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Energy, economy, and climate interactions: Challenges and opportunities

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Energy, economy, and climate interactions: Challenges and opportunities

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Editorial: Energy, economy, and climate interactions: challenges and opportunities

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Editorial on the Research Topic
Energy, economy, and climate interactions: challenges and opportunities

Climate change has become one of the most prominent problems facing the world today and climate change prevention and adaptation are effective means of response (Shi et al., 2023). In contemporary world, energy plays an important role in all aspects of economic development. However, excessive energy use also leads to a rapid increase in greenhouse gas emissions, which eventually bring about climate change and have a negative impact on environment, economy, agriculture, and society. Global climate change mainly includes extreme climate, such as global climate warming, which has disrupted social organizations, housing, and food systems. In detail, climate change enhances species extinction risk, causes melting of glaciers, and even destroys the development of the world and human wellbeing. The Sixth Assessment Reports of IPCC assessed the impacts of climate change, looking at ecosystems, biodiversity, and human communities at global and regional levels, and emphasized the development path of climate adaptation.

In addition, global energy supply shortage and worldwide economic downturn at present might magnify this poor influence. These phenomena indicate a sense of urgency in the collaborative promotion of addressing energy security, economy growth and climate change issues. In other words, the consequences and costs caused by climate change will be significantly magnified and thus hardly affordable. Elshkaki believes that if the current vicious cycle of environmental degradation, such as climate change, caused by the consumption of traditional energy through carbon emissions is maintained, then in the near future, the natural resources of developing countries may not be sufficient to meet the sustainable economic growth of the new generation (Elshkaki, 2023). Therefore, it is advisable for our world to coordinate the promotion of energy security, economic growth, and climate mitigation, although this process consists of various challenges, opportunities and even failures. More importantly, climate change is the result of a complex process of social transformation, which we all need to understand and respond to the challenges it brings.

In order to reduce future climate change and ensure that our economy can grow in a sustainable manner, green and low-carbon transformation of energy is considered as an effective approach, which focuses on greenhouse gas emissions reduction and utilizes technologies of the information age to promote green and low-carbon transformation in many aspects, such as urbanization, transportation, finance, and construction industry.

Extreme climate that remains a fundamental pressing global environmental challenge warns us to focus on low-carbon transformation and sustainable development (Mei et al., 2020; Ren et al., 2023). Gül et al. analyze the influence of different variables on securing energy and reducing carbon emissions and achieves this goal through economic indicators (Gül et al., 2022). They get the results eventually that the global electricity generation by solar and wind is beneficial for securing energy and climate change mitigation. Russo et al. emphasize one of the main reasons for climate change is the use of fossil fuels for energy production (Russo et al., 2022). Then they demonstrate that reducing the use of non-renewable energy and making renewable energy play an important role in achieving carbon neutrality is a key link strategy to weaken the impact of climate change on society and the environment. The above findings confirm the viewpoint of the interaction between energy, economy and climate in this study, and emphasize the necessity of mitigating climate change.

Facing these challenges, many scholars have also put forward their own opinions to mitigate and adapt to climate change. Correctly quantifying uncertainties in future climate variation is useful to design low-carbon energy systems towards sustainable cities (Liu et al., 2022). Green finance, as the factor of mitigating climate change, can support to develop green and renewable energy and reduce carbon dioxide emissions (Yu et al., 2022; Lang et al., 2023; Lorente et al., 2023). It is sensible for us to improve climate adaptability through sustainable urban development and make the cities leading force for climate change adaptation and resilience (Mehryar et al., 2022).

Although the impact of climate change has been widely recognized, there is the shortage of understanding the process of green and low-carbon transformation and exploring green transformation methods. As emphasized in the AR6 reports of IPCC, which consider emission pathways and corresponding mitigation measures for the 21st century, technological development and innovation are key to mitigating climate change. Meanwhile, the reports discussed mitigation opportunities, related risks, and common interests in energy, agriculture, land use, settlements, construction, transportation, and industry. Thus, this Research Topic closely follows the theme of the above reports and attempts to explore innovative green transformation from multiple perspectives and fields, including economic development, transportation, monitoring model, finance and trade, and urbanization.

In terms of economic development, Zhou et al. explored whether digital economic growth has a reducing effect on carbon emissions. For transportation, Ma et al. analyzed carbon emissions efficiency in the transportation industry and Semab et al. analyzed carbon offsetting costs of ocean transportation in developing countries. In terms of monitoring model, Li and Chen established a multi-dimension long-term carbon emissions analysis model. For finance and trade, Yang et al. discussed carbon transfer in trade and economic spillover effects of employment and Xue et al. analyzed the development of green finance under the goal of carbon neutrality. In terms of urbanization, Lv and Wang deemed that green city efficiency is the key to national green growth. The common feature of these papers in the Research Topic is that they analyzed the development of green and low-carbon energy transformation in different fields or regions.

In the nutshell, the aim of this Research Topic addressing challenging problems is to highlight and show knowledge on the social, economic, and cultural implications of climate change, as well as reflect the transformation in social-cultural strategies to accelerate mitigation, adaptation and prevention. This Research Topic collection of articles discussed the challenge and opportunity of energy, economy and climate interaction by introducing the development status of green energy transformation in different fields and provides evidences indicating the urgency of reducing greenhouse gas emissions and mitigating climate change, which helps to identify key areas for further research and development. The articles included in this Research Topic address a variety of themes seeking to clarify the need to understand and act on climate change and green transformation, as well as provide insightful information that can help reduce carbon emissions related to energy utilization, mitigate and adapt to climate change, and promote sustainable development in the future.

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Spatial imbalance and factors influencing carbon emission efficiency in China's transport industry

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Exploring the regional differences of transport carbon emission efficiency (TCEE) and accurately identifying its influencing factors are crucial for achieving carbon neutrality in transport industry as soon as possible. The TCEE of 30 provinces in China from 2003 to 2018 was measured, and its spatial imbalance and influencing factors were determined. The following conclusions are drawn. First, previous studies have shown that the TCEE is increasing at an overall low level with significant regional differences. Second, the total regional differences of China's TCEE presents a trend of rising first and then falling, and the intra-regional differences are the main source of total differences. Third, this study shows that certain factors, such as the economic level, transport structure, energy structure, and technical level, significantly influenced the TCEE, but there were notable spatial-temporal differences in each factor. Finally, targeted and differentiated carbon emissions reduction policies were proposed for transport departments to realize carbon neutrality as rapidly as possible.

KEYWORDS

carbon emissions efficiency, transport industry, spatial imbalance, influencing factor, Dagum gini coefficient, geographically and temporally weighted regression model

1 Introduction

Global warming has become an important obstacle to sustainable economic and social development. Effectively controlling and reducing greenhouse gas emissions, mainly carbon dioxide (CO_2), has become an important issue facing mankind (Duan et al., 2019; Jiang et al., 2021; Zandalinas et al., 2021). According to official data, carbon emissions in China accounted for 31% of the total global carbon emissions in 2020, ranking first in the world in emissions (International Energy Agency, 2020). However, transport is the foundation and leading industry supporting social and economic development; it is also an important part of energy consumption and CO_2 emissions (Bai et al., 2020; Ma et al., 2021). Data show that CO_2 emissions from the transport industry account for approximately 10% of the total carbon emissions in China. They have thus become the third-largest source of CO_2 emissions after industry and construction (Wang et al., 2020a; Jiang et al., 2020).

In response to global climate change, China declared its intention to achieve peak carbon emissions by 2030 and carbon neutrality by 2060 (Lin and Wang, 2020; Zheng et al., 2021). In February 2021, the Chinese government issued the Guidelines on Developing Comprehensive Transport Network, emphasising the need to accelerate the development of green and low-carbon transport and achieve peak carbon emissions in the transport sector as soon as possible (Xu et al., 2021). The carbon emissions efficiency is an important indicator of the development level of a low-carbon economy. Improving the transport carbon emission efficiency (TCEE) is the most effective means of achieving emissions reduction targets.

To date, many studies have discussed various aspects of transport carbon emissions, including their calculation (Wang et al., 2018; Yuan et al., 2019), spatial evolution characteristics (Requia et al., 2015; Solaymani, 2019), peak predictions (Li and Yu, 2019; Lu et al., 2020), and influencing factors (Grubb et al., 2015; Guo and Meng, 2019), thus contributing to a better understanding of these aspects. However, few studies have investigated TCEE. Related research mainly focuses on energy or environmental efficiency evaluation in the transport field (Cheng et al., 2019; Omrani et al., 2019; Palander et al., 2020).

The methods used to measure the TCEE first included single-factor evaluation methods, such as those involving the determination of carbon emissions per unit freight turnover, per unit energy and per unit GDP (Greening et al., 1999; Jobert et al., 2012). With the wide application of production boundary theory and the complexity of traffic carbon emissions, the single-factor evaluation method has gradually been replaced by the total-factor evaluation method (Hampf and Kruger, 2014; Wang et al., 2020b; Wang et al., 2021). The total factor evaluation method can measure the allocation efficiency of traffic factors, especially the data envelopment analysis method, which is favored by researchers in the field of efficiency evaluation because it does not need any weight assumption, does not need to determine the input-output function relationship in advance, does not need dimensionless data processing, and can quickly deal with the evaluation problem of complex multi-input and multi-output systems (Cucchiella et al., 2018; Xie et al., 2018; Zhou et al., 2018; Ma et al., 2022). For example, Yang et al. (2021) established a life cycle DEA model, and measured the management performance of CO2 and PM 2.5 in China. Chen et al. (2021) combined with four-stage DEA and non-radical direction distance function (NDDF) model, considering the bad output and environmental factors, the energy efficiency of China's transport sector is calculated.

The exponential decomposition, input-output methods and econometric regression model can identify the influencing factors of the TCEE. The exponential decomposition method usually uses the IPAT, STIRPAT, and Kaya equations to decompose the influencing factors of the carbon emissions efficiency into population scale, wealth, and technology effects (De Oliveira-De Jesus, 2019; Liu et al., 2020). The input-output method mainly relies on the Malmquist index to separate carbon emissions efficiency into pure technical efficiency, scale efficiency, and technological changes (Zhang et al., 2015; Jiang et al., 2020; Ma et al., 2021). The econometric regression model generally adopts the vector autoregression (VAR) (Zhou and Hong, 2018), Tobit (Cui and Li, 2015), wavelet analysis (Raza et al., 2019), and spatial econometric models (Yu et al., 2020; Zhao et al., 2022) to test the relationship between the influencing factors and carbon emissions efficiency. Among these models, the spatial econometric models can consider spatial effects and thus have gradually become the mainstream method to explore the factors affecting carbon emissions efficiency.

However, existing studies still have the following shortcomings. First, the spatial effect of TCEE in the existing literature is limited to the analysis of spatial-temporal pattern evolution and spatial correlation, which ignores the regional differences. According to previous studies, there are obvious differences in the development of regional transport industry in China (Xu and Lin, 2016; Xia, et al., 2018). First, previous studies mostly used qualitative methods to describe the difference distribution of regional TCEE, but did not conduct in-depth research on the source, degree and dynamic evolution law of the difference (Peng et al., 2020). Second, the TCEE is influenced by various factors, such as economic level, population density, transport mode, and energy structure (Shao and Wang, 2021; Zhao et al., 2022). However, due to the differences in transport infrastructure, economic levels, population distributions and technical competence among provinces, the leading factors affecting the TCEE in different provinces are unclear, which leads to different effects from the carbon reduction policies. The spatial econometric model can only measure the overall effect of the influencing factors on the TCEE, but it cannot identify the temporary and spatial differences. This leads to a lack of pertinence in the evaluation results, thus affecting the implementation of carbon emissions reduction policies.

In view of this, the SBM model was used to calculate the TCEE in China. The Dagum Gini coefficient model were used to study the spatial disequilibrium of TCEE. Subsequently, the GTWR model were used to measure the spatial-temporal differences in the influencing factors on the TCEE. We propose two major innovations in this study. First, this paper presents an in-depth analysis of TCEE's spatial disequilibrium, identifies the source of regional differences. Second, we use the GTWR model to determine the influencing factors of the TCEE, and verify the spatial and temporal differences of each influencing factor on the TCEE in China. The overall purpose of this study is to determine the impact mechanism of the TCEE, provide decision support for transport departments to formulate targeted emission reduction measures and aid the transport industry in rapidly achieving carbon neutrality.

TABLE 1 Descriptive statistics of the variables.

Variables	Obs	Mean	Std. Dev	Min	Max
Y	480	0.475	0.264	0.091	1
GDP	480	31,054.54	25,704.47	3,701	149,573.4
POP	480	4,442.248	2,670.915	534	11,346
IS	480	0.431	0.090	0.283	0.831
ES	480	0.709	0.189	0.159	1.028
TS	480	0.327	0186	0.006	0.716
TI	480	0.455	0.401	0.068	3.961
TP	480	0.128	0.024	0.011	0.210
TL	480	0.898	0.408	0.229	2.825

2 Materials and methods

2.1 Data

We use input-output data of transport industry from 2003 to 2018 for 30 mainland provinces in China (excluding Tibet). The data are obtained from the China Statistical Yearbook (2004–2019) and the China Energy Statistics Yearbook (2004–2019). Infrastructure, labor, capital, and energy consumption are selected as input indicators, the traffic added value are regarded as expected outputs, and carbon emissions of transport industry are regarded as unexpected outputs. Among them, the infrastructure is expressed in terms of total mileage of road, railway, waterway and pipeline transport network. The labor force is represented by employees in the transport industry. The capital stock of the transport industry is calculated using the perpetual inventory method (Li and Zhang, 2016). The data are converted to 2003 base period prices; the added value of the transport industry is also treated. Additionally, according to the conversion coefficient of standard coal, as published in the China Energy Statistics Yearbook, all types of energy are standardized and converted to calculate the energy consumption of the transport industry. Transport carbon emission data is calculated according to Liu et al. (2021).

For the influencing factors, We refer to the previous research (Heinold and Meisel, 2018; Kimbrough et al., 2018; Shao and Wang, 2021; Zhao et al., 2022), and finally selected 8 indicators such as economic level (*GDP*), population size (*POP*), industrial structure (*IS*), energy structure (*ES*), transport structure (*TS*), transport intensity (*TI*), transport price (*TP*), and technical level (*TL*) to explore the impact mechanism of transport carbon emission efficiency (Table 1). Before regression, we calculated the variance inflation factor (VIF) of each variable to prevent multicollinearity between the explanatory variables (Table 2). The results showed that the VIF values were all <5, indicating that no multicollinearity was present among the variables.

The following describes all of the variables used in this study.

Economic level. An improvement in the economic level leads to an increase in the transport demand and changes in residential travel modes. Economically developed provinces often have more advanced technologies, which can reduce CO_2 emissions and affect changes in the TCEE. In this study, the per capita GDP was selected as the index of regional economic development, with 2003 as the base period, to reduce the influence of price changes.

Population size. The impact of the population size on the TCEE is bidirectional (Zhao et al., 2022). The expansion of the population scale accelerates the spatial flow of people and goods between provinces, resulting in an increase in the transport demand, which in turn leads to an increase in energy consumption and CO_2 emissions and a decrease in the TCEE. Furthermore, an increase in the transport demand due to population expansion increases the economic output of the transport industry and improves the TCEE. We used the total population of a province to determine its population size.

Industrial structure. The optimisation of and upgrades to the industrial structure can promote regional economic growth, increase transport demand, and change transport intensity. Furthermore, the evolution of the industrial structure can change the energy consumption structure and transition economic development from relying on fossil fuels, such as coal and petroleum, to clean energy, which effectively reduces carbon emissions and improves the TCEE (Shao and Wang, 2021). In this study, the proportion of the tertiary industry was used to represent the industrial structure.

Energy structure. The impact of the energy structure on the TCEE mainly depends on the consumption ratio of diesel oil and gasoline. Owing to its high carbon emissions coefficient and maximum consumption, the higher the ratio of the energy structure, the lower the TCEE (Yuan et al., 2017). Therefore, the energy structure was expressed as the ratio of diesel and gasoline consumption to the total energy consumption of the transport industry.

Transport structure. Energy consumption mainly reflects the impact of the transport structure on the TCEE. As a “green” mode of transport, an increased proportion of railway and waterway transport use yields reduced energy consumption, which is conducive to improving the TCEE. Conversely, the higher the proportion of road transport, the lower the TCEE (Zhao et al., 2022). Based on the large proportion of current road

TABLE 2 Results of the multicollinearity test.

Variables	*GDP*	*POP*	*IS*	*ES*	*TS*	*TI*	*TP*	*TL*	Mean
VIF	2.61	1.43	2.89	2.25	1.26	1.21	1.23	1.25	1.77

transport in China, we used the ratio of road turnover and comprehensive turnover to measure the transport structure.

Transport intensity. Transport intensity can reflect the relationship between transport and economic development, which is usually expressed as the ratio of the transport turnover to the regional GDP. A lower transport intensity usually indicates a higher technical level of transport organisation and management (Shao and Wang, 2021); thus, the TCEE is higher. When calculating this index, passenger and freight volumes were converted into a comprehensive conversion turnover according to the conversion coefficient specified by the Chinese statistical system.

Transport price. The transport price significantly affects the transport demand and supply, which in turn affects the economic output of the transport system, leading to changes in the TCEE (Ma et al., 2021). The transport price variable was expressed as the per capita annual traffic and communication expenditure/per capita annual consumption expenditure of urban households.

Technical level. Advanced energy-saving technologies can effectively reduce CO_2 emissions. At the same time, an improvement in the technology level can reduce the production costs of an industry, promote economic growth, and form a cycle of economic growth and environmental improvement, thus improving the TCEE (Ma et al., 2021; Zhao et al., 2022). In this study, the reciprocal of the energy intensity was used to express the level of energy-saving technologies.

2.2 Methods

2.1.1 DEA model for TCEE calculation

The DEA model is the most popular method for measuring the carbon emissions efficiency (He et al., 2013; Park et al., 2016; Chu et al., 2021). Among the various DEA models (e.g., the CCR, BCC, and SBM, among others), the SBM model proposed by Tone (2001) considers unexpected output and reveals the influence of slack variables on the measured value. Therefore, we selected the SBM model to measure the TCEE with MaxDEA software. According to Tone (2001), the SBM formula is as follows:

$$\theta = min \frac{1 - \frac{1}{N}\sum_{n=1}^{N} s_n^x / x_{kn}^t}{1 + \frac{1}{M+I}\left(\sum_{m=1}^{M} \frac{s_m^y}{y_{km}^t} + \sum_{i=1}^{I} \frac{s_i^b}{y_{ki}^t}\right)} \quad (1)$$

where θ represents the value of TCEE, N, M, and I represent the number of inputs, expected outputs and unexpected output indicators, respectively. s_n^x and s_i^b denote the redundancy of inputs and unexpected outputs, respectively. s_m^y represents the insufficient expected output. x_{kn}^t, y_{km}^t, b_{ki}^t is the input-output value of the t period for the k DMU. Objective function θ on s_n^x, s_m^y, s_i^b is strictly monotone decreasing and $0< \theta \le 1$. When $\theta = 1$, $s_n^x = s_m^y = s_i^b = 0$, the DMU is indicated effective and there is no redundancy and deficiency of input-output. When $\theta < 1$, there is a loss of efficiency in the DMU; that is, the DEA is invalid and the comprehensive transportation efficiency needs to be improved by optimizing the input-output quantity (Ma et al., 2021).

2.1.2 Dagum Gini coefficient

The Dagum Gini coefficient is widely used by researchers because it decomposes the Gini coefficient into three parts, intra-regional difference contribution (G_w), inter-regional difference contribution (G_{nb}), and super-variable density contribution (G_t). It effectively compensates for the fact that the traditional Gini coefficient and Theil index cannot solve the overlap between samples and cannot reveal the source of the overall difference (Dagum, 1998; Sun and Zhu, 2020). The formula is as follows:

$$G = \sum_{j=1}^{k} \sum_{h=1}^{k} \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} \left| y_{ji} - y_{hr} \right| \Big/ 2n^2\mu \quad (2)$$

$$G_{jj} = \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} \left| y_{ji} - y_{jr} \right| \Big/ 2\bar{Y}_j n_j^2 \quad (3)$$

$$G_{jh} = \sum_{i=1}^{n_j} \sum_{r=1}^{n_k} \left| y_{ji} - y_{jr} \right| \Big/ n_j n_h \left(\bar{Y}_j + \bar{Y}_h\right) \quad (4)$$

$$G_w = \sum_{j=1}^{k} G_{jj} p_j s_j \quad (5)$$

$$G_{nb} = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh}\left(p_j s_h + p_h s_j\right) D_{jh} \quad (6)$$

$$G_t = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh}\left(p_j s_h + p_h s_j\right)\left(1 - D_{jh}\right) \quad (7)$$

$$p_j = \frac{n_j}{n}, \quad s_j = \frac{n_j \bar{Y}_j}{n\bar{Y}_j}, \quad j = 1, 2, 3, \cdots, k \quad (8)$$

$$D_{jh} = \frac{d_{jh} - p_{jh}}{d_{jh} + p_{jh}} \quad (9)$$

$$d_{jh} = \int_0^{\infty} dF_j(y) \int_0^{y} (y - x) dF_h(x) \quad (10)$$

$$p_{jh} = \int_0^{\infty} dF_h(y) \int_0^{y} (y - x) dF_j(x) \quad (11)$$

where G represents the total Gini coefficient, n represents the number of provinces, μ is the average value of TCEE in China, and k represents the number of regions divided. In this study, China was divided into three regions, east, central, and west, with $k = 3$. y_{ji} refers to the TCEE value of any province in region j, n_j refers to the number of provinces in region j, and y_{hr} and n_h have the same meanings as indicated previously herein. G_{jj} stands for the Gini coefficient in region j, and G_{jh} is the Gini coefficient between regions j and h. The G_w, G_{nb}, and G_t satisfy the following relationship: $G_w + G_{nb} + G_t = 1$. Among them, G_t represents the influence of the interaction item between intra-regional differences and inter-regional differences of TCEE in the three regions on the overall regional differences. D_{jh} indicates the degree of influence of the relative TCEE contribution rate between j and h regions, d_{jh} indicates the difference in TCEE contribution rates between regions, and p_{jh} is the first moment of over-variation. We use MATLAB software to realize the above calculation.

2.1.3 Geographically and temporally weighted regression model

Huang et al. (2010) added time information to the geographically weighted regression (GWR) model and proposed a GTWR model, which aims to solve the inability of the GWR model to process time data and analyse the time heterogeneity of the influencing factors. GWR model can both describe the relationship between the dependent and explanatory variables, and reflect spatial heterogeneity. By introducing the spatial position of the data into the regression coefficients, based on the estimated values of the regression coefficients at each geographical location, regional heterogeneity and spatial non-stationarity of the parameters can be explored (Guo et al., 2020; Liu et al., 2021). However, GWR model only considers the spatial position of the influencing variables and ignores the time parameters, and can not accurately explore the "spatio-temporal" nonstationarity. The GTWR model just makes up for this shortcoming (Rong et al., 2020). We using the spatial analysis tool in ArcGIS 10.2 software, the GTWR model is used to discuss the influencing factors of TCEE. The formula is as follows:

$$\boldsymbol{Y_i} = \boldsymbol{\beta}_0(\boldsymbol{\mu}_i, \boldsymbol{v}_i, \boldsymbol{t}_i) + \sum_{j=1}^{m} \boldsymbol{\beta}_k(\boldsymbol{\mu}_i, \boldsymbol{v}_i, \boldsymbol{t}_i)\boldsymbol{X}_{ij} + \boldsymbol{\varepsilon}_i \qquad (12)$$

where Y_i represents the TCEE in province i, X_{ij} represents the jth explanatory variable in province i, (μ_i,v_i,t_i) indicates the Mercator projection coordinates of province i in year t, β_0 is the intercept term coefficient, $\beta_k\ (\mu_i,v_i,t_i)$ is the estimated coefficient of the kth explanatory variable, and ε_i is a residual item.

The estimated coefficient of $\beta_k(\mu_i,v_i,t_i)$ can be expressed as follows:

$$\hat{\boldsymbol{\beta}}(\boldsymbol{\mu}_i, \boldsymbol{v}_i, \boldsymbol{t}_i) = \left[\boldsymbol{X}^T\boldsymbol{W}(\boldsymbol{\mu}_i, \boldsymbol{v}_i, \boldsymbol{t}_i)\boldsymbol{X}\right]^{-1}\boldsymbol{X}^T\boldsymbol{W}(\boldsymbol{\mu}_i, \boldsymbol{v}_i, \boldsymbol{t}_i)\boldsymbol{Y} \qquad (13)$$

where $\hat{\beta}(\mu_i, v_i, t_i)$ is the estimated coefficient, W is the weight matrix, X is the independent variable matrix, X^T is the transpose operation of matrix X, and Y is the dependent variable matrix.

3 Results

3.1 TCEE spatial and temporal evolution

Figure 1 shows the time-varying trends in carbon emissions and TCEE of China. The transport carbon emissions in all China's provinces have steadily increased, but the rate of increase has gradually decreased, among which the CO_2 emissions level are as follows: eastern > central > western. For the TCEE, the eastern, central, and western regions are all transitioned from high to low values; the efficiency value in the eastern region was always higher than the national average. For changes in the trend, the TCEE showed the same characteristics; before 2009, it fluctuated and declined, whereas after 2009, it increased, but the ranges were different. The central region had the largest decline in the TCEE, with a slow recovery. The eastern region ranked second but recovered the fastest. The western region had the smallest decline and a relatively stable recovery rate.

This is because there is a large gap between the development level of the economy and the transport network in various regions. Before 2009, eastern and central regions experienced rapid economic growth with a limited focus on environmental restoration, which led to a substantial increase in carbon emissions. In particular, when affected by emergency problems (such as the economic crisis in 2008), the prosperous eastern and central regions bear the brunt, resulting in a sharp decline in TCEE. However, compared to the central region, the eastern region has a large amount of financial support and technical support, and its resistance and recovery ability are stronger, which makes TCEE recover quickly after implementing environmental protection policies. As the western region is located in inland China, the level of economic development and completeness of the transport network is significantly less than those in the eastern and central regions. Emergencies have less of an effect on carbon emissions, thus showing the weakest fluctuations in the TCEE.

Figure 2 describes the spatial distribution patterns of the CO_2 emissions and TCEE in China. We divide the carbon emissions into 4 intervals with natural breakpoints, and they are represented by different colors. The darker the color, the more carbon emissions. Similarly, the TCEE is expressed by a histogram, and the larger the TCEE is, the higher the histogram is. The transport CO_2 emissions decreased from the east coast to the western interior. For the TCEE, the high-value provinces were mainly distributed in the Bohai Rim and Yangtze River Delta, whereas the efficiency values in the central and western regions and northeast China were lower. Specifically, only Tianjin, Shanghai, and Hebei had a TCEE of 1 from 2003 to 2018, indicating that the allocation of transport resources in these provinces had reached the optimal level. The other provinces must change the input-output ratio to improve their TCEE values. Among the non-effective provinces, those with an increasing TCEE were mainly distributed in the eastern regions, such as Beijing, Shandong, Jiangsu, and Guangdong, whereas the TCEE in the West, especially in Yunnan, Qinghai, Gansu, and Xinjiang, was always at its lowest level, indicating a significant spatial imbalance in the TCEE and large regional differences in the improvement potential across China.

3.2 Spatial imbalance of TCEE

To further reveal the TCEE regional difference level in China, we calculated the total, intra-regional, inter-regional, and source of difference in China from 2003 to 2018 using the Dagum Gini coefficient decomposition method. The results are listed in

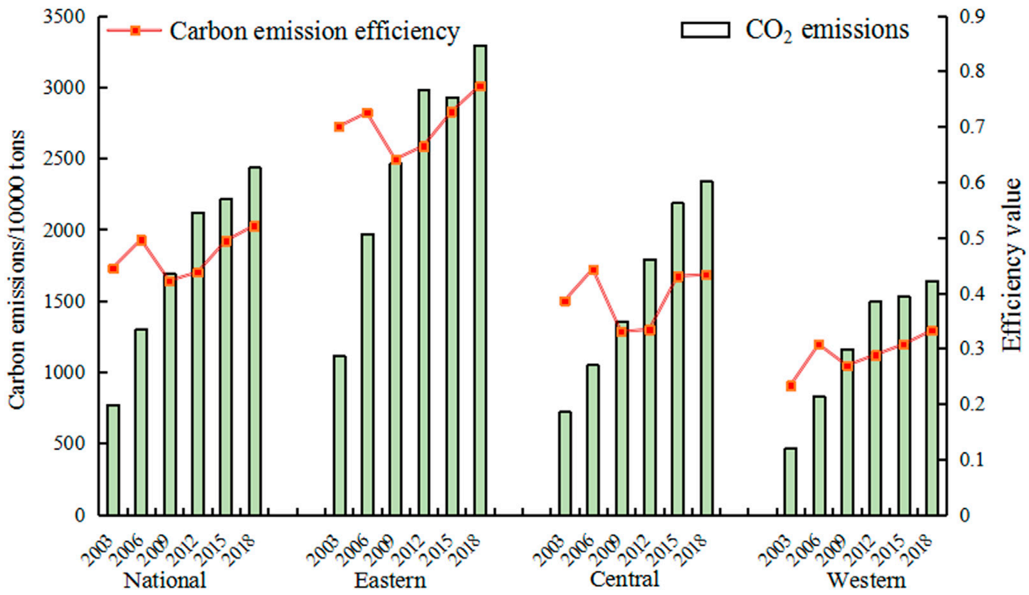

FIGURE 1
Trends in the carbon emissions and carbon emissions efficiency in the transport industry.

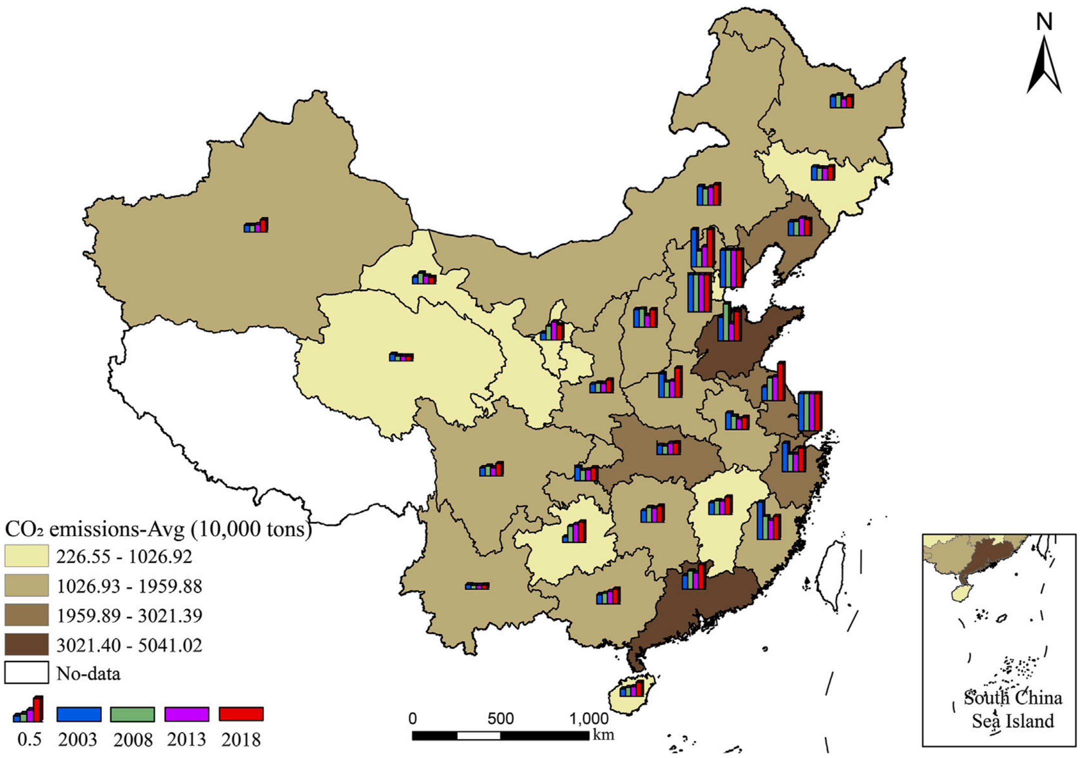

FIGURE 2
Distribution pattern of the carbon emissions and carbon emissions efficiency in the transport industry.

TABLE 3 Gini coefficient and decomposition of TCEE in China.

Year	G	Intra-regional gap			Inter-regional gap			Contribution rate		
		East	Central	West	East-Central	East-West	Central-West	G_w	G_{nb}	G_t
2003	0.296	0.273	0.291	0.319	0.301	0.308	0.285	0.334	0.172	0.494
2004	0.288	0.267	0.286	0.307	0.293	0.304	0.273	0.336	0.137	0.527
2005	0.303	0.281	0.293	0.326	0.315	0.321	0.290	0.335	0.214	0.451
2006	0.298	0.274	0.292	0.315	0.306	0.313	0.290	0.334	0.210	0.456
2007	0.300	0.276	0.295	0.315	0.307	0.314	0.294	0.334	0.208	0.458
2008	0.319	0.294	0.313	0.335	0.326	0.332	0.313	0.333	0.195	0.472
2009	0.325	0.294	0.322	0.342	0.333	0.339	0.324	0.332	0.205	0.463
2010	0.335	0.299	0.332	0.352	0.343	0.351	0.337	0.330	0.226	0.444
2011	0.340	0.298	0.344	0.356	0.352	0.355	0.344	0.328	0.220	0.452
2012	0.327	0.282	0.344	0.334	0.344	0.349	0.338	0.327	0.209	0.464
2013	0.321	0.301	0.330	0.319	0.334	0.345	0.327	0.336	0.156	0.508
2014	0.326	0.303	0.324	0.345	0.331	0.343	0.323	0.336	0.136	0.528
2015	0.315	0.284	0.321	0.341	0.324	0.343	0.306	0.336	0.164	0.500
2016	0.311	0.275	0.320	0.338	0.320	0.339	0.303	0.335	0.175	0.490
2017	0.304	0.257	0.316	0.338	0.321	0.336	0.296	0.330	0.170	0.500
2018	0.292	0.252	0.318	0.345	0.318	0.334	0.293	0.334	0.137	0.529
Mean	0.313	0.282	0.315	0.335	0.333	0.323	0.308	0.333	0.183	0.484

Table 3. In order to make the results more intuitive, we visualized the results (Figures. 3–6).

3.2.1 The total regional differences and evolution trends

As shown in Figure 3, the total regional differences of TCEE in China showed a rising trend first and then declined in fluctuation, and the Gini coefficient was between 0.288 and 0.340, with a large overall difference. From the evolution process, the total Gini coefficient in 2003–2004, 2005–2006, 2011–2013, and 2014–2018 showed a downward trend, and the total regional disparities in TCEE narrowed. In 2004–2005, 2006–2011, and 2013–2014, the total Gini coefficient showed an upward trend, and the total regional disparities in TCEE widened. Specifically, from 2003 to 2004, the total regional disparities of TCEE in China showed a downward trend, with the Gini coefficient dropping to the lowest level (0.288) in 2004, and then rising to the highest level (0.340) after a short decline in 2004–2011. After that, except for an increase in 2014, the total Gini coefficient showed a downward trend year-by-year. Since the 21st century, with the acceleration of China's market economy and the rapid growth of transport demand, China's transport industry has entered a booming period. However, due to the huge differences in geographical location, capital supply, and technical level, the gap in TCEE is widening. After 2011, China attached great importance to the green development of transport, accelerated the structural reform of the transport supply side, and optimized resource allocation. The TCEE of various regions increased significantly, and the regional differences gradually narrowed.

