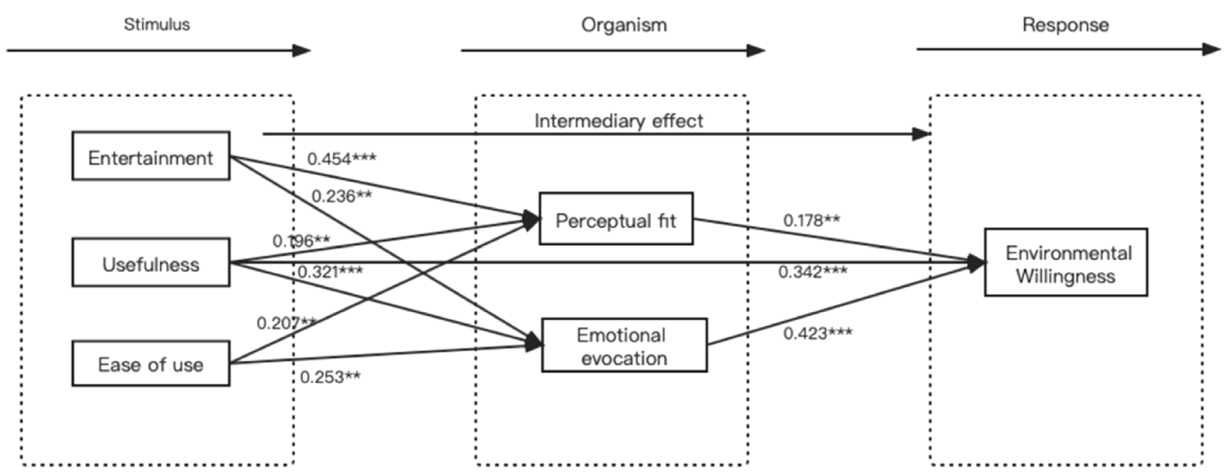

FIGURE 2
Diagram of the model for the study of factors influencing short science videos on individual environmental willingness.

such as purchasing green products (new energy cars, etc.); it also provides users with information on environment-related knowledge, which helps them absorb new information, acquire new knowledge, and master new skills.

Implications for environmental propaganda

This study found that science videos have a significant positive impact on users' environmental willingness. This means that the following aspects can be taken into account to optimize the publicity effect of short science videos.

No environmental advertising, emphasis on knowledge output, and reflecting usefulness

This study found that usefulness has a significant positive impact on users' environmental willingness, and the correlation is strong and has the greatest impact on environmental

TABLE 3 Results of the model analysis of factors influencing science short videos on users' environmental willingness.

Stimulus	Organism	Direct effect	Indirect effect	Total effect	*p*-value
Usefulness	Emotional evocation	0.321	—	0.321	***
Usefulness	Perceptual fit	0.196	—	0.196	0.008
Ease of use	Emotional evocation	0.253	—	0.253	0.004
Ease of use	Perceptual fit	0.207	—	0.207	0.009
Entertainment	Emotional evocation	0.236	—	0.236	0.006
Entertainment	Perceptual fit	0.454	—	0.454	***
Emotional evocation	Environmental willingness	0.423	—	0.423	***
Perceptual fit	Environmental willingness	0.178	—	0.178	0.010
Usefulness	Environmental willingness	0.342	0.171	0.512	***
Ease of use	Environmental willingness		0.142	0.142	
Entertainment	Environmental willingness		0.181	0.181	

TABLE 4 Mediation effect test.

	Environmental willingness		
	Model 1	Model 2	Model 3
Usefulness	0.342***	0.317***	0.268***
Ease of use	0.142	0.202**	0.170**
Entertainment	0.185	0.125*	0.133*
Perceptual fit		0.162**	
Emotional evocation			0.302***
F-value	81.259	64.048	76.271

willingness, which is the key influencing factor of users' environmental willingness.

Usefulness, on the one hand, refers to the fact that short science videos help users understand, compare, and judge environmental behaviors and ultimately make decisions on environmental behaviors; on the other hand, short science videos cannot provide a comprehensive introduction and interpretation of everything but can only select a certain point in the recommended environmental protection, such as a certain point of view, conclusion, story, or scene for interpretation, in essence, by sharing knowledge and information to achieve the purpose of environmental protection publicity. The aim is to share knowledge and information to promote environmental protection.

Therefore, science videos should not be defined as short environmental protection advertisements but should be based on the user's point of view to refine the environmental protection information that can solve the user's pain points and meet the user's needs, in order to share the knowledge information for the purpose. In order to grab the attention of users, science videos must pay attention to the aforementioned influencing factors, meet user needs, solve user pain points, provide users with a new way of thinking, output a new point of view, solve a small problem, share a new skill, and transform environmental recommendations into knowledge output. The distinctive point of view, thought-provoking conclusion, story with twists and turns, and immersive scenes are precisely the important influencing factors that trigger users' likes, attention, sharing, and discussion in the new social media era. Only when users find the ideas, opinions, skills, and techniques shared and conveyed in short science videos useful, will their environmental willingness be enhanced and the effect of short science videos in empowering environmental marketing can be truly achieved.

No environmental preaching and innovative communication techniques to reflect entertainment

This study found that entertainment has a significant positive impact on users' environmental willingness through emotional evocation and perceptual fit and is an important influencing factor on users' environmental willingness. The function of short science videos has changed from environmental recommendation to knowledge output, and the style has also changed. Although it is knowledge output, it is not one-dimensional and does not include formal explanation and introduction but is interesting and fun for achieving humor and jest so that users can receive ideas, gain knowledge, and master skills in a relaxed and pleasant way. Therefore, the style of the narration, the title of the short video, the text of the release, the actions and expressions of the narrator, and the postproduction effects all focus on the entertainment side. The fact that the content of the short video is interesting or not directly affects the narration style of the narrator and also affects the editing effect of the short video, while the title of the short video and the text of the short video, when it is released, plays a significant role in guiding users' comments.

Popular science short videos are interesting and fun, innovative interpretation is a proven method from the short video content itself, short video titles and short video release copy and can be combined with the current relevant topics, such as social issues, short video platform hot list design creation, some environmental short videos to break the gender stereotypes of men and women, some inspirational short video subverting people's stereotypes of occupation, etc. The effect of humor can be very good.