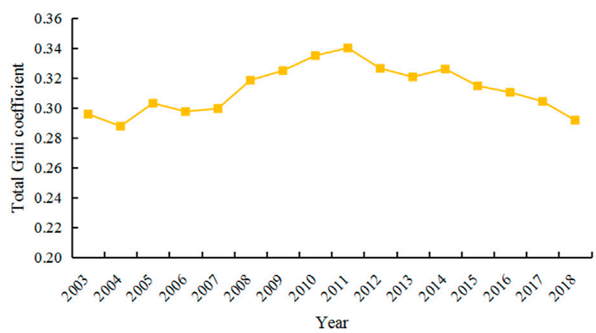

FIGURE 3
Total regional differences of TCEE in China.

3.2.2 Intra-regional differences and evolutionary trends

According to Figure 4, the evolution trend of the intra-regional Gini coefficient in China's TCEE, shows the following. First, on the whole, the regional differences in the three regions (eastern, central, and western) had the same trend before 2011, and the intra-regional Gini coefficient gradually increased in fluctuation. After 2011, the trends were different.

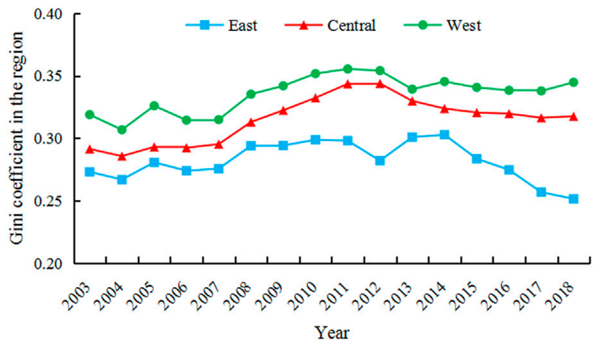

FIGURE 4
Intra-regional differences of TCEE in China.

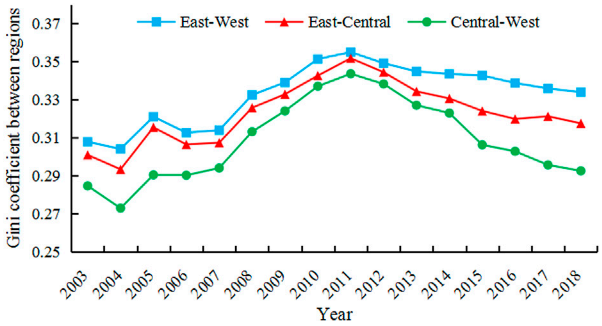

FIGURE 5
Inter-regional differences of TCEE in China.

After a short increase, the eastern region declined year-by-year, whereas the intra-regional Gini coefficient in the western region increased slowly in fluctuation, and in the central region was relatively stable. Second, the intra-regional differences of TCEE were the largest in the west and smallest in the east, which is the same as the research results of Zhang and Chen (2019). Owing to the advantages of location, capital, and technology, TCEE is generally higher in the eastern region, and it is closest to the frontier of technological production, resulting in the smallest intra-regional difference. Because the western region is an inland region, the passenger flow, logistics and capital flow are far lower than those in the eastern region, and the resource allocation level of each province is quite different, leading to the largest intra-regional difference in TCEE. Specifically, the Gini coefficient in western China ranged from 0.307 to 0.356, with an average of 0.335, which is always higher than that in eastern and central regions. The Gini coefficient in the central region ranges from 0.286 to 0.344, with an average value of 0.315, which is between the eastern and western regions. The Gini coefficient in the eastern region ranged from 0.267 to 0.303, with an average value of 0.282. The level of intra-regional differences was always lower than that in the central and western regions.

3.2.3 Inter-regional differences and evolutionary trends

Figure 5 shows the trend in inter-regional differences of TCEE from 2003 to 2018. First, the inter-regional Gini coefficient of TCEE fluctuations increased before 2011 but declined after 2011, which indicated that the inter-regional differences in the three regions showed a trend of expanding at first and then decreasing. Second, the inter-regional differences in east–central, east–west, and central–west regions fluctuated greatly from 2003 to 2005, dropping from 0.301, 0.308, and 0.285 in 2003 to 0.293, 0.304, and 0.273, in 2004, respectively, and then increased rapidly to 0.315, 0.321, and 0.290 in 2005. From 2005 to 2011, the inter-regional differences in the East–central, East–west, and central–west regions gradually increased to the highest point, which were 0.352, 0.355, and 0.344, respectively, and the relative fluctuation degree among them decreased. Third, from 2011 to 2018, the inter-regional differences in the east–central, east–west, and central–west regions all showed a downward trend. However, the speed of decline is different. The descending speed is the fastest in the central-west region, the second in the east-central region, and the lowest in the east-west region. Fourthly, the inter-regional differences in the central-west region have been at the lowest level throughout the study period, and the convergence rate is the fastest. The inter-regional differences between the east-west region are always at the highest level, and the convergence rate is the slowest, indicating that the regional differences in China's transport carbon emission efficiency have not been effectively changed.

3.2.4 Source and contribution rate of differences

Figure 6 shows the evolution trend of the regional difference contribution rate of the TCEE. Overall, the G_t was largest, the G_w was second, and the G_{nb} was smallest. Moreover, the distribution of the three were roughly symmetrical. With regard to the evolution trend, the G_{nb} and G_t have changed greatly, and the changing trend was opposite. The G_t increased in fluctuation, whereas the G_{nb} decreased slowly, and the changing trend of G_w was stable. Specifically, the evolution trend of G_t was approximately "W", rising from 49.4% in 2003 to 52.7% in 2004 and then decreasing to 45.1% in 2005 and remaining relatively stable, slowly rising to 52.8% in 2014, and then rising to the highest point of 52.9% in 2018 after a short decline. This was the main source of the total regional disparities in the TCEE. The evolution trend of G_{nb} was roughly "M," which was opposite to G_t. It decreased from 17.2% in 2003 to 13.7% in 2004 and then increased to 21.4% in 2005 and remained relatively stable, slowly decreasing to 13.6% in 2014. After a short increase, it fell to the lowest point of 13.2% in 2018. The G_{nb} contribution rate to the total regional differences in TCEE was always the lowest. The trend in

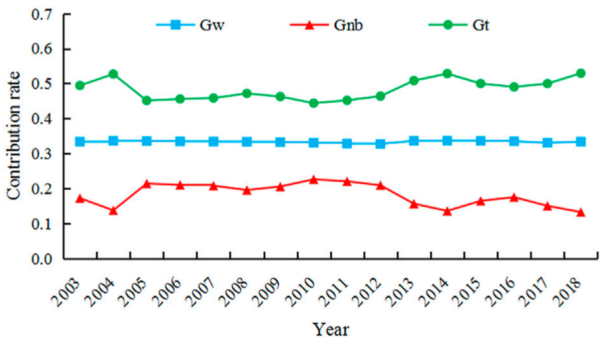

FIGURE 6
Contribution rate of regional differences in TCEE.

G_w was relatively stable, accounting for approximately 33% of the total study period, which was the second largest source of regional differences in TCEE. Although Gt had the highest contribution rate to the total Gini coefficient, G_t and G showed the opposite trend, indicating that it play inhibitory role in the growth of total regional differences. Combining Figures 3, 6, it can be seen that the total Gini coefficient showed a "W" growth trend from 2003 to 2011 and then fell to the lowest point in fluctuation, whereas the G_t fluctuated to its highest point in 2018 after experiencing an "M" changing trend from 2003 to 2010, which indicates that the G_t hindered the growth of the total Gini coefficient. As mentioned earlier, the G_t represents the influence of interaction between intra-regional and inter-regional differences in TCEE among the three regions on the total regional differences. The G_t was large, indicating that the cross-overlapping problem of transport industry in the eastern, central, and western regions of China is prominent, and thus, the main reason for the regional difference in TCEE is intra-regional differences.

3.3 Analysis of TCEE influencing factors

3.3.1 The temporal evolution characteristics of influencing factors

We used the GTWR model to discuss the spatial and temporal differences in the TCEE influencing factors. The results showed that the R^2 and adjusted R^2 values were 0.9264 and 0.9252, respectively, indicating that this model had a good fitting effect and strong interpretability.

Figure 7 shows the time variation in the regression coefficients of the various influencing factors. Figures 7A–H show the impact of economic level (GDP), population size (POP), industrial structure (IS), energy structure (ES), transport structure (TS),transport intensity (TI), transport price (TP), and technical level (TL) on transport carbon emission efficiency in year 2003 to 2018, respectively. From 2003 to 2018, the regression coefficient of the economic level was always positive (Figure 7A), indicating that the economic growth was beneficial to the TCEE. There was a downward trend and large range from 2003 to 2009, followed by a slow upward trend from 2009 to 2018, which conformed to the typical environmental Kuznets curve; its discrete state also changed with time. China's economy grew rapidly in the initial stages of this study, but the carbon emissions increased significantly at the expense of the environment, which led to a significant decline in the promotion of economic growth with respect to the TCEE. In the later stage of the study period, the government focused on improving the ecological environment, emphasised the importance of civil ecological construction in the production process, and achieved remarkable results, which led to a steady increase in the positive role that economic development had on the TCEE.

The regression coefficient for the population size showed a steady upward trend (Figure 7B); the sign of the coefficient also changed from negative to positive, showing that the increase in the population had a positive effect on improving the TCEE. As the world's most populous country, the "demographic dividend" has greatly promoted the growth of China's economy. With the advancement of urbanisation, the population's "quantitative dividend" has gradually changed to a "structural dividend," which has improved the resources allocation efficiency and further promoted improvements to the TCEE.

The impact of the industrial structure on the TCEE was approximately identical to that of the population size (Figure 7C). The regression coefficient increased yearly, and the sign changed from negative to positive, indicating that the development of the tertiary industry is conducive to improvements to the TCEE. The influence mechanism of the industrial structure on the TCEE mainly relied on reducing the energy intensity, improving the energy consumption structure, promoting economic growth, and significantly reducing CO_2 emissions. Therefore, optimising upgrades to industrial structures is an important means to improve the TCEE.

The regression coefficients of the energy and transport structures showed a slow downward trend (Figures 7D,E); the coefficients were negative throughout the entire study period, indicating that the energy and transport structures negatively impacted the TCEE with a gradually increasing degree of influence. With the growth of the economy, acceleration of urbanisation, and rapid increase in the number of motor vehicles, there has been a rapid increase in transport demand. The consumption of gasoline and diesel (primary fuels in the transport industry) has increased annually, accounting for approximately 70%, whereas electricity consumption in the transport industry accounts for <5%. Additionally, according to the Statistical Bulletin on the Development of the Transport Industry in 2020, road transport accounted for 71.3% of national

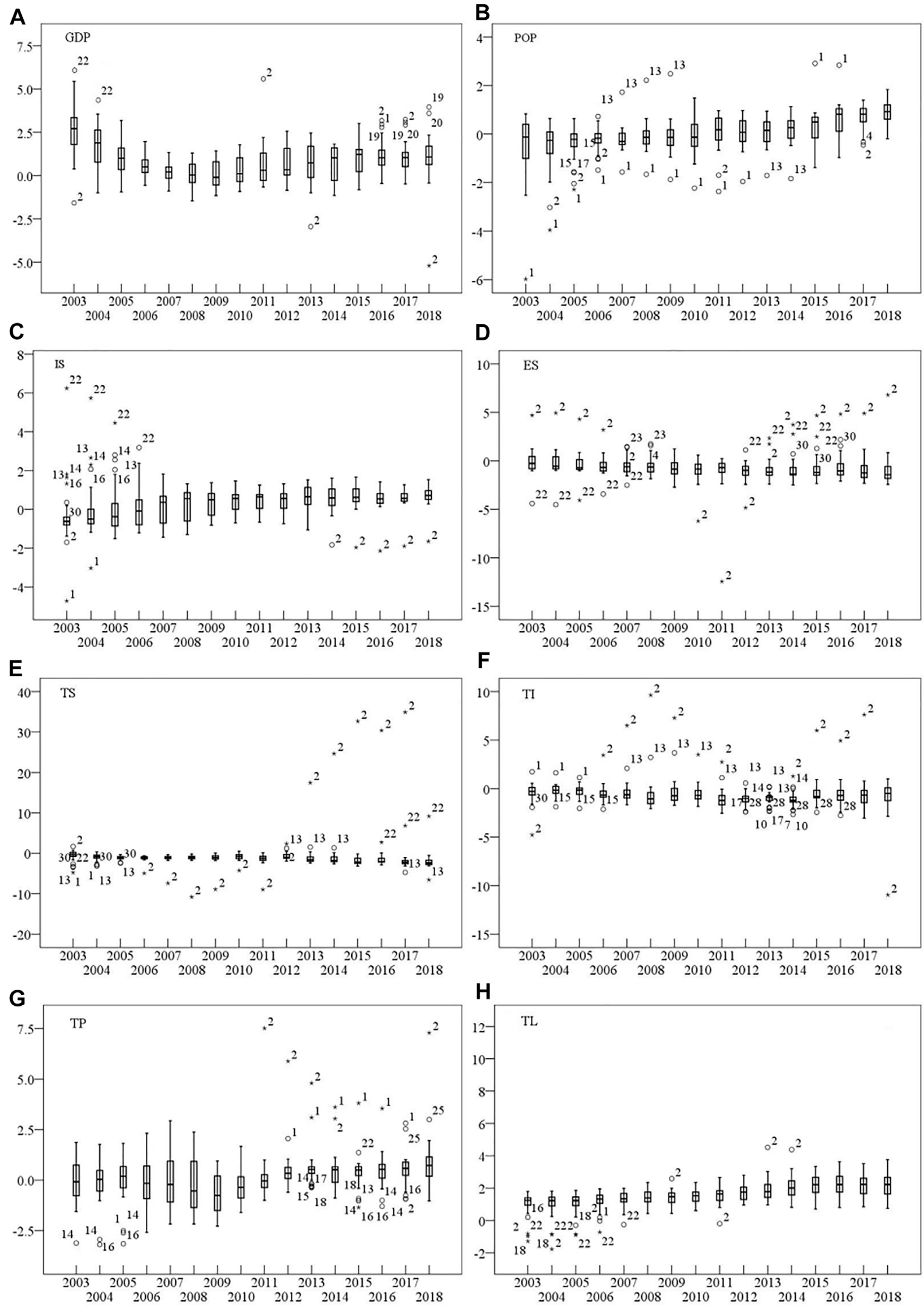

FIGURE 7
Time variation trends for the regression coefficients of the influencing factors.

passenger traffic and 73.8% of total freight traffic. Road transport mainly consumes fossil fuels, such as gasoline and diesel, while railway transport mainly consumes electricity; however, railway passenger traffic only accounts for 22.8% and a freight volume of <10%. Research has shown that high-speed rail, as a brand-new clean public transport mode, has changed people's travel mode and contributed to the development of low carbon transport (Jin et al., 2020; Yang J. et al., 2021). Therefore, these unreasonable energy and transport structures have led to a rapid increase in CO_2 emissions, which hinders improvements to the TCEE.

The regression coefficient of the transport intensity changed smoothly (Figure 7F), but the sign of the coefficient was negative, indicating that the transport intensity is not conducive to TCEE improvements. The transport intensity reflects the relationship between transport and economic growth. A reduction in the transport intensity indicates a reduction in turnover per unit GDP. Therefore, the transport intensity has a negative impact on the TCEE through economic growth; in other words, the transport intensity decreases while simultaneously improving the TCEE.

The regression coefficient of the transport price showed a fluctuating upward trend (Figure 7G); the sign of the coefficient also changed from negative to positive, indicating that the transport price had a negative impact on the TCEE in the early stages of the study period. In contrast, improvements to the transport price positively impacted the TCEE in the later stages of the study period. This is because China's economy grew rapidly during the initial stages of the study period; there was a rapid increase in the spatial transfer frequency and transport volume of people and goods. Price increases have partially reduced the spatial flow of transport services, which is not conducive to economic growth. With steady economic growth, all levels of government have focused heavily on environmental issues and implemented a series of transport carbon emissions reduction policies, including measures to adjust energy consumption and transport structures through price leverage, which have achieved remarkable results. Therefore, in the later stages of the study period, the transport price positively impacted the TCEE.

The regression coefficient of the technical level showed a steady upward trend (Figure 7H), with a large value and constantly positive sign throughout the study period, indicating that improvements to the technical level significantly promoted increases in the TCEE. Science and technology were the primary productivities. Technological progress can optimise the resources allocation efficiency at the input side and reduce production costs. Furthermore, technological progress can significantly promote economic growth and reduce bad output by reducing energy consumption. Therefore, improving the technology level can promote steady improvements to the TCEE.

3.3.2 Spatial differences of influencing factors

To observe the difference of each driving factor in spatial distribution more intuitively, this paper selects the average fitting result of each driving factor in each region for visualization (see Figure 8). Figure 8A shows that the economic level had a positive impact on the TCEE in all provinces, with coefficients ranging from 0.0394 to 1.2665, i.e., significant variations among all of the provinces. The provinces with high coefficients were mainly distributed in the northwest and southwest regions, such as Xinjiang, Inner Mongolia, Gansu, Ningxia, Hainan, Guangxi, and Yunnan, while the low coefficient regions were mainly in the eastern coastal provinces. This may have been due to the low TCEE in the western regions, which are far from the production frontier. Less economic output can produce greater marginal benefits, the TCEE in eastern developed regions located near the production frontier was generally higher. Compared with underdeveloped provinces, the same economic output had a more negligible effect on improving the TCEE.

The distribution range of the population size regression coefficient was −0.7419 to 0.9346. Figure 8B shows that positive areas were mainly distributed in the low-population density provinces in northeast, northwest, and southwest China, while negative provinces were concentrated in high-population density provinces in eastern and central China, such as Henan, Shandong, Beijing, Tianjin, and Shanghai. Influenced by the economic level, industrial agglomeration, policy support, and other factors, China's population and talent are concentrated in the eastern regions, which leads to insufficient developmental momentum in underdeveloped provinces, especially in northeast China, which has shown negative population growth. Therefore, increasing the population of these provinces can aid in promoting production, accelerating economic growth, and improving the TCEE. For central and eastern China, population expansion aggravates the contradiction between the transport supply and demand, resulting in serious congestion and environmental pollution. Therefore, population had a negative impact on the TCEE.

The coefficient of the tertiary industry ranged from −0.7562 to 1.6264; its spatial distribution pattern was opposite that of the population size (Figure 8C). Positive areas were concentrated in the central and eastern regions of China. The coefficients in north-eastern, north-western, and south-western China were generally small and negative in most provinces, especially in north-eastern and north-western China, where primary and secondary industries dominate economic development. In contrast, the tertiary industry accounted for a relatively small proportion, resulting in a weak driving effect on the economy. For the central and eastern regions, the proportion of the tertiary industry was relatively high, especially in Chongqing, Hainan, and other tourist cities. As the leading industry in terms of economic development, the expansion of the tertiary industry can attract more people, generate more

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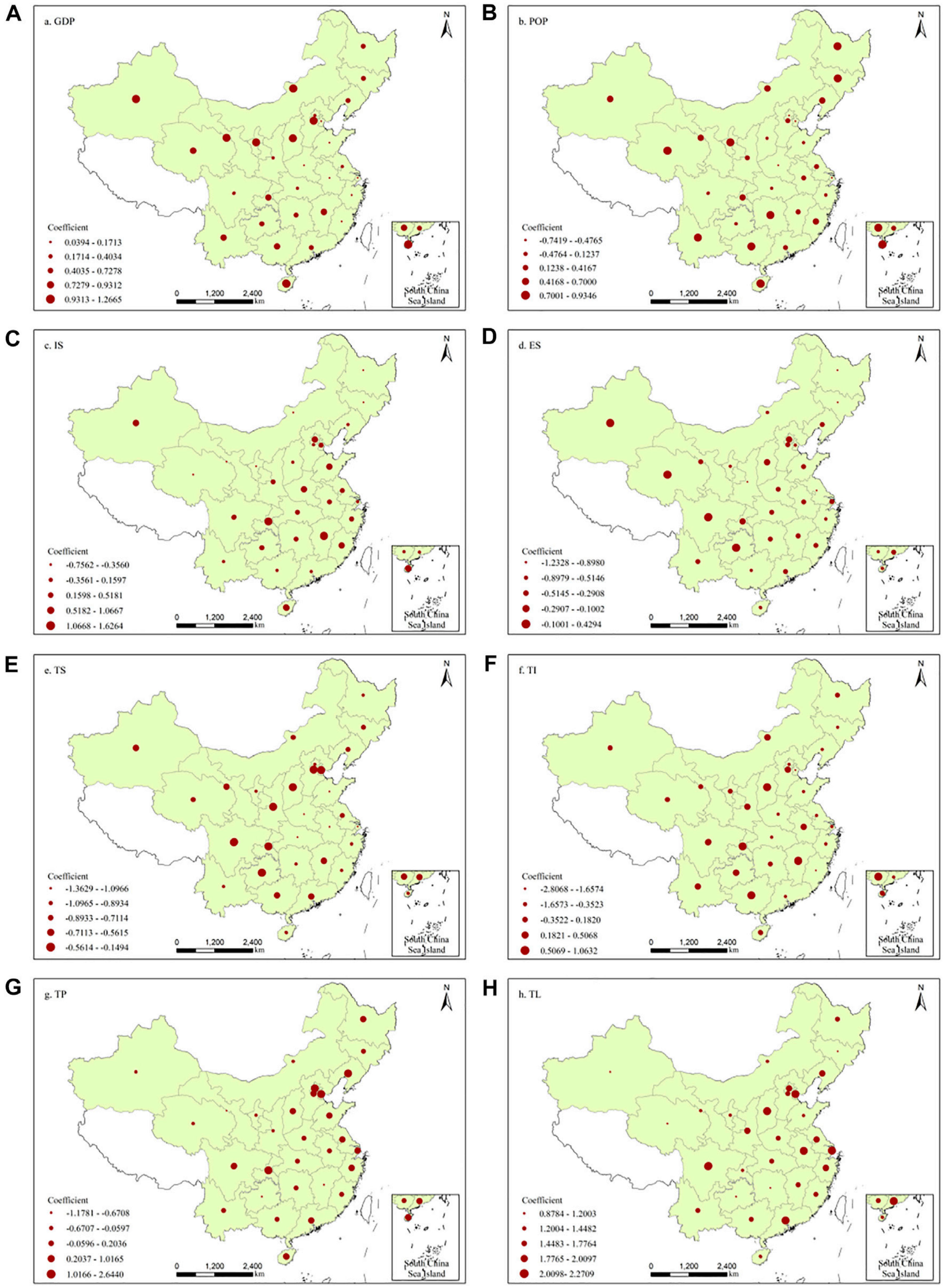

FIGURE 8
Spatial distribution characteristics of the coefficients for the influencing factors.

transport services, stimulate economic growth, and promote improvements to the TCEE.

Figure 8D shows the spatial distribution characteristics of the energy structure coefficient, it had a negative impact on the TCEE in most provinces, indicating that increases in gasoline and diesel consumption reduced the TCEE. In terms of the spatial distribution, positive areas were mainly distributed in western provinces, such as Xinjiang, Qinghai, Sichuan, and Guizhou, while provinces with larger absolute negative coefficient values mainly included Heilongjiang, Jilin, Inner Mongolia, and Shaanxi. There are more heavy industries in these provinces such that the fossil energy consumption is higher, resulting in higher carbon emissions. Therefore, the unreasonable energy structure has hindered improvements to the TCEE.

The impact of the transport structure on the TCEE in all regions was negative (Figure 8E). The provinces with higher absolute coefficient values were mainly distributed in the western, while the absolute coefficient values were generally smaller in the central and eastern provinces. This may be related to the more reasonable transport structure in the central and eastern provinces. Compared with the western provinces, the railway and waterway transport systems in the eastern and central provinces were more optimal. With capital and technology support, the eastern and central provinces are leaders in reforming the transport structure, such as expediting "road-to-waterway" and "road-to-railway" processes, developing smart cars, and promoting the use of clean energy. Owing to limitations associated with topography, capital, and technology, the transport services in the western provinces are still dominated by road transport, which leads to more substantial TCEE inhibition in the western provinces than that in the eastern and central regions.

The effect of the transport intensity on the TCEE varied significantly in different provinces (Figure 8F); the regression coefficients ranged between −2.8008 and 1.0632. From a spatial distribution perspective, the negative areas were concentrated in the eastern and central regions, while the positive areas were mainly confined to the western regions, showing notable gradient characteristics. The transport intensity reflects the degree of dependence that regional economic growth had on the transport services. The increase in the transport turnover not only yielded economic value but also increased carbon emissions. For the western region, the level of economic development was relatively low; economic growth depended more on increases in the transport volume. Increasing the transport turnover of the same unit can yield greater economic benefits in the western regions than that in the eastern and central regions. Therefore, the transport intensity promoted the TCEE in the west but inhibited it in the eastern and central regions.

The coefficients of the transport price variable ranged between −1.1781 and 2.6440 (Figure 8G). The positive areas were mostly distributed in the eastern coastal provinces; the coefficients were smaller or even negative for the inland provinces, showing notable ladder characteristics. The eastern provinces have developed transport and large-scale flow processes for people and goods, which has led to a series of transport problems, such as congestion and pollution. Raising transport prices could encourage people to favour public transport and clean transport modes, thus reducing congestion and pollution while promoting the TCEE. For the central and western provinces, the economic development level was lower than that of the eastern provinces; therefore, we must increase the spatial transfer of people and goods by reducing transport costs to drive economic development and promote improvements to the TCEE.

The coefficient of the technical level was between 0.8784 and 2.2709, showing that improvements to the technical level had a positive impact on the TCEE in all provinces (Figure 8H). The coefficient decreased from the south-eastern coast to the northwest inland, indicating that the influence of the technology level on the TCEE was the greatest in the east, followed by the central and western regions. According to Ma et al. (2021), improvements to transport efficiency in the central and eastern provinces is mainly a result of technological progress and improvements to the management level. In contrast, the western provinces mainly rely on production scale expansion, which supports the perspective of this study. Therefore, all provinces should increase their investments in science and technology, attach importance to the transformation of scientific research achievements, especially in the western provinces, and focus on undertaking technology spillovers in the eastern provinces. Technological progress can become a new driving force for TCEE growth by implementing these initiatives.

4 Discussion and conclusion

4.1 Discussion

Achieving the goal of "peak carbon emissions and carbon neutrality" is an important political initiative that faces China in the 21st century. As the third largest source of carbon emissions, the transport industry must make substantial strides to reduce their carbon emissions. Therefore, it is of great significance to measure the TCEE, explore the regional differences of transport carbon emissions in China, and identifying the influencing factors of carbon emission efficiency, so as to formulate differentiated transport carbon emission policies and promoting carbon emission reduction.

Our research shows that, although China's transport carbon emission efficiency has been improving in recent years, the overall level is low (only 0.475), which is mainly due to the uncoordinated development of various transportation modes and the lack of horizontal connection between them. Moreover, the sharing rate of road transport is much higher than that of railway and water transport, which leads to unreasonable resource allocation, sharp increase in energy consumption and carbon emissions, and huge waste of transportation system investment. In addition, there are significant regional differences in carbon emission efficiency of transport, and the root of this difference lies in intra-regional differences. Many factors, such as economy, population distribution, scientific and technological level, etc., lead to the unbalanced development of the transportation in various provinces. Reducing the carbon emission from transportation and improving the efficiency of carbon emission are the hot spots of all countries in the world. Future improvements to China's TCEE should focus on the following aspects:

Industrial structure optimisation and economic growth promotion. First, we must construct an institutional system conducive to upgrading the regional industrial structure. In contrast, for provinces with a large proportion of secondary industries, we must avoid the tendency of "de-industrialisation," optimise the industrial structure, and actively promote industrial transformation and high-quality development. Furthermore, creating differentiated population policies is necessary. For provinces with a low population density and serious population loss in north-eastern and western China, the government should encourage childbearing, formulate preferential settlement policies, and attract people and talent to drive economic growth and improve the TCEE.

Changes in the energy and transport structures and improvements to the energy efficiency. Highway transport consumes a large amount of fossil energy and generates a lot of carbon emissions, which seriously hinders the promotion of TCEE. On the one hand, the government should vigorously develop new energy vehicles, such as those using pure electric power, hybrid power and hydrogen energy, to reduce the consumption of fossil fuels such as gasoline and diesel. On the other hand, vigorously promote the transformation from road to water and rail transport, and adopt new transport organization methods such as multimodal transport to promote container transport and reduce transport intensity, in order to optimize the energy and transport structure, and improve TCEE.

Establishment of a rational pricing system. In terms of freight transport, the government should reduce the price of railway and waterway transport and encourage a transition from roads to railways and waterways for the long-distance transport of bulk goods. In terms of passenger transport, the government should reduce the cost of public transport, improve the service quality of public transport, encourage citizens to choose public transport and clean energy vehicles, and reduce energy consumption through policy and price leverage.

Increased investment in science and technology and technical upgrades. First, increase support for scientific and technological research, and upgrade the regional scientific and technological level. In contrast, strengthening the exchange and cooperation of talent, capital, and technology between provinces; giving full recognition to the leading roles of developed provinces, such as the BR (Bohai Rim), YRD (Yangtze River Delta), and PRD (Pearl River Delta) in western and north-eastern China; promoting the overflow of new technologies, methods, and knowledge; reducing regional differences; and realising overall improvements to the TCEE are all necessary.

I have to say, there are still some shortcomings in this article. Considering the availability and convenience of the data, all the data in this paper come from the National Bureau of Statistics, and the calculation results are rough. In the future, the completeness and accuracy of the data need further refinement. In addition, this paper takes the provincial units as the research object, and the research scale is large, lacking the first-hand data verification support. In the future, it is necessary to refine the grain size, take prefecture-level cities as evaluation units, and conduct specific case analysis based on actual investigation or monitoring data to evaluate China's transport carbon emission efficiency, so as to improve the scientificity and credibility of the research results.

4.2 Conclusion

The transport carbon emissions in China showed an upward trend with a decreasing growth rate. The TCEE first showed a decreasing and then increasing trend, but was characterised by an overall low level. The spatial distribution characteristics of the CO_2 emissions and TCEE had the following distribution across the provinces: eastern > central > western, with significant regional differences.

The total regional differences of TCEE in China are quite large. The intra-regional differences is greatest in the western, then in the central, and next the eastern. The inter-regional differences in the eastern–western regions were determined to be the largest, followed by the eastern–central regions, and the smallest in the central–western regions. Intra-regional differences are the main source of regional differences in TCEE.

The estimated results for the GTWR model confirmed that the influencing factors of the TCEE had notable spatial differences and changed over time. Generally, the economic level and technological progress played a significant role in promoting the TCEE in all provinces while the energy and transport structures played a significant role in its inhibition.

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

Methodology, PJ; software and validation, QM; formal analysis, QM; writing—original draft preparation, QM; writing—review and editing, PJ and HK; visualization, QM; supervision, PJ and HK. funding acquisition, PJ and HK. 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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Does the growth of the digital economy boost the efficiency of synergistic carbon-haze governance? evidence from China

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As global urbanization continues to accelerate, so does the amount of harm to the natural ecological environment caused by excessive resource extraction. In several Chinese cities, haze and excessive greenhouse gas emissions have become crucial to the development of an ecological society. To break the previous energy-intensive development model, the data element has emerged as a key driver of the new cycle of high-quality development. Therefore, additional investigation into the synergistic influence of the digital economy as a new factor on air pollution and CO_2 emissions is warranted. This study examines the effects, spatial effects, and transmission mechanisms of the digital economy on the synergistic control of carbon and haze using panel data from 30 provinces in China from 2013 to 2019. The study concludes that the digital economy has an overall significant inhibiting effect on carbon dioxide emissions and haze pollution levels (the regression coefficients are -1.090 and -0.714 respectively), a significant driving effect on the efficiency of synergistic carbon and haze management, a spatial spillover effect, and a positive effect on neighboring regions (the regression coefficient is more than 0.239). By region, the digital economy in the eastern region has a greater impact on the effectiveness of carbon and haze management, whereas the digital economy in the western region has a greater impact on CO2 emission reduction, and the digital economy in the central region has an effect that is more consistent with the overall situation. Moreover, the digital economy may successfully encourage technical innovation, which in turn supports synergistic carbon and haze governance, and technological innovation plays a very important mediating role in this transmission mechanism, a finding that is resilient to geographical interaction effects. Consequently, relevant policy recommendations are presented.

KEYWORDS
digital economy, synergistic carbon-haze governance, spatial spillover effect, mediating effect, CO2

1 Introduction

China has started to pay attention to energy conservation and environmental preservation since the reform and opening up, particularly in the 1990s, but for a long time, economic growth still followed a primitive development model with high energy consumption and high emissions. Environmental pollution levels and CO_2 emissions peaked in the first decade of the twenty-first century (Figure 1), and in 2007, China surpassed the United States as the world's top carbon emitter (Liu, Z. et al., 2022). This was the result of a decade of strong economic expansion and increased industrialization. However, since 2013, different parts of the nation have faced differing levels of haze pollution (Figure 2), with $PM_{2.5}$ concentrations in some places surpassing 1,000 micrograms per cubic meter, more than 40 times the permissible limit[1]. The Chinese government, at all levels, has implemented a number of initiatives to "tackle the haze with an iron fist," including the adoption of the world's strictest ultralow emission limits for flue gases and the widespread use of "coal-to-gas" (Xu and Ge, 2020) and "coal-to-electricity" (Xu et al., 2020). Particulate matter (PM) and sulfur dioxide (SO_2) emissions, two of the three common air pollutants currently under control, have decreased by more than 80% from their pre-2014 peaks, while nitrogen oxide (NO_x) emissions have decreased by 30% from their peaks. Indicators show that conventional pollutants have been reduced, but actual haze control is far less successful than anticipated. To maintain a particular level of air quality in the autumn and winter, the northern regions had to rely on extensive work stops and output limitations. Haze still appeared frequently, though. Widespread and protracted severe haze pollution was nevertheless inevitable in some locations, especially during the new coronavirus epidemic's first emergence in early 2020, when the Chinese economy was nearly at a stop, seriously harming public health and the quality of economic growth (Huang et al., 2020), and even endangering lives (Han, C. et al., 2022).

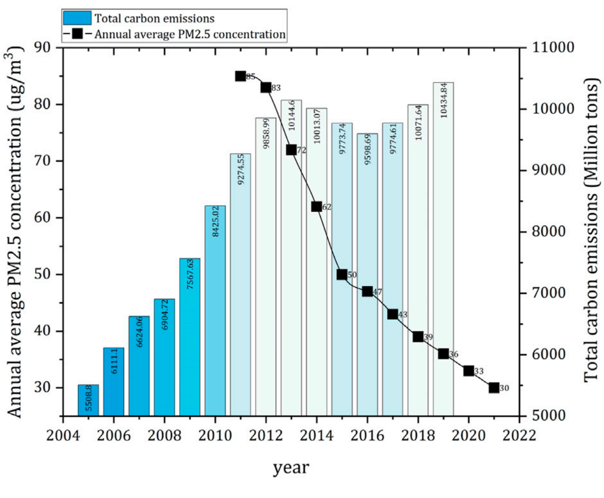

FIGURE 1
The total carbon emissions and average annual haze concentration of China[2]

At this stage, the concept of green, low-carbon and sustainable development has become a mainstream trend in the world's economic development, and the digital economy is an economic activity that uses data as a factor of production, using data computing, data sharing and other means[3]. It can efficiently increase social production efficiency and optimize the economic and industrial structure of the economy, acting as a major force behind the transformation of the traditional model of economic development and the advancement of the creation of an ecological civilization. Information components can now play an innovative role in the value chain because of the digital economy's use of information technology to integrate and deploy resources to increase production efficiency (Miao, 2021). It is specifically suggested to encourage the integration of digitalization, intelligence, and greening in the industrial sector in the State Council's "Action Plan to Reach the Carbon Peak by 2030." A crucial step towards attaining carbon peaking and carbon neutrality (Liu, Z. et al., 2022) and fostering high-quality economic development is the deep integration of the digital economy and green development. However, few studies have been conducted on the digital economy and environmental pollution management, with most of the previous studies ranging from economic growth (Xiong and Xu, 2021), foreign investment (Xu et al., 2019),

1 In 2005, the WHO air quality guidelines set a safe $PM_{2.5}$ concentration of 10 micrograms per cubic meter, with a reduction to 5 micrograms per cubic meter by 2021.