Not mass communication, serving specific groups, and reflecting verticality

This study found that perceptual fit has a fully mediated effect and has a significant positive impact on users' environmental willingness, hence being an important factor influencing users'' environmental willingness. The so-called fit, in the context of short video communication, is the degree to which the knowledge information conveyed in the video matches the user's class orientation and cultural preferences. Therefore, whether in terms of account positioning, content type, or video format, it is necessary to narrow the audience rather than mass. The ultimate goal of short videos is to drive sales for environmental protection, and the subdivision of the environmental marketing vertical is more conducive to strengthening commercial realization. Studies have shown that the more vertical and purposeful the account on the short video platform, the stronger the realization ability. Some accounts that do not have a particularly large fan base have a high degree of stickiness due to their distinctive features, and their ability to realize cash is greater than that of some large pure entertainment accounts. Some short videos based on anchors can be positioned in the direction of IP building by positioning their users and their characteristics and creating a clear and distinctive persona to occupy the minds of users and gain their continuous attention.

In this sense, some environmental organizations should create short video accounts as a branch or even re-categorize their fan base and set up different short video accounts based on the attributes of their fans. For example, for users with some economic power, they can recommend information on new energy vehicles.

No elite education, focusing on the bottom perspective, and reflecting ease of use

This study found that ease of use has a significant positive impact on users' environmental willingness through emotional evocation and perceptual fit and is an important influencing factor on users' environmental willingness. To ensure ease of use, the short science video must be of reasonable length and high definition, Must be focused on the topic, have a clear viewpoint and vivid details, and be able to provide solutions while strengthening the user's sense of immersion. Through detailed portrayal, it strengthens the sense of immersion, establishes a link with users, and triggers emotional resonance; in conclusion, it seeks user attention to continue watching and increases the completion rate; through specific methods, it solves users' pain points strengthens their sense of identity, and carries out knowledge sharing and value output. So, in this sense, the information provided by popular science videos should not be vague but should be able to provide users with a new way of thinking, a new point of view, and a solution to a small problem in every short video.

Instead of an environmental guide, using sound and pictures to create a sense of identity

This study found that emotional evocation has a partial mediating effect and has a significant positive impact on users' environmental willingness, which is an important factor among the factors influencing environmental willingness.

On the one hand, science videos should focus on copywriting, whether it is the text of the short video itself, the cover title of the short video, the release text, or the commentary text, all of which should serve the purpose of inspiring users' emotional resonance and strengthening their sense of identity. The video should also be edited in post-production. Through the combined efforts of the aforementioned elements, users can have a personal feeling of the problems, difficulties, troubles, worries, and pains presented in the short videos, as well as a heartfelt recognition of the beautiful emotions of family, friendship, and love, and a sense of "common experience and the same emotions despite being strangers," thus triggering more likes, retweets, and comments.

Research limitations and future research directions

This study uses questionnaire data to explore the impact of environmental short video features on viewers' willingness to protect the environment and its underlying mechanisms, which can shed some light on existing environmental campaigns. However, there are still some shortcomings in this study, mainly in the data source. This study uses questionnaire data, although derived from more established scales. However, the findings would be more solid if secondary data could be used to test the research hypotheses. Therefore, in future studies, the use of secondary data could be considered, such as in the well-known short video application—Tik Tok, where a web crawler was used to collect users' behavioral data (e.g., retweets, comments, likes, etc.) to express their environmental intentions. In addition, the dependent variable measured in this study is environmental intention, although in many studies of consumer behavior, intention is used as a proxy variable for behavior. However, we know that environmental behavior is an ongoing behavior. Therefore, just because an audience has environmental intentions today does not mean that their intentions can be effectively converted into environmental behavior over a sustained period of time in the future. Therefore, in future research studies, we can use experimental methods to directly measure the conversion rate of their environmental intentions, i.e., the efficiency of performing environmental behavior.

Data availability statement

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

Ethics statement

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

Author contributions

Conceptualization and methodology, XW and XY; writing—original draft preparation, XW and XY; writing—review and editing, XW and XY. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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A comparative study on LinkedIn and Sina Weibo users' perceptions of the carbon-neutral city

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A carbon-neutral city is one of the most critical topics in carbon neutrality. To study the general public and professionals' focus, we analysed the posts on Weibo and LinkedIn through Pycharm, Navicat Premium, KHCoder, and Tableau. This study included 1908 microposts (14,668 sentences) on Weibo and 533 posts (3733 sentences) on LinkedIn. On Weibo, the most influential users were governments and organisations; for example, Baotou Daily, Beijing Ecological Environment, 922 Green Travel, Baotou Evening News, and Baoding Evening News. On LinkedIn, the most influential person was the co-director of Carbon Neutral Cities Alliance. The most popular topics on LinkedIn included "city," "carbon," "climate," "neutral," "energy," "emission," "sustainability," "sustainable," "neutrality" and the keywords of "world"; while "carbon," "city," "energy," "development," "new," "green," "promote," "neutrality," "construction" and "industry" are more prevalent in Weibo. Both LinkedIn and Weibo users focus on "energy" and related issues. LinkedIn users mentioned "climate" and "sustainability" most in their posts, but Weibo users concerned about green development in the construction industry.

KEYWORDS
carbon neutral city, Linkedlin, Weibo, python, data analysis

Introduction

Climate change is one of the serious problems facing humankind today. It affects almost all natural processes and threatens the species and biodiversity (Demirhan, 2020). Driven by excessive carbon dioxide emissions, global warming has seriously threatened human society's sustainable development (Shi and Feng, 2021). Carbon dioxide remains in the atmosphere for hundreds of years, longer than typical air pollutants, typically hours to days (Dryden et al., 2018). Reducing greenhouse gas emissions, especially carbon dioxide emissions from fossil fuel combustion, is an effective way to minimise climate change and avoid global temperature increases (Zhang et al., 2017; Moomaw et al., 2020). Reducing carbon dioxide emissions has become a common goal in the global community (Shi and Feng, 2021). Some scholars have explored the impact of climate change due to carbon emissions from fossil fuel combustion, cement production, land-use change emissions, and land and ocean carbon sinks (Redlin and Gries, 2021). Human activities raise carbon dioxide in the atmosphere to an unprecedented high level in human history (Karnauskas et al., 2020). Societies have recognised the need to rapidly reduce artificial carbon dioxide emissions to avoid potentially catastrophic impacts (Keller et al., 2019). However, confusion about the causes and consequences of climate change could have far-reaching implications in reducing carbon dioxide and other greenhouse gas emissions (Dryden et al., 2018).

WTO's suggestions for controlling carbon dioxide emissions

As carbon dioxide emissions are mainly driven by consumption, countries that accept the Paris Climate Agreement should focus on consumption-based but not production-based carbon emissions (Su et al., 2020). To meet consumers' needs, developing countries turn on their production engines which emit much carbon dioxide as a side product. If developed countries continue to consume at the present levels, importing products with a large carbon footprint, developing countries are encouraged to produce. All these mean that developed countries shall continue transferring carbon dioxide emissions to developing countries.

Actions to reduce emissions since 1990 have not led to significant improvements. Only five countries (Russia, Germany, UK, Italy and France) achieved carbon reductions. Factors affecting carbon dioxide emissions vary from country to country. In most developing countries, the reduction in carbon dioxide emissions is due to poverty (Kang et al., 2020).

Some scholars examine the carbon dioxide emissions per capita and their components, such as coal, oil, and natural gas, in 53 countries between 1980 and 2016. Results show that natural gas is the main component driving the carbon emissions (Haider and Akram, 2019). Carbon intensity, energy mix, and intensity negatively impact carbon dioxide emissions, while affluence and population raise carbon dioxide level (Kone and Buke, 2019).

Research question, aim, potential theoretical contribution and structure

We selected Sina Weibo and LinkedIn users as two primary research samples to study the public concern about carbon-neutral cities. The research questions included: *1*) what were the most popular words mentioned, word clusters and influential users on Sina Weibo and LinkedIn in a carbon-neutral city; *2*) what the differences between influential users were and focuses between Weibo and LinkedIn in the carbon-neutral city. Studying the public perception on Sina Weibo and LinkedIn about carbon-neutral cities shall provide helpful information to government officials who wish to share related information and policy makers when they plan and implement the policies.

This article comprises five sections: Section 2 reviews and summarises the relevant literature. Section 3 covers research methods and data descriptions. Section 4 shows the results and discussion, and Section 5 summarises the results and provides conclusions, practical implications, limitations, and further research directions.

Literature review

In view of the ever increases in carbon emissions, the green energy revolution is needed to combat global climate change and ensure the sustainable development of all humankind (Kang et al., 2020). The adjustment of energy and industrial structure is the main way for reducing carbon emissions, while economic growth and urbanisation are the two main reasons for the increase in carbon emissions. This section mainly goes through previous research on carbon dioxide emissions, the means to control it, and the carbon-neutral city, as well as Weibo and LinkedIn. It also highlights the research gaps.

Carbon dioxide emission and gross domestic product (GDP)

A long-run equilibrium exists between regional economic development and per capita carbon dioxide emissions. Exports and consumption-based carbon emissions are negatively correlated (Su et al., 2020). In contrast, imports and GDP are positively correlated with consumption-based carbon emissions (Su et al., 2020). In the short run, carbon emission reduction impacts GDP growth, but the degree of impact is uncertain. Due to the differences in regional economic development, the degree of correlation between per capita carbon dioxide emissions and economic growth is different. Economic growth and development must be achieved by adjusting the industrial structure, supporting the tertiary industry, using clean energy, and developing a low-carbon economy (Zhao et al., 2018). The impact of carbon emission reduction on GDP in the medium and long run are gradually weakened, exhibit a decoupling trend. For example, carbon emission reduction in the carbon peak phase affects the GDP growth rate in China, and the impact of the carbon-neutral phase on China's GDP growth tends to be weakened.

The countermeasure to control carbon dioxide emission

Clean energy development (CED) is of great practical significance in reducing carbon dioxide emission (CDE), ensuring energy security, and achieving green economic growth (Jia et al., 2022). Coal procurement, blending, and distribution strategies play an increasingly important role in large coal-fired power plants due to the need to reduce carbon dioxide emissions and operating costs (Xu et al., 2020). Technological innovation reduces the adverse effects of carbon dioxide growth (Su et al., 2020).

The modern coal chemical industry is essential in ensuring national energy security. The primary sources of carbon emissions are process and combustion emissions (Wang and Xu, 2022). Process emissions can be solved by improving product structure with hydrogen for energy production, while combustion emissions can be driven by electric drive (Wang and Xu, 2022). It is recommended that the industry explore ways to reduce emissions intensity through innovative processes (Wang and Xu, 2022). Alternative solutions such as steam flooding can reduce overall carbon emissions by more than 90% (Wang and Xu, 2022). The government can attract more investors to explore and implement renewable energy technologies by developing other renewable energy policies and related institutions. This, in turn, will promote the use of renewable energy (Wang and Zhang, 2021). It can also reduce risk due to oil price volatility.

Tools that control carbon dioxide emission

Scholars conducted modelling research and data analysis for exploring means to reduce carbon dioxide emissions. Previous studies compared simple and complex models of the global carbon and climate system (Thompson, 2018). The analysis studied how these models could be used for estimating the monetary costs of future damage due to an increase in carbon dioxide emissions (Thompson, 2018). Scholars have studied the impact of climate change on technological innovation by collecting panel data from 67 countries (regions) from 1980 to 2016 (Qin et al., 2019). They indicated that there were more climate technology innovation among countries with higher carbon dioxide emission. Yet, government investment in projects such as energy does not always promote the development of climate technology innovation (Qin et al., 2019).

Previous studies also focused on the relationship between carbon intensity, energy mix, energy intensity, affluence, and demographic effects. A disaggregated analysis of historical and projected carbon dioxide emissions from fossil fuel combustion in Turkey was performed by using the Logarithmic Mean Divisia Index (Kone and Buke, 2019). It included carbon intensity, energy mix, energy intensity, affluence, and population as variables for projecting carbon emissions (Kone and Buke, 2019).