2 Annual average haze concentrations in China only became publicly available after 2013.

3 There is still disagreement in the current academic community on the definition of the digital economy, and this study builds on the existing foundation by referring to China's National Bureau of Statistics, "Statistical Classification of the Digital Economy and its Core Industries (2021)" (China's National Bureau of Statistics, 2021. (China's National Bureau of Statistics, 2021. http://www.stats.gov.cn/tjgz/tzgb/202106/t20210603_1818129.html. Accessed 21 June 2022), OECD, 2014. Measuring the Digital Economy: A New Perspective, Pan et al., 2022. Digital economy: An innovation driver for total factor productivity. Journal of Business Research 139, 303–311. and Zhang W et al., 2022. Digital economy and carbon emission performance: Evidence at China's city level. Energy Policy 165, 112,927. The digital economy refers to a series of economic activities that use data resources as a key production factor, modern information networks as an important carrier, and the effective use of information and communication technology as an important driving force for efficiency improvement and economic structure optimization, mainly including digital development, digital innovation and digital application.

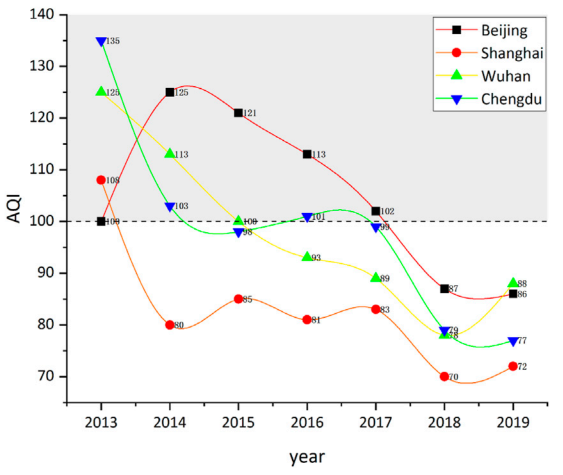

FIGURE 2
The changes in Chinese Air quality Index of Four typical cities from 2013 to 2019.

industrial structure (Su et al., 2021; Liu Y et al., 2022), environmental regulation (Wang et al., 2022) He, 2015), industrial agglomeration (Zeng and Zhao, 2009; Dong et al., 2020), technological innovation (Wang and Luo, 2020; Ding et al., 2022; Li et al., 2022), and other perspectives on the causes of environmental pollution and the paths of pollution abatement.

Therefore, this study constructs a spatial panel regression model using interprovincial panel data in China from 2013–2019 to measure the impact of the digital economy on the efficiency of synergistic carbon and haze management. It also examines whether technological innovation plays a mediating role between the two and better identifies the impact effect of the digital economy on atmospheric environmental management. The main innovation points are as follows. 1) Based on the perspective of atmospheric pollution, this study provides empirical evidence from China to study the pathway of synergistic management of the digital economy and carbon-haze, and enriches the research on the relationship between the digital economy and environmental pollution. 2) An input–output model is used to evaluate the efficiency of regional carbon and haze management, taking into account the differences in economic development between the eastern, central and western regions, to examine the effects of the digital economy on the management of two major pollutants, carbon dioxide and haze pollution, and to identify the similarities and differences in the effects of the digital economy on both, providing a feasible method for measuring the efficiency of environmental management, especially air pollution management. 3) To comprehensively reflect the true development of China's digital economy at the provincial level, this paper constructs a comprehensive digital economy index evaluation system for Chinese cities from three aspects: the level of information infrastructure construction, the level of digital industrialization and the level of industrial digitization. 4) To improve the study of the transmission mechanism of the digital economy on the synergistic management of carbon-haze and to verify the mediating effect of the mechanism of technological innovation between the two in consideration of spatial interaction.

The rest of this paper is arranged as follows: Section 2 details the literature review. Section 3 presents the theoretical analysis and research hypothesis. Section 4 introduces the model construction, election and setting of variables, and data sources. Section 5 presents the spatial agglomeration characteristics of air pollution, the benchmark regression results, and the transmission mechanism. A robustness test is presented in Section 6. Section 7 summarizes the main research conclusions and discusses policy enlightenment. Figure 3 illustrates the digital economy the graphical abstract of this research. The abbreviations and terms used in the text are in Supplementary Appendix SA, while the models and equations involved are in Supplementary Appendix SB.

2 Literature review

In terms of sectors related to the digital economy, Chen and Yan (2020) explored the impact and working mechanism of e-commerce development on SO_2 air pollution prevention and control in Chinese cities and found that compared to e-commerce services, e-commerce development can significantly reduce the level of SO_2 air pollution in Chinese cities and contribute more significantly to the reduction of SO_2 emissions per unit of GDP. Cao et al. (2021) used the Multiperiod Difference-in-Difference method to examine the impact of the National E-commerce Demonstration Cities (NEDC) pilot on green total factor productivity (GTFP) and found that the cities' GTFP increased by an average of 1.24% after the NEDC policy shock. The average increase in GTFP after the NEDC policy shock was 1.24%, which was more effective for western and resource-based cities, providing new evidence on the relationship between e-commerce and green development. Yang et al. (2021b) verified that there is an inverted U-shaped curve relationship between the development of the Internet industry and haze pollution in China and that haze pollution can be curbed through technological innovation in communication.

In fact, the ICT (information and communication technology) industry, the predecessor of the digital economy, has been studied in relation to the effects of environmental governance for much longer. Toffel and Horvath (2004) make a distinction between the two-way effects of ICT development on energy consumption. On the one hand, ICT development makes it possible to replace the capital-driven model with a drive to replace the costs of traditional trading, production and distribution processes, increasing the efficiency of energy and

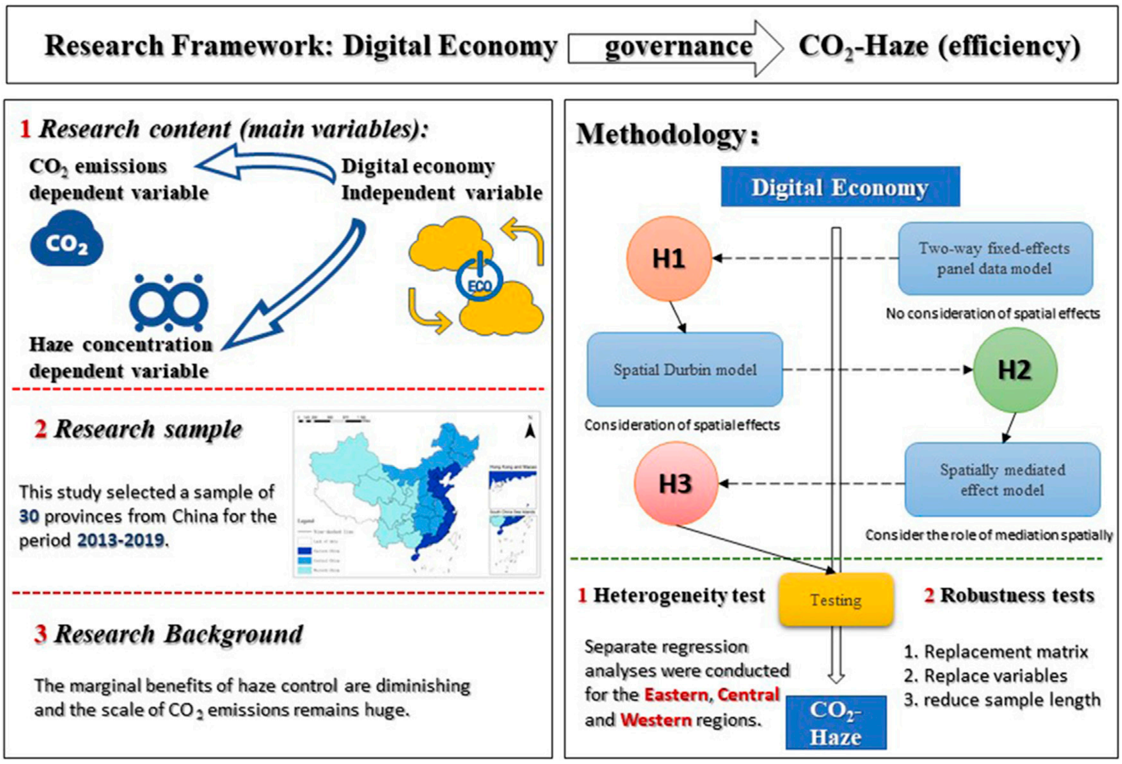

FIGURE 3
The digital economy and the synergistic management of carbon-haze.

reducing the intensity of energy consumption. On the other hand, the increased efficiency of distribution stimulates market consumption demand, which in turn can lead to a sudden increase in energy consumption and exacerbate environmental pollution. There has been a great deal of debate around this idea, with some scholars arguing that ICT can improve the efficiency of companies in organizing production management, making production planning better and thus avoiding wasted energy. In addition, ICT itself is characterized by technological advances that can effectively eliminate redundancies in the production process and increase output efficiency (Moyer and Hughes, 2012). ICT at scale can drive changes in manufacturers' production automation, reducing production costs and improving energy efficiency. In contrast, other scholars have argued that in addition to the increased energy consumption associated with the expansion of consumption, the development of the ICT sector requires a large amount of energy to keep it functioning and that the electricity consumption-driven nature of China's economic development has become more pronounced as the ICT sector continues to grow (Peng, 2013), a finding that also holds true in emerging market economies and developed regions such as the United Kingdom, United States and Korea (Sadorsky, 2012; Kim and Heo, 2014). This also suggests that while the ICT sector can drive technological advances in production through factor substitution, it can also trigger new consumption growth and generate significant energy rebound effects.

At the same time, the issue of global warming caused by greenhouse gases has received widespread and sustained attention. The factors contributing to excessive CO_2 emissions are complex and involve urbanization (Zhao and Wang, 2022), industrial production, human life and even transportation, with the burning of fossil fuels for electricity generation being the most important influence (Xu et al., 2017). It is generally accepted that the main way to control carbon emissions from industrial electricity use is to reduce the use of fossil fuels or to seek new alternative energy sources (Minx et al., 2011). Thus, increasing the efficiency of existing energy use or improving production technologies can, to some extent, mitigate or curb the increase in the greenhouse effect (Lorenzoni et al., 2007). However, there is a certain path dependency for the production technology factor, and the tendency of manufacturers to make technological progress is implicit (Acemoglu et al., 2012). In the absence of external constraints, technological progress can in turn increase CO_2 emissions (Jaffe et al., 2002). Thus, the digital economy, as a development model with innovative technologies, has a similar dual effect on CO_2 emissions.

Finally, a large number of studies have been conducted on the synergistic reduction of air pollutants and carbon dioxide. Qian et al. (2021) constructed a data set of over 170,000 observations and used a scenario simulation approach to reveal the huge potential for synergistic air pollutant and CO_2 emission reduction in China's industrial sector from the perspective of microenterprises and suggested that continuous improvement of energy efficiency, rationalization and restructuring of production in the existing industrial sector, accelerated electrification and vigorous development of non-fossil energy generation are important ways to achieve synergistic emission reduction benefits. Yang et al. (2022) used a pilot policy-oriented approach to empirically analyse the impact of haze pollution in the pilot provinces of the Emissions Trading System (ETS) and its surrounding provinces by using the difference-in-difference (DID) and propensity score matching-DID (PSM-DID) methods based on data from 2000 to 2017 from 31 provinces in mainland China. They found that the ETS in the pilot areas could alleviate regional haze pollution and achieve a win–win situation of controlling haze pollution and promoting CO_2 emission reduction. In provinces adjacent to the pilot areas, it played a spillover effect, but the impact on $PM_{2.5}$ concentrations was weaker than in the pilot areas, and there was a lag period. Zhang Q-Y. et al. (2022) argue that most studies have focused on the best measures or pathways for co-control, but there is a lack of studies that have assessed multiple cities comparatively. Only Li et al. (2020) analysed the co-control performance of Chinese cities in terms of the spatial distribution of CO_2 and $PM_{2.5}$ concentrations.

In conclusion, most studies have only explored the digital economy and environmental governance from one aspect or discussed the path of synergistic management of CO_2 emissions and haze, without exploring the synergistic management of CO_2 and haze from the perspective of the digital economy. This paper will focus on the construction of an evaluation index system for the digital economy, study the spatial effects of the digital economy and synergistic carbon-haze governance, and propose pathways for the synergistic governance of carbon and haze.

3 Theoretical analysis and research hypothesis

A review of the above literature reveals that the effect of the digital economy on environmental pollution is uncertain, and the relationship between economic development and the governance of haze and carbon emissions is inconclusive. However, some studies suggest that the development of the digital economy can play a role in the synergistic management of CO_2 and haze. Unfortunately, relatively little literature has been published on the transmission pathways of this effect, and the underlying mechanisms of the digital economy's influence on the synergistic management of CO_2 and haze have not been systematically clarified. This paper therefore discusses this mechanism based on the questions raised above and proposes the following research hypothesis.

First, the digital economy runs on Internet technology, and data, as its main production factor, have fewer negative effects on the ecological environment in the process of circulation, exchange and storage, and the output side does not cause direct pollution to the environment. Compared to traditional industrial manufacturing, it has strong technological attributes and a green production model (Zhou et al., 2021). Again, the relatively high threshold of the digital economy industry means that digital enterprises need to meet the conditions of diversified business capabilities, mature structure and management, and focus on sustainable development. To enhance the visibility of enterprises and form positive social demonstration effects, policy makers will pay more attention to public opinion monitoring, to ecological and environmental benefits, and to optimize the industrial structure of enterprises when developing enterprises (Li, X. et al., 2021). The digital economy will bring a new round of production innovation driven by technological innovation. To improve factor productivity, enterprises will strengthen technological information cross-collaboration and cooperation through industrial digitization and mobile internet, ensure that the production behavior of enterprises is consistent with the objectives of digital governance, use digital technology to combine enterprise resources to achieve technological innovation and improve the digital level of enterprises, thus improving the efficiency of factor use and reducing unnecessary. This will improve the efficiency of factor use and reduce unnecessary resource loss, thus laying the consciousness and material foundation for the transformation of production methods to scale and green in the future (Liu, Y. et al., 2022). To break the dilemma of private data and fragmented information between departments, cutting-edge technologies such as big data, blockchain and cloud computing will be further promoted and applied in the dynamic environmental monitoring system, accelerating the transparency of data resources with the help of the Internet platform, enhancing the data collection capacity of government departments, improving the accuracy of data analysis and prediction, and improving the environmental monitoring system. This will enable the government to introduce reasonable control measures to regulate the green production of manufacturers (Su et al., 2021). Based on the above analysis, Hypothesis 1 is proposed.

H1: Digital economy development has a positive spatial effect on the efficiency of synergistic CO_2 and haze management.

Second, urban agglomerations, as the main strategic form in the current evolution of China's urbanization, have led to economic exchanges between localities and neighboring cities, promoting cooperation and coordinated development between various types of cities. However, there are still problems with the uneven distribution of resources and regional economic differentiation among cities. In addition, waste pollutants from factories and enterprises located in the upper reaches of cities may cause additional pollution in the downstream areas along rivers, while air pollution caused by factories and enterprises located at the edges of cities may easily lead to cross-border cross-pollution along with atmospheric dispersion, resulting in the spatial aggregation effect of environmental pollution and leading to an increase in government pollution. The spatial agglomeration effect of environmental pollution has led to increased costs and pressure on governments to control pollution (Li, Z. et al., 2021; Sun et al., 2021). The rise of the digital economy, with its fast, convenient and highly permeable characteristics, has broken the traditional geographical boundaries and transcended spatial and temporal limitations, with the Internet as its main information transmission tool, linking regions together and making the exchange, collection and processing of information more convenient, open and transparent (Li and Liu, 2021). Furthermore, because the production activities of enterprises are closely related to the level of their own production technology, for example, resource-based enterprises, which mainly consume natural resources, cause far more damage to the environment than green enterprises, and thanks to the convenience of the economic model, the digital economy can play a role in promoting the exchange and promotion of green manufacturing technology among enterprises, enhancing the efficiency of enterprise learning, and urging enterprises to monitor each other. It also helps to reduce the average amount of emissions and the cost of managing polluting waste (Han C et al., 2022). Once again, the reusability and non-zero sum nature of the data itself lead to a minimal marginal cost of natural resources consumed in the process of acquisition and exchange, and its low-input, high-yield nature perfectly suits the current government's requirements for green development. This will accelerate cross-regional cooperation and the outreach of the digital economy, which is conducive to improving regional collaborative governance policies and enhancing environmental quality (Wang et al., 2021). Based on the above analysis, hypothesis 2 is proposed.

H2: The digital economy can promote the efficiency of synergistic carbon-haze management in neighboring regions through spatial spillover effects.

Third, the literatures have pointed out that the development of the digital economy can significantly promote technological innovation, leading to changes in production models. In the context of the digital economy era, the emergence of new technologies such as big data, blockchain, cloud computing and artificial intelligence has accelerated the high-speed flow of technological information between enterprises, stimulating them to constantly learn to imitate new technologies and actively use the latest advanced intelligent equipment to optimize their production processes to maximize the use of natural resources, reduce waste per unit of production, provide a competitive advantage in the marketplace, and help reduce the amount of polluting waste and final emissions generated during the production process (Li et al., 2022). For example, enterprises will combine new digital technologies with traditional industrial and manufacturing industries to analyse whether there is avoidable waste of resources or excessive emissions in the last round of production by looking at the various types of data collected during the production process, seeking the most rational allocation of resources and optimizing the efficiency of the combination of production factors (Meng and Wang, 2021; Ding et al., 2022). In addition, the digitalization of industries can contribute to the change of traditional production models and the optimization of industrial structures, gradually transforming resource-intensive enterprises into knowledge- and technology-intensive ones while fostering new industries, new business models and new economic growth points. The digital economy, as a new development model, can provide a driving force for economic development and industrial upgrading. The establishment of an information technology sharing mechanism through blockchain attracts corporate investment and accelerates the integration of enterprises with the ecosystem, with economic benefits as the core and environmental benefits as a supplement, thus achieving innovative management of the ecological environment and promoting environmental awareness in related fields (Pan et al., 2022). Based on the above analysis, Hypothesis 3 is proposed.

H3: The digital economy influences the synergistic management of carbon-haze through technological innovation.

4 Methodology and variable selection

4.1 Econometric methodology

To test whether Hypothesis 1 holds, a two-way fixed effects panel data model is constructed (Ding et al., 2022).

$$Y_{it} = \gamma_0 + \gamma_1 \ln de_{it} + \gamma_2 C_{it} + u_i + v_t + \varepsilon_{it} \tag{1}$$

where i is individual, t is time, Y is the explanatory variable, and the three variables selected in this paper are carbon haze co-governance efficiency (ln*csce*), carbon dioxide emissions ($\ln CO_2$), and haze concentration (ln*smog*); ln*de* is the level of development of the digital economy; C is other control variables; u and v denote individual and time effects, respectively, and $\varepsilon$is a stochastic error term.

Furthermore, a spatial Durbin model is constructed on the basis of (1) considering spatial interaction effects to test whether hypothesis 2 holds.

$$Y_{it} = \rho\sum_{j=1}^{n} w_{ij}Y_{it} + \alpha_0 + \beta_1 \ln de_{it} + \beta_2 C_{it} + \lambda_1\sum_{j=1}^{n} w_{ij} \ln de_{it} + \lambda_2\sum_{j=1}^{n} w_{ij}C_{it} + u_i + v_t + \varepsilon_{it} \quad (2)$$

where ρdenotes the spatial autocorrelation coefficient, reflecting the degree of correlation between the geographical unit and the surrounding area; w_{ij} is the spatial weight matrix; α_0 is the constant term; β is the regression coefficient of the explanatory variable; and λ denotes the spatially correlated regression coefficient of the explanatory variable.

Finally, to examine whether technological innovation acts as a mediating variable in this process, the paper constructs a mediating effects model to test hypothesis 3.

$$Y_{it} = \rho\sum_{j=1}^{n} w_{ij}Y_{it} + \varphi_0 + \eta_1 \ln de + \eta_2 C_{it} + \chi_1\sum_{j=1}^{n} w_{ij} \ln tec_{it} + \chi_2\sum_{j=1}^{n} w_{ij}C_{it} + u_i + v_t + \varepsilon_{it} \quad (3)$$

$$\ln tec_{it} = \rho\sum_{j=1}^{n} w_{ij} \ln tec_{it} + \varphi_0 + \eta_1 \ln de_{it} + \eta_2 C_{it} + \chi_1\sum_{j=1}^{n} w_{ij} \ln de_{it} + \chi_2\sum_{j=1}^{n} w_{ij}C_{it} + u_i + v_t + \varepsilon_{it} \quad (4)$$

$$Y_{it} = \rho\sum_{j=1}^{n} w_{ij}Y_{it} + \varphi_0 + \eta_1 \ln de_{it} + \eta_2 \ln tec + \eta_3 C_{it} + \chi_1\sum_{j=1}^{n} w_{ij} \ln de_{it} + \chi_2\sum_{j=1}^{n} w_{ij} \ln tec_{it} + \chi_3\sum_{j=1}^{n} w_{ij}C_{it} + u_i + v_t + \varepsilon_{it} \quad (5)$$

where *lntec* is the mechanism variable technological innovation, η is the regression coefficient of the explanatory variable, χ denotes the spatially correlated regression coefficient of the explanatory variable, and the rest of the items are the same. Here, we refer to Baron and Kenny (1986) and test the equation coefficient method sequentially to examine the mechanistic role of technological innovation in the synergistic role of the digital economy and carbon-haze governance. The testing process is divided into three equations. First, we examine the role of the direct effect of the digital economy on the efficiency of the synergistic management of carbon-haze with Eq. 3, which is the same as Eq. 2; second, examining the role of the digital economy on technological innovation, with Eq. 4. Finally, incorporating technological innovation into Eq. 2 and examining the effect of technological innovation and the digital economy on the synergistic management of carbon haze in combination, with Eq. 5, with all models using a two-way fixed effect under the spatial Durbin model.

4.2 Variable selection and description

4.2.1 Explained variable

To comprehensively examine the effect of the digital economy (ln*csce*) on carbon dioxide emissions as well as haze governance, a super-efficiency SBM model (Supplementary Appendix SC) is used to construct an input–output system (Tone, 2001; Li et al., 2019). Among the input indicators, the total investment in environmental pollution control in each province is selected for measurement in this paper, and this indicator can reflect the overall level of environmental pollution control in the region in that year. Among the expected outputs, the air quality index is chosen for measurement, and there are two kinds of indicators for evaluating air quality, API and AQI, with the latter being more commonly used by meteorological observation stations in China, so the AQI index is chosen in this paper.

As the AQI is daily data, it is necessary to first find the annual average air quality index of each city, and then weight the sum according to the share of the area of the city and the sum of the cities as weights, and then obtain the annual average air quality index of the province for the year, and finally inverse the data after dimensionless processing. For the undesirable output, the provincial CO_2 emissions and the provincial haze averages were selected, and the calculation used for provincial CO_2 emissions was consistent with the national emission inventory accounting method (Shan et al., 2017). To further refine the impact of the main pollutant $PM_{2.5}$, the annual average $PM_{2.5}$ values for the 30 Chinese provinces assigned by the Atmospheric Composition Analysis Group (ACAG) at Dalhousie University on the basis of NASA raster data were chosen for this paper, while the statistical years for the main pollutants of the haze are limited. These data are relatively more current than the publicly available data from Columbia University and provide a more refined count of the major pollutants (Southerland et al., 2022). At the same time, a nonnegative treatment is applied to the efficiency of the carbon and haze co-governance. In addition, carbon dioxide emissions ($\ln CO_2$) and mean haze (ln*smog*) are also considered as explanatory variables (Yang. et al., 2022a; Yang et al., 2022b).

4.2.2 Explanatory variables

The Digital Economy Index (ln*de*), to measure the level of development of the digital economy, is divided into "level of information infrastructure", "level of digital industrialization" and "level of industrial digitization" (Supplementary Appendix SD).

Information infrastructure reflects the level of demand for information services and the capacity of information services in the region, mainly in terms of the construction of communication hardware facilities, so the length of fiber-optic cable lines and the number of mobile internet users and 4G users are taken into account (Han D et al., 2022).

The level of digital industrialization refers to the scale of ICT-related industries involving e-commerce and software business; therefore, the number of e-commerce transaction enterprises, e-commerce sales, software business revenue, software product revenue, and electronic information manufacturing assets are included in this section (Wang et al., 2021).

The digitalization of industry is mainly reflected in the process management and automated production of enterprises through digital technology, and this series of digitalization processes are all part of technological change. Therefore, expenditures on introducing technology, expenditures on technological improvement, the number of websites per 100 enterprises, and the number of computers per 100 people are taken as variables to be investigated in this section (Li et al., 2022). The weighting of each indicator is based on the entropy method (Supplementary Appendix SE).

4.2.3 Controlled variables

The level of economic development (ln*pgdp*), measured as the natural logarithm of regional GDP per capita, is a variable that reflects the level of regional economic development and the overall level of consumption of the population. In general, regions with a high level of economic development will have cleaner production technologies by manufacturers, which can, to some extent, reduce the pollution of the regional atmosphere from production (Meng and Wang, 2021). However, an increase in consumer demand can also contribute to energy consumption by inducing an increase in the scale of production, which in turn exacerbates pollutant emissions, a factor that potentially affects the efficiency of carbon haze control; therefore, this variable should also be taken into account in the model (Ding et al., 2022).

Population density (ln*pd*), measured by the natural logarithm of the ratio of the number of permanent residents at the end of the year to the area of the built-up area in that year, is a variable that affects the efficiency of CO_2 and haze control through scale and agglomeration effects (Pan et al., 2022). Agglomeration effects can lead to pollution reduction through cost savings and technology spillovers (Zeng and Zhao, 2009; Dong et al., 2020). However, as the size of the economy continues to increase, the scale effect may diminish when production activities exceed the carrying capacity of the environment, thereby exacerbating pollutant emissions and inhibiting the efficiency of carbon haze management. Therefore, the effect of population density on the efficiency of carbon haze management depends on the relative size of the scale and aggregation effects.

The level of external openness (ln*fdi*) is measured here as the natural logarithm of actual foreign investment utilized in the year. There are two classical opposing hypotheses on the relationship between foreign investment and environmental pollution control: the ‘pollution haven’ hypothesis (Copeland and Taylor, 1994) and the ‘pollution halo’ hypothesis (Dean, 2002). The pollution haven hypothesis suggests that foreign investors prefer to invest in countries or regions with low environmental access standards to avoid the costs of pollution control, thereby increasing environmental pollution in the host country. The halo hypothesis, on the other hand, suggests that green technologies have a spatial spillover effect and can improve environmental governance in host countries. Given these two contrasting accounts, the direction of the impact of foreign direct investment (FDI) on the level of carbon-haze governance is to be determined (Zhao and Wang, 2022).

The level of finance (ln*fl*), measured here by the natural logarithm of the Digital Inclusive Finance Index from the Digital Finance Research Centre of Peking University, is chosen to show that financial capital has an expansionary effect on energy consumption by stimulating market consumption and manufacturers’ production (Ge L. et al., 2022). However, given the externalities of environmental pollution control, the environmental standards set by regions for manufacturers are becoming more stringent, and therefore, manufacturers need to invest more in R&D in the technology factor, which in turn increases desired output (Mesagan et al., 2022). Therefore, the direction of the impact of financial development on the efficiency of carbon-haze governance is also undetermined.

Environmental regulation intensity (ln*er*), at this stage, is usually assessed through government pollution control costs and environmental taxes, which has the advantage of integrating informal and formal environmental regulation (Shan et al., 2017; Wang et al., 2022). Thus, by using the logarithm of the total investment in environmental pollution control in the current year as a proxy variable, manufacturers’ willingness to emit pollutants will be discouraged when the total investment in environmental control tends to be stringent, thus improving the efficiency of environmental control.

4.2.4 Mediator variable mechanism variable

Technological innovation (ln*tec*) is measured by the total number of patent applications granted in the year, as the digital economy itself has a certain technological threshold and is highly knowledge intensive, it is more likely to produce some innovations than other industries, and these achievements can play a catalytic role in the production process, thus improving the overall production efficiency. In addition, the development of the digital economy can lead to the development of digital finance, the promotion of financial technology can also effectively improve the efficiency of enterprise financing, and enterprises can invest more capital in technology factors, while technological innovation is also an important path to reduce pollution emissions, so this indicator is used as a mediating variable (Ma et al., 2022).

4.2.5 Data resource

Among the explanatory variables, data on carbon dioxide emissions are obtained from the provincial energy inventory of the CEADs database, air quality index and total investment in environmental pollution control are obtained from the global warming database and carbon neutral database of the CSMAR platform, and total investment in pollution control is obtained from the environmental research database of the EPSDATA platform. Among the explanatory variables, the data related to the digital economy index were obtained from the digital economy database of the CSMAR platform. For the control variables and mechanism variables, the data are taken from the regional research database of the EPSDATA platform, and some missing values in the database are filled in from the public data in the official website of the National Bureau of Statistics, with no missing values. Descriptive statistics for the data areshown in Table 1.

5 Empirical results

5.1 Baseline regression

First, a baseline regression was conducted based on Model 1) to examine the effects of digital economy development on CO_2 emissions, haze pollution and synergistic governance efficiency under individual and temporal two-way fixed effects. Theregression results are shown in Table 2.

The regression coefficient of the core explanatory variable of this paper, digital economy (ln*de*), is negative for both carbon dioxide emissions (lnCO_2) and haze averages (ln*smog*), indicating that the digital economy has a significant inhibitory effect on both, while the regression coefficient of the digital economy is positive for the efficiency of synergistic carbon-haze management (ln*csce*), indicating that the development of the digital economy has a significant driving effect, and hypothesis 1 was verified. Further analysis of the controlled variables shows that three indicators, namely, the level of economic development, the level of FDI and the level of finance, are able to suppress carbon dioxide emissions and haze pollution while improving the efficiency of the region's collaborative carbon-haze management. Specifically, with the development of the economic level, the effect of industrial agglomeration becomes more obvious, and manufacturers produce cleaner technology and cause less damage to the environment. In the case of carbon dioxide and haze pollution, an increase in the level of external openness does not produce a pollution haven effect, and the results are more in favor of the halo hypothesis, which is able to improve the level of environmental governance in the host country through the introduction of foreign investment. In addition, the level of finance can likewise have a dampening effect on carbon-haze management.

The variables different from the digital economy are population density and environmental regulation intensity. Population density has a significant positive effect on CO_2 emissions, which indicates that the scale effect of industry formation at this stage exceeds the environmental carrying capacity, and the innovation compensation brought by the agglomeration effect has not significantly changed this situation. The intensity of environmental regulation has a negative effect on the efficiency of synergistic carbon-haze management, a significant positive effect on carbon dioxide emissions, and an insignificant inhibitory effect on haze pollution, which may be due to the large coverage of investment in environmental regulation and the small amount of investment involving carbon dioxide and haze pollution. In addition, pollution control has a lagging effect, and the effect of environmental regulations on the current year's control may not be obvious. The rising investment in environmental management is also related to the rising indicators of carbon dioxide, respirable particulate matter and three wastes in China, which laterally indicates that there is still room for improving the strength of environmental management at this stage.

5.2 Spatial regression analysis

To study the spatial structure characteristics of carbon-haze pollution and considering that the research scope of this paper is provincial panel data and the administrative area of each province varies in size, the use of a simple neighboring spatial weight matrix may increase the error. A geographical distance matrix is constructed by combining the diffusion transfer effect of atmospheric particulate matter as well as carbon compounds in the atmosphere. The geographic distance weight matrix is a matrix constructed from spatial distances. The use of a geographic distance matrix helps to distinguish the strength of the interaction between different regions, and the influence between regions tends to gradually decrease as the geographic distance increases. The inverse of the geographical distance between the administrative centers of two provinces (urban areas) is used here. In addition, China's economic development shows a spatially distributed characteristic of high in the east and low in the west, the level of economic development between provinces may also have a certain correlation in space, and the level of economic development of one region is most likely to be influenced by the spatial dependence of related regions. Therefore, this paper starts from the regional GDP per capita and simultaneously constructs an economic distance weight matrix. The economic distance weight matrix can better describe the economic development differences between regions; the greater the development differences between different geographical units are, the less relevant they are, and the smaller the development differences are, the greater the correlation. The inverse of the average value of regional GDP per capita of each province during the period 2013–2019 is used here. In addition, to take into account both the

TABLE 1 Descriptive statistics of variables.

Variable type	Symbol	Average	Standard deviation	Minimum value	Maximum value
Explained variable	Ln*csce*	0.849	0.151	0.385	1.084
	lnCO_2	5.656	0.788	3.785	7.438
	Ln*smog*	3.506	0.452	2.293	4.436
Explanatory variable	Ln*de*	1.270	0.372	0.711	2.451
Controlled variable	Lnpgdp	1.675	0.410	0.830	2.799
	Ln*pd*	0.948	0.332	0.235	1.617
	Ln*fdi*	6.710	1.343	3.401	9.880
	Ln*fl*	5.451	0.271	4.771	6.017
	ln*er*	4.901	0.884	1.960	6.478
Mediator variable	ln*tec*	10.813	1.336	7.002	13.609

TABLE 2 Baseline regression coefficients of the digital economy on the synergistic management of carbon and haze

Variable	Ln*csce*	lnCO_2	Ln*smog*
Ln*de*	0.231** (2.47)	−1.090*** (-3.58)	−0.714*** (-3.38)
Ln*pgdp*	0.541* (1.73)	−0.919*** (-3.87)	−0.166* (-1.66)
Ln*pd*	−0.698 (-1.55)	0.733*** (3.93)	−0.296*** (-2.73)
Ln*fdi*	0.210*** (3.12)	−0.248*** (-4.18)	−0.056 (-1.22)
Ln*fl*	0.873*** (4.57)	−1.862*** (-3.41)	−0.486*** (-3.81)
Ln*er*	−0.251** (-2.28)	0.544*** (9.66)	−0.033 (-1.45)
Cons	0.245*** (7.81)	15.093*** (4.96)	6.961*** (11.08)
Year	YES	YES	YES
Province	YES	YES	YES
N	210	210	210
R^2	0.5371	0.4294	0.6034

t values in (), *, **, *** indicate significance at the 10%, 5% and 1% levels, respectively.

economic development level and geographical distance indicators, an economic-geographic nested spatial weight matrix is constructed with the coefficient set at 0.5. Meanwhile, all three matrices involved in this paper (the adjacency matrix in the robustness test does not need to be normalized) are normalized.

Accordingly, the main variables were further tested for spatial correlation, and the indices were selected from the classical Moran index. The results are shown in Table 3.

According to Table 3, it can be found that during the period 2013–2019, each of the main variables passed the significance test at the 10% level conditional on the three spatial weight adjacency matrices, and the global Moran index was positive, which indicates that there is a positive spatial correlation between digital economic development, CO_2 emissions and the mean values of haze. Therefore, spatial spillover needs to be taken into account in the model, and a spatial econometric regression model is used for analysis.

The SDM can be transformed into a spatial error model (SEM) or a spatial lag model (SLM) under certain conditions. To determine the specific form of the spatial econometric model, the LM test and the Wald test were carried out in turn, and the results showed that both the spatial error model and the spatial lag model passed the LM test, so the spatial Durbin model could be chosen. Further Wald tests were conducted, and the results showed that the original hypothesis was also rejected at the 1% level, indicating that the SDM cannot be reduced to a spatial error model or a spatial lag model. Therefore, the SDM is the optimal choice for this study.