While achieving this goal solely by reducing emissions could be very difficult (Keller et al., 2019). Carbon dioxide removal has been proposed to supplement and compensate for insufficient emission reductions by adding and designing new carbon sinks or combining natural absorption with engineered storage (Keller et al., 2019). Scholars reviewed the responses of the carbon cycle to different carbon dioxide removal approaches and highlighted factors that determined carbon dioxide removal efficacy (Keller et al., 2019). Results indicated that carbon intensity, energy mix, and intensity effects on carbon dioxide emissions were negative, while affluence and population were positive.

Carbon neutral city

Cities are the protagonists of anthropogenic greenhouse gas emissions (Qiu, 2021). Some studies found that carbon dioxide emissions in urban areas accounted for more than 60% of the total carbon emissions. The urban development model of disorderly expansion has caused damage to the urban ecological environment, traffic congestion, and dense population in central urban areas. Carbon neutrality goals are the "new norm" in cities and regions worldwide. These goals require rapid transformation outside the ordinary traditional urban regional planning. Through research into carbon neutrality in Greater Manchester, academics demonstrated that "collaborative scenario planning" dramatically contributes to "new norms" in cities and regions (Ravetz et al., 2020). Academic research showed that better urban and transport planning could result in carbon-neutral, healthy cities, mainly through land-use change, a shift from private motorised transport to public and active transport, and urban greening (Nieuwenhuijsen, 2020). Carbon neutral city required five main changes in urban energy, industry, construction, transportation, and consumption. In Melbourne, for example, the carbon-neutral route includes the utilisation of 100% renewable energy such as solar energy, wind energy, hydropower, LED energy-saving street lamp renovation, zero-carbon buildings, shared bicycles and shared cars, etc. to achieve zero-carbon transportation and reduce waste carbon emissions. The research results show that the city's annual carbon emissions consist of 67.6% of building carbon emissions, 30.5% of transportation carbon emissions and -1.9% of carbon sink absorption (Chang et al., 2019).

In the EU, buildings accounted for 40% of energy consumption and 36% of greenhouse gas emissions, mainly caused by construction, use, renovation and demolition (Bonoli et al., 2021). Scholars conducted a case study for a low-carbon demonstration city in China and showed that carbon emissions mainly result from the buildings' electricity use (79%), followed by refrigerant release emissions (12%) in

Shenzhen (Wang et al., 2021). The building factor is important in achieving a carbon-neutral city (Qiu, 2021). Some scholars researched carbon dioxide emissions evaluations and mitigations in the building and traffic sectors in the Taichung metropolitan area of Taiwan (Chang et al., 2019). Green buildings can not only achieve energy, land, water, and material saving in the whole life cycle and coexist harmoniously with nature. Under the support of existing renewable energy technologies, buildings can be transformed from pure energy consumers into renewable energy providers, which play an indispensable and essential role in the urban carbon neutrality (Qiu, 2021).

Scholars estimated that New York City can eliminate the carbon footprint of its buildings by 2050 (Wright et al., 2015). Based on city documents and national statistics, a significant measure directly controlled by New York is the elimination of carbon emissions from municipal district heating, which may account for up to 30% of New York city's reported carbon emissions and 58% of the energy-related carbon emissions (Laine et al., 2020). Tozer and Klenk (2019) applied textual network analysis to interpret the socio-technical configuration of planned mobilisation to constitute a carbon-neutral built environment. They analysed three essential building and energy configurations: *1*) district energy cities, *2*) zero net energy cities and *3*) natural gas transition cities. Scholars used scenario analysis to explore opportunities for decarbonized development and carbon neutrality potential through case studies of residential redevelopment. The results showed that buildings redevelopment with higher energy efficiency and increased penetration of renewable energy contributed to a long-term positive impact on the carbon performance of urban areas (Huang et al., 2020). Chang et al. (2019) used a multiple regression model to calculate the floor area of each building and showed the multi-scale carbon reduction hotspots, which could help government agencies formulate follow-up priority carbon reduction strategies and urban carbon neutrality policies. Using computer modelling, citywide data, and insights from experts in the construction industry, technology available today, Wright et al. (2015) showed how New York City (NYC) could mitigate climate change by improving building sector efficiency (accounted for 75% of its greenhouse gas emissions) by 2050.

Sina Weibo and LinkedIn

As social network development promotes scientific research in various fields, online social networking has become very popular in recent years, and online information sharing has become important during COVID-19 and lockdown (Cheng and Fu, 2017; Yue et al., 2020). Sina Weibo is the largest microblogging network among these sites in China (Cheng and Fu, 2017), with millions of users (Ye et al., 2021). It has a tremendous amount of information that reflects all aspects of social life (Liu et al., 2015). Sina Weibo's platform is popular for its real-time information and has become a new communication method and research tool for public opinion topics (Li, 2021). Wu et al. (2021) extracted disaster information based on Sina Weibo in China and conducted a case study on Typhon Lekima. Some other researchers studied the public concerns based on Sina Weibo, such as the human papillomavirus vaccine (Xiang and Feng., 2021), urban spatial patterns and functional zones (Miao et al., 2021), low-carbon cities' popularity (Yang et al., 2017), and construction safety (Zeng and Li, 2022) etc. Among them, users play an essential role in influencing other users, promoting network information dissemination, and leading the trend of public opinion (Ye et al., 2021). Thus, some identified influential users on social networks-cases from Sina Weibo (Ma and Ma, 2021).

Compared with Sina Weibo, LinkedIn is the leading social network site focusing on the professional field (Andres et al., 2022) with over 500 million customers. However, it has received far less research attention than Facebook and other personal networks (Brewer, 2018). People with more informational advantages are more likely to use LinkedIn (Utz and Breuer, 2019). It is commonly associated with utilitarian career-oriented motives rather than socialising (Brewer, 2018). LinkedIn is also considered as the most effective social network website for recruiters (Fernandez et al., 2021). For the past few decades, it has been the website for connecting freelancers and recruiters (Fernandez et al., 2021). LinkedIn users use it to connect to different industries and keep them informed about current events (Hoda et al., 2022). This paper aims to analyse the data of carbon-neutral cities on LinkedIn and obtain research hot topics, users, and institutions related to carbon-neutral cities by obtaining posts from LinkedIn and Weibo.