In addition, a Hausman test of the model was needed, and the results showed that both significantly rejected the original hypothesis at the 1% confidence level; therefore, a fixed effects model was selected. Finally, an LR test was carried out, and again, the original hypothesis was rejected, and the estimation results and significance of the time and individual two-way fixed effects were selected. In this paper, the individual and temporal two-way fixed spatial Durbin model with fixed benefits was selected for estimation. Accordingly, regressions were conducted in the case of the geographical distance matrix, the economic distance matrix and the economic-geographical nested matrix, and the results are shown in Table 4.

From Table 4, it can be found that the regression coefficients of the digital economy on the synergistic management of carbon-haze are positive and pass the significance test at the 10% level under the three spatial weight matrix settings, while the digital economy has a significant negative effect on both carbon dioxide emissions and haze, which is not different from the baseline regression results. The comprehensive results show that the digital economy can effectively promote the improvement of the efficiency of the synergistic management of carbon-haze, which again supports hypothesis 1. Meanwhile, the lag term coefficients of the digital economy on synergistic carbon haze management have a positive effect of 10% under the geographic distance matrix and the economic-geographic nested matrix and a significant positive effect at the 1% level under the economic distance matrix, indicating that the development of the digital economy has a significant effect on improving the efficiency of carbon-haze management in the surrounding areas, with a

TABLE 3 Moran index coefficients for each of the main variables

Type	Variable	Year						
		2013	2014	2015	2016	2017	2018	2019
Geographical distance matrix	ln*cecs*	0.110*** (2.639)	0.116*** (2.708)	0.108* (1.837)	0.116** (2.394)	0.136*** (2.972)	0.126* (1.799)	0.113* (1.721)
	lnCO_2	0.236** (1.980)	0.232* (1.849)	0.233*** (2.879)	0.227*** (2.699)	0.222*** (2.677)	0.219*** (2.694)	0.198* (1.747)
	ln*smog*	0.560*** (2.650)	0.586*** (3.140)	0.502*** (3.268)	0.507*** (3.393)	0.579*** (2.753)	0.470*** (3.741)	0.493*** (3.484)
	Ln*de*	0.185*** (3.352)	0.80*** (3.180)	0.199*** (3.688)	0.196*** (3.631)	0.182 *** (4.093)	0.173*** (2.977)	0.171*** (2.925)
Economic distance matrix	ln*cecs*	0.286** (2.207)	0.224*** (2.979)	0.230** (1.993)	0.317** (2.494)	0.325*** (2.783)	0.242*** (2.756)	0.315** (2.492)
	lnCO_2	0.108** (1.982)	0.109** (2.435)	0.098* (1.885)	0.096* (1.799)	0.111* (1.954)	0.127* (1.907)	0.121* (1.638)
	ln*smog*	0.251** (2.364)	0.260** (2.237)	0.204*** (2.685)	0.178** (2.432)	0.226* (1.909)	0.216* (1.812)	0.286* (1.696)
	Ln*de*	0.329*** (3.628)	0.317*** (3.494)	0.322*** (3.518)	0.285*** (3.168)	0.291*** (3.226)	0.277*** (3.097)	0.286*** (3.189)
Nested distance matrix	ln*cecs*	0.220** (2.372)	0.257* (1.876)	0.218*** (2.869)	0.256*** (2.674)	0.277*** (2.885)	0.260*** (2.809)	0.235* (1.874)
	lnCO_2	0.142** (2.426)	0.128*** (2.622)	0.133*** (2.866)	0.118*** (2.740)	0.129*** (2.990)	0.121* (1.785)	0.115* (1.934)
	ln*smog*	0.406*** (3.619)	0.483*** (4.198)	0.452*** (3.954)	0.467*** (4.095)	0.435*** (3.841)	0.438*** (3.855)	0.441*** (3.827)
	ln*de*	0.379*** (3.843)	0.356*** (3.621)	0.370*** (3.717)	0.325*** (3.319)	0.324*** (3.306)	0.396*** (3.056)	0.302*** (3.093)

Z statistics in () here, *, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively.

significant positive spatial spillover effect. The spatial spillover effect of carbon dioxide emissions and haze averages on neighboring regions is obvious, and the spatial spillover coefficients of carbon and haze collaborative management on neighboring regions are both positive at the 5%, indicating that carbon dioxide and haze pollutants emitted in the region will cause diffuse pollution to neighboring regions with atmospheric flow. The digital economy will not only benefit the management of the local ecological environment but also have a positive effect on other areas within the agglomeration, thus improving the efficiency of the synergistic management of carbon and haze in multiple regions, and there is a spatial spillover effect.

As the spatial Durbin model incorporates the explanatory variables in different geographical units as well as the explanatory variables, where spatial lags can produce some bias in the regression results, the regression coefficients of the explanatory variables do not explain the true situation well, and it is necessary to decompose the coefficients into direct effects, indirect effects and total effects. The direct effect indicates the influence of the explanatory variables in the region on the explanatory variables in the region, the total effect indicates the influence of the explanatory variables in the region and the surrounding regions on the explanatory variables in the region, and the indirect effect indicates the influence of the explanatory variables in the surrounding regions on the explanatory variables in the region. Accordingly, the effects of the model were decomposed, and Table 5 demonstrates the results of the effects of the core variable ln*de* on each of the explanatory variables.

Analysis of Table 5 shows that the direct, indirect and total effects of the digital economy on carbon-haze management are all significantly positive at the 10% level under the three spatial weight matrices, and the coefficient of the indirect effect is higher than that of the direct effect, indicating the existence of a spatial spillover effect. The coefficient of the indirect effect is higher than the coefficient of the direct effect, indicating the existence of a spatial spillover effect. In contrast, the development of the digital economy in the surrounding areas will also lead to the improvement of the efficiency of the region's collaborative carbon-haze control.

Considering China's vast territory, the level of economic development varies greatly from region to region, and the industrial structure varies. This may lead to a certain characteristic of digital economy development in spatial distribution. This paper adopts the kriging interpolation method, logarithmically processing the digital economy index of each province in 2013, 2016 and 2019 after interpolation prediction analysis, considering that the pankriging interpolation method can be well applied to the

TABLE 4 Spatial regression coefficients of the digital economy on the synergistic management of carbon and haze

	Geographical distance matrix			Economic distance matrix			Economic geography nested distance matrix		
	ln*csce*	lnCO_2	ln*smog*	ln*csce*	lnCO_2	ln*smog*	ln*csce*	lnCO_2	ln*smog*
Ln*de*	0.239* (1.72)	−0.155* (−1.79)	−0.453*** (−4.34)	0.444*** (2.96)	−0.171* (-1.73)	−0.227*** (-3.10)	0.333* (1.74)	−0.457*** (-3.08)	−0.328*** (-3.07)
Ln*pgdp*	0.014 (0.79)	−0.192** (−2.06)	−0.081 (−0.92)	0.030* (1.73)	0.107* (1.92)	−0.102** (−1.96)	0.042 (0.95)	0.145* (1.91)	−0.163* (-1.67)
Ln*pd*	−0.178 (-1.55)	0.389*** (2.67)	0.237** (2.45)	−0.169 (−1.39)	0.035 (1.41)	0.299*** (2.83)	−0.175** (−1.98)	0.128 (0.99)	0.287*** (2.77)
Ln*fdi*	0.217*** (3.04)	0.029 (1.02)	−0.244* (−1.91)	0.124** (2.13)	−0.154** (−1.98)	−0.019 (-1.56)	0.003 (0.21)	0.051* (1.85)	−0.026 (−0.78)
Ln*fl*	0.306*** (2.70)	−0.551*** (−2.70)	−0.144 (−0.64)	0.119 (0.88)	−1.145*** (−4.26)	−0.583 (−3.33)	0.177 (1.22)	−1.221*** (−4.92)	0.197 (0.64)
Ln*er*	−0.122** (−1.99)	−0.070 (-1.48)	−0.036* (−1.75)	−0.029** (-2.49)	−0.009 (−0.48)	−0.150** (−2.02)	−0.028** (−2.31)	−0.013 (−0.66)	−0.050** (−1.97)
W×ln*de*	0.297* (1.73)	−0.584*** (−3.83)	−2.782*** (−3.57)	0.434*** (3.52)	−0.129* (−1.84)	−0.308*** (−2.85)	0.218* (1.94)	0.163 (1.29)	−0.626*** (−3.22)
W×ln*pgdp*	0.049 (0.24)	0.270 (1.18)	0.397 (0.99)	−0.178 (−1.48)	−0.502*** (−2.92)	0.172 (0.67)	−0.099 (−0.86)	−0.276 (−1.39)	0.125 (0.60)
W×ln*pd*	−0.344** (−1.98)	0.308 (1.12)	1.700*** (2.72)	−0.101 (−1.22)	0.215 (1.24)	−0.025 (−0.14)	−0.138 (−1.43)	0.363** (2.22)	0.026 (0.13)
W×ln*fdi*	0.037 (1.33)	−0.262 (−1.33)	−0.381* (−1.75)	−0.053 (−1.33)	−0.006 (−0.78)	−0.017 (−0.19)	−0.040 (−1.08)	−0.039 (−0.62)	−0.057 (−0.73)
W×ln*fl*	−1.671*** (−2.72)	1.292*** (3.07)	−0.529*** (−3.40)	0.096 (0.40)	1.972*** (4.78)	−1.444*** (−2.81)	0.037 (0.16)	1.891*** (4.75)	−0.761 (−1.52)
W×ln*er*	−0.111** (-2.15)	−0.310** (−2.31)	−0.222 (−1.50)	−0.034 (−1.10)	−0.324** (−2.54)	−0.009 (−0.13)	−0.033 (−1.11)	−0.024 (−0.46)	−0.031 (−0.50)
Rho	0.769*** (3.37)	0.579*** (2.83)	0.684*** (6.24)	0.227* (1.93)	0.215** (2.13)	0.246* (1.71)	0.293* (1.87)	0.266* (1.70)	0.252* (1.74)
Year	YES	YES	YES	YES	YES	YES	YES	YES	YES
Province	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	210	210	210	210	210	210	210	210	210
R^2	0.1237	0.0821	0.3372	0.1901	0.1471	0.5647	0.1375	0.0885	0.5697

Z statistics in () here, *, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively.

TABLE 5 Decomposition of the effects of the digital economy on carbon-haze governance

	ln*csce*	Direct effect			Indirect effect			Total effect	
		lnCO_2	ln*smog*	ln*csce*	lnCO_2	ln*smog*	ln*csce*	lnCO_2	ln*smog*
Geographical distance	0.043* (1.90)	−0.038 (−1.42)	−0.737** (−2.10)	0.212*** (2.78)	−0.356** (−2.12)	−1.261*** (−4.53)	0.255*** (2.56)	−0.394* (−1.74)	−1.998*** (−3.54)
Economic distance	0.134*** (2.67)	−0.028 (−1.32)	−0.309*** (−2.88)	0.234* (1.79)	−0.134** (−2.10)	−0.133* (−1.76)	0.368** (2.08)	−0.162* (−1.81)	−0.442*** (−2.78)
Nested	0.035* (1.69)	−0.012 (−0.23)	−0.335*** (−2.95)	0.112** (1.99)	0.123 (1.30)	−0.425** (−2.27)	0.147* (1.77)	0.111 (1.29)	−0.760*** (−2.91)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES	YES	YES
Province	YES	YES	YES	YES	YES	YES	YES	YES	YES

Z-statistics in (), *, **, *** indicate significance at the 10%, 5% and 1% levels, respectively.

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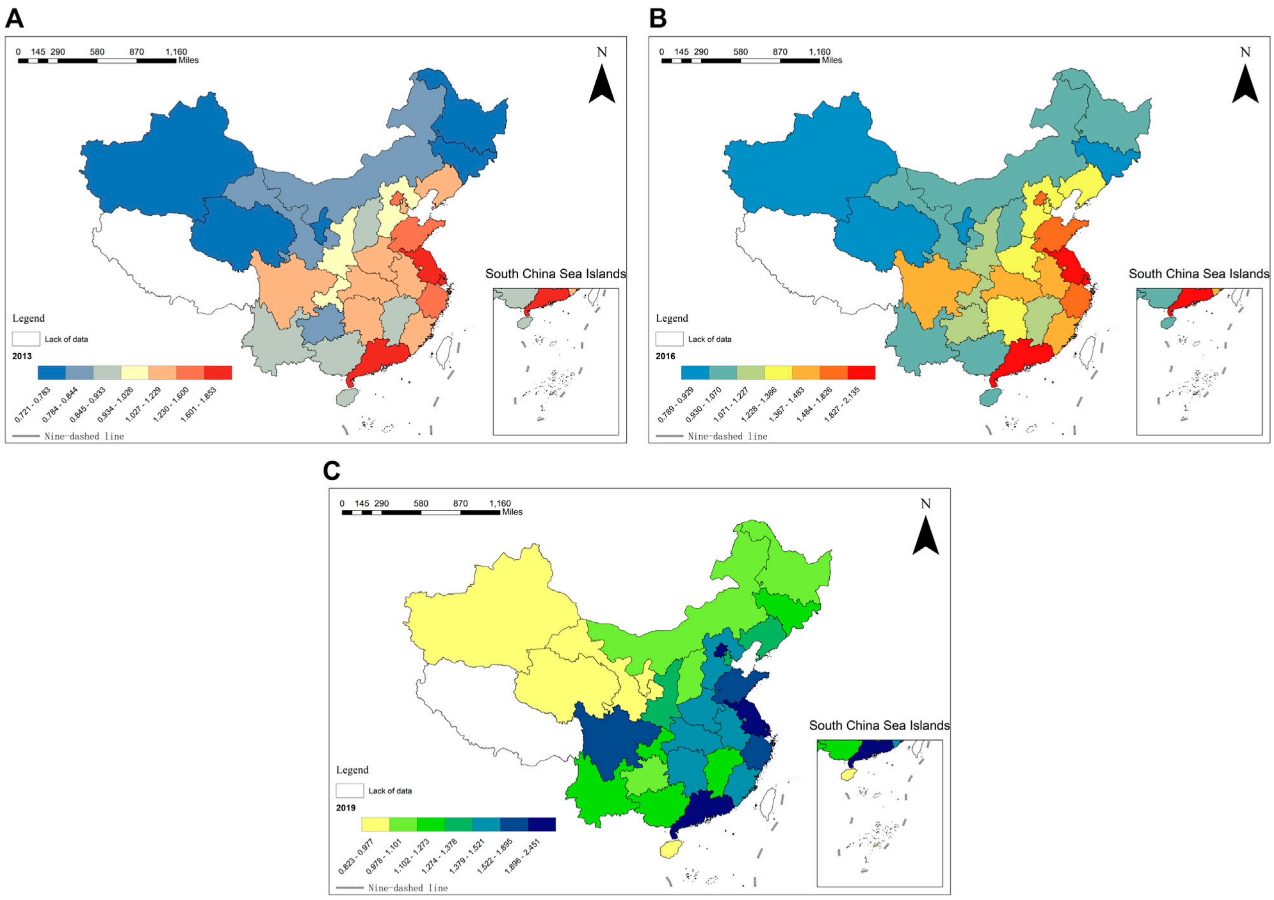

FIGURE 4
Digital economy development in 30 provinces and regions in China, 2013 **(A)**, 2016 **(B)** and 2019 **(C)**.

prediction between discontinuous geographical units, so in the figure, the non-study area of this paper is also taken into account, and the overall still distribution can be seen in Figure 4.

According to Figure 4, there are significant spatial differences in the regional distribution of the core explanatory variables in this paper, consistent with the development characteristics of a high east and low west. It is therefore necessary to run subsample regressions for different regions, which are divided into three regions: eastern, central and western[4]. This section focuses on examining the heterogeneity in regional distribution, whereby a matrix of geographical distance weights is constructed for the eastern, central and western regions, and the two-way fixed spatial Durbin model under all controlled variables is still followed except for matrix changes, the results of which are shown in Table 6.

According to the results in Table 6, the effect of the digital economy on the synergistic management of carbon haze is spatially heterogeneous, with the indirect effect in the eastern region being significantly positive at the 5% level and the coefficient being higher than that in the central and western regions, and the coefficient in the central region passing the significance test at the 10% level and the regression coefficient being higher than that in the western region. The effect of the digital economy on the synergistic governance of carbon-haze is the strongest in the eastern region, with a gradual decrease from east to the west in a stepped pattern. This may be due to the high level of development of the digital economy in the eastern region, where the cost of imitation is low and learning efficiency is high. Different enterprises can promote innovation in their products and production models by imitating the practices of competing enterprises and at the

4 Eastern region includes: Beijing, Tianjin, Hebei, Shanghai, Zhejiang, Fujian, Shandong, Guangdong, Hainan; Central region includes: Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan; Western region includes: Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Ningxia, Xinjiang, Liaoning, Jilin, Heilongjiang (Supplementary Figure S5).

TABLE 6 The effects coefficients of the digital economy on synergistic management of carbon-haze in different regions.

Effect	Variable	Eastern	Central	Western
Direct effect	ln*csce*	0.057* (1.89)	0.055** (2.21)	0.076 (1.12)
	lnCO_2	0.022 (0.70)	0.018* (1.77)	0.031** (1.99)
	ln*smog*	0.485*** (2.79)	0.276*** (3.09)	0.124*** (2.80)
Indirect effect	ln*csce*	0.289** (2.09)	0.162* (1.80)	0.113 (0.81)
	lnCO_2	−0.189* (−1.70)	−0.160 (−1.02)	−0.286*** (−2.66)
	ln*smog*	−1.832*** (−3.41)	−1.513*** (−2.68)	−0.983*** (−3.11)
Total effect	lncsce	0.346** (1.98)	0.217** (2.04)	0.189 (1.31)
	ln*csce*	−0.211* (−1.72)	−0.178* (−1.87)	−0.317** (−2.52)
	ln*smog*	−2.317*** (−4.99)	−1.789*** (−3.19)	−1.107*** (−3.23)

The Moran index for all three area matrices was found to be significantly positively correlated at the 5% level, with the Z statistic in (), *, ** and *** indicating significance at the 10%, 5% and 1% levels, respectively.

same time sharing the production methods and innovative ideas of high-efficiency enterprises with low-efficiency enterprises through blockchain technology, thereby improving the allocation of market factors, optimizing the efficiency of resource use, and driving the transformation of industrial production intensification. As the level of digital economy development in the eastern region far exceeds that of other regions, there are also differences in digital economy development between the central and western regions, leading to a gradual weakening of the synergistic effect of the digital economy on carbon haze management from east to west, confirming the existence of spatial spillover effects. In addition, the mean coefficients of the digital economy on CO_2 emissions and haze in the three regions are positive, while the indirect effects are mostly significantly negative at the 1% level, inferring that the digital economy can suppress air pollutant emissions through spatial spillover effects across the region. In summary, it was possible to confirm hypothesis 2.

5.3 Analysis of the mediating effects

Hypotheses 1 and Hypotheses 2 were tested above, namely, that the digital economy has a positive impact on the efficiency of carbon haze governance and has a spatial spillover effect. However, the transmission mechanism is still unclear. Based on the previous theoretical analysis, the regression analysis of Eqs 3–5 in turn is used to examine whether technological innovation acts as a mediating variable in the transmission mechanism, and since this part is mainly about the mechanism of the variable of technological innovation. Therefore, to facilitate the analysis, only the results of the analysis under the economic distance weight matrix are considered. The consideration for this is that the level of technological innovation tends to be closely linked to the level of regional economic development, which is more appropriate compared to the other two matrices, still using the two-way fixed spatial Durbin model. Table 7 shows the regression results for each of the three models.

Without considering the coefficients of spatial spillover effects, the results of model 3) indicate that the regression coefficients of the digital economy and the mean values of CO_2 emissions and haze are significantly correlated, and the results of model 4) show that the digital economy can significantly contribute to the development of technological innovation. The results of model 5) show that the sign and significance between the digital economy and the explanatory variables remain unchanged, and technological innovation also has a significant effect on the explanatory variables, so it can be inferred that technological innovation plays the role of a mediating variable in this process. Specifically, the total effect of the digital economy on the efficiency of synergistic carbon and haze management, CO_2 emissions and haze mean are 0.444, -0.171 and -0.227, respectively, while the direct effects are 0.328, -0.131 and -0.194, respectively, and the indirect effects are 0.116, -0.040 and -0.033, respectively.

In terms of coefficients that take spatial spillover effects into account, the above findings still hold true, with the sign direction remaining consistent across the board. The development of the digital economy in the surrounding areas (in this case based on a matrix of economic distances) can drive technological innovation in the region, and the effect is more pronounced, probably due to the dividends of regional competition. This may be because the

TABLE 7 Regression coefficients for the intermediary effects

	Lncsce	Model (3)		Model (4)		Model (5)	
		lnCO_2	ln*smog*	Ln*tec*	ln*csce*	ln*CO2*	ln*smog*
Ln*de*	0.444*** (2.96)	−0.171* (−1.83)	−0.227*** (−3.10)	0.295** (2.48)	0.328*** (2.96)	−0.131* (−1.78)	−0.194*** (−2.64)
W×ln*de*	0.534*** (3.52)	−0.129* (−1.84)	−0.308*** (−2.85)	0.212*** (2.94)	0.502*** (3.78)	−0.102* (−1.75)	−0.251* (−1.74)
Ln*tec*					0.396*** (2.62)	−0.136** (−2.41)	−0.114*** (−2.76)
W× ln*tec*					0.151*** (3.98)	−0.131* (−1.79)	−0.273*** (−3.00)
Rho	0.165*** (2.78)	0.110*** (2.98)	0.290*** (3.12)	0.246** (2.13)	0.159* (1.72)	0.198** (2.43)	0.272*** (2.89)
Control	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES
Province	YES	YES	YES	YES	YES	YES	YES
R^2	0.3644	0.1586	0.6172	0.5901	0.6112	0.1659	0.6222

diffusion of carbon haze does not follow an economic distribution spatially, and the effect of distant but similar economic regions on each other's carbon-haze pollution is limited. Similarly, in terms of specific coefficients, all results are guaranteed to be significant, so it can be inferred that technological innovation also has a mediating effect in space.

Specifically, the total effect of the surrounding region's digital economy on the efficiency of the region's synergistic carbon-haze governance, CO_2 emissions and haze averages are 0.534, -0.129 and -0.308, respectively, while the direct effects are 0.502, -0.102 and -0.251, respectively, and the indirect effects are 0.032, -0.027 and -0.057, respectively. Simple multiplication of coefficients may result in coefficients that are significant but not actually significant, so a test for mediating effects was conducted using the widely used bootstrap method, with a set sample of 500, and the results were still robust and significant at the 1% level. In summary, hypothesis 3 was tested.

TABLE 8 Coefficients of the impact of the digital economy on the synergistic carbon and haze management efficiency, CO_2 emissions and haze mean values with adjacency matrix

	Variable		
	ln*csce*	lnCO_2	ln*smog*
Ln*de*	0.439*** (4.72)	−0.515*** (−7.70)	−0.689*** (−7.88)
ln*pgdp*	−0.084 (−0.29)	−0.352*** (−4.86)	−0.104* (−1.69)
Ln*pd*	−0.278** (−2.15)	0.689*** (5.07)	0.107 (0.96)
Ln*fdi*	0.120*** (2.74)	0.032 (1.42)	−0.299*** (−2.69)
Ln*fl*	−0.570*** (−4.10)	−0.208* (−1.70)	−0.588*** (−3.60)
Ln*er*	−0.301*** (−2.93)	−0.070 (−1.48)	−0.201 (−1.10)
W×ln*de*	0.508*** (3.53)	−0.400*** (−3.17)	−1.778*** (−5.29)
W×ln*pgdp*	−0.049 (−0.24)	0.152 (0.78)	0.209 (0.45)
W×ln*pd*	−0.258** (−2.13)	0.245* (1.72)	1.963*** (5.63)
W×ln*fdi*	0.007 (0.31)	−0.251 (−1.50)	−0.414*** (−2.88)
W×ln*fl*	−1.480*** (−5.11)	1.479*** (3.89)	−0.103 (−1.20)
W×ln*er*	−0.321*** (-2.79)	−0.113** (−2.01)	−0.019 (−0.05)
Rho	0.872*** (5.35)	0.589*** (6.96)	0.502*** (4.47)
Year	YES	YES	YES
Province	YES	YES	YES
N	210	210	210
R^2	0.2178	0.3860	0.2105

6 Robustness test

6.1 Differences in the spatial weight matrices

In spatial econometric regression, robustness analysis is generally carried out by replacing the spatial weight matrix. Three common matrices are involved in the study of this paper: the geographical distance weight matrix, the economic distance weight matrix and the economic-geographical nested weight matrix, so the regression analysis of Eq. 2 is carried out using the classical adjacency matrix with the Queen adjacency. Again, all control variables were included in the model. The regression results in Table 8 show that the effects of the digital economy on the efficiency of carbon and haze co-governance, CO_2 emissions and haze averages are unchanged in sign. Although the coefficients and significance have changed compared to the other three metrices, they remain convergent overall.

6.2 Replacement of explained variables

This paper is about the relationship between the digital economy and atmospheric respirable particles and CO_2, but

TABLE 9 Coefficients of the regression of the digital economy on industrial waste gases

ln*so2*	*Coef.*	*St.Err.*	*Z*	*P>z*
Ln*de*	−0.0798	0.0406	−1.97	0.049
ln*pgdp*	−0.0297	0.0084	−3.54	0.000
Ln*pd*	−0.0322	0.0190	−1.69	0.090
Ln*fdi*	−0.6952	0.2070	−3.36	0.001
Ln*fl*	−0.2600	0.1844	−1.41	0.159
Ln*er*	0.1785	0.2150	0.83	0.406
W×ln*de*	−0.1080	0.0475	−2.27	0.023
W×ln*pgdp*	0.0150	0.2030	0.07	0.941
W×ln*pd*	−0.0220	0.0540	−0.41	0.684
W×ln*fdi*	−0.5920	0.1360	−4.35	0.000
W×ln*fl*	−0.2978	0.0879	−3.39	0.001
W×ln*er*	−0.1350	0.0775	−1.74	0.082
Rho	0.1602	0.0449	3.56	0.000
N = 210,Square-R = 0.1176				

environmental pollution management involves three aspects: water pollution, air pollution, and soil pollution. Despite the fact that excessive emissions of carbon dioxide have caused a serious greenhouse effect, this indicator is still not classified as an air pollutant. However, the production of industrial waste gas or wastewater requires a certain amount of energy, which in turn increases the combustion of fossil fuels, resulting in the formation of large amounts of CO_2 or CO, and some of the soot and respirable particulate matter are also emitted into the atmosphere. Therefore, this paper considers that CO_2, respirable particulate matter and industrial emissions are correlated, so the explanatory variables are replaced by the logarithm of industrial emissions, and the parameters are estimated using a two-way fixed spatial Durbin model by choosing an economic-geographic nested matrix with no change in the controlled variables. The regression results are shown in Table 9.

6.3 Changing the length of this study

A phased return to different periods of digital economy development, taking the "G20 Digital Economy Development and Cooperation Initiative" proposed at the G20 Summit in Hangzhou in 2016 as the node, classifies the digital economy development before 2016 as the starting stage (2013–2016). At the same time, 2016 was used as a transition year, after which the full development phase of the digital economy (2016–2019) was entered. Considering that the panel is changed to a short panel, only individual effects are fixed, while all control variables are included and parameter estimation is carried out in an economic-geographic nested matrix. The results show that the sign of the coefficients of the digital economy on each of the explanatory variables does not change, among which the efficiency of the synergistic management of carbon-haze in the start-up period fails to pass the test at the 10% level, which may be caused by the small sample size due to the shortened panel. This may be due to the small sample size caused by the shortened panel, but overall, the model is still robust.

7 Conclusion and recommendation

7.1 Conclusion

Using interprovincial panel data in China during 2013–2019 as a sample, this paper explores the impact of the digital economy on the efficiency of collaborative carbon-haze governance based on theoretical analysis and empirical research by constructing a spatial panel regression model, using a two-way fixed effects model, a spatial Durbin model and a mediating effects model for empirical analysis, and further examining whether technological innovation plays an intermediary role in the spatial transmission process of the digital economy.

The results of the study show that (1) the development of the digital economy can effectively reduce carbon-haze emissions in the production process, which has a positive effect on improving the efficiency of carbon-haze synergistic management. Specifically, for every 1% growth in the digital economy, the efficiency of synergistic carbon and haze management also increases by 0.231%. At the same time, the suppression effects on carbon dioxide and haze are stronger, with their regression coefficients of -1.090 and -0.714 respectively. At the same time, whatever the spatial matrix used, the digital economy can improve the efficiency of carbon-haze co-governance in neighbouring regions through spatial spillover effects. This means that every 1% growth in the local digital economy increases the efficiency of the surrounding area by at least 0.239%. 2) For the region itself, the regression coefficient for technological innovation is 0.295 ($p < 0.05$). For the surrounding area, this result is 0.212 ($p < 0.01$). This suggests that technological innovation acts as a mediating variable in the effect of the digital economy on the efficiency of synergistic carbon haze management, taking into account spatial effects. 3) Digital economy development has a significant spatial spillover effect only in the eastern and central regions (the regression coefficients are 0.346 and 0.217 respectively), with the eastern region having the greatest effect on improving the efficiency of synergistic carbon and haze management.

7.2 Recommendation

Based on the above findings, this paper makes the following policy recommendations.

First, build an inclusive digital economy and increase the penetration rate of data elements. The digital economy has become a new driving force in reducing air pollutant emissions and curbing the haze phenomenon. Governments at all levels should increase investment in the internet industry and effectively promote the construction of digital China, especially by accelerating the construction of 5G services, big data technology, artificial intelligence and other related infrastructure, to further consolidate the advantages of the information technology dividend and thus achieve the development of a high-quality green and low-carbon economy (Yang et al., 2021a).

Second, reduce the digital divide between regions and breakdown the barriers to digital technology transfer (Ge W. et al., 2022). At present, the level of development of the digital economy in China's various regions is unbalanced, and geographically, it shows an overall spatial distribution characteristic of high in the east and low in the west. From a global perspective, the spatial spillover effect of the digital economy should be reasonably utilized, and efforts should be made to narrow the gap in the development of the digital economy within the region. At the same time, each local government should introduce relevant policies to actively guide large high-tech enterprises in the region to help small and medium-sized enterprises, play a leading role, and urge leading digital enterprises in the province to provide technical support to less developed areas of the digital economy.

Third, create a digital city system and realize information technology to assist city operations. Transform the government's concept of digital governance, attach importance to the value of digital assets, improve the efficiency of digital operations, and reasonably revitalize digital dividends. Regional information sharing systems and emergency management mechanisms should be established, atmospheric carbon-haze detection and early warning services should be increased, and highly polluting enterprises should be digitally controlled through monitoring means, thereby scientifically bringing into play the scale and agglomeration effects and improving the efficiency of green urban development (Yang et al., 2022b).

Data availability statement

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

Author contributions

BZ: Conceptualization, Methodology, Writing–original draft, Supervision, Funding acquisition. HZ: Methodology, Project administration, Writing–original draft, Writing–review and editing, Data curation. JY: Formal analysis, Writing–original draft. TH: Validation, Investigation, Writing–review and editing. JL: Methodology, Writing–original draft, Writing–review and editing.

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Conflict of interest

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

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Development of greenhouse gas emissions baseline and identification of carbon offset cost for maritime vessels of a developing country

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Maritime transportation has drawn international attention due to the gradual rise and projected growth of Greenhouse Gas (GHG) emissions resulting from fossil fuel consumption. It is alarming that the overall maritime transportation emissions are neither attended to nor mainstreamed under the transportation sector. The actual national inventory of GHG emissions vis-à-vis all types/sizes of maritime vessels is so far not established particularly in developing countries, which clearly indicates the inadequacy of their climate mitigation response. Accurate assessment of GHGs is essential to provide reliable input for climate policy, strategies, and decision-making processes by flag states. Therefore, the establishment of a baseline reference scenario by considering all types/sizes of maritime vessels is crucial to know the actual gravity of the problem, which is still unknown. This entailed the need to explore the actual extent of GHG emissions from the maritime transportation sector. In this context, the present study tried to assess the potential GHG emissions from maritime vessels by undertaking the case of Pakistan and using the top-down approach, which took into account fuel consumption and emission factors for GHGs. It revealed that 2,468,789.21 tonnes of GHGs (CO_2e) are being emitted annually from the maritime vessels of Pakistan, which is 4.9% of the overall transport sector emissions of the country. Carbon offset cost of 37, 031, 838.14 US$/annum and approximately 20,020 hectares of mature mangrove forest to remove 2,468,789.21 metric tonnes of CO_2e emissions from the atmosphere in a timeline of 1 year are required to become carbon neutral. It is anticipated that this study's outcome will serve as a baseline reference scenario for national GHG inventory and help in devising climate mitigation responses for maritime vessels by bridging the existing knowledge gap.

KEYWORDS

GHG emissions, maritime transportation, climate mitigation, sea-going vessels, fuel consumption, carbon offset

1 Introduction

Climate change is quickly becoming a survival concern because it brings multiple challenges globally (GoP, 2021b). Since about 1750, the observed rise in Greenhouse Gases (GHGs) is clearly due to anthropogenic activities (IPCC, 2021). The burning of fossil fuels due to anthropogenic activities including transportation is one of the main causes of the increase in CO_2 emissions (IPCC, 2014; Notte et al., 2018; Hussain et al., 2020). Over the last century, international sea transportation has been the primary means of transit (Halim et al., 2018) accounting for 80–90% of global trade (Chang, 2012; Chu-Van et al., 2019; MERSIN et al., 2019; Yang and Ma, 2019; Zhou et al., 2020; Al-Enazi et al., 2021). Maritime vessels are directly involved in climate change by releasing the substances of global warming because of the utilization of fossil fuels (Fitzgerald et al., 2011; Kokosalakis et al., 2020). Emissions depend on the type of fuel used, the type of engine, and its efficiency. Marine fuel oil, Heavy fuel oil, and Marine diesel oil are the most often utilized fuels in maritime vessels (Walker et al., 2018; Schnurr and Walker, 2019; Zincir, 2020). In 2019, annual atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have reached averages of 410 ppm, 1866 ppb, and 332 ppb respectively (IPCC, 2021) and if storage and use methods are not developed, future increases will lead to catastrophic problems of climate change (Al Baroudi et al., 2021). It is critical to highlight that global warming, in the 21st century, will increase by 1.5°C and 2°C unless GHG emissions are significantly reduced in the next few decades (IPCC, 2021).

The fourth International Maritime Organization (IMO) GHG study demonstrated that shipping transportation is accountable for 2.89% of global CO_2 emissions (IMO, 2021a) whereas CO_2 emissions from the business-as-usual scenario of shipping will probably increase up to 250% by 2050 (IMO, 2015; Bouman et al., 2017; Gritsenko, 2017; Tatar and Ozer, 2018) if no mitigation action will be taken (Bouman et al., 2017; Inal et al., 2021). Paris Agreement aimed to keep the century's average temperature rise to 2°C; however, reductions in GHG emissions from maritime transportation were not included in the plan (Halim et al., 2018; Muhammad and Long, 2020). In abatement strategies that seek to preserve global GHG concentrations around 450 ppm or 550 ppm, all forms of transportation would be needed to significantly increase fuel efficiency, utilize more low-carbon fuels, and implement behavioral changes (Cames et al., 2015). The objective of the Paris Agreement for limiting the global temperature rise would be jeopardized unless the maritime sector contributes towards climate mitigation strategies (Halim et al., 2018).