Research gap

Some researchers compared Twitter to Sina Weibo, LinkedIn and Facebook, or among three social networks. Alsini et al. (2021) reviewed hashtags recommendation methods for Twitter and Sina Weibo. Stokes et al. (2019) used Facebook and LinkedIn to recruit nurses for an online survey. Some academics studied users' profiles on social network websites, such as LinkedIn and Sina Weibo, which allowed users to tag themselves as parts of their profiles (Zhou et al., 2021). Previous research utilised Facebook, YouTube, Twitter, Flickr, Instagram, Pinterest, Google+, LinkedIn and Sina Weibo for examining the role of social media in the marketing of the world's top airlines (Zelenka and Hruska, 2018). Scholars used not only users' self-tags but also their friend relationships (often not hidden) on Sina Weibo and LinkedIn to expand the tag list and measure the effectiveness of different types of friendship links and their self-tags (Liang et al., 2014). Yet, research that compared Sina Weibo and LinkedIn in the context of a carbon-neutral city is scarce. It is the first of its kind that used quantitative semantics to explore clusters of words in LinkedIn and Sina Weibo regarding carbon-neutral cities.

Research method

Social media is an emerging tool researchers use (Stokes et al., 2019). This study obtained data from Sina Weibo and LinkedIn. It compared Sina Weibo and LinkedIn's contents in carbon-neutral cities.

Twitter, Facebook and LinkedIn, *etc*., are predominantly in English, but there are posts in other languages, while Sina Weibo is predominantly Chinse. Nevertheless, the abovementioned scholars mainly compared Twitter and Sina Weibo (Alsini et al., 2021), Facebook and LinkedIn (Stokes et al., 2019), LinkedIn and Sina Weibo (Zhou et al., 2021), etc. Although these social media are in different predominant languages, some scholars, for example, (Chao and Florenthal, 2016), chose English posts on Twitter to compare with the Chinese posts on Weibo. In the study, English keywords were used to collect "carbon-neutral city" or "carbon-neutral cities" on LinkedIn while Chinese keyword "碳中和城市" (same meaning as English keywords) were used for Weibo by using Python 3.6.6. This was because there were only one English Weibo microposts and four Chinese LinkedIn posts, which were negligible compared to all the posts on both Weibo and LinkedIn.

There are 533 posts on LinkedIn in English and 1908 microposts on Weibo in Chinese. The research samples are saved in MYSQL, including user name, publish time, institute, content/description, the number of likes, forwards and comments, contents through Navicat Premium 16.

The co-occurrence word network generated by the data analysis in this paper included information such as word frequency, lexical connections and sub-networks. By constructing a co-occurrence network of high-frequency words, the relationship between subjects was visualised to study the public focus on Weibo and LinkedIn about carbon-neutral cities. The size of the circle reflects the word frequency, the lexical connection and degree of the association are reflected by the connections and coefficients between the words, and the algorithm determines the sub-network. Different sub-networks are given different colours to distinguish them. Words with characteristic differences will be divided into the same sub-network.

Data analysis

Word frequencies, users and institutes on LinkedIn

533 LinkedIn posts (3733 sentences and 2451 paragraphs) were analysed through KHcoder 3. By choosing "Select Words to Analysis" and "Word Frequency List" in KHcoder, some unrelated words, ProperNone, PRP, Verb, and Interrogative Pronouns were excluded, such as "step," "great," "very," "today," "next," "last," "first," "still," "as," "many," "I," "am," "is," "be," "you," "not," "do," "it," "Day," "%," "more," "also," etc. The top 150 most frequently mentioned keywords were selected and visualised *via* Tableau, as shown in Figure 1. The size of the texts visualises the frequencies of each word. Thus, "city" (639), "carbon" (550), "climate" (321), "neutral" (288), "energy" (185), "emission" (144), "sustainability" (143), "sustainable" (143), "neutrality" (137), "world" (127), "change" (122), "plan" (114), "new" (108), "building" (103), "business" (103), "target" (88), "action" (84) and "future" (83) are top 20 of these 150 words.

All users are visually analysed in Tableau. As shown in Figure 2, different colours indicate the different usernames on LinkedIn, and the text's size visualises the contributions of the carbon-neutral city posts made by the same usernames. The largest size is Michael Shank, PhD, the "key opinion leader" on LinkedIn in carbon-neutral cities topic. The study further analysed the position of these users, and the most authoritative was the co-director of Carbon Neutral Cities Alliance (CNCA). "The Carbon Neutral Cities Alliance (CNCA) collaborates with leading global cities working to achieve carbon neutrality in the next 10–20 years – the most aggressive GHG reduction targets undertaken anywhere by any city" (CNCA, 2022). The visualisation diagram shows that people with most LinkedIn posts are individuals. Their number of posts on this topic is quite even.

To analyse the co-occurrence network in KHCoder, minimum word frequencies was set at 30, type of edges is words – words. On LinkedIn, there are 11 clusters that are visualised in 11 colours, including themes like "city," "power," "energy," "electric, fuel," "technology," "environment," "industry," "business," "sustainability," and "work" (Figure 3).

As the most popular institute, CNCA mobilised transformative climate action in cities to achieve prosperity, social equity, resilience, and a better quality of life for all on a prosperous planet. CNCA mobilises transformative, game-changing climate action (CNCA, 2022). The largest cluster, including "city," "carbon," "neutral," "neutrality," "emission," "climate," "change" and "target," suggested that the most potent idea from the public would be climate change action. The second-largest cluster included "power," "electricity," "generation," "waste," "reduction," "infrastructure," "sector," "support,", "economy," "country," "role," "panel," "discussion," and "collaboration." Thus, power and electricity were hot topics in carbon-neutral cities. For example, power raw materials and fuels development and electrification improvements of key sectors are one of China's strategies to achieve carbon neutrality by 2060.

"Building," "energy," "renewable," "green," "global," "plan," "goal" and "leader" belong to the third-largest cluster. The building industry has always been a major energy consumer; it is one of the critical areas to achieving the carbon-neutral goal. For example, the construction industry is a pillar industry of the national economy and is related to more than 50 related industries such as building materials, metallurgy, lighting, and electronics in China. Decarbonising the urban built environment

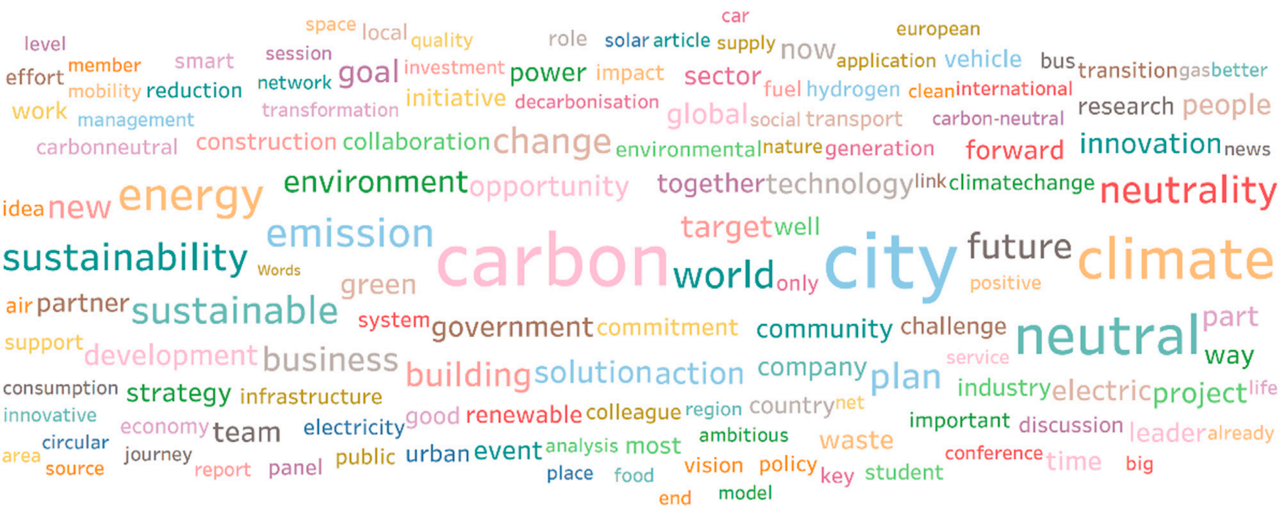

FIGURE 1
Word frequency in the carbon-neutral city from LinkedIn.

FIGURE 2
Influential LinkedIn users in the carbon-neutral city.

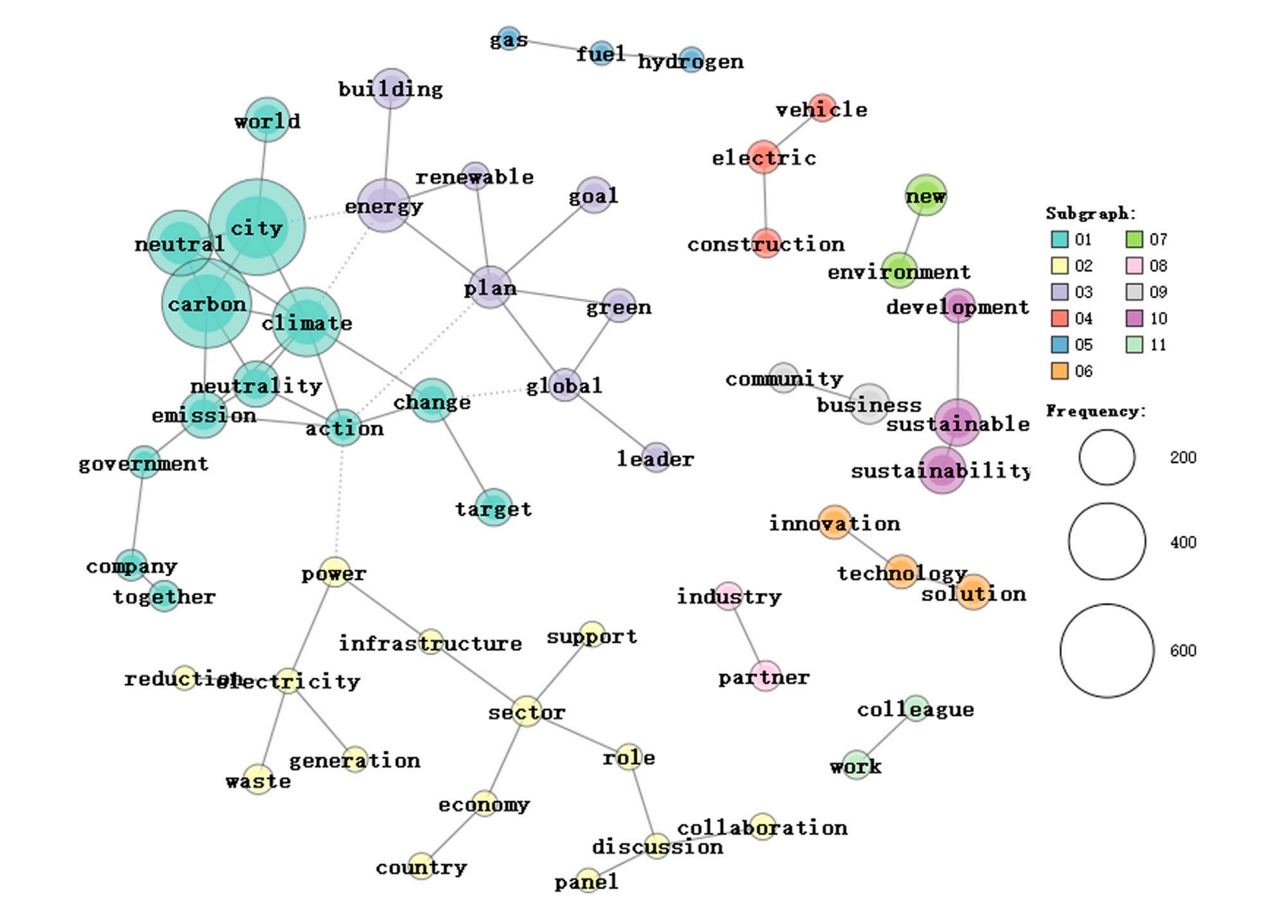

FIGURE 3
Clusters analysis in the context of carbon-neutral city from LinkedIn.

FIGURE 4
Word frequency in the carbon-neutral city from Sina Weibo (note: colour indicates information of words, the size of the word represents the keyword frequencies).