However, the IMO approved a resolution in 2018 to cut shipping emissions by at least 50% and CO_2 emissions by at least 70% by 2050 (Chen et al., 2019; IMO, 2019; Muhammad and Long, 2020; Zincir, 2020). Considerable resources and investments are required to achieve this goal (UNCTAD, 2020). Merk (2014) projected that Asia and Africa will witness the largest increases in emissions because of substantial port traffic development and insufficient mitigating efforts. Therefore, mitigation strategies are necessary for all types of sea-going vessels, but the gravity of the problem needs to be identified first which is a major challenge in developing countries including Pakistan.

Existing studies now including the IMO studies have some sort of shortcomings, for instance, the fourth IMO GHG study has only covered ships of 100 GT and above. The omission of fishing vessels and other small commercial vessels from IMO's GHG studies is also reported in a study in the United Kingdom (Coello et al., 2015). In addition, the national GHG emission scenario is also not provided. So, there is a question that arises where Pakistan is ranked among other countries in the breakdown of GHG emissions. It is critical to mention that significant gaps regarding the under-reporting of fuel data (IMO, 2009), the unavailability of Automatic Identification System (AIS) data for some years during the study period (IMO, 2015), and no reporting of fuel consumption data to International Energy Agency (IEA) by countries except a few ones (IMO, 2015; 2021b) have been reported in IMO's GHG Studies. Accurate estimation of GHG emissions is vital for providing credible input to policy-making processes and climate response (Notte et al., 2018). So, the aforementioned gaps raise the question regarding the accurate calculation of global GHG emissions from maritime vessels of all types and sizes.

On the other hand, in the case of Pakistan, the actual national inventory of GHG emissions vis-à-vis all types/sizes of vessels is so far not established. Moreover, the allocation of emissions from ships has been hotly disputed based on the nationality of the transporting firm, country of departure, or the area where the fuel is sold, etc (Villalba and Gemechu, 2011a). GHGs and other air pollutants are considered transnational issues because they have no boundaries. However, a transnational issue doesn't mean that you should put your emissions in the hands of others; rather, everyone must come up with climate mitigation plans and strategies. Therefore, the case of Pakistan is significant due to the large number of fishing vessels that are active in the Arabian Sea. Their cumulative effect, along with other types/sizes of vessels, on GHG emissions is unknown. Therefore, the establishment of a baseline reference scenario and knowing the carbon offset cost is crucial to know the actual gravity of the problem to contribute toward climate mitigation response as well as fulfillment of objectives and targets set under the National Climate Change Policy (NCCP) 2021 (GoP, 2021a) and Nationally Determined Contribution (NDC) 2021 (GoP, 2021b).

Hence, this entailed the need to explore and assess the overall GHG emission scenario from the most ignored and unattended segment of the maritime economy. In this context, this paper tried to analyze the potential GHG emissions for all types and sizes of sea-going vessels and their carbon offset cost by taking the case of a developing country i.e. Pakistan. The outcome of the study provides a baseline reference scenario for the GHG inventory and adds knowledge to the existing pool of literature which would help in developing policy and climate mitigation strategies specific to all types of maritime vessels.

2 Materials and methods

2.1 Review of methodologies and emission factors

In the literature, the main available methodologies to calculate shipping emissions are classified into the top-down approach and bottom-up approach (Eyring et al., 2010) proposed by Intergovernmental Panel on Climate change (IPCC) (Yang and Ma, 2019). In a top-down approach, emissions are calculated without regard to location. Emissions are calculated by gauging fuel use by power generation first and then it is multiplied by the emission factor. Whereas, in a bottom-up approach, ship, and route-specific emissions within a geographical context are directly estimated depending on vessel characteristics, vessel movements, and vessel emissions factors (Eyring et al., 2010). Several publications scientifically research the problem of GHG emissions from the combustion of fuel oil in maritime vessels (Kokosalakis et al., 2020). Tokuslu (2021) examined the GHG emissions from maritime vessels in four of Georgia's main ports using the bottom-up approach. Kramel et al. (2021) presented a bottom-up evaluation of GHGs and aerosol emissions from the shipping industry. Johansson et al. (2017) estimated worldwide emissions from shipping for the year 2015 by using the Ship Traffic Emission Assessment Model (STEAM3), specification data of ships, and Automatic Identification System (AIS) data. Chen et al. (2016) evaluated ship exhaust emissions using activity-based methods and AIS data for the Tianjin Port, China. Styhre et al. (2017) examined the GHG emissions from ships in four ports using yearly data from the Ports of Gothenburg, Long Beach, Osaka, and Sydney using a model developed by IVL Swedish Environmental Research Institute. Olukanni and Esu (2018) calculated the quantity of GHGs released by port vessel activities in the Nigerian ports of Lagos and Tin Can using a bottom-up technique based on individual vessel characteristics. Chang et al. (2013) examined GHG emissions from port shipping activities in Korea's Port of Incheon and found significant differences when comparing the results of the bottom-up approach with the top-down approach. Additionally, several studies have discussed the best possible measures for climate mitigation in the maritime transportation sector (Li et al., 2019; MERSIN et al., 2019; Prasad and Raturi, 2019; Jiang et al., 2020; Joung et al., 2020; Zincir, 2020; Al-Enazi et al., 2021; Inal et al., 2021). However, no study has been found that explores and compares the overall GHG emission scenario from the maritime transportation sector by taking into account all types and sizes of maritime vessels – a research gap that is explored in this study.

This section, as a whole, demonstrates the methodology used for the calculation of GHG emissions from all types and sizes of maritime vessels in Pakistan. The review of methodologies used for calculations of GHG emissions globally and emission factors are briefed in sub-section 2.1. Sub-section 2.2 deals with the implications of existing methodologies for this study. Similarly, the selection of the GHG emissions method and variables involved are described in sub-section 2.3 and sub-section 2.4 respectively. Sub-section 2.5 explains the data acquisition of maritime vessels from concerned departments and authorities. The scope of GHGs under this study, selection, and normalization of GHG emissions factors, and selection of GHG emission calculation method for this study is described in sub-section 2.6 to sub-section 2.9 respectively.

Various methodologies and emission factors relating to GHG emissions were scrutinized during the methodological review process. It has been identified that various GHG methodologies and emission factors remained in leading practice globally by Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006), International Maritime Organization (IMO) (IMO, 2015), United States Environmental Protection Agency (US-EPA) (US EPA, 2022a), European Monitoring and Evaluation Program/European Environment Agency (EMEP/EEA), and Core Inventory of Air Emissions (CORINAIR) Guidebooks (EEA, 2021).

2.1.1 Methodologies developed by IPCC

Over the time, IPCC has provided different methodological approaches and emissions factors for measuring GHG emissions generated from all water-borne navigation, which are followed globally. IPCC guidelines 2006 for national GHG inventories are the recent ones to which significant refinements were made in May 2019. IPCC, in its 2006 Guidelines, has presented two methodological tiers for the estimation of Carbon Dioxide, Methane, and Nitrous Oxide emissions. In the Tier one method, emissions of the above-mentioned gases can be calculated based on fuel consumption data and default emissions factors by applying the following equation:

$$\textbf{Emissions} = \sum \left(\textbf{Fuel consumed}_{ab} \bullet \textbf{Emission factor}_{ab}\right)$$

Where "a" is fuel type and "b" is water-borne navigation type.

However, Tier two also uses the same equation for estimating shipping emissions yet country-specific emission factors with higher precision in fuel type, classification mode, and engine type are required. Based on these variables, the EMEP/CORINAIR emission inventory guidebook provides an in-depth methodology for estimating shipping emissions (IPCC, 2006).

2.1.2 EMEP/EEA Air pollutant emission inventory guidebook

EMEP/EEA air pollutant emission inventory guidebook was previously known as the EMEP CORINAIR emission inventory guidebook. EMEP/EEA emission inventory guidebooks are available from 2006 to 2019. EMEP/EEA air pollutant emission inventory guidebook 2019 was updated in December 2021 (EEA, 2021) and provides three detailed methodological tiers for estimating shipping emissions which include Tier 1 (Default approach), Tier 2 (Technology Specific approach), and Tier 3 (Ship movement methodology). The Tier one method simply uses the mass of fuel consumed with fuel-specific-emissions factors for the type of fuel used. This guidebook also presents emission factors for air pollutants of different types of fuels for all three tiers but it doesn't cover specific GHG emission factors under its scope. However, Tier two and Tier three methodological approaches are only useful when detailed information is available about all required variables i.e. engine types, fuel types, vessel trip phases, etc.

2.1.3 Methodologies used by IMO

IMO has used top-down and bottom-up methodological approaches to estimate global shipping emissions in all its previous studies (IMO, 2009, 2015; 2021b). The top-down approach is based on fuel statistics and the bottom-up approach is based on activity datasets.

2.2 Implications of the existing methodologies for this study

IMO's GHG Studies are based on AIS-transmitted data for the bottom-up approach and fuel consumption data from International Energy Agency (IEA) for the top-down approach. However, significant gaps exist regarding fuel consumption records at the international level for the years i.e. 2012 and 2018 as reported in the third and fourth IMO GHG Studies (IMO, 2015; 2021b). IMO doesn't have the breakdown of actual fuel consumption data vis-à-vis all types/sizes of maritime vessels as they just relied on fuel consumption data provided by IEA. Given the unavailability of data for the study, the period is further challenging in determining the actual extent of global shipping emissions which indicates that the global shipping emissions would be much higher when actual fuel consumption data of all types/sizes of vessels will be incorporated. Moreover, IMO has relied on AIS data for a bottom-up approach; AIS data covers ships of 100 GT and above only associated with an IMO number. Ships below 100 GT don't have an IMO number and mostly fishing crafts and harbor crafts fall in this category hence their record is missing.

Collecting fishing vessel data is technically a difficult task. There is no check and balance on how much fuel vessels consume. Record maintenance is also not streamlined particularly in developing countries. Operational aspects of fishing vessels are not on record to determine the actual fuel consumption by these vessels. So, it raises the question regarding the trend of global shipping emissions when all the missing aspects will be considered. All the aforementioned methodologies evolved over time and have come up to an advanced level where various variables are accounted towards the calculation of GHG emissions. National maritime emission scenarios towards global GHG emissions matter a lot since climate change has no boundaries and these emissions impact globally. So, in developing countries, particularly in the case of Pakistan, the share of all types and sizes of sea-going vessels might be higher than ships for national transportation which is unattended. Given the constraints vis-a-vis time, resources, and the size and scope of the study, this study is trying to attempt an initial preliminary assessment.

2.3 Selection of GHG emissions method for this study

Owing to the limitation of AIS Data for the bottom-up approach and considering the unattended vessels having no IMO number, the best possible method is the top-down method (based on fuel consumption) which is adopted for the current study. To narrow it down further to cover all aspects, an in-depth study is needed, which can be undertaken in the future but this study is also authentic as it is relying on the actual data of fuel consumed by sea-going vessels. This initial preliminary assessment would provide an initial baseline upon which an in-depth study needs to be built. Moreover, it would provide insight into the actual gravity of the problem and scale and trend to foresee its share in national transportation.

2.4 Variables involved

In this study, GHG emissions are taken as a dependent variable, and fuel consumption as a major independent variable. The GHG emissions and fuel consumption of maritime vessels are depending on the type of vessel, size of the vessel, type of fuel used, the average amount of fuel consumed, emission factor of specific greenhouse gas (i.e., CO_2, CH_4, and N_2O) and respective global warming potential. Therefore, GHG emissions depend on a wide range of independent variables as a subgroup of the fuel consumption, which includes type and size of the vessel, type of fuel, fuel consumption vis-a-vis different phases of trips, type of engine, size of the engine, engine speed, engine nominal power, engine load factor, and emission factor of pollutant, etc. (IPCC, 2006; EEA, 2021). However, the GHG emissions will vary depending on the range of variables vis-a-vis methodology selected for the calculation of GHG emissions from maritime vessels.

2.5 Data acquisition

Fleet data of PNSC were collected from Pakistan National Shipping Corporation (PNSC). This data includes annual fuel consumption data of ships vis-à-vis ship type and fuel type for the fiscal year 2021-2022. Data on PMSA's own fleet including ship type, engine type/size, and annual fuel consumption vis-a-vis fuel type were collected from the Pakistan Maritime Security Agency (PMSA). Fuel consumption data of fishing vessels and other crafts of both provinces i.e. Sindh and Balochistan were acquired from the PMSA as well as from consultations with various boat owners and *nakhudas*. A consultation session was arranged with the technical and administrative assistance of WWF-Pakistan (World Wide Fund for Nature) in Karachi to get information and data about the business-as-usual case of fishing vessels' fuel consumption per trip vis-a-vis different types and sizes of boats i.e. big sized (local term: *Launch*), medium-sized (local term: *Hora*) and small-sized (local term: *Dhonda*). Moreover, telephone interviews with random boat owners and *nakhudas* of fishing vessels at fish harbors of Karachi, Korangi, Keti Bandar, Ormara, Pasni, Gwadar, Gadani, and Jiwani were conducted to determine the fuel consumption per trip. Based on PMSA's input and consultation with various relevant actors, gathered data was scrutinized and rationalized to determine the average annual fuel consumption. First of all, fuel consumption data of vessels per trip viz vessels type/size was determined, and then annual fuel consumption was estimated. Annual fuel consumption data of harbor crafts such as dredgers, tugs, barges, floating cranes, and ferry boats were obtained from Karachi Port Trust (KPT) and Port Qasim Authority (PQA).

2.6 Scope of GHGs in this study

Mainly six GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) are considered by the UNFCCC (United Nations Framework Convention on Climate Change) and its Kyoto Protocol (UNCTAD, 2009). Over 90% of the fuel used for transportation is petroleum based such as gasoline and diesel (US EPA, 2022b). As a result of fuel combustion, the majority of the GHGs emitted are carbon dioxide (CO_2) with relatively small amounts of methane (CH_4) and nitrous oxide (N_2O). Moreover, a small amount of hydrofluorocarbons (HFCs) emits from refrigerators and air conditioners (IMO, 2015; US EPA, 2022b). The scope of this study primarily covers three GHGs namely carbon dioxide, methane, and nitrous oxide, resulting from fuel consumption in all types/sizes of sea-going vessels except naval ships. GHGs and their source of emissions from maritime vessels are given in Table 1.

2.7 Selection of GHG emission factors (EFs)

The following emission factors (Table 2) have been selected after a thorough review and cross-examination of factors either developed or remained in use by US-EPA, IMO, and IPCC.

2.8 Normalization of GHG emission factors

As aforementioned, various emission factors of GHGs for various categories of fuels have been retrieved from the literature. All these emission factors were having different units so for avoiding any confusion these emission factors have been normalized and converted to the same unit i.e., kg/gallon. Emissions factors of GHGs for various fuel categories are as follows:

2.8.1 Diesel

The GHG emission factors for diesel are provided in Table 3 hereunder.

2.8.2 Gasoline/petrol

The GHG emission factors for gasoline/petrol are provided in Table 4 hereunder.

TABLE 1 Data retrieved from Third IMO GHG study 2015 and US-EPA.

GHGs	Source of emissions
CO_2	Fuel combustion in internal combustion engines
CH_4	Incomplete combustion of LNG, fuel combustion of heavy fuel oils (HFO), and distillates
N_2O	Fuel combustion
HFCs	Leaks from cooling systems, air conditioners, and refrigerators
PFCs	Fire-fighting foams and leakage from remaining stockpiles
SF_6	Not used in significant quantities on ships however compressed gas cylinders are used to distribute and transport Sulfur Hexafluoride (SF_6) supplies

2.8.3 Marine gas oil (MGO)

The GHG emission factors for marine gas oil (MGO) are provided in Table 5 hereunder.

2.8.4 Very low sulfur fuel oil (VLSFO)

The GHG emission factors for very low Sulfur fuel oil (VLSFO) are provided in Table 6 hereunder.

2.9 Selection of GHG emission calculation method for this study

Tier one method developed by IPCC is selected for this study to calculate GHG emissions and customized according to the need under the scope of the study. The equation is as follows:

$Emissions = \sum (Fuel\ consumed_{ab} \bullet Emission\ factor_{ab})$ (IPCC, 2006)

In the above equation, "a" represents the type of fuel, and "b" represents water-borne navigation type such as boat or ship and possibly the type of engine.

2.9.1 Basis of formulae

Based on fuel consumption data and taking three gases, the following two formulas were developed and used for the calculation of GHG emissions load and GHG emissions in CO_2e with respect to global warming potential (GWP) of all types and sizes of maritime vessels (except naval platforms) in terms of national baseline maritime emissions reference scenario of Pakistan.

Formula Equation 1 - GHG emissions load estimation:

$$\mathbf{GHG\ emissions\ load} = \mathbf{Fuel}_{ac}{}^{*}\left(\sum \mathbf{CO}_2^{ef} + \mathbf{CH}_4^{ef} + \mathbf{N_2O}^{ef}\right), \quad (1)$$

Where;

$ac = average\ consumption$

$CO_2^{ef} = GHG\ Emission\ Fcator\ for\ Carbon\ Dioxide$

$CH_4^{ef} = GHG\ Emission\ Factor\ for\ Methane$

$N_2O^{ef} = GHG\ Emission\ Factor\ for\ Nitrous\ Oxide$

Formula Equation 2 – GHG emissions (CO_2e with respect to GWP):

$$\mathbf{GWP}_{CO2e} = \mathbf{Fuel}_{ac}{}^{*}\left(\sum\left(\propto^{a*}\mathbf{CO}_2^{ef}\right) + \left(\propto^{b*}\mathbf{CH}_4^{ef}\right) + \left(\propto^{c*}\mathbf{N_2O}^{ef}\right)\right), \quad (2)$$

TABLE 2 GHG Emission Factors (EFs) for various fuel categories.

GHG emission factors					
Sr No.	Fuel type	Vessels using fuel	GHG emissions	Emission factors (EFs)	Source of EFs
1	Diesel	PMSA Fleet	CO_2	10.21 (Kg/gallon)	US-EPA - GHG Emission factors Hub 2022 (Pg no. 02)
		Fishing Vessels			
		Passenger Boats	CH_4	6.41 (g/gallon)	US-EPA - GHG Emission factors Hub 2022 (Pg no. 03)
		Water and Fuel carrying Boats			
		Pleasure Boats	N_2O	0.17 (g/gallon)	US-EPA - GHG Emission factors Hub 2022 (Pg no. 03)
		Harbour Crafts (KPT & PQA)			
2	Gasoline/Petrol (2 Stroke)	PMSA Fleet	CO_2	69,300 (kg/TJ)	IPCC Guidelines 2006
		Skiff Boats	CH_4	4.58 (g/gallon)	US-EPA - GHG Emission factors Hub 2022 (Pg no. 03)
			N_2O	0.08 (g/gallon)	US-EPA - GHG Emission factors Hub 2022 (Pg no. 03)
3	Marine Gas Oil (MGO)	PNSC fleet	CO_2	3.206 (g/g fuel)	Third IMO GHG Study 2015
			CH_4	0.00006 (g/g fuel)	Third IMO GHG Study 2015
			N_2O	0.00016 (g/g fuel)	Third IMO GHG Study 2015
4	Very low Sulfur fuel oil (VLSFO)	PNSC fleet	CO_2	3.114 (g/g fuel)	Third IMO GHG Study 2015
			CH_4	0.00006 (g/g fuel)	Third IMO GHG Study 2015
			N_2O	0.00015 (g/g fuel)	Third IMO GHG Study 2015

TABLE 3 GHG emission factors (EFs) for diesel.

GHG emissions	Emission factors (kg/gallon)	Source of EFs
CO_2	10.21	US-EPA - GHG Emission factors Hub 2022 (Pg no. 02)
CH_4	0.00641	US-EPA - GHG Emission factors Hub 2022 (Pg no. 3)
N_2O	0.00017	US-EPA - GHG Emission factors Hub 2022 (Pg no. 03)

TABLE 4 GHG emission factors (EFs) for gasoline/petrol.

GHG emissions	Emission factors (kg/gallon)	Source of EFs
CO_2	9.132	IPCC Guidelines 2006
CH_4	0.00458	US-EPA - GHG Emission factors Hub 2022 (Pg no. 03)
N_2O	0.00008	US-EPA - GHG Emission factors Hub 2022 (Pg no. 03)

Where;

$GWP = Global\ \ warming\ potential$

$CO_{2e} = Equivalent\ to\ Carbon\ Dioxide$

$ac = average\ consumption$

$\propto^{a} = 1\ Global\ Warming\ Potential\ for\ Carbon\ Dioxide)$

$\propto^{b} = 25\ (Global\ Warming\ Potential\ for\ Methane)$

$\propto^{c} = 298\ (Global\ Warming\ Potential\ for\ Nitrous\ Oxide)$

$CO_2^{ef} = GHG\ Emission\ Fcator\ for\ Carbon\ Dioxide$

$CH_4^{ef} = GHG\ Emission\ \ Factor\ for\ Methane$

$N_2O^{ef} = GHG\ Emission\ Factor\ for\ \ Nitrous\ Oxide$

TABLE 5 GHG emission factors (EFs) for marine gas oil (MGO).

GHG emissions	Emission factors (kg/gallon)
CO_2	12.13603
CH_4	0.000227124707
N_2O	0.0006056658854

TABLE 6 GHG emission factors (EFs) for VLSFO.

GHG emissions	Emission factors (kg/gallon)
CO_2	11.787772
CH_4	0.000227124707
N_2O	0.0005678117676

3 Results

This section demonstrates the amount of greenhouse gas emissions resulting from the maritime transportation sector of Pakistan and the carbon offsetting costs for maritime vessels. This assessment would provide insight into the most neglected sector that how all types of vessels vis-à-vis sizes are contributing towards national emissions as a silent contributor. As part of this study, the GHG emissions load of all sea-going vessels and their respective Global Warming Potential (CO_2e) is studied separately.

3.1 GHG emissions from the maritime transportation sector of Pakistan

In this study, Pakistan maritime vessels are classified into six different categories i.e. PNSC's merchant ships; PMSA's surveillance vessels at sea; KPT's port operations' assistance crafts; PQA's port operations' assistance crafts; fishing vessels; and recreational and other crafts. Figure 1 illustrates the total share of GHG emissions (CO_2e) with respect to global warming potential contributed by each category of the sea-going vessel in the maritime transportation sector. Total GHG emissions and warming potential of each gas i.e., carbon dioxide, methane, and nitrous oxide by each category of the sea-going vessel are presented in Table 7 and Table 8. The total greenhouse gas (GHG) emissions with respect to their global warming potential (GWP, CO_2e) including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), of Pakistan's maritime transportation sector, are 2,468,789.21 tonnes (CO_2e) based on annual fuel consumption for the year 2021-2022. Maritime vessels consumed a total of 310,885.75 tonnes of fuel for the aforementioned period including diesel, petrol, marine gas oil (MGO), and very low sulfur fuel oil (VLSFO).

The results demonstrate that carbon dioxide is the highest emitting GHG from the maritime transportation sector of Pakistan. Carbon dioxide emissions from all types and sizes of maritime vessels amounted to 2,423,211.88 tonnes while

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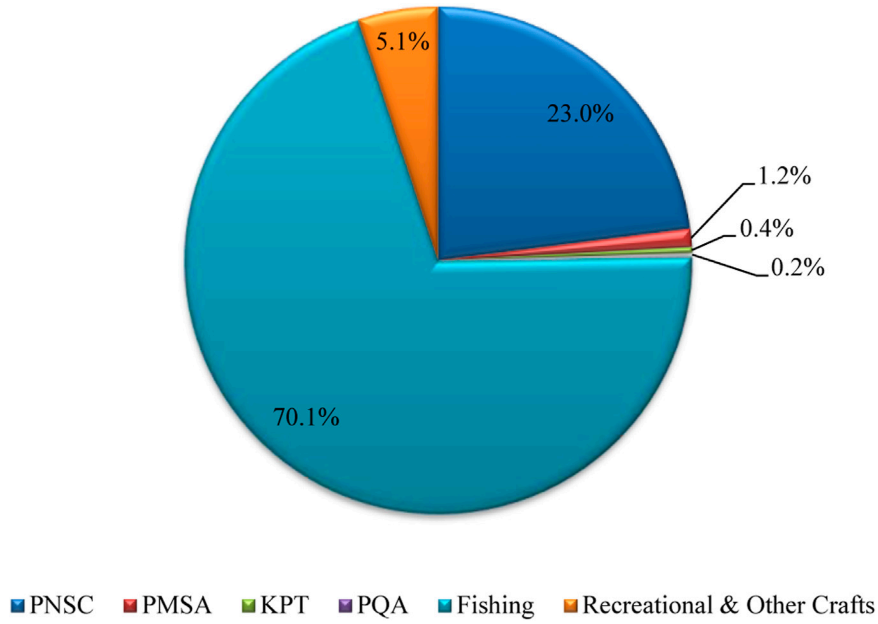

FIGURE 1
Share of GHG emissions (CO_2e) from maritime vessels **(A)**PNSC: Pakistan National Shipping Corporation **(B)** PMSA: Pakistan Maritime Security Agency **(C)**KPT: Karachi Port Trust **(D)** PQA: Port Qasim Authority **(E)**Fishing vessels **(F)**Recreational and other crafts such as skiff boats, passenger boats, water and fuel carrying boats.

TABLE 7 Total GHG emissions load from each category of maritime vessels.

Categories of Maritime vessels	Annual fuel consumption (tonnes/annum)	GHG emissions load (tonnes/annum)			
		CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions load
PNSC	63,393.17	559,309.84	10.77	26.96	559,347.57
PMSA	3,691.85	28,172.62	17.66	0.47	28,190.75
KPT	1,122.60	8,573.98	5.38	0.14	8,579.51
PQA	722.97	5,521.74	3.47	0.09	5,525.30
Fishing vessels	224,261.22	1,697,300.77	1,049.00	27.22	1,698,376.99
Recreational and other crafts	17,693.94	124,332.93	66.50	1.35	124,400.78
Total	**310,885.75**	**2,423,211.88**	**1,152.77**	**56.23**	**2,424,420.89**

Bold are used for total values.

methane (CH_4) and nitrous oxide (N_2O) emissions are 1,152.77 tonnes and 56.23 tonnes respectively. Results show that fishing vessels are the largest contributors to maritime GHG emissions. Fishing vessels are responsible for 1,731,638.31 tonnes of GHG emissions (CO_2e) having a total share of 70.1% of the country's total maritime vessel emissions. Similarly, PNSC's merchant ships are the second largest emitters of GHGs which corresponds to a 23% share with emissions of 567,613.48 tonnes (CO_2e). The third GHG contributor i.e. recreational and other crafts accounting for 126,397.07 tonnes (CO_2e) have a total of 5.1% share in maritime emissions followed by sea-going vessels of PMSA, KPT, and PQA. PMSA's surveillance vessels are responsible for 28,753.46 tonnes (CO_2e) emissions, along with port operations' assistance crafts of KPT and PQA accounting for 8,751.10 and 5,635.80 tonnes (CO_2e) and these three collectively have a share of 1.8% in total GHG emissions from the maritime sector of Pakistan.

TABLE 8 Global Warming Potential (GWP, CO_2e) from each category of maritime vessels and respective carbon offset cost.

Categories of Maritime vessels	Annual fuel consumption (tonnes/ annum)	Global warming potential (tonnes CO_2e/annum)				Carbon offset cost/ annum (US$)
		CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions	
PNSC	63,393.17	559,309.84	269.26	8,034.38	567,613.48	8,514,202.20
PMSA	3,691.85	28,172.62	441.53	139.30	28,753.46	431,301.84
KPT	1,122.60	8,573.98	134.57	42.54	8,751.10	131,266.47
PQA	722.97	5,521.74	86.67	27.40	5,635.80	84,537.02
Fishing	224,261.22	1,697,300.77	26,224.88	8,112.66	1,731,638.31	25,974,574.64
Recreational and other crafts	17,693.94	124,332.93	1,662.45	401.68	126,397.07	1,895,955.98
Total	**310,885.75**	**2,423,211.88**	**28,819.36**	**16,757.96**	**2,468,789.21**	**37,031,838.14**

Bold are used for total values.

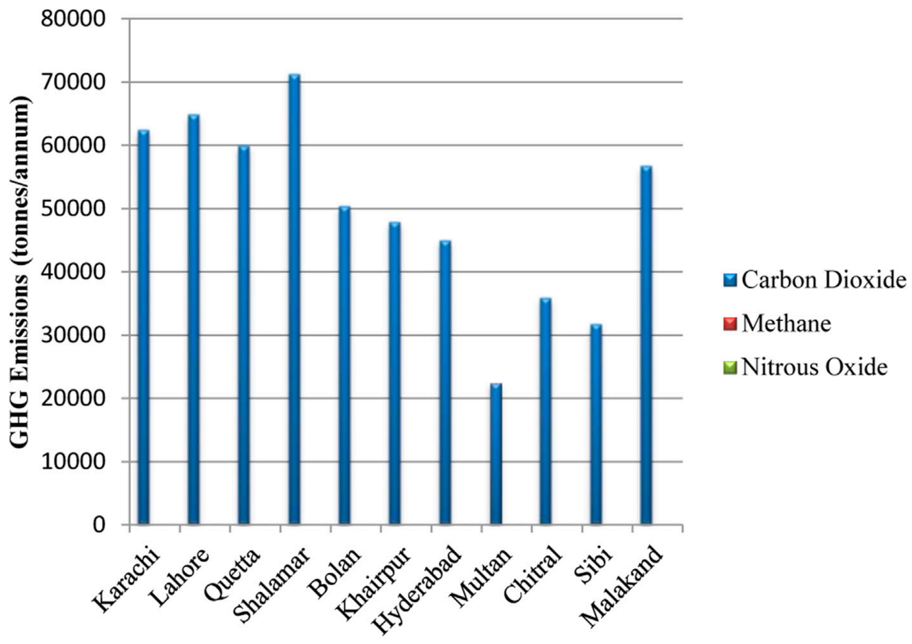

FIGURE 2
Breakdown of annual GHG emission load from all vessels of PNSC based on fuel consumption (VLSFO).

3.2 Breakdown of GHG emissions from sea-going vessels

A detailed breakdown of GHG emissions from each type of sea-going vessel is given below:

3.2.1 PNSC's merchant ships

Pakistan National Shipping Corporation (PNSC) is a national flag carrier and provides effective shipping services to other countries and seaborne trade in Pakistan (PNSC, 2015). Currently, Pakistan National Shipping Corporation (PNSC) has

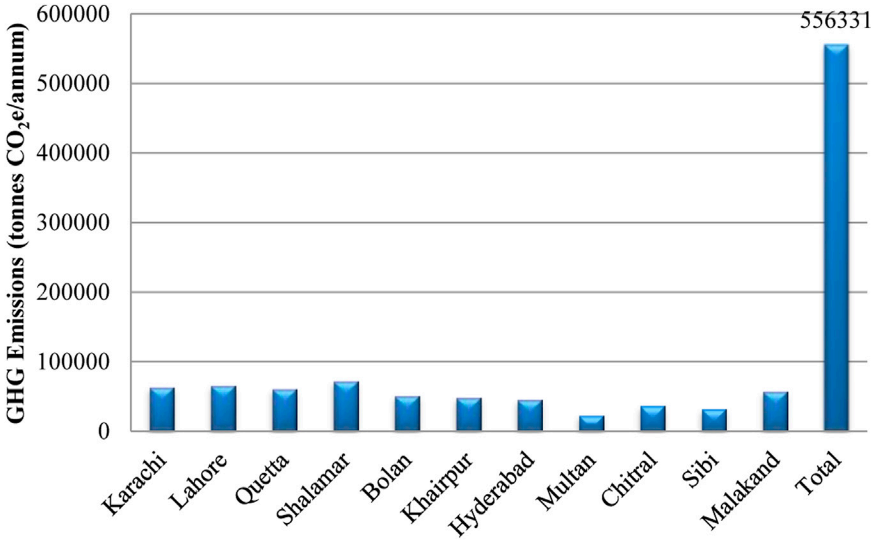

FIGURE 3
Total annual GHG emissions (CO_2e) from PNSC fleet based on fuel consumption (VLSFO).

TABLE 9 Breakdown of total GHG Emissions from PNSC's fleet based on fuel consumption of VLSFO.

Vessel type	Vessel name	Annual GHG emissions load (tonnes/annum)				Total annual GHG emissions (tonnes CO_2e/annum)			
		CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions
Tanker	Karachi	62421.67	1.20	3.01	62425.88	62421.67	30.07	896.03	63347.77
Tanker	Lahore	64837.77	1.25	3.12	64842.14	64837.77	31.23	930.72	65799.71
Tanker	Quetta	59908.58	1.15	2.89	59912.62	59908.58	28.86	859.96	60797.40
Tanker	Shalamar	71239.54	1.37	3.43	71244.34	71239.54	34.32	1022.61	72296.46
Tanker	Bolan	50350.01	0.97	2.43	50353.41	50350.01	24.25	722.75	51097.02
Tanker	Khairpur	47828.10	0.92	2.30	47831.33	47828.10	23.04	686.55	48537.69
Bulk Carrier	Hyderabad	44953.48	0.87	2.17	44956.51	44953.48	21.65	645.29	45620.42
Bulk Carrier	Multan	22432.65	0.43	1.08	22434.16	22432.65	10.81	322.01	22765.47
Bulk Carrier	Chitral	35835.81	0.69	1.73	35838.22	35835.81	17.26	514.41	36367.47
Bulk Carrier	Sibi	31664.96	0.61	1.53	31667.09	31664.96	15.25	454.54	32134.74
Bulk Carrier	Malakand	56725.33	1.09	2.73	56729.16	56725.33	27.32	814.27	57566.92
Total		**548197.90**	**10.56**	**26.41**	**548234.87**	**548197.90**	**264.06**	**7869.12**	**556331.09**

Bold are used for total values.

a total of 13 ships; out of which eight are tankers and five are bulk carriers. The vessel names of the tankers are Khairpur, Bolan, Quetta, Lahore, Karachi, Shalamar, Mardan, and Sargodha whereas Chitral, Malakand, Hyderabad, Sibi, and Multan are bulk carriers. Two tankers (Mardan and Sargodha) have been added to PNSC's fleet recently however only 11 ships were

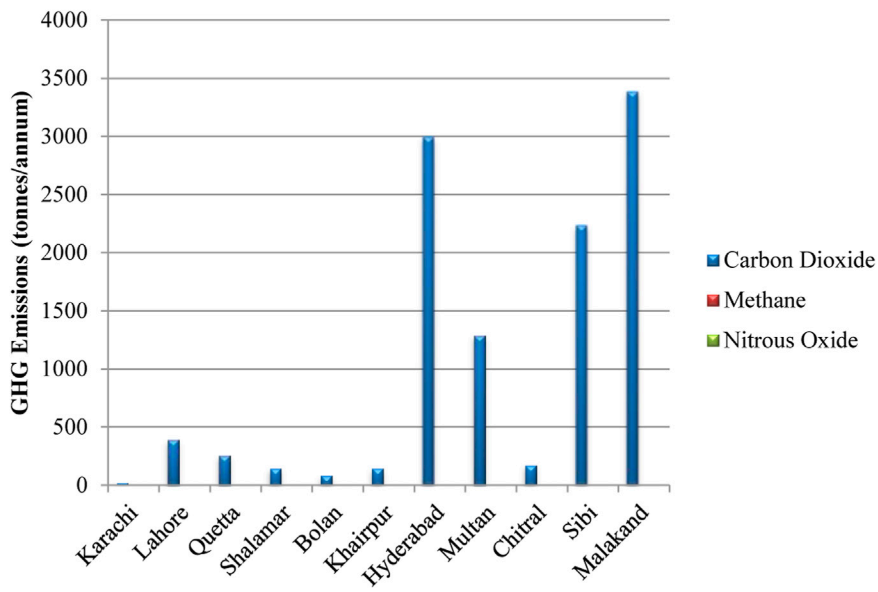

FIGURE 4
Breakdown of annual GHG emissions load from all vessels of PNSC based on fuel consumption (MGO).