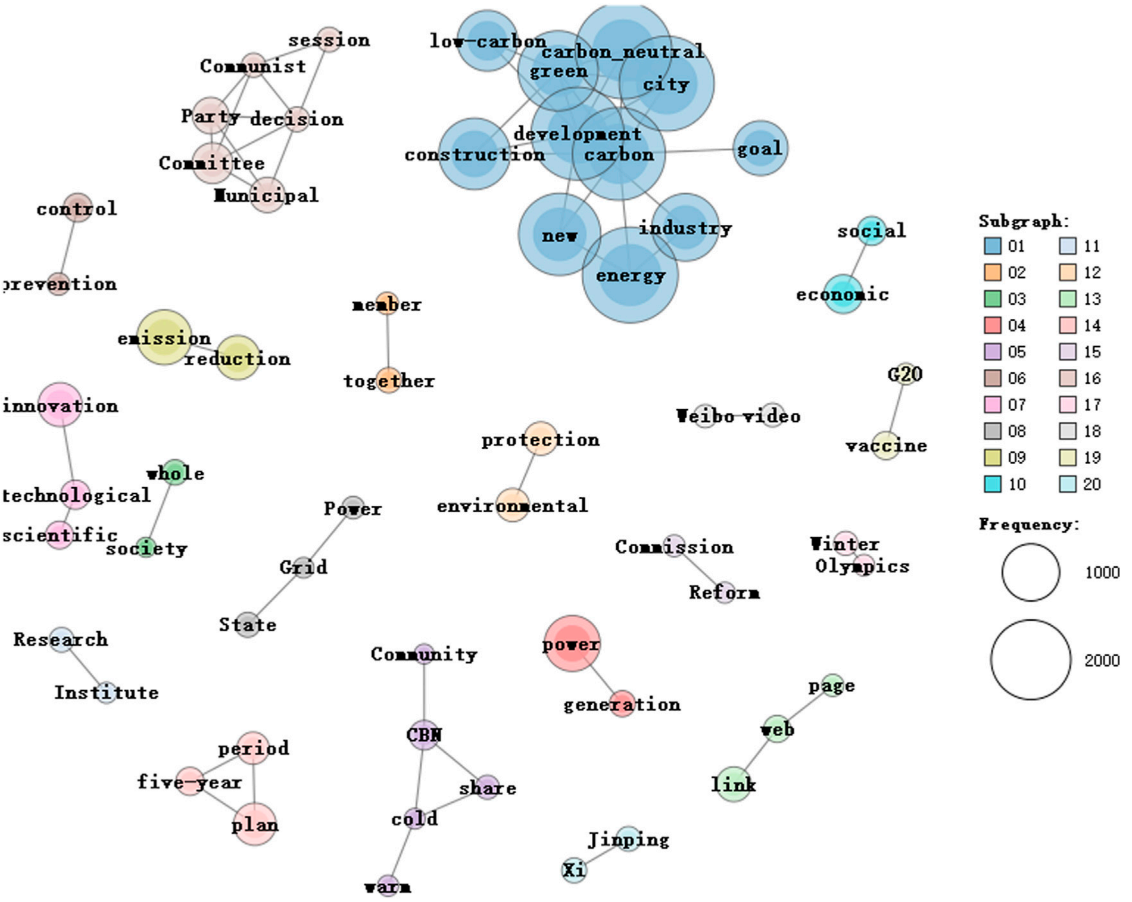

FIGURE 5
Co-occurrence network of words from Sina Weibo.

to achieve carbon neutrality is a priority in many cities due to rapid urban sprawl (Huang et al., 2020). Scholars suggest that cities wishing to achieve carbon neutrality should promote and advance distributable carbon-free energy production (Laine et al., 2020). Under the existing renewable energy technologies, green buildings could achieve energy, water, and material saving in the life cycle and coexist harmoniously with nature (Qiu, 2021). While greenhouse gas emissions can only be eliminated using carbon-free energy, more than 60 percent of emissions can be reduced by energy efficiency alone (Wright et al., 2015).

Sina Weibo

There were 1908 "carbon-neutral city" microposts in Weibo, 14,668 sentences and KHCoder analysed 1908 paragraphs. After deleting some stop words, such as "be," "have," "-LSB-," "-RSB-," "you," "not," "do," "it," "Day," "%," "year," "time," "when," "0," "o," "they," "we," "other," "go," "such," "day," "yuan," "year-on-year," "The," "Week," "put," "more," "also," etc., this study identified the most frequently mentioned keywords with more than 700 times: "carbon_neutral" (2983), "energy" (2928), "city" (2880), "development" (2754), "carbon" (2749), "new" (2138), "green" (2030), "construction" (1608), "industry" (1422), "China" (1339), "Chengdu" (1158), "project" (1149), "low-carbon" (1140), "urban" (1095), "country" (1070), "power" (959), "emission" (929), "goal" (919), "building" (745), "system" (729). This study then visualised and analysed the top 150 keywords *via* Tableau (Figure 4).

This study filtered words by setting term frequency (TF) of minimum is 100, minimum document frequency (DF) of 1,405 words were plotted. From Figure 5, there are 23 clusters. The blue cluster is the most influential network. These include "carbon," "development," "city," "carbon-neutral," "green," "construction," "low-carbon," "new," "goal," "energy," and "industry." After that, the "Party" cluster includes "municipal," "committee," "communists," "decision," and "session." The third-largest cluster includes "CBN," "Community," "cold," "warm," and "share." "CBN" propose the first carbon-neutral environmental protection movement.

FIGURE 6
Influential users in the carbon-neutral city from Sina Weibo.

It was developed by a top international development team and blockchain enthusiasts. The project party gave up ownership and is now fully autonomous in the community. It is expected that the price of the global carbon market will continue to rise in the next few years, and industry expansion, carbon futures, the introduction of institutional and individual investors, and the carbon quota market will attract much attention. We can also see a cluster including "scientific," "technological," and "innovation."

Compared with the co-occurrence word network of LinkedIn, different clusters were connected weakly. The users mentioned climate change most on LinkedIn, while Sina Weibo users focused more on energy and the construction industry.