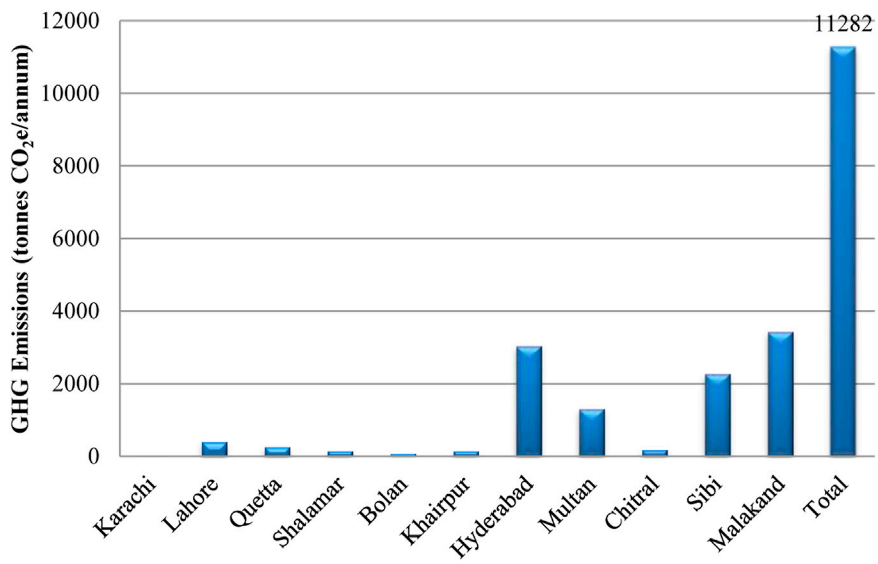

FIGURE 5
Total annual GHG emissions (CO_2e) from PNSC fleet based on fuel consumption (MGO).

operational on the ground during the study period. Figure 2 represents the breakdown of GHG emission (CO_2, CH_4, N_2O) load from all merchant ships of PNSC based on annual fuel consumption i.e. Very Low Sulfur Fuel Oil (VLSFO) for the fiscal year 2021 to 2022. Whereas6, Figure 3 illustrates the total annual GHG emissions (CO_2e) from the PNSC fleet. A detailed breakdown of GHG emissions from PNSC's fleet resulting from the consumption of VLSFO is presented in Table 9.

The results depict that PNSC's fleet accounted for a total of 556,331.09 tonnes of GHG emissions (CO_2e) annually based on the fuel consumption of VLSFO. As shown in Figure 2, Shalamar is contributing the highest amount of

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TABLE 10 Breakdown of total GHG Emissions from PNSC fleet based on fuel consumption of MGO.

Vessel type	Vessel name	Annual GHG emissions load (tonnes/annum)				Total annual GHG emissions (tonnes CO_2e/annum)			
		CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions
Tanker	Karachi	18.16	0.00	0.00	18.16	18.16	0.01	0.27	18.44
Tanker	Lahore	390.37	0.01	0.02	390.40	390.37	0.18	5.81	396.36
Tanker	Quetta	254.19	0.00	0.01	254.21	254.19	0.12	3.78	258.09
Tanker	Shalamar	145.25	0.00	0.01	145.26	145.25	0.07	2.16	147.48
Tanker	Bolan	81.71	0.00	0.00	81.71	81.71	0.04	1.22	82.96
Tanker	Khairpur	145.25	0.00	0.01	145.26	145.25	0.07	2.16	147.48
Bulk Carrier	Hyderabad	2995.87	0.06	0.15	2996.07	2995.87	1.40	44.55	3041.82
Bulk Carrier	Multan	1289.13	0.02	0.06	1289.22	1289.13	0.60	19.17	1308.91
Bulk Carrier	Chitral	172.49	0.00	0.01	172.50	172.49	0.08	2.57	175.14
Bulk Carrier	Sibi	2233.28	0.04	0.11	2233.43	2233.28	1.04	33.21	2267.54
Bulk Carrier	Malakand	3386.24	0.06	0.17	3386.47	3386.24	1.58	50.36	3438.18
Total		**11111.94**	**0.21**	**0.55**	**11112.70**	**11111.94**	**5.20**	**165.26**	**11282.40**

Bold are used for total values.

carbon dioxide emissions i.e. 71,239.54 tonnes followed by Lahore and Karachi with emissions of 64,837.77 tonnes and 62,421.67 tonnes respectively. Malakand, Quetta, Bolan, Khairpur, Hyderabad, Chitral, Sibi, and Multan also have a significant share of global CO_2 emissions. On contrary, methane (CH_4) and nitrous oxide (N_2O) emissions from all vessels are negligible**.**

Figure 4 represents the breakdown of GHG emissions (CO_2, CH_4, N_2O) load from all vessels of PNSC based on annual fuel consumption i.e. Marine gas oil (MGO) whereas, Figure 5 illustrates total annual GHG emissions (CO_2e) for PNSC's fleet. A detailed breakdown of GHG emissions from PNSC's fleet resulting from the consumption of MGO is presented in Table 10. Results depict that PNSC's fleet accounted for a total of 11,282.40 tonnes of GHG emissions (CO_2e) based on annual fuel consumption i.e. Marine Gas Oil (MGO) for the fiscal year 2021 to 2022. As shown in Figure 4, Malakand, followed by Hyderabad and Sibi, are the leading contributors to global carbon dioxide emissions, contributing 3,386.24 tonnes, 2,995.87 tonnes, and 2,233.28 tonnes per annum respectively. On the other hand, methane (CH_4), and nitrous oxide (N_2O) emissions from all merchant's vessels are very low.

3.2.2 PMSA's fleet

Pakistan Maritime Security Agency (PMSA) is a law enforcement agency that is controlled and managed by Pakistan Navy. Currently, PMSA has a total of 34 vessels which includes 15 hundred tons maritime patrol vessels (15 HT MPVs); 6 hundred tons maritime patrol vessels (6 HT MPVs); corvettes (397 tons); island class (250 tons), and inland patrol boats. Figure 6 illustrates the breakdown of annual GHG emissions load from all types of vessels of PMSA. Figure 7 shows the total annual GHG emissions (CO_2e) from the PMSA fleet. A detailed breakdown of annual GHG emissions from PMSA's fleet is presented in Table 11. Results show that the total GHG emissions from the PMSA fleet accounted for 28,753.46 tonnes (CO_2e) based on annual fuel consumption of 3,691.85 tonnes for the period 2021-2022. As shown in Figure 6, 6HT MPVs are leading contributors to carbon dioxide with emissions of 17,505.40 tonnes followed by the second highest contributor i.e. 15HT MPVs with emissions of 8,549.84 tonnes annually. However, Corvettes (397 tons), Island Class (250 tons), Inland Patrol Boats (caterpillar-C9), and Inland Patrol Boats – OBM (outboard motor) are responsible for 1,090.34 tonnes, 418.71 tonnes, 205.25 tonnes, and 403.07 tonnes of carbon dioxide. Whereas, on other hand,

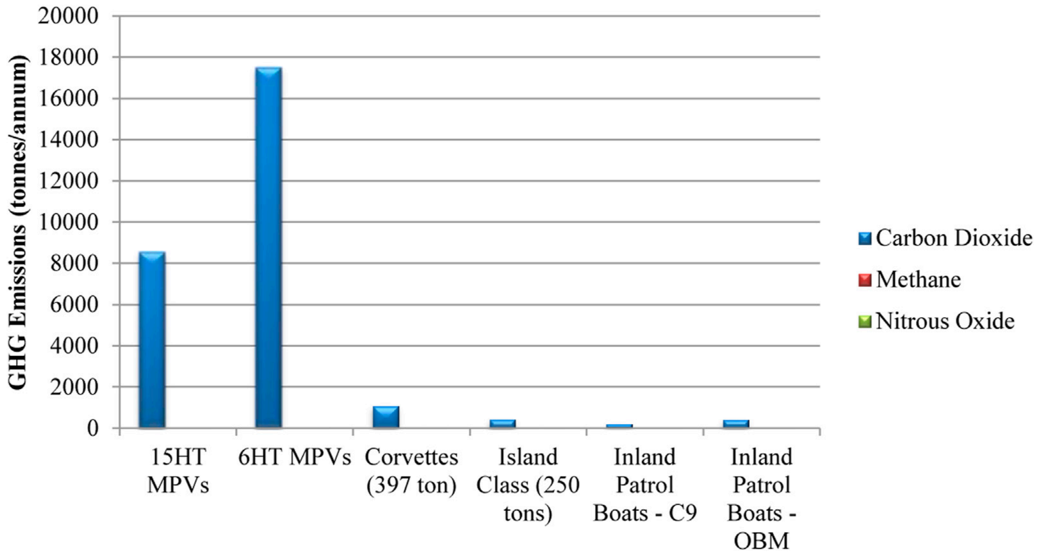

FIGURE 6
Breakdown of annual GHG emissions load from all types of PMSA vessels.

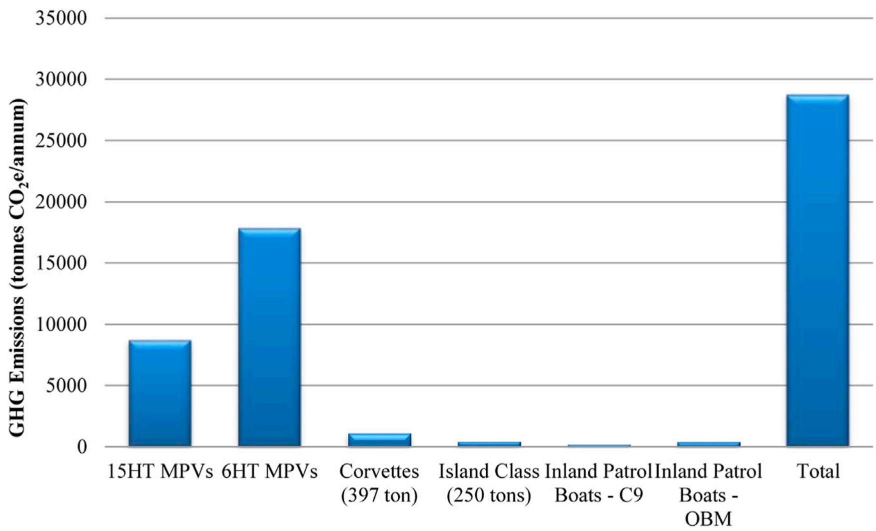

FIGURE 7
Total annual GHG emissions (CO_2e) from PMSA fleet.

annual emissions of methane (CH_4) and nitrous oxide (N_2O) are very low.

3.2.3 Karachi port trust

Karachi Port Trust (KPT) is a federal government agency administered by Federal Maritime Secretary. KPT manages the operations of the Karachi port through several harbour crafts which include dredgers, tugs, barges, floating cranes, and ferry boats. Figure 8 illustrates the breakdown of GHG emissions load from all types of harbour crafts of KPT. Figure 9 shows the total annual GHG emissions (CO_2e) from harbour crafts of KPT. Table 12 presents a detailed breakdown of annual GHG emissions resulting from fuel consumption of harbour crafts of KPT. Results show that

TABLE 11 Breakdown of total GHG Emissions from PMSA Fleet.

Vessel type	Annual GHG emissions load (tonnes/annum)				Total annual GHG emissions (tonnes CO_2e/annum)			
	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions
15HT MPVs	8549.84	5.37	0.14	8555.35	8549.84	134.19	42.42	8726.46
6HT MPVs	17505.40	10.99	0.29	17516.68	17505.40	274.75	86.86	17867.02
Corvettes (397 ton)	1090.34	0.68	0.02	1091.04	1090.34	17.11	5.41	1112.87
Island Class (250 tons)	418.71	0.26	0.01	418.98	418.71	6.57	2.08	427.36
Inland Patrol Boats-C9	205.25	0.10	0.00	205.35	205.25	2.57	0.54	208.36
Inland Patrol Boats-OBM	403.07	0.25	0.01	403.33	403.07	6.33	2.00	411.40
Total	**28172.62**	**17.66**	**0.47**	**28190.75**	**28172.62**	**441.53**	**139.30**	**28753.46**

Bold are used for total values.

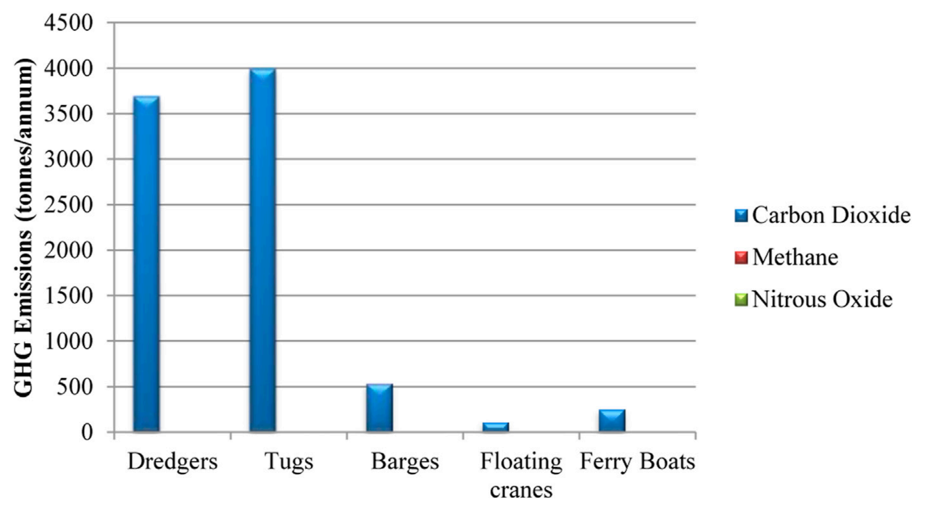

FIGURE 8
Breakdown of GHG emissions load from all types of harbour crafts of KPT.

the total annual GHG emissions from the harbour crafts of KPT accounted for 8,751.10 tonnes of CO_2e emissions based on annual fuel consumption of 1,122.60 tonnes of diesel and petrol for the years 2021-2022. Figure 8 depicts that tugs are the leading emitters of carbon dioxide among all other types with an annual emission of 3,994.14 tonnes followed by dredgers with emissions of 3,689.77 tonnes of CO_2. On other hand, barges, ferry boats, and floating cranes are responsible for 534.04 tonnes, 248.14 tonnes, and 107.89 tonnes of CO_2 respectively with negligible amounts of CH_4 and N_2O.

3.2.4 Port qasim authority

Several harbour crafts are used by Port Qasim Authority (PQA) to manage and facilitate the operations at Port Qasim including tugs, pilot boats, and small boats. Figure 10 presents the breakdown of the annual GHG emissions load and Figure 11 illustrates the total annual GHG emissions (CO_2e) from the harbour crafts of PQA. Results illustrate that the total GHG emissions from harbour crafts of PQA are 5,635.80 tonnes (CO_2e) per annum based on annual fuel consumption of 722.97 tonnes of high-speed diesel (HSD). Carbon dioxide is the highest emitted greenhouse gas with emissions of

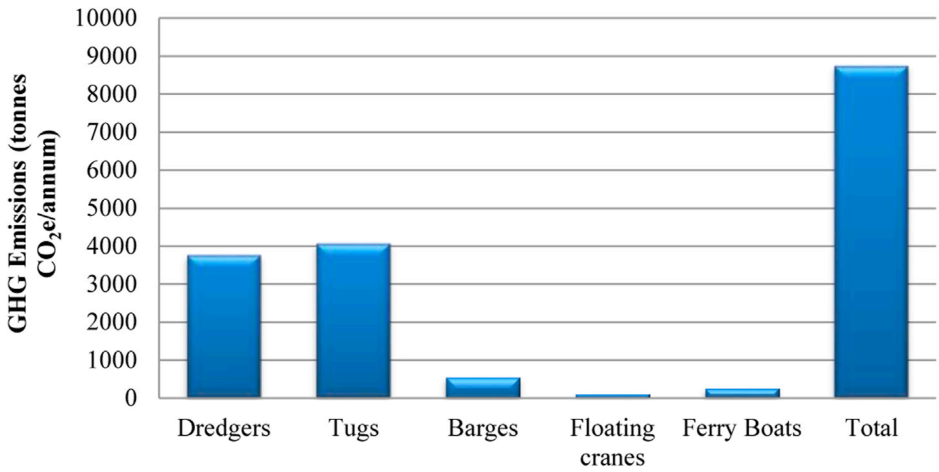

FIGURE 9
Total annual GHG emissions (CO_2e) from harbour crafts of KPT.

TABLE 12 Breakdown of total annual GHG emissions from harbour crafts of KPT.

Vessel type	Annual GHG emissions load (tonnes/annum)				Total annual GHG emissions (tonnes CO_2e/annum)			
	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emission	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emission
Dredgers	3689.77	2.32	0.06	3692.14	3689.77	57.91	18.31	3765.99
Tugs	3994.14	2.51	0.07	3996.72	3994.14	62.69	19.82	4076.65
Barges	534.04	0.34	0.01	534.39	534.04	8.38	2.65	545.08
Floating cranes	107.89	0.07	0.00	107.96	107.89	1.69	0.54	110.12
Ferry Boats	248.14	0.16	0.00	248.30	248.14	3.89	1.23	253.27
Total	**8573.98**	**5.38**	**0.14**	**8579.51**	**8573.98**	**134.57**	**42.54**	**8751.10**

Bold are used for total values.

5,521.74 tonnes annually as shown in Figure 10. Relatively, annual emissions of methane and nitrous oxide are very low i.e. 3.47 and 0.09 tonnes respectively.

3.2.5 Fishing and other crafts in sindh

There are a total number of 21,899 ships currently operational in the Sindh Province of Pakistan which includes fishing vessels, skiff boats, passenger boats, water and fuel carrying boats, and pleasure boats. Figure 12 shows the breakdown of GHG emissions load from all types of sea-going vessels in Sindh based on annual fuel consumption. Figure 13 presents the total annual GHG emissions (CO_2e) from fishing vessels and other crafts in Sindh. A detailed breakdown of GHG Emissions from fishing and all other types of crafts in Sindh is provided in Table 13. Results demonstrate a total amount of 1,467,672.71 tonnes of GHG emissions (CO_2e) emitted from fishing vessels and all other types of crafts in Sindh based on annual fuel consumption of diesel and petrol for the period 2021–2022. Fishing vessels are the largest contributor to carbon dioxide emissions among all other types of sea-going vessels. Fishing vessels are responsible for 1,391,615.06 tonnes of CO_2 emissions. Emissions from skiff boats are 42,719.30 tonnes of CO_2. Water and fuel-carrying boats, passenger boats, and pleasure boats are responsible for 2,623.92 tonnes, 753.21 tonnes, and 487.37 tonnes of CO_2 respectively. On contrary, methane and nitrous oxide emissions are very low.

3.2.6 Fishing and other crafts in balochistan

A total number of 6,837 ships are currently operational in the Balochistan Province of Pakistan which includes fishing vessels, skiff boats, passenger boats, and water and fuel-

TABLE 13 Breakdown of GHG Emissions from Fishing and other crafts in Sindh, Pakistan.

Vessel type	Annual GHG emissions load (tonnes/annum)				Total annual GHG emissions (tonnes CO_2e/annum)			
	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions
Fishing vessels (Big-Sized)	628394.34	394.52	10.46	628799.32	628394.34	9862.90	3117.97	641375.21
Fishing vessels (Medium-Sized)	518000.96	325.21	8.62	518334.80	518000.96	8130.23	2570.22	528701.41
Fishing vessel (Small-Sized)	39779.99	24.97	0.66	39805.63	39779.99	624.36	197.38	40601.74
	205439.77	128.98	3.42	205572.17	205439.77	3224.46	1019.35	209683.58
Skiff Boats	42719.30	21.43	0.37	42741.10	42719.30	535.63	111.52	43366.45
Passenger Boats	753.21	0.47	0.01	753.69	753.21	11.82	3.74	768.77
Water and fuel carrying Boats	2461.46	1.55	0.04	2463.05	2461.46	38.63	12.21	2512.31
	162.46	0.10	0.00	162.56	162.46	2.55	0.81	165.81
Pleasure Boats	487.37	0.31	0.01	487.68	487.37	7.65	2.42	497.44
Total	**1438198.86**	**897.53**	**23.61**	**1439120.00**	**1438198.86**	**22438.23**	**7035.62**	**1467672.71**

Bold are used for total values.

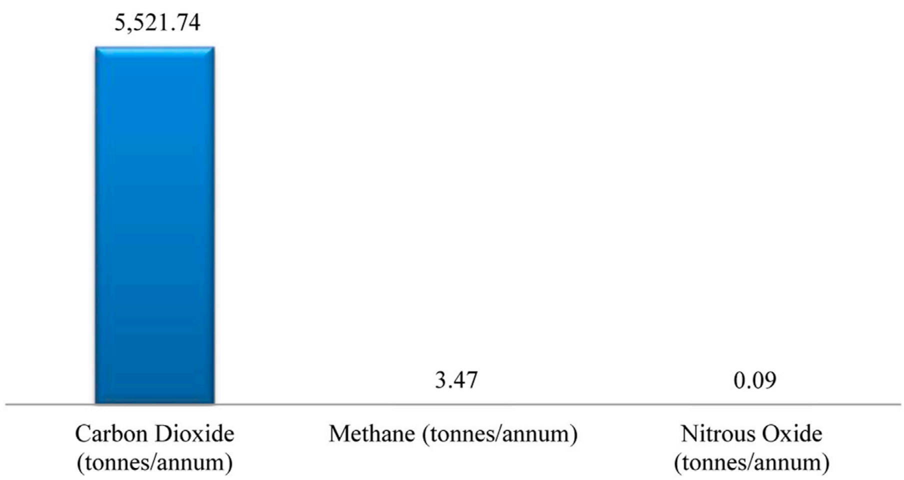

FIGURE 10
Annual GHG emissions load (tonnes/annum) from harbour crafts of PQA.

carrying boats. Figure 14 shows the breakdown of GHG emissions (CO_2, CH_4, and N_2O) from all types of sea-going vessels in Balochistan based on annual fuel consumption. Figure 15 illustrates the total annual GHG emissions (CO_2e) from fishing vessels and other crafts in Balochistan. A detailed breakdown of GHG Emissions from fishing and all other types of crafts in Balochistan is provided in Table 14 The results demonstrate a total amount of 390,362.66 tonnes of GHG emissions (CO_2e) emitted from fishing vessels and all other types of crafts in Balochistan based on annual fuel consumption for the period 2021–2022. Figure 14 depicts that fishing vessels are the largest contributor to carbon dioxide emissions among all other types of sea-going vessels. Fishing vessels are responsible for 305,685.70 tonnes of CO_2 emissions. Emissions from skiff boats are 48,822.06 tonnes of CO_2. Passenger boats and water and fuel-carrying boats are responsible for 24,102.61 tonnes and 4,824.46 tonnes of CO_2. On contrary, methane and nitrous oxide emissions from all types of sea-going vessels are very low.

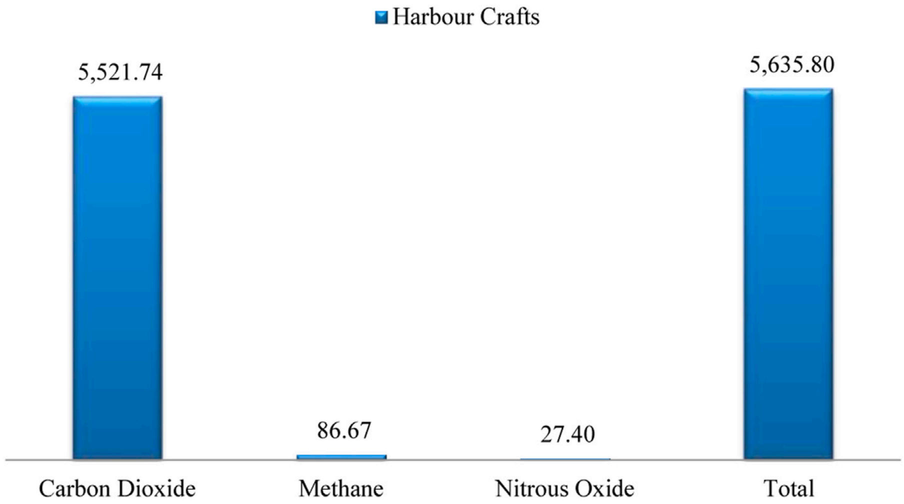

FIGURE 11
Total annual GHG emissions (tonnes CO_2e/annum) from harbour crafts of PQA.

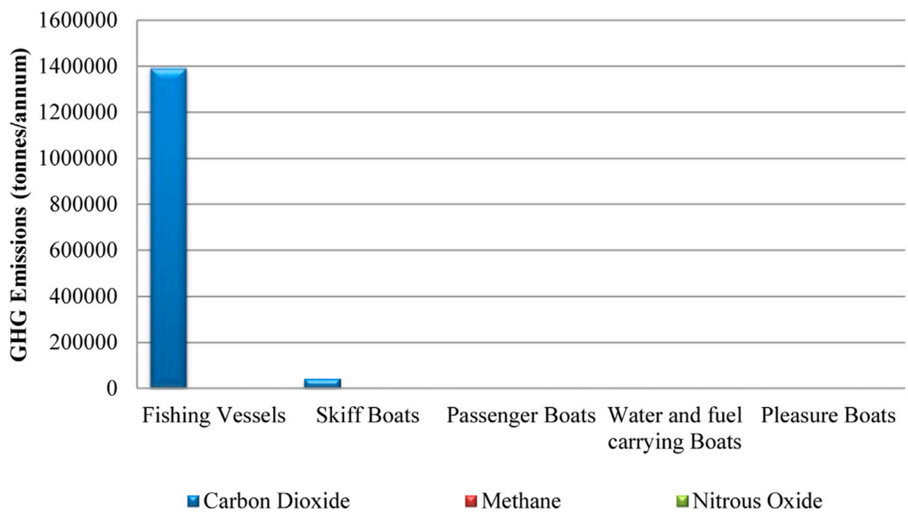

FIGURE 12
Breakdown of GHG emissions load from fishing vessels and other crafts in sindh, Pakistan.

3.3 Comparison among all types of sea-going vessels in Pakistan

Figure 16 presents the share of all types/sizes of maritime vessels in the country's total maritime transportation sector emissions. Results depict that fishing vessels are the largest contributor to maritime GHG emissions. Fishing vessels are responsible for 1,731,638.32 tonnes of GHG emissions (CO_2e) having a total share of 70.14% of the country's total emissions from the maritime transportation sector. Tankers are the second largest contributors accounting for 362,926.87 tonnes of GHG emissions (CO_2e). Tankers have a share of 14.70% of overall maritime transportation sector emissions. Tankers are followed by bulk carriers and skiff boats. Bulk carriers account for 204,686.61 tonnes of CO_2e emissions with a share of 8.29%. Similarly, Skiff boats have a share of 3.76% with annual GHG emissions of 92,928.11 tonnes of CO_2e. 6HT MPVs and Passenger Boats represent around 2% of GHG emissions having a value of 17,867.02 and 25,369.28 tonnes of CO_2e respectively. The rest of the vessels altogether contributes 1% of the share towards national maritime GHG emissions.

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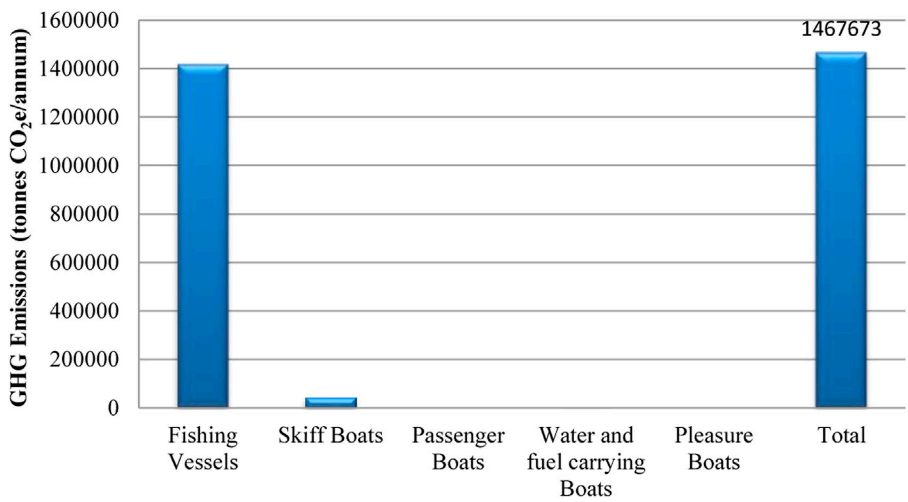

FIGURE 13
Total annual GHG emissions (CO_2e) from fishing and other crafts in sindh.

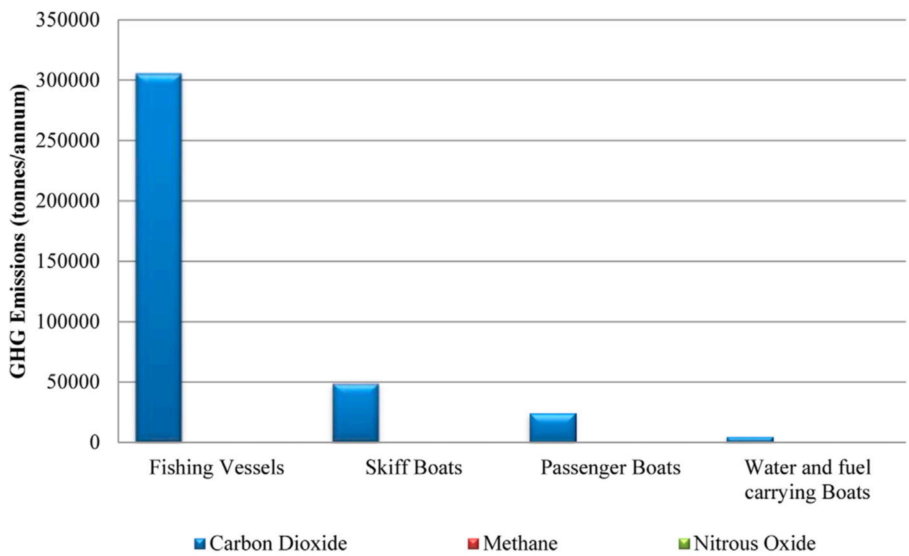

FIGURE 14
Breakdown of GHG emissions from fishing vessels and other crafts in Balochistan, Pakistan.

3.4 Calculations of mangroves vis-a-vis carbon offset cost

The area required for mangrove forest vis-à-vis carbon offset scheme is given in Table 15. Mangroves which are recognized as "Blue carbon sinks" sequester 308 kg of carbon dioxide emissions from the atmosphere per tree and 3,082.8 metric tonnes of CO_2e are sequestered by mature mangrove forests per hectare based on average growth life i.e. 25 years (Donato et al., 2011; Fatoyinbo et al., 2018; Projects, 2020). Results show that 1 ha of mature mangrove forest will remove 123.312 metric tonnes of CO_2e per year hence 20,020 hectares of mature mangrove forest are required to remove 2,468,789.21 metric tonnes of CO_2e emissions from the atmosphere in a timeline of 1 year.

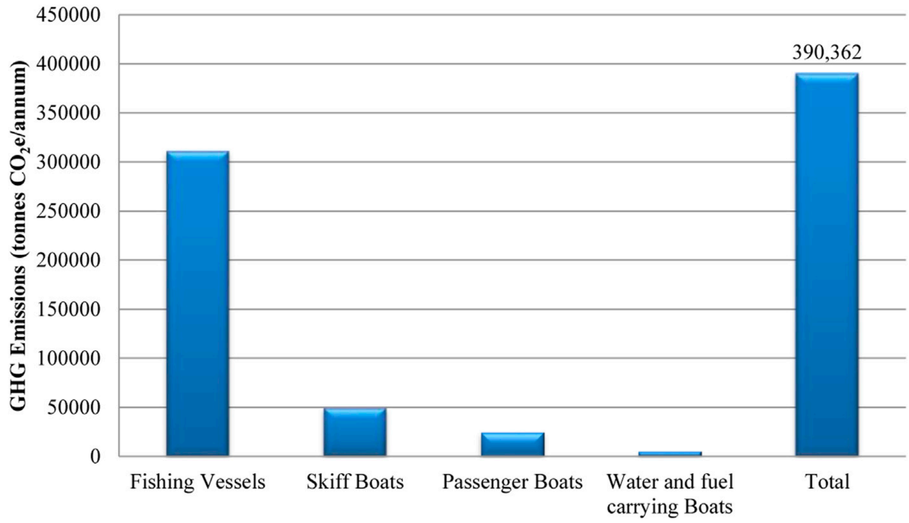

FIGURE 15
Total annual GHG emissions (CO_2e) from fishing and other crafts in Balochistan.

TABLE 14 Breakdown of GHG Emissions from fishing and other crafts in Balochistan, Pakistan.

Vessel type	Annual GHG emissions load (tonnes/annum)				Total annual GHG emissions (tonnes CO_2e/annum)			
	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions
Fishing vessels (Big-Sized)	138504.25	86.96	2.31	138593.51	138504.25	2173.88	687.23	141365.36
Fishing vessels (Medium-Sized)	35753.61	22.45	0.60	35776.65	35753.61	561.17	177.40	36492.18
Fishing vessel (Small-Sized)	3711.28	1.86	0.03	3713.18	3711.28	46.53	9.69	3767.51
	127716.56	64.05	1.12	127781.73	127716.56	1601.35	333.42	129651.33
Skiff Boats	48822.06	24.49	0.43	48846.97	48822.06	612.15	127.45	49561.66
Passenger Boats	24102.61	15.13	0.40	24118.15	24102.61	378.30	119.59	24600.51
Water and fuel carrying Boats	4824.46	3.03	0.08	4827.57	4824.46	75.72	23.94	4924.12
Total	**383434.84**	**217.96**	**4.96**	**383657.76**	**383434.84**	**5449.10**	**1478.72**	**390362.66**

Bold are used for total values.

4 Discussion

The overall results of the study revealed that the total GHG emissions from all types and sizes of maritime vessels (excluding naval platforms) in Pakistan are 2,468,789.21 tonnes (CO_2e) as a result of annual fuel consumption of 310,885.75 tonnes for the period 2021–2022. The business-as-usual case of all types and sizes of maritime vessels in Pakistan has a 4.9% share of reported total emissions from the transportation sector i.e. 51.3 million tonnes (CO_2e) in Pakistan's updated NDC 2021 (GoP, 2021b). Whereas, Pakistan's Second Communication on Climate Change had reported only a 1% share (0.413 million tonnes CO_2e) of maritime vessels in overall transportation sector GHG emissions i.e. 41.197 million tonnes CO_2 (GoP, 2018). (Villalba and Gemechu 2011a) highlighted that the allocation of shipping emissions has been the subject of significant controversy (Villalba and Gemechu, 2011b). Although there

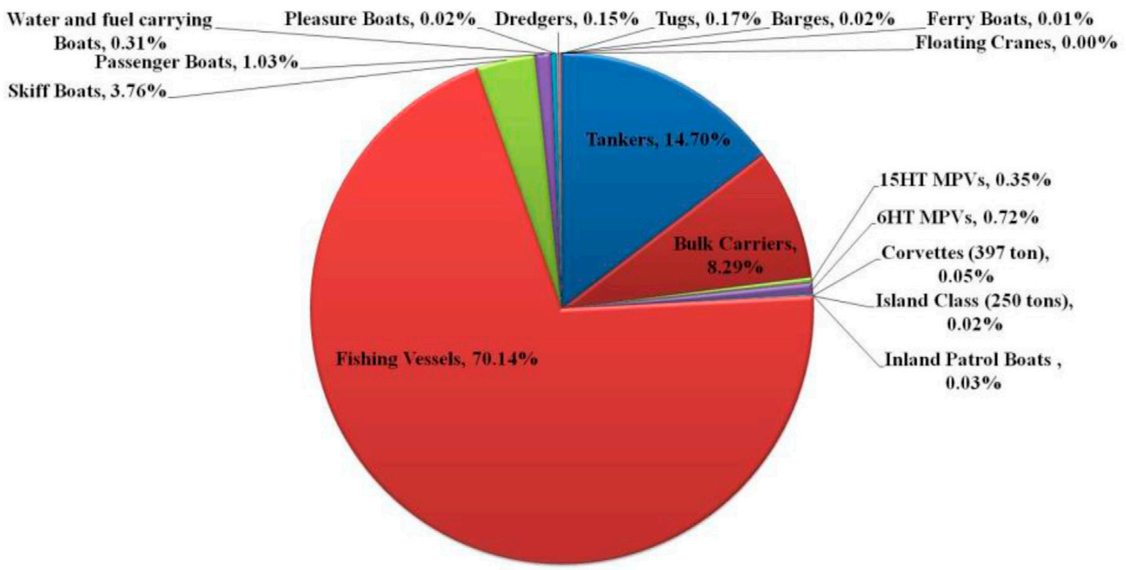

FIGURE 16
Share of GHG emissions (CO_2e) from all types/sizes of maritime vessels.