According to Figure 6, the most active users were Baotou Daily (government, with 299,000 followers), Beijing Ecological Environment (government with 2,661,000 followers), azure map (organisation, fans are 430,000), 922 Green Travel (organisation, with 160,000 followers), Baotou Evening News (government, with 739,000 followers), Baoding Evening News (government, with 804,000 followers). Most were governments or academic departments. For example, 922 Green Travel was related to the Chinese Academy of Urban Planning & Design (CAUPD).

Conclusion

Theoretical contribution

Increasing global industrialisation and overexploitation of fossil fuels have resulted in greenhouse gases emission, increased global temperatures and environmental problems (Chen et al., 2022). Taking cities as the principal target to carry out urban carbon neutrality strategies enables cities to meet carbon-neutrality targets and construction plans for local market conditions and productivity levels (Qiu, 2021). This research is the first to compare public perception *via* Sina Weibo and LinkedIn in the context of a carbon-neutral city. Sina Weibo is one of China's most popular social media platforms and microblog networks (Ye et al., 2021). LinkedIn is a professional web platform worldwide. The two databases had different foci on the carbon-neutral city. This research used the keywords, e.g. "carbon-neutral city" or "carbon-neutral cities," to obtain the relevant content from LinkedIn and Sina Weibo. Pycharm, Navicat Premium, and Selenium are used to obtain the data. There were 1908 microposts on Weibo and 533 posts on LinkedIn. By using KHCoder and Tableau, the influential users and keywords were analysed.

Governments and organisations were popular users on Sina Weibo, while famous persons were receiving more attention on LinkedIn on a carbon-neutral city topic. On Weibo, the most influential users are governments and organisations, for example, Baotou Daily, Beijing Ecological Environment, azure map, 922 Green Travel, Baotou Evening News, and Baoding Evening News. On LinkedIn, the most influential person is Dr Michael Shank, the co-director of Carbon Neutral Cities Alliance. The most popular topics on LinkedIn were "city," "carbon," "climate," "neutral," "energy," "emission," "sustainability," "sustainable," "neutrality," "world," while "carbon," "city," "energy," "development," "new," "green," "promote," "neutrality," "construction," "industry" are more prevalent on Weibo. Both focused on energy, worldwide carbon emission problems, LinkedIn focused more on climate and sustainability. Furthermore, Sina Weibo bloggers focused more on green development in the construction industry. Analysing social media data on Sina Weibo and LinkedIn provides insights to members of the public, enterprises and governments when they wish to share knowledge and information effectively.

Practical contribution

This study offers practical contribution: *1*) data analysis from different social media allows government officials and policy makers to learn more about the public perception in carbon-neutral city, benefit them to plan and implement relevant measures for carbon-neutral city; *2*) Content analysis of social media offer insights on public concerns, for example, the green development in construction, climate change, sustainable development, new and green energy were the major concerns on Weibo and LinkedIn regarding a carbon-neutral city; *3*) Weibo and LinkedIn users share the information can encourage and help the members of public pay more attention on low-carbon travel and green infrastructure, *etc*.; *4*) Both Sina Weibo and LinkedIn focused on "energy," the enterprise could produce and design more green products with new energy, for example, photovoltaic applied on the buildings, with products advantage, competitiveness, market potential, market standard.

Limitations and further research direction

Limitations

The study researched the two leading social media, Sina Weibo and LinkedIn. As far as we know, LinkedIn is predominantly in English, but there are posts in other languages, while Weibo is predominantly Chinese. This study only used English keywords to collect data from LinkedIn as there were four Chinese carbon-neutral city LinkedIn posts. On the other hand, it only used Chinese word of carbon neutral city to collect data from Weibo microposts as there was only one post in English on this topic. Although some scholars use a similar method to collect data from social media, it probably has implications for the demographics of the posters.

Further research direction

In this study, we only collected data from two social media, Sina Weibo and LinkedIn. Others might shed light on social media such as Facebook, Instagram or Twitter. Crowdsourcing that outsources tasks to the crowd in analysing and interpreting the data may contribute to citizen science (Moltchanova et al., 2022). Besides, studying traditional media with a strong focus on climate and carbon neutrality could be the next step. A comparison between social media and traditional Chinese media like Xinhua or People's Daily may offer us a meaningful and a new research direction. Furthermore, as compliance is related to statutory measures (Lai et al, 2007), other topics might include people's perceptions on carbon neutrality laws and regulations.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Weibo.com; LinkedIn.

Author contributions

Conceptualisation, LZ, RL, YM; methodology, LZ and HZ; software, LZ; validation, LZ, RL, and YM; formal analysis, LZ; investigation, LZ and YM; resources, LZ; data curation, LZ; writing—original draft preparation, LZ, RL, HZ; writing—review and editing, LZ, RL, and HC; visualisation, LZ; project administration, LZ and RL. All authors have read and agreed to the submitted version of the manuscript.

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Conflict of interest

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

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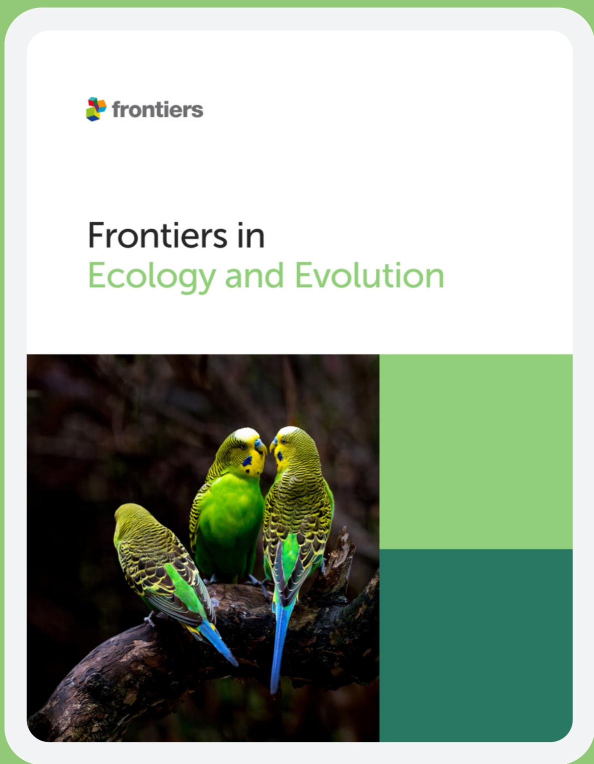

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