TABLE 15 Mangroves vis-a-vis carbon offset scheme.

Description	Mangrove forest area (Hectare)	Carbon offset (Metric tonnes of CO_2e)
Carbon offset/Area based on average life span (25 years)	1	3,082.8
Carbon offset/Area based on 1 year duration	1	123.312
	20,020	2,468,789.21

is a conflict about which emissions should be counted or not counted in the national GHGs inventory vis-à-vis concerns about international voyage-based emissions, the emissions of PNSC's merchant ships and other crafts should be counted towards the flag state of maritime vessels considering the responsibility, commitments, and strategies of a country towards climate mitigation response.

It is significant to mention that fishing vessels are the largest emitters of GHG emissions (CO_2e) accounting for 1,731,638.32 tonnes among all types of sea-going vessels and have a 70% share of the total GHG emissions from the maritime transportation sector. During interviews with various boat owners and *Nakhudas* from Sindh and Baluchistan, it was found that all kinds of fishing are banned during breeding seasons in June and July. Above mentioned fishing vessels' emissions are for 10 months excluding June and July. Even then, fishing vessels have dominated as the highest emitters of greenhouse gases.

On one side, fishing vessels, recreational and other crafts collectively are responsible for 75% of the total maritime emissions which are ignored and unaccounted for in the national GHG inventories. It is also quite evident from the study of Parker et al. (2018) that marine fishing fleet is often excluded from global GHGs assessments. The findings of this study revealed that the global fishing fleet accounted for 179 million tonnes of CO_2e as a result of 40 billion liters of fuel consumption in 2011 (Parker et al., 2018). On the other side, IMO covered ships of 100 GT and above only for the estimation of global GHG emissions, ignoring ships below 100 GT in which a large number of maritime vessels fall. Fishing vessels, recreational and other crafts are used for multiple purposes in a huge number, and a substantial amount of fuel is consumed, which has not received due attention from authorities or policymakers at the national or international levels. How can the role and impact of the aforementioned vessels be ignored when they have the highest and most significant share of GHG emissions in the maritime sector? Supporting evidence is also reported by Coello et al. (2015) and Endresen et al. (2007) that a significant underestimating of emissions from the maritime sector is non-etheless anticipated to occur from the exclusion of fishing vessels below 100 GT.

Alarmingly, the contribution of GHG emissions from the business-as-usual case of maritime vessels would exceed the calculated value when the fuel consumption of naval ships will be taken into account. Moreover, this study's results are based on the tier one approach developed by IPCC which relies on fuel consumption data of ships viz-a-viz fuel type. Emissions from maritime vessels would be much higher when detailed studies will be done based on activity-based methods including various aspects of vessel characteristics. The same evidence is also reported by Chang and Wang (2012) and Chang et al. (2013) which highlights the need for a more in-depth analysis of GHG emissions from ports.

The findings of the study by Chang et al. (2013) indicated that the results of GHG emissions from port vessel operations based on an activity-based approach were five times higher than that estimated employing a top-down approach. Therefore, in-depth analysis will assist port authorities in better monitoring GHG emissions and developing GHG emission reduction policies (Chang et al., 2013). However, this study is also significant because this initial preliminary assessment provides insight into the actual gravity of the problem and scale and trend to foresee its share in national transportation. It is critical to highlight that the Government of Pakistan would require 37, 090, 381.57 US$/annum for offsetting carbon emissions i.e. 2,468,789.21 tonnes (CO_2e) with an average current market price factor of 15$/tonne CO_2e. However, a developing country like Pakistan which is least responsible for the global rising level of GHG emissions (GoP, 2021b) than developed countries but is among the top ten most vulnerable countries (Eckstein and Kreft, 2020) needs to adapt to and mitigate by ensuring a vibrant climate governance framework to combat the emerging climate crisis.

As long as the implication of the carbon offset scheme vis-à-vis mangrove forests is concerned, Pakistan needs approximately 20,020 hectares of mature mangrove forests to remove 2,468,789.21 metric tonnes of CO_2e emissions from the atmosphere in a timeline of 1 year. Mangroves are considered one of the most economically effective methods for offsetting carbon emissions because of their massive carbon sequestration potential ranging from 4–10 times more than terrestrial forests (dslb; GreenBiz Group, Inc., 2022). Taillardat et al. (2018) also suggested that mangrove blue carbon strategies are the most effective for climate mitigation at the national level. Now is the time to wake up and take necessary actions and measures to fight against the frightening level of GHG emissions at all levels. The Government of Pakistan must encourage the afforestation of mangroves to deal with the real issue of climate change by offsetting carbon emissions and combatting the climate crisis, successful and effective implementation of which will prove to be fruitful in the years to come.

5 Conclusion

The findings of this study revealed that the total greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), from the maritime transportation sector of Pakistan, are 2,468,789.21 tonnes (CO_2e) resulting from fuel consumption for the period 2021–2022. The business-as-usual case of all types and sizes of maritime vessels in Pakistan has a 4.9% share of the reported total transportation sector's emissions in Pakistan's updated NDC (2021) whereas, Pakistan's Second Communication on Climate Change had reported only a 1% share of maritime vessels in overall transportation sector GHGs emitted in 2015. Carbon dioxide emissions from maritime transportation amounted to 2,423,211.88 tonnes whereas methane (CH_4) and nitrous oxide (N_2O) emissions are 1152.77 tonnes and 56.23 tonnes respectively. It is identified that 37, 090, 381.57 US$/annum is required for offsetting carbon emissions. As long as the implication of the carbon offset scheme vis-à-vis mangrove forests is concerned, Pakistan needs approximately 20,020 hectares of mature mangrove forests to remove 2,468,789.21 metric tonnes of CO_2e emissions from the atmosphere in a timeline of 1 year. The study's findings provide a baseline reference scenario for future studies and national GHG inventory and add knowledge to the existing pool of literature which would help in decision-making processes, policy development, and climate mitigation strategies for all types of maritime vessels. Based on the findings of this study, the federal government is suggested to devise a proper mechanism for monitoring of carbon footprint of sea-going vessels and maintaining a periodic GHG emissions inventory by considering the outcome of this study as a baseline reference scenario and launch a GHG emissions reduction programme through shifting maritime vessels to low-carbon or zero-carbon alternative fuels. Besides, this study gives dimensions to future studies to assess the GHG emissions scenario of maritime vessels by employing a bottom-up approach and proposing effective climate mitigation measures for the maritime transportation sector of Pakistan. In addition, this study is limited to the assessment of three GHGs (CO_2, CH_4, and N_2O) resulting from fuel consumption only hence it opens doors for future researchers to explore and analyze the rest of GHGs and other non-GHGs emissions from the maritime transportation sector of Pakistan depending on data availability.

Data availability statement

The data that support the finding of this study are available from the first and corresponding authors on request.

Author contributions

All authors contributed to the article and approved the submitted version. BS developed methodology, data collection, analysis, writing-original Draft; SA supervision, assist in data analysis, Writing-Review and Editing; KMJI Conceptualization, co-supervision, resources, overseeing administration during research work, assist in formal analysis, discussion, writing-review and editing; MAURT writing-review and editing, assist in drawing conclusions, proofread and assistance in submission to the journal by providing resources to cover APC.

Conflict of interest

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1076585/full#supplementary-material

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Exploring the wicked problem dilemmas and driving mechanism of green transition: Evidence from the Yellow River Basin, China

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The green transition of the Yellow River Basin (YRB) plays an important role in China's economic and social development, as well as its ecological security. In view of the wicked problem dilemmas of development and emissions reduction in the YRB, this study theoretically and empirically examines the driving forces of its green transition. A six-sector green endogenous growth model reveals that low-carbon governance and innovation activities are the main drivers of green transition. Subsequently, a panel econometric model empirically explores how these drivers can solve the challenges of green transition. The findings are summarized as follows: low-carbon governance and innovative human and physical capital are key elements of green transition. The investment and innovation-driven periods regression results confirm that these elements drive green transition in the latter period. The regional heterogeneity show that drivers can promote green transition in highly developed areas. At the same time, with the inflow of innovative human capital, the promotion of low-carbon governance and innovative human capital to green transition has increased to an extent. Hence, combining the urban development stage and level to avoid a uniform policy may be key to the green transition in the YRB.

KEYWORDS

Yellow River Basin, green transition, wicked problem, low-carbon governance, innovative human capital, innovative physical capital

1 Introduction

Environmental deterioration is a disastrous consequence of the global industrial revolution. Extreme weather events such as excessive precipitation, droughts, floods, cold waves, heat waves, and storms have become more frequent and intense, affecting regions worldwide (Hao et al., 2018; Zhu et al., 2022). The climate change phenomenon has forced nations to stress on global green transition, with its first aim being adherence to the Paris Agreement and systematic upgrades to eco-friendly human development (Roberts et al., 2018; Mao et al., 2019).

Carbon emissions reduction has long been a path to green transition (Zhou et al., 2022). According to Net Zero Tracker, most countries are now actively and systematically exploring emissions reduction; indeed, more than 68% of the 198 countries worldwide have thus far proposed carbon neutral, climate neutral, net zero, and other independent contribution emissions reduction targets. Countries that have reached the carbon peak have completed the historical mission of industrialization and urbanization (Dong et al., 2019). In terms of gross domestic product (GDP), the *per capita* GDP of some countries that have already reached their carbon peak (BP Statistical Review of World Energy, 2020) ranges from United States$ 26,000 to 44,000. The service industry often accounts for over 65% of the GDP, with the United States and Japan revealing shares as high as 76.8% and 73.8%, respectively (Word Bank, 2022). In 2021, for instance, China's *per capita* GDP was United States $12,600, exceeding the global average for the first time; its service industry's share of GDP and urbanization rate were 53.3% and 64.7%, respectively (CNBS, 2020). Still, China's industrialization and urbanization are far from complete, leaving it vulnerable to the wicked dilemma of balancing development and emissions reduction to achieve carbon neutrality.

At a length of 5,464 km, Yellow River is only the second largest river in China after the Yangtze. Its origin lies in the Qinghai Tibet Plateau. Its vastness and richness has made the Yellow River the seat of China's prosperity since the start of its civilizations, and it continues to serve as an important ecological barrier and economic growth rod. Thus, the sustainable development of the Yellow River YRB (from here, "YRB") is essential to China's economic, social, and environmental security (Sun et al., 2022). In September 2019, the General Office of the State Council of the People Republic of China listed ecological protection and high-quality development of the YRB as its prime national strategy, justifying the urgency of green transition therein. The cities surrounding the YRB comprise more than 27% of the national population but contribute only 21% to China's GDP. Despite this relative underdevelopment, the YRB produces 33% of the total CO_2 emissions, confirming the wicked dilemma between development and protection of the YRB (Figure 1).

To progress in our research, we must understand two points. First, to scientifically judge the quality of regional green transition we must accurately measure green transition. Regional green transition refers to high efficiency and low emissions economic growth pattern that meets the concept of sustainable development (Zeng et al., 2023). Compared to the traditional development mode of high consumption and high emissions, both energy and environment are endogenous variables of sustainable development goals (Sun et al., 2019; Su and Zhang, 2020). We risk greatly overestimating green productivity if it is calculated without reflecting environmental factors. Indeed, Chen (2010) shows that the average annual productivity growth *exclusive* of environmental factors was more than 5% during 1980–2008, and only 2.29% *inclusive* of them. To address this problem, scholars now employ data envelopment analysis with energy and environmental variables as key factors for measuring green development (Lin and Benjamin, 2017; Huang et al., 2021). Still, research continues to stress on energy input in the measurement of green transition, while ignoring water as a resource and output.

Second, factors that drive green transition in river basins and urban agglomerations have been a popular—often singular—focus of scrutiny (Chen Y. et al., 2020). Environmental regulation is one such critically important factor (Wang et al., 2019). However, there are generally three types of cognition regarding the role of environmental regulation in green transition: *promotion*, *inhibition*, and *uncertainty* (Tian et al., 2022). Regarding promotion, studies show that environmental regulation has a direct positive role in promoting green transition or indirectly improves green total factor productivity (GTFP) through technological innovation or government actions (Zhai and An, 2020). A corresponding critique is that environmental regulations require enterprises to reduce pollution emissions in a way that increases the cost of pollution prevention and production. Ultimately, regulations are not conducive to improving GTFP (Ambec et al., 2013). The uncertainty view suggests that the relationship between environmental regulation and regional green transition is not simple and linear, but significantly U-shaped and curvilinear (Song et al., 2020). Empirical research in China also gives credence to this claim—various scholars show that environmental regulation may have a restraining effect on GTFP in the short term, but significantly promotes green transition in the long run (Wu et al., 2020; Du et al., 2021; Qiu et al., 2021).

Since China's entry into information-based and innovation-driven development, the innovation vitality in environmental regulation is another key driver of green economic growth. Fan and Sun (2020) show that environmental regulation and green technology innovation are major drivers that promote green economic growth. Shangguan and Ge (2020) further discuss the synergistic effect of environmental regulation and technological innovation in promoting green economic growth. Despite the literature incorporating environmental regulation and technological innovation into a unified framework, the description of innovation activities still emphasizes a single output. The close relationship between innovation human capital and innovation material capital in promoting green transition continues to be ignored.

To address the question of how the YRB's internal mechanism leads to the antagonistic characteristics of green transition, we first identify the mechanism that drives green transition at the theoretical level, and then construct regression models to test the driving mechanisms of the dilemmas of green transition in the YRB.

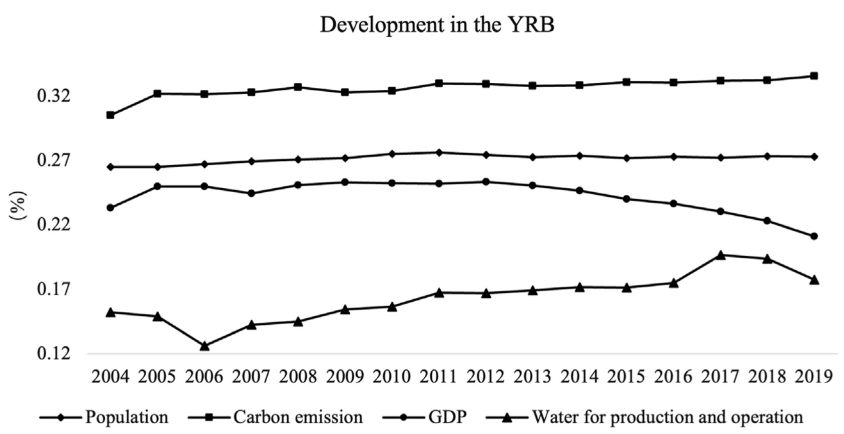

FIGURE 1
Trend of the proportion of population, economy, water resources and carbon emissions in the YRB of China from 2004 to 2019.

2 Theoretical framework

With the emergence of the endogenous growth model, economists began to introduce pollution into production functions and environmental quality into utility functions when discussing environmental deterioration and sustainable development under the framework of the new model. Representative models, such as Bovenberg and Smulders' (1995) model, introduced environmental factors into a production function based on the Romer model. By extending Barro's AK model and introducing a pollution index as one of the control variables of representative consumers. Stokey's (1998) study focuses on the externality of environmental pollution and sustainable economic growth. Aghion and Howitt (1998) reasonably changed the Stokey's (1998) model assumptions, stipulating a threshold value for environmental quality; if the level falls below this value, environmental damage would become irreversible. They then introduced environmental pollution into the new Schumpeter model to investigate the effect of environmental resource constraints on sustainable development. Then, Howitt and Aghion (1998) added pollution and non-renewable resources into the production function and environmental quality into the utility function to build an endogenous growth analysis framework. Although they did not perform further solution analysis, they employed Schumpeter and AK's methods for comparative analysis. Later, Barbier (1999) introduced resource scarcity and population growth into the Romer Stiglitz model to explore the optimal equilibrium growth path.

Brock and Taylor (2005) regard nature both as a sink that accepts human waste and a source of economic growth. The "source and sink" approach simultaneously introduces energy and environmental constraints into the economic growth model. However, the model also introduces environmental pollution or environmental quality into the production function as exogenous variables instead of directly introducing environmental quality into the production function as a production factor. Thus, the model does not comprehensively consider the effect of environmental regulation and technological innovation on green transition from an endogenous perspective, and ultimately fails to systematically reveal its internal coupling mechanism.

The present study is based on the Romer model and introduces human capital development, natural resources development, and environmental management sectors. Among these, the human capital development sector conducts human capital development through investing of a certain amount of human capital, and its output is a human capital increment $\dot{H}$. The natural resources development sector inputs a certain amount of natural resource elements S and labor L_R and sells the natural resource product R to the final product sector. In addition to providing the final product sector with the environmental quality element E required for production, the environmental management sector also conducts environmental governance by investing a certain amount of environmental governance investment I to improve environmental quality and ensure that this environmental quality can support all social production activities.

a) Maximize consumer utility. It is assumed that both consumption and environmental pollution affect consumer utility, and the intertemporal utility function is as follows:

$$\int_0^{\infty} U(C,P)e^{-\rho t}dt = \int_0^{\infty}\left(\frac{C^{1-\sigma_1}-1}{1-\sigma_1} - \frac{\rho^{1+\sigma_2}-1}{1+\sigma_2}\right)e^{-\rho t}dt \quad (1)$$

where $U(C,P)$ is the function of transient aging; σ_1 reflects consumers' desire to change consumption in different periods; σ_2 is the environmental awareness parameter, which measures environmental pollution's effect on consumers; and ρ is the time discount rate, which reflects the current consumption preference.

b) Product production sector. Natural resources and environmental factors are included in the Cobb–Douglas production function, and the total production function of the final product sector is expressed as:

$$Y = A_1 H_Y^{\alpha_1} K^{\alpha_2} L_Y^{\alpha_3} R^{\alpha_4} (E_0 - P)^{\alpha_5} \quad (2)$$

where $A_1 > 0$ is the final product sector productivity parameter, $E_0 - P$ is the environmental quality that supports economic development in period t, α_1, α_2, α_3, α_4, and α_5 denote the output elasticity of human capital, material capital, the labor force, natural resources, and environmental quality, respectively.

c) Human capital sector. The total amount of human capital of the whole economic system is assumed to be H; of this, the amount of human capital investment engaged in human capital development is H_H. The corresponding production function or human capital increment, $\dot{H}$, is expressed as:

$$\dot{H} = A_2 H_H \quad (3)$$

where $A_2 > 0$ is the human capital development sector's productivity parameter.

d) R&D sector. It is assumed that intellectual capital is a non-competitive investment; that is, when the R&D sector is developing new product design schemes or patents, it can freely obtain all knowledge. Here, the stock of knowledge capital represents the level of regional technological innovation. Assuming that the output level of the R&D sector mainly depends on the sector's human capital input, innovation efficiency, and innovation quality, the R&D sector's production function is set as:

$$\dot{A} = A_3 H_A^{\beta_1} A^{\beta_2}, \quad \beta_1, \beta_2 > 0 \quad (4)$$

where $A_3 > 0$ is the R&D sector's productivity parameter, $\dot{A}$ is the increment of knowledge capital, and β_1 and β_2 are the output elasticities of innovation human capital and innovation material capital, respectively.

e) Natural resources sector. Natural resources are the resources obtained from nature and consumed by human production activities. They include renewable and non-renewable natural resources. Non-renewable natural resources (e.g., oil and coal) are essential input factors in current economic development. As water is the key factor for high-quality development in the YRB, natural resources here mainly refer to water resources and non-renewable natural resources. It is assumed that the production function of the natural resources development sector is:

$$R = A_4 S^{\gamma_1} L_R^{\gamma_2} \gamma_1 > 0, \quad \gamma_2 > 0 \quad (5)$$

where A_4 is the productivity parameter of the natural resources development sector; S is the amount of natural resources invested in the natural resources development sector; γ_1 and γ_2 refer to the output elasticity coefficients of natural resources and the labor force, respectively; and L_R is the labor force input into the natural resources development sector.

f) Environmental management sector. From the production perspective, the environment is included in the endogenous growth model as a production factor. Assuming E_0 is the economic system's initial environmental quality, which is also environmental quality's upper limit, then the environmental quality supporting economic development at time t is as follows:

$$E = E_0 - P \tag{6}$$

where P is the economic system's pollutant emissions at time t. The environmental management sector improves environmental quality by investing in environmental governance. Assuming that each unit of economic output will emit h units of pollutants, the environmental management sector will invest a certain amount of material capital $I_E = \pi K$, where $\pi \in (0,1)$ is the proportion coefficient of the environmental treatment investment and material capital required to promote improving and upgrading production technology and reducing pollutant emission. After comprehensively considering how environmental consumption, treatment, and capacity for self-purification affect the environmental stock, the accumulation equation of pollutant P can be set as follows:

$$\dot{P} = h\pi^{\eta_1}K^{\eta_2}Y - \xi P = ZY - \xi P \left(Z = h\pi^{\eta_1}K^{\eta_2}\right) \tag{7}$$

where ZY represents the current pollutant emission. $\eta_1, \eta_2 \in (-1,0)$ indicates that investment in environmental treatment can reduce pollutant emission; and $\xi \in (0,1)$ is expressed as the pollutant self-purification coefficient.

Under the condition of the optimal growth path, the growth rate of any economic variable is constant, and $g_X = \dot{X}/X$ represents the growth rate of any variable X. According to the relationships between final output, material capital, consumption, and environmental investment, the variables Y, C, and K have the same equilibrium growth rate. Through dynamic optimization, the green economic growth rate can be obtained as follows:

$$g_Y \propto \frac{\left(\alpha_3 + \frac{\alpha_4\gamma_2}{1-\gamma_1}\right)n + \left[\alpha_1 + \frac{\alpha_2(1-\omega)}{\omega}\frac{\beta_1}{1-\beta_2}\right](A_2 - \rho)}{1 - \alpha_1(1-\sigma_1) - \alpha_2 - \frac{\alpha_2(1-\omega)}{\omega}\frac{\beta_1}{1-\beta_2}(1-\sigma_1) + \alpha_5(1+\eta_2)} \tag{8}$$

Comparative static analysis yields two propositions:

Proposition 1. When other conditions remain unchanged, innovative human capital and innovative material capital have a positive marginal effect on the long-term steady-state green economic growth rate. Specifically, $\partial g_Y/\partial\beta_1 > 0$ and $\partial g_Y/\partial\beta_2 > 0$, indicating that the long-term steady-state green economic growth rate will increase with improvements in the innovation sector's innovative human and material capital.

Proposition 2. When other conditions remain unchanged, improvements in the investment efficiency of environmental governance can reduce pollutant emissions, which can not only reduce the constraints of environmental pollution on economic growth but improve the long-term steady-state green economic growth rate, that is, $\partial g_Y/\partial\eta_2 < 0$.

3 Methodology

3.1 Research area

This study takes the YRB as its research area. Based on the Yellow River Yearbook, the YRB's outline for ecological protection and high-quality development planning, we take the prefecture level cities of Shandong, Henan, Shanxi, Inner Mongolia, Shaanxi, Ningxia, Gansu, and Qinghai, as well as some cities in Anhui and Hebei through which the Yellow River flows, as our research area. The YRB comprises 87 prefecture level cities (see Figure 2).

3.2 Research method

3.2.1 Measurement of green transition

Green transition is a transformation process (Kemp and Never, 2017; Song et al., 2020). It refers to the transformation of regional economy from traditional extensive development mode to intensive sustainable development under resources and environment constraints (López-Gamero et al., 2010). The measurement of the green transition is the relative efficiency of various inputs and outputs in the sustainable development model (Shen et al., 2019). Total factor productivity (TFP) is used to represent traditional economic efficiency. While GTFP including "good" and "bad" outputs allows for evaluating the performance of green transition with ecological constraints (Chen et al., 2018; Huang et al., 2022).

To evaluate the GTFP of the YRB, we use a global Malmquist Luenberger productivity index based on the directional distance function of a Slacks-based model that includes environmental input factors and undesirable output (Oh, 2010; Liu and Xin, 2019). In most research, labor, capital, and energy are input factors (Fare et al., 2007; Li et al., 2016; Long et al., 2018), while economic output and industrial pollution emissions (e.g., the three industrial wastes, sulfur dioxide, wastewater, and soot) are output factors in the GTFP calculation (Wu et al., 2017; Li et al., 2018).

Considering the particularity and importance of water as a natural factor in the YRB's study area, we consider water resource endowment a resource input factor (Miao et al., 2010; Chen Y. P. et al., 2020). Correspondingly, we make sewage discharge as an unexpected output of the water environment (Song et al., 2020). As air pollution is an important component of environmental pollution, carbon emissions (Li and Lin, 2017) and fine particulate matter are selected as undesirable outputs to describe the green transition accurately, especially given the need for complying with the "double carbon" goal.

The regional carbon emissions are derived from the 1997–2017 China county carbon emissions dataset simulated and retrieved by the CEADs database based on DMSP/OLS and VIIRS/NPP night light data (Chen J. et al., 2020). The 2018 and 2019 data are inversely extrapolated based on the trend of the chain-based growth rate in the past 5 years and proportion of various cities' carbon emissions in the province in the past 5 years. We cover the period from 2004 to 2019. Specific measurement indicators are provided in Table 1.

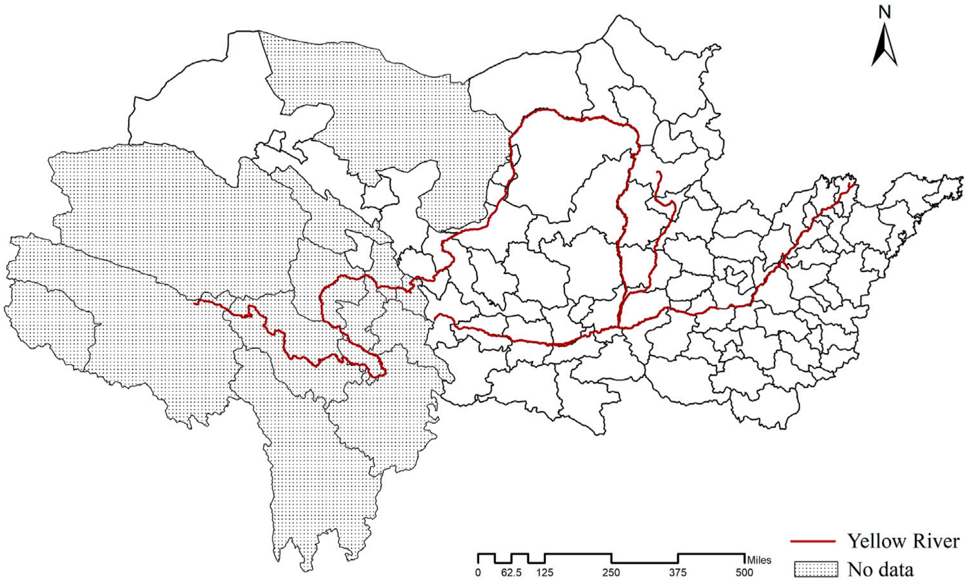

FIGURE 2
The Yellow River Basin.

TABLE 1 Description of the indicators of green total factor productivity measurement.

Category	Index	Measurements	Data sources
Input	Labor input	Persons employed in urban units at year-end	China City Statistical Yearbook
	Capital input	Fixed asset investment	
	Energy input	Annual electricity consumption	China City Statistical Yearbook
	Water input	Total quantity of water supply	China Urban-Rural Construction Statistical Yearbook
Desirable output	Economic output	Gross domestic product (GDP)	China City Statistical Yearbook
Undesirable output	Greenhouse gas pollution	Carbon emission	https://www.ceads.net.cn/data/county/
	Air pollution	$PM_{2.5}$	https://sites.wustl.edu/acag/datasets/surface-pm2-5/
	Water pollution	Annual quantity of wastewater discharged	China Urban-Rural Construction Statistical Yearbook

3.2.2 Empirical model

To test the research hypothesis of the effect of environmental governance, innovative human capital, and innovative material capital investment on green transition, we constructed the following benchmark measurement model:

$$GTFP_{it} = \alpha_0 + \alpha_1 ER_{it} + \alpha_2 \text{human\_e}_{it} + \alpha_3 patent\_e_{it} + \lambda \sum X_{it} + u_i + \varepsilon_{it} \quad (9)$$

where i represents a prefecture city, t represents a year, $GTFP$ represents GTFP, ER represents government environmental governance, $human\_e$ and $patent\_e$ represent a series of innovative activities of innovative human capital and innovative physical capital, X is a series of control variables, u_i represents an individual effect, and ε_{it} is a random item. Eq. 9 is further decomposed into investment- and innovation-driven stages to establish a segmented measurement model.

The traditional linear regression framework cannot be used test the non-linear effect of low-carbon governance and innovation activities on green transition when cities have non-linear characteristics. A panel threshold model can be used to study the heterogeneous effects of dependent variables on independent variables when urban characteristics are inconsistent (Hansen, 1999). Take the single threshold panel model as an example:

$$y_{it} = \mu + \alpha_1 x_{it}\left(q_{it} \le \gamma\right) + \alpha_2 x_{it}\left(q_{it} > \gamma\right) + u_i + \varepsilon_{it} \quad (10)$$

In the formula, q_{it} is the threshold variable and γ is the threshold parameter. Eq. 9 is divided into two parts by the parameters α_1 and α_2; u_i is the individual effect and $\varepsilon_{it} \sim (0, \delta^2)$ is the random disturbance term. This single-threshold panel model is equivalent to the following piecewise function:

$$y_{it} = \mu + \alpha_1 x_{it} + u_i + \varepsilon_{it}, \quad q_{it} \le \gamma \quad (11)$$

$$y_{it} = \mu + \alpha_2 x_{it} + u_i + \varepsilon_{it}, \text{and} \quad q_{it} > \gamma \quad (12)$$

when $q_{it} \le \gamma$, the coefficient of x_{it} is α_1; when $q_{it} > \gamma$, the coefficient of x_{it} is α_2.

The first step is to use Tsay's permutation regression to find the threshold estimated value; the second step is to use the bootstrap method to test for a possible threshold effect. If a threshold effect exists, the likelihood ratio statistic is further used to detect whether the true value and the threshold estimate are the same (Wang, 2015). Generally, there may be multiple threshold values, making it necessary to test the number of threshold values. Consequently, the panel threshold model is set as follows:

$$\begin{aligned} GTFP_{it} = {} & \alpha_0 + \alpha_{11} ER_{it} (\gamma \le \gamma_i) + \alpha_{12} ER_{it} (\gamma > \gamma_i) \\ & + \alpha_{21} \text{human\_}e_{it} (\gamma \le \gamma_i) + \alpha_{22} \text{human\_}e_{it} (\gamma > \gamma_i) \\ & + \alpha_{31} patent\_e_{it} (\gamma \le \gamma_i) + \alpha_{32} patent\_e_{it} (\gamma > \gamma_i) + \lambda \sum X_{it} \\ & + u_i + \varepsilon_{it} \end{aligned} \tag{13}$$

In this equation, γ is the threshold variable and γ_i, the threshold parameter, is the threshold value that needs to be estimated. The equation is divided into two parts by the parameters α_{i1} and α_{i2}, u_i is the individual effect, and $\varepsilon_{it} \sim (0, \delta^2)$ is the random disturbance item.

3.3 Data description

The core explanatory variables and control variables are set as follows.

3.3.1 Low-carbon governance variable (ER)

Most studies choose the total investment in (industrial) environmental pollution or composite indicators that include measures such as SO_2 removal, smoke removal, comprehensive utilization of industrial solid waste, domestic sewage treatment, and industrial sewage treatment rates as a surrogate indicator of environmental governance (Wang and Shen, 2016; Ren et al., 2018; Wang and Zhang, 2022). We use the carbon intensity reduction rate index as a proxy for the effect of low-carbon governance to test the effect of environmental governance on green transition.

3.3.2 Innovation activities

Innovation activities include innovative human capital investment and innovative physical capital investment. Of these, the level of innovative human capital reflects the labor force's ability to imitate technology, absorb knowledge, and innovate and create; it is a more suitable proxy indicator to measure the labor force's skill level (Ang et al., 2011). Among various industries, scientific research, technical services and geological exploration is the key industy that serve the R&D sector. Hence, the scientific research, technical services, and geological exploration industry is selected for this study. The number of employees in the exploration industry and in the information transmission, computer services, and software industry are used as proxy variables for innovative human capital (*human_e*) to estimate the green growth elasticity of human capital changes; innovation material capital investment (*patent_e*) is measured using scientific and technological financial expenditure required for unit patent application.

3.3.3 Control variables

To alleviate bias in the model estimation results caused by variables that are potentially omitted, it is necessary to include control variables that could affect the TFP of urban greening. In the literature, the factors that affect GTFP include government intervention, foreign investment level, and population density.

TABLE 2 Descriptive statistical results.

Variables	Nobs	Mean	Sd	Min	Max
GTFP	1392	1.002	0.022	0.838	1.214
ER	1392	0.048	0.132	−3.306	0.761
human_e	1392	1.19	2.309	0.03	29
patent_e	1392	27.18	44.33	0.676	755.25
fina	1392	311.277	235.705	100.36	1839.854
fdi	1392	1.362	1.651	0.001	19.783
pd	1392	425.29	311.431	4.7	1440.371

Fiscal pressure (*fina*), expressed as the proportion of fiscal expenditure to fiscal revenue, is used as a proxy for government intervention. The foreign investment level (*fdi*) is measured as the proportion of total foreign investment divided by GDP, and population density (*pd*) is represented by the urban population density. To weaken the influence of the dimensional gap and sample heteroscedasticity on the regression results, we take the logarithms of innovation material capital investment, financial pressure, and population density. The descriptive statistics of the original data are presented in Table 2.

4 Mechanism test of green transition in the YRB

4.1 Identifying the characteristics of the wicked problem

Wicked problems are complex and marked by deep uncertainty, and climate change is one such problem (Rittel and Webber, 1973; Head, 2014; Sun and Yang, 2016). The green transition of the YRB is characterized by a typical wicked problem dilemma of balancing development with emissions reduction (Figure 3). The overall dilemma is manifested in a mismatched development, where the YRB proportion of secondary industry increment between 2004 and 2019 continued to decline, while its carbon emissions increased.

To further verify the dilemmas above, the GTFP of the 87 prefecture-level cities in the YRB is measured to represent green transition. The GTFP of the YRB increased from .987 in 2004 to 1.009 in 2019, with parallel trends in economic development and green and low-carbon development (Figure 4). Among these, GTFP rose rapidly from 2004 to 2008. This stage corresponds to the factor-driven stage in China, which mainly relies on a large amount of labor, capital, and other factors to drive economic growth. With the emergence of the 2008 financial crisis, the overall economic downturn coupled with the environmental consequences of high investment in the early stage, as well as extensive and extended high-carbon development mode led to a continuous decline in the growth rate of green total factors. Although there was a substantial short-term increase in 2012 that led to a continuous increase in efficiency from 2013 to 2015, we see a downward trend in efficiency after 2015. Although the GTFP of the YRB has significantly improved, the task of

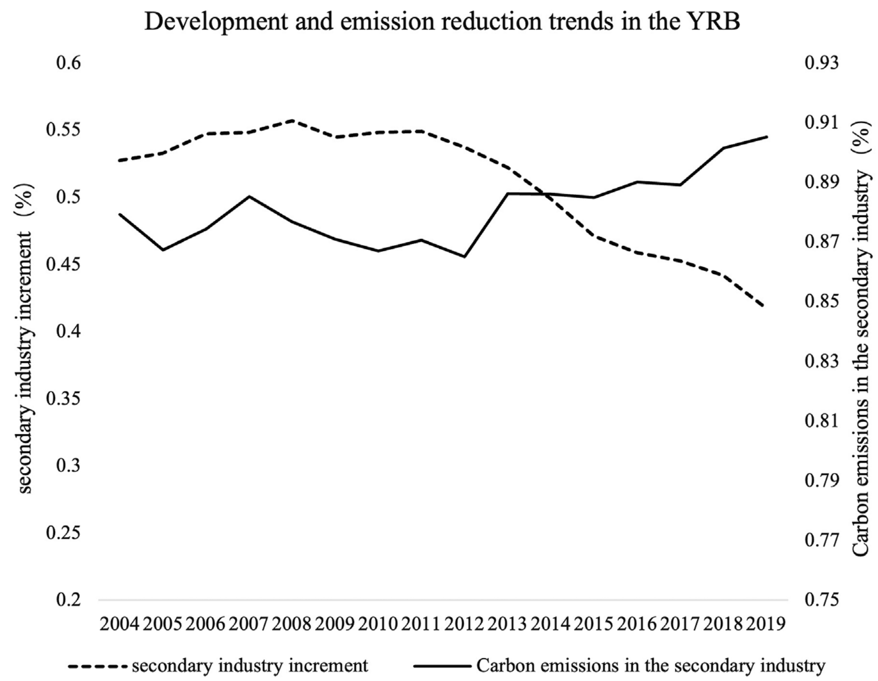

FIGURE 3
Development and emission reduction trends in the YRB of China from 2004 to 2019.

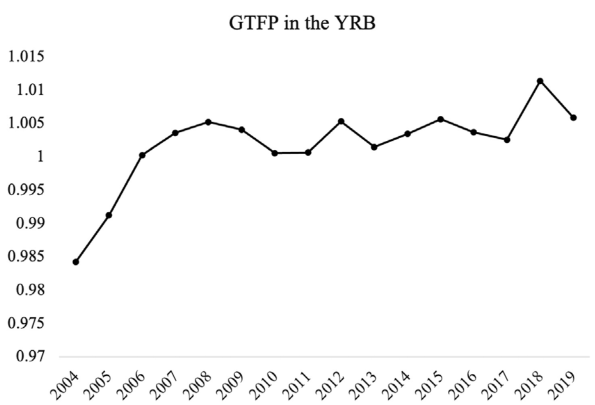

FIGURE 4
GTFP evolution trends in the YRB.

ensuring a high-quality development-oriented green and low-carbon transition are facing dilemmas between development and emissions reduction.

4.2 Result of overall sample regression

This study addresses a overall sample regression model to examine the main factors that led to the dilemmas above in the transition of the Yellow River basin.

Table 3 reports the regression results of the benchmark model; columns 1 to 3 present the regression results after adding low-carbon governance, innovative human capital, and innovative physical capital as input variables, respectively. The three main explanatory variables are all positive and significant at the 10% level. After adding all explanatory and control variables (column 3), the R^2 significantly improves, indicating that the selection of control variables is effective.

Specifically, the estimated coefficient on ER is .013 and significant at the 1% level (column 4), which shows that the overall low-carbon governance in the YRB has achieved remarkable results through playing a role in promoting green transition. Importantly, the test results are consistent with Proposition 1.

The carbon intensity reduction rate is essentially the degree of reduction in pollutant emissions brought about by low-carbon governance; that is, the more obvious the reduction in carbon intensity, the better the low-carbon governance effect. To reflect the effect of low-carbon governance intensity on the YRB's GTFP from an intuitive point of view, we use the ratio of environment-related words to the total word count of the report on the government's work as a proxy variable for the government's environmental governance (Chen et al., 2018; Zhong et al., 2021). The results in column 2 show that low-carbon governance intensity also has a significant effect on GTFP, indicating that the carbon intensity reduction rate is properly characterized. Environmental governance investment efficiency (η) in the model is reasonable and effective.

From the perspective of the two core explanatory variables on innovation, the coefficients on innovative human capital (*human_e*) and innovative physical capital (*patent*_e) are both significantly positive, indicating that the greater the input of innovative human and physical capital, the higher the GTFP, supporting the effectiveness of Proposition 2. Thus, innovative human and physical capital, as the key factors promoting technological progress, play key roles in

TABLE 3 Benchmark results and robustness checks of the full sample.

Variables	(1)	(2)	(3)
ER	1.20*** (4.12)	0.012** (2.36)	0.013** (2.49)
human_e		0.001** (1.99)	0.001* *(1.85)
patent_e			0.002** (2.36)
C	0.881*** (12.55)	0.799*** (11.34)	0.821*** (11.57)
fina	0.006 (1.58)	0.006 (1.55)	0.005 (1.46)
fdi	0.0002 (0.54)	0.0003 (0.67)	0.0005 (0.90)
pd	0.036*** (2.93)	0.030** (2.34)	0.025** (1.97)
N	1357	1392	1392
Year FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
R^2	0.154	0.185	0.23
F-value	8.34***	4.89***	5.01***

Note: *, **, and *** indicate significance at the 1%, 5%, and 10% levels, respectively. T-statistics are in parentheses.

increasing the ability to digest, absorb, and apply existing technologies. As we empirically demonstrate, they are of great significance to the YRB's green and low-carbon transition of the YRB.

Above all, low-carbon governance has obviously promoted the green transition of the Yellow River basin. In contrast, innovation activities, as important factors of sustainable and high-quality economic and social development, have played a very weak role in the green transition of the YRB. We believe that the lack of innovative vitality may be the key reason for the slow and even backward process of low-carbon transformation in the Yellow River basin.

To ensure robustness, four approaches were used to re-estimate the relevant parameters and test the robustness of the empirical conclusions (Table 4). We replaced explanatory variable ER (column 4), replaced the GTFP value from the global Malmquist-Luenberger index with the adjacent reference global Malmquist-Luenberger index as the explained variable (column 5), removed the provincial capital city (column 6), and performed a generalized method of moments regression with a one-period lag of the explained variable (column 7). In column (4), the proportion of the word frequency related to the word "environmental protection" in the work report of each city's government in the total number of words in the report is used as a substitute variable for the intensity of environmental governance. The results show that ER-new has also significantly improved the GTFP, which fully shows that it is reasonable and effective to characterize the investment efficiency of environmental governance in the model by the reduction rate of carbon intensity. The results of the robustness tests show that the estimation results of the three main explanatory variables are consistent with the model's benchmark regression results. Thus, the results are relatively robust.

4.3 Regression results of development period

At present, China is transitioning from a high-speed development period that is driven by factors and investment to a high-quality development stage that is driven by innovation. The effect of low-carbon governance and innovation activities on green transition is further examined in two periods, namely 2004–2011, the investment-driven period, and the innovation-driven period after 2012. Table 5 reports the regression results. It is obvious that low-carbon governance and innovation activities have significant temporal heterogeneity in these two periods.

First, low-carbon governance plays a significant role in enhancing GTFP only in the innovation-driven period. That is, in the rapid economic growth stage, development-oriented high investment and high consumption lead to weak low-carbon governance effects. Second, although innovative human capital has made insufficient contribution to green transformation in the investment-driven period. While it has accumulated rich human capital. As a result, human capital in innovation-driven period begin to play a role in promoting green transformation. Third, innovative physical capital significantly improved GTFP in the investment-driven period, but did not play a significant role in promoting the innovation-driven period. The drive of physical capital investment has been unable to promote high-quality economic development in the YRB, and physical capital has gradually weakened against innovative human capital. One possible explanation is that with the arrival of the high-quality development, division of labor based on specialization is deepened. Material capital is gradually replaced by innovative human capital.

According to the results, the factors driving green transition are changing at different stages of development. This also means that at different stages of development, the factors leading to the dilemma of green transformation will also change. For example, in innovation driven period, innovative physical capital may be the main reason for the decline of green transformation. To solve the dilemma of green transformation in the current and future time of the innovation driven stage, we should not only reverse the negative effect of innovative material capital, but further enhance the impetus of innovative human capital and low-carbon governance to green transformation.

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TABLE 4 Robustness tests.

Varibales	(4)	(5) GTFP-new	(6) Exclude provincial capital cities	(7) SYS-GMM
ER		0.014***	0.012**	0.015**
		(2.89)	(2.15)	(1.98)
ER − new	0.043**			
	(0.75)			
human_e	0.0014**	0.0007*	0.002*	0.001**
	(0.32)	(1.22)	(.73)	(2.31)
patent_e	0.003**	0.0008**	0.002*	0.001**
	(0.48)	(1.10)	(2.05)	(1.85)
C	0.156***	0.725***	0.804***	1.061***
	(2.73)	(10.92)	(9.43)	(15.26)
fina	0.020	0.008*	.005	.007*
	(0.72)	(2.31)	(1.30)	(1.91)
fdi	0.001	0.001	0.001	0.00001
	(0.29)	(1.41)	(0.93)	(0.17)
pd	0.081***	0.041***	0.028*	0.015
	(1.22)	(3.37)	(1.83)	(1.31)
l.GTFP				−0.190***
				(−7.68)
N	1392	1392	1280	1392
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
R^2	0.055	0.313	0.173	0.562
AR (2)P				0.746
Sargan P				0.572

TABLE 5 Estimated results at different periods of development.

Variables	Investment driven period (2004–2011)	Innovation driven period (2012–2019)
ER	0.008 (1.0)	0.017** (2.01)
human_e	0.001 (.36)	0.0001* (0.19)
patent_e	0.004*** (2.83)	−0.003 (−0.29)
C	0.996*** (5.65)	0.966*** (8.08)
Control variable	Yes	Yes
N	783	696
R^2	0.243	0.141
F-value	2.49**	0.83**

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. T-statistics are in parentheses.

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TABLE 6 Regression results of the panel threshold model.

Variables	Coefficients	Variables	Coefficients
***ER* (dev<8.9)**	−0.034 (−1.32)	*ER* (dev >8.9)	0.015*** (2.86)
human_e (dev <8.9)	−0.001 (−0.14)	*human_e* (dev >8.9)	0.001*** (1.88)
patent_e (dev <8.9)	−0.001 (−1.00)	*patent_e* (dev >8.9)	0.002*** (2.67)
C	0.879* (12.22)	Control variable	Yes
N	1392	F-value	6.44***

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. T-statistics are in parentheses.

5 Further study

The YRB not only exhibits non-linear coupling characteristics between development and emissions (Figure 3), but its green transition quality also fluctuates with time (Figure 4). GFTP increased from .987 in 2004 to 1.009 in 2019; during this time, it went through multiple stages of decline. This may be because the driving effects of low-carbon governance and innovation activities on the YRB's green transition have different effects owing to the idiosyncratic characteristics of each city. Therefore, a panel threshold model was established to explore the non-linear characteristics of the driving mechanism of the YRB's green transition, which is also a realistic path to address its third dilemma.

5.1 Non-linear test of urban development levels

The development gap among the regions along the YRB is large. In 2019, Qingdao, which has the highest level of economic development, had a GDP over 40 times that of Jiayuguan City. Therefore, the effect on GTFP of low-carbon governance and innovation activities are further examined when cities have different levels of development. Specifically, the logarithm (*dev*) of *per capita* GDP is used as the threshold variable in Hansen's panel threshold model, and the likelihood ratio is simulated 1,000 times using the bootstrap method. The results show that the panel threshold model has only a single threshold value, which is 8.9, and the F value is 28.95, which is significant at the 10% level.

The results in Table 6 show that, as the level of urban development crosses the threshold, the effects of low-carbon governance, innovative human capital, and innovative physical capital on GTFP change from insignificant to significant at the 1% level. That is, in cities with low levels of urban development, increasing the government's low-carbon governance and enriching innovation activities cannot effectively improve GTFP. The effect of the green development of low-carbon governance and innovation activities can be fully demonstrated only when urban development reaches a certain level.

5.2 Non-linear test of the spatial configuration of innovation elements

The YRB has long faced a relatively low quality of human capital and generally high degree of brain drain, a bottleneck of "talent collapse," and the misallocation of innovative talent elements in urban agglomerations. Existing research shows that innovative human capital has a weak effect on GTFP, and hence the difference in the spatial allocation of innovative factors may be an important source of the non-linear characteristics of development and transition. Therefore, the key to breaking through the human capital dilemma is to weaken the spatial mismatch of innovative elements, among which the spatial allocation of innovative talent is the most important.

This study further examines the effect of innovative talent influx on low-carbon governance, innovative activities, and urban green transition to explore solutions from the perspective of the spatial allocation of innovative talent.

Using the China Migrants Dynamic Survey, the proportion of the immigrant population in prior years with college education or above is calculated to measure the inflow of regional innovative talent (*talent*), and then a panel threshold model is established as a threshold variable. The threshold test results show that the model passes only the single threshold test, with a threshold value of .866 and an F value of 10.57. The regression results confirm a continuous inflow of innovative talent that has significantly enhanced the effect of low-carbon governance and local innovative human capital on GTFP (Table 7). However, as regions have had high performance in eliminating fragmentation and improving transportation efficiency, the speed and intensity of the inflow of innovative talent has greatly improved. This has been accompanied by a collision of knowledge and thinking between foreign talent and local innovative human capital, thus enhancing regional low-carbon governance power and technology, which is more conducive to GTFP growth.

The role of innovation material capital investment is relatively more obvious at the beginning of innovation talent flow. This may be because innovation output is more dependent on local science and technology financial expenditure when local human innovation capital plays a dominant role in the market. Establishing a unified national market has brought the inevitable trend of multi-center network development to the forefront. Adhering to the urban network concept that cities have boundaries while urban networks do not, inter-regional innovation networks have been promoted in all directions. Therefore, when the amount of innovative foreign talent exceeds a certain threshold, traditional innovation output driven by physical capital cannot keep up with the improvement in the green economy's efficiency in the new era. This further reinforces importance of the spatial allocation of innovative talent in this new development stage.

TABLE 7 Regression results of panel threshold.

Variables	Coefficients	Variables	Coefficients
ER (talent<.866)	0.012** (2.14)	*ER* (talent >0.866)	0.036** (1.87)
human_e (talent <0.866)	0.001** (2.01)	*human_e* (talent >0.866)	0.002** (1.73)
patent_e (talent <0.866)	0.002** (2.55)	*patent_e* (talent >0.866)	−0.003 (−0.30)
C	0.827*** (10.82)	Control variable	Yes
N	1305	F-value	4.29***

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. T-statistics are in parentheses.

6 Conclusion

China has publicly committed to transforming into an "ecological civilization," that requires green development. This study explores a path to solving the dilemmas affecting the YRB's green transition process. We constructed a six-sector green endogenous growth model including natural resources, environmental quality, environmental governance investment, knowledge spillovers, environmental self-purification capabilities, and the impact mechanism of green economic growth. Then, a Slacks-based model using the directional distance function measured the degree of green transition of cities in the YRB from 2003 to 2019. In this model, we incorporated undesired outputs such as air, greenhouse gas, and water pollution. Finally, we used a panel econometric model to test the driving role of carbon governance and innovation activities on the YRB's green transition.

The results of our varied methodological approach confirm the role of low-carbon governance, innovative human capital, and innovative material capital investment in promoting green transition. When the research period is divided into investment- and innovation-driven development stages, low-carbon governance and innovative human capital are shown to have played positive roles in the YRB's green transition in the innovation-driven development stage. Further research based on urban development levels and the spatial allocation of innovation elements revealed that the effects of low-carbon governance and innovation activities on green transition are non-linear. On the one hand, green transition can benefit from low-carbon governance only when urban development is above a certain level. On the other hand, the spatial allocation effect of innovative talent has significantly improved the driving force of low-carbon governance and innovative human capital on the YRB's green transition.

We propose that the YRB's triple wicked problem requires governments to further improve the level of innovative human capital and enhance the density and quality of green technologies. The YRB's green transition is largely driven by innovative physical capital investment than innovative human capital. Three paths arise from this result: intensify R&D in green technology innovation, promote independent innovation, and improve green technology progresses.

Green transition also requires increased publicity of green technology, active promotion and use of green technology, saving of resources, protecting the environment from root causes of degradation, and realizing a green economy. First, the innovative output of human capital, especially innovative talent, should be fully stimulate. Scientific researchers need to be better compensated particularly through incentivizing technological achievement We believe these measures could enhance innovation vitality. Second, the motivation for retaining, attracting, and utilizing talent requires a combination of efforts. The support services of the whole talent industrial chain should be expanded to ensure the quality of new talent. Acquiring and retaining talent from abroad should be further prioritized. We also suggest combining green transition with the stage and development level and avoiding accelerating transition in a one-size-fits-all manner. Efforts should be made to narrow the green economic development gap between the upstream and the middle and lower reaches, especially for upstream areas with high locations. This will further strengthen the construction of compact urban forms, compressing spatial distance and eliminating divisions. Constructing regionally coordinated and efficient environmental regulation policies should also be explored. As water is the YRB's core element, urban agglomeration policies for water environment, atmospheric environment, and low-carbon governance should be formulated to avoid uncoordinated environmental governance caused by economic competition and improvements.

Data availability statement

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

Author contributions

WX: Conceptualization, methodology, writing–review and editing. YD: Supervision, review and editing. TJ: Additional review and editing.

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Conflict of interest

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

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A characteristics analysis of carbon emission based on multi-dimensional carbon emission accounting methods and structural decomposition analysis: A case study of Beijing, China

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The city's industrial transformation leads to a large amount of carbon emissions, which poses a thorny problem for the allocation of carbon responsibilities. This study established a multi-dimension long-term carbon emission analysis model to explore the characteristic of Beijing's embodied carbon emissions, which could calculate the production-based, consumption-based and income-based carbon emissions. Then, structural decomposition analysis was adopted to quantify the contribution of socioeconomic factors in local and imported carbon emissions. In addition, emission linkage analysis was used for revealing the long-term evolutionary trajectories of sectors. The key discovery can be summarized as follows: 1) the fluctuation trend of production-side and income-side carbon emissions in Beijing is stable and decreased by 3.53% from 2002 to 2017, while consumption-side carbon emissions increased rapidly by 795.45%. 2) The energy, transportation and other services sectors from the supply, production and consumption perspectives. 3)Per capita consumption, production structure and consumption structure are the major contributors of carbon emissions. The study is expected to provide decision support for policymakers to reasonably formulate carbon mitigation policies and allocate carbon mitigation responsibilities from multiple perspectives, and promote the realization of the "carbon peak and carbon neutrality" strategy.

KEYWORDS

carbon emissions analysis, consumption-based accounting, production-based accounting, income-based accounting, structural decomposition analysis, emission linage analysis

1 Introduction

Modern cities and industries have significantly improved people's living conditions, but they have also brought enormous pressure on the ecological environment (Giannakis et al., 2019; Sun et al., 2022). Climate disasters caused by greenhouse gas emissions, especially carbon dioxide, have become a serious problem that threatens the survival of all human beings. China, as the world's largest emitter of carbon dioxide, has announced a series of climate commitments and policies to achieve carbon mitigation goals in order to curb climate warming and promote global carbon neutrality (Guilhot, 2022; Zhang and Wang, 2022). The Chinese government pledged to peak carbon by 2030 and achieve carbon neutrality by 2060 at the international summit (Xinhua News Agency, 2020). Domestically, the Chinese government has issued a series of detailed policy documents to provide guidance for carbon mitigation, such as the *Action Plan for Carbon Dioxide Peaking Before 2030* and the *14th Five-Year Plan for Circular Economy Development*. However, the formulation of current policies was mostly based on production-based carbon accounting method, which could not adequately assess the complex impacts of cities on the carbon emissions system (Zhai et al., 2020a). The lack of scientific carbon emission accounting methods will mislead the allocation of urban carbon emission responsibilities and have a negative impact on the implementation of carbon mitigation policies (Xu et al., 2020). Therefore, it is necessary to explore scientific and multi-dimension urban carbon emission accounting method, and propose policy suggestions from multiple perspectives to promote the realization of carbon mitigation goals.

Previously, many scholars have conducted extensive research on carbon emission accounting methods to analyze key emission sectors in cities, many of which focused on the production-based carbon emission (PBE) (Zhang et al., 2016; Liu et al., 2020; Wang and Yang, 2021). Production-based accounting method can calculate carbon emissions from local production, which is caused by local and export demand (Peters, 2008; Wiedenhofer et al., 2017; Mi et al., 2020). For example, Xu et al. (2021) argued that production-based accounting method can be used to compile provincial carbon inventories and track the flow of implied carbon emissions. In addition, Luo et al. (2020) and Li et al. (2022) showed that the production-based accounting method can analyze the trend of carbon emission changes in specific sectors. It was widely used in the United Nations Framework Convention on Climate Change (UNFCCC) and gas emission inventories at the national and city level. However, with the development of international and inter-provincial trade, more and more emissions are implied in the trade of goods and services (Wu et al., 2022). Production-based accounting method cannot calculate the carbon emissions contained in imported goods, and ignores the important role of the final consumer in the carbon emissions process (Atkinson et al., 2011; Chen et al., 2020). This will negatively impact the allocation of overall carbon responsibility (Shao et al., 2020). A consumption-oriented city is often regarded as a low-carbon city from the perspective of production, because many cities transferred production activities to other regions in the industrial transformation (Wen and Wang, 2020). This is obviously unfair. It interferes with the reasonable allocation of carbon emission reduction responsibilities and hinders the realization of carbon emission reduction goals.

To address the above problem, some studies have proposed a consumption-based carbon emission (CBE) accounting method (Feng et al., 2014; Mi et al., 2016; Mi et al., 2019). Compared with production-based accounting method, consumption-based accounting method could calculate the carbon emissions contained in regional imported products, and assess the carbon responsibility of consumers (Peters and Hertwich, 2008; Wiedmann, 2009; Kim and Tromp, 2021). For example, Hubacek et al. (2017) indicated that consumption-based accounting method can estimate the contribution of final demand on carbon emissions. Steininger et al. (2014) concluded that consumption-based accounting method can improve the cost-effectiveness and justice of carbon mitigation. In addition, this method is also increasingly applied to the analysis of national perspective (Steininger et al., 2016; Rocco et al., 2020). Based on consumption accounting method, Zhang and Liang (2022) and Ma et al. (2022) studied the heterogeneity of carbon intensity in China's inter-provincial trade, and discussed the impact of consumption on regional carbon emissions responsibility. In summary, consumption-based accounting method promotes the understanding of the relationship between inter-regional trade and carbon transfer, and provides a theoretical basis for the allocation of carbon mitigation responsibilities in consumption-oriented cities. Although consumption-based accounting method can track various types of carbon emissions driven by demand at the end of the industrial chain and complement the blind spots of production-based perspective (Harris et al., 2020), but it ignores the role of primary inputs (e.g., labor forces, capital and government services) in the industrial chain, and underestimates the carbon mitigation potential on the supply side (Roca and Serrano, 2007). Therefore, scientific assessment of the carbon emission structure of cities requires more research perspectives.

Fortunately, income-based accounting method can assess the impact of primary inputs on the production process and identify the key supply-side sectors (Li et al., 2018; Xu et al., 2019), which can be used by policymakers to quantify the responsibility of supply-side sectors in the industrial chain (Xie et al., 2017). Liang et al. (2017) found that resource exporters such as Russia and Saudi Arabia should be more responsible for carbon emissions from primary inputs between 1995 and 2009. In addition, income-based accounting method can also provide support for the formulation of supply-side policies for industrial clusters

(Chen et al., 2019). Liang et al. (2016) used income-based accounting method to calculate greenhouse gas emissions across United States industries and identified key sectors on the supply side. This method has also been used in many researches to study the situation in China (Zhang, 2015; Yan et al., 2018; Chen et al., 2019). In general, most of the previous studies on urban income-based carbon emissions (IBE) are from an isolated perspective (Xu et al., 2020), lacking a systematic analysis linked to the production and consumption sides. This will lead to unscientific carbon emission policies. Therefore, it is necessary to explore a comprehensive carbon emission accounting model from multiple perspectives, which is a preliminary preparation for formulating urban carbon mitigation policies.

Analyzing the socioeconomic factors that cause changes in carbon emissions is critical for developing urban carbon mitigation targets and policies. To investigate this problem, the decomposition analysis (DA) provides a practical tool to quantify the effect of different socioeconomic factors on specific objects (Hoekstra and Bergh, 2002). There are two commonly used DA tools, namely index decomposition analysis (IDA) and structural decomposition analysis (SDA), which are widely used in the study of changes in environmental indicators (Wang et al., 2017; Jiang et al., 2022). The advantage of SDA is that the impacts of changes in socioeconomic factors on environmental indicators can be analyzed from a macro perspective, which is achieved by decomposing the change in environmental indicators into multiple components. Due to the flexibility and practicality of this approach, this method is widely used in carbon emission studies based on input-output (IO) table (Chen and Zhu, 2019; Wang and Yang, 2021; Wen et al., 2022). For example, Wen et al. (2022) analyzed the carbon emission drivers of 38 industrial sub-sectors in China through SDA, and identified potential emission reduction strategies. Wang and Yang (2021) argued that SDA can be used to compare the differences in the economic structure of regions or countries, and provide systematic recommendations for industrial policy. Findings from SDA are helpful to explore the impacts of important socioeconomic factors on carbon emissions. However, previous SDA studies on carbon emissions rarely focused on the changing mechanism of urban CBE, and most of them regard cities as a producer of carbon emissions (Zhai et al., 2020a). In addition, many studies ignored the heterogeneity of carbon emission structure between local and imported products. Therefore, there are fewer studies decomposing the socioeconomic influences of local and imported CBE. A comprehensive analysis of urban CBE from the two perspectives of local and imported consumption will help to deepen the comprehension of urban carbon emission mechanism.

Neither the three-perspective carbon emission accounting (i.e., production-based, consumption-based, income-based) method nor SDA can analyze the internal relationship of urban industries, but carbon emission linkage analysis (ELA) can fill this research gap. There are two forms of interaction between sectors in the industrial chain, which are called forward linkage effect (FLE) and backward linkage effect (BLE) (Lenzen, 2003). This method can analyze the upstream and downstream relationships between sectors, quantify the influence of sectors in the industrial chain, and discover important production and consumption sectors (Wang et al., 2013; Wang G et al., 2022). For example, Zhang et al. (2018) identified high-priority sectors for environmental emissions using ELA, while Xu et al. (2020) analyzed the long-term impact of carbon mitigation policies on the industrial chain by tracking and observing changes in sectoral roles. In summary, ELA can help city managers understand the carbon interaction mechanism within the industrial chain and study the changes in carbon structure caused by industrial transformation.

In previous studies, a lot of important work has been carried out to analyze carbon emissions and formulate the scientific carbon mitigation strategies. However, several research gaps still need to be remedied. First, the majority of studies focus on the singleness perspective carbon analysis from consumption or production sides, and few of them analyze the carbon emissions from multi-dimension perspectives. It may lead to unreasonable allocation of carbon emission responsibilities. Second, many studies assumed that cities are producers of carbon emissions, ignoring the contribution of cities on the consumption side when using SDA. Furthermore, research on the distinction between local and imported products in the SDA of CBE remains insufficient. Third, few studies focused on the upstream and downstream linkages between sectoral carbon emissions in the production process at the city level. Filling the existence of these research gaps is of great significance for exploring the internal mechanism of urban carbon emissions.

In order to bridge the research gaps, this contribution of this study are as follows: 1) different from most previous studies based on single perspective analysis, this paper proposes a multiple-dimension carbon emission accounting model based on production, consumption and income perspectives, and studies the characteristics in sectoral carbon emissions from different perspectives. This model can be used to analyze the carbon emissions of different types of cities. 2) In order to further study the carbon emission structure of consumption-oriented cities, this paper conducts structural decomposition analysis on the local and import parts of CBE respectively, and studies the difference and change mechanisms of socioeconomic factors (e.g., population, per capita consumption, consumption structure, production structure, carbon emission intensity) that affect the change of carbon emissions. 3) Analyze the direction of carbon transfer and observe the changes in carbon relationship between sectors after urban industrial transformation through ELA. 4) Conduct a dynamic analysis from long-term coherent data (2002–2017) and study the change characteristics of carbon emissions in different periods in Beijing. In summary, this study establishes a multi-dimension long-term carbon emission analysis model, which can identify key sectors from multiple perspectives and explore the carbon emission characteristics and development trends of the sectors. This study is expected to provide decision support for decision makers' carbon reduction strategies and provide a theoretical basis for the rational allocation of carbon reduction responsibilities, which will facilitate the realization of "carbon peak and carbon neutrality" strategy.

As the capital of China, Beijing is the epitome of China's urban industrial transformation (Yang et al., 2018), as evidenced by the share of the tertiary industry increased from 23.69% to 83.09% between 1978 and 2018 (National Bureau of Statistics, 2019). Meanwhile, the energy consumption intensity in Beijing is decreasing rapidly, from 0.377 in 2013 to 0.182 in 2021 (tons of standard coal consumed per 10,000 Yuan of GDP). In 2021, Beijing's urban forest cover is 44.6%, while annual GDP per capita is 184,000 Yuan, ranking first in the country (Beijing Municipal Bureau of Statistics, 2022). This data shows that Beijing is striking a balance between carbon reduction and economic development. However, Beijing is a typical consumption-oriented city, and most of the energy and commodities consumed by household consumption and commercial activities are dependent on imports. In this case, the heavy burden of reducing carbon emissions will fall on producers, and the responsibility of consumer is underestimated under traditional production-based accounting methods (Mi et al., 2019; Wu et al., 2019; Dong B et al., 2022; Du et al., 2022). The lack of regulation of carbon emissions from multiple perspectives will have a negative impact on the achievement of the overall regional carbon emission target. Therefore, Beijing as a typical consumption city, is selected as a research case in this study, and a multi-dimension long-term carbon emission analysis model is established to explore the characteristics and evolution mechanism of carbon emissions in Beijing from various perspective.

The rest of this study is organized as follows: Section 2 introduces the main research methodology, Section 3 reveals the computational results and interpretation of the results, Section 3.6 discusses issues encountered in the research, and Section 4 presents conclusions and policy recommendations.

2 Method

2.1 Three-perspective carbon emission accounting method

The IO model designed by Leontief can quantify the inflow and outflow relationship between sectors by counting the monetary flows of economic sectors (Leontief, 1936). It can reveal the potential environmental impacts caused by production activities such as resource exploitation, so it was widely applied in the accounting of carbon emissions (Fan et al., 2018; Zha et al., 2022), air pollution (Dong J et al., 2022; Sun et al., 2022), fossil energy (Li et al., 2020; Wang Q et al., 2022), water utilization (Zheng et al., 2020; Wang P et al., 2022), and other environmental studies (Zhang et al., 2018; Shi et al., 2021; Jiang and Hao, 2022). According to the different compilation scopes of the IO table, it can be divided into single-region input-output (SRIO) table and multi-region input-output (MRIO) table. Compared with the MRIO table, SRIO table assumes that local and imported goods in the same sector are homogeneous, and it is more commonly used to analyze inter-sectoral characteristics in a specific area (Zhang et al., 2022). Production-based, consumption-based and income-based carbon emissions can all be calculated through the SRIO model. In this study, a three-perspective accounting method based on SRIO table is conducted to calculate the sectoral carbon emissions in Beijing.

The basic formula of the SRIO table can be expressed by Eq. 1 and Eq. 2:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} = \boldsymbol{LY} \quad (1)$$

$$\boldsymbol{X} = \boldsymbol{V}(\boldsymbol{I} - \boldsymbol{B})^{-1} = \boldsymbol{VG} \quad (2)$$

where **X** denotes the total output of each sector. **I** is the identity matrix. **Y** represents the final demand of each sector, **V** represents the primary input of each sector. **A** and **B** are the direct requirement coefficient matrix and the direct distribution coefficient matrix, respectively, which can reveal the inter-sectoral flow relationship. $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ and **L** represent the Leontief inverse matrix (Leontief, 1936), which can reflect the input of each sector required to satisfy the final demand of the industrial chain. $(\boldsymbol{I} - \boldsymbol{B})^{-1}$ and **G** represent the Gosh inverse matrix (Ghosh, 1958), which can reflect the output in the industrial chain caused by the primary input of each sector.

The IO table published by Beijing is a competitive IO table, which does not distinguish between local and imported products. Since there are differences in the production process between imported and local products in Beijing, the embodied carbon emission of them will be different. For example, the average carbon emission intensity of Inner Mongolia is significantly higher than that of Beijing (Chen et al., 2019). If the same method is used to calculate the carbon emissions of local and imported products, the calculation result of the imported part will be significantly lower. Therefore, in order to improve the rationality of the calculation process and avoid underestimating the embodied carbon emissions, it is necessary to calculate the carbon emissions of local and imported products separately. The import coefficient matrix **K** is introduced to distinguish the monetary flows matrix and final demand matrix of the import part from the original SRIO table (Xu et al., 2021). The import coefficient matrix **K** can be calculated by Eq. 3:

$$\boldsymbol{K} = (k_i) = \frac{im_i}{\sum_j z_{ij} + \sum_t y_{it}} \quad (i = 1, 2, 3, \cdots, n) \quad (3)$$

where, **K** is the import coefficient matrix, which means the proportion of imported products in the industrial chain. im_i represents the import vector, including domestic and international imports. $\sum_j z_{ij}$ represents the sum of the intermediate demands of sector i, and $\sum_t y_{it}$ represents the sum of the final demands of sector i.

Under this framework, PBE can be calculated by Eq. 4:

$$\boldsymbol{PE} = \boldsymbol{E}(\boldsymbol{I} - \boldsymbol{A}^l)^{-1}\boldsymbol{Y}^l \tag{4}$$

where $\boldsymbol{PE}$ is PBE, represents the carbon emission from production (excluding the imported part). Row vector **E** represents the carbon emissions intensity of each sector. $\boldsymbol{A}^l$ is the direct requirement matrix of the local part and $\boldsymbol{Y}^l$ is the final demand matrix of the local part.

CBE can be calculated using the relationship between PBE and CBE: "CBE = PBE—carbon emissions embodied in exports + carbon emissions embodied in imports" (Mi et al., 2016). By replacing $\boldsymbol{Y}^l$ with $\boldsymbol{Y}^{ex}$, which represents domestic and international exports in final demand, $\boldsymbol{PE}^{ex}$, carbon emissions embodied in exported products can be calculated. However, since detailed data on imports are not available, national carbon emission intensity data is used to estimate the carbon emissions embodied by imported products:

$$\boldsymbol{CE}^{im} = \boldsymbol{E}^{im}(\boldsymbol{I} - \boldsymbol{A}^{im})^{-1}\boldsymbol{Y}^{im} \tag{5}$$

where, $\boldsymbol{CE}^{im}$ is the carbon emissions embodied in imports, $\boldsymbol{E}^{im}$ is the vector of domestic average carbon emission intensity, $\boldsymbol{A}^{im}$ is the direct requirement matrix of the imported part, and $\boldsymbol{Y}^{im}$ is the final demand matrix of the imported part. Then, CBE can be calculated by Eq. 6:

$$\boldsymbol{CE} = \boldsymbol{PE} - \boldsymbol{PE}^{ex} + \boldsymbol{CE}^{im} \tag{6}$$

where CE is CBE.

IBE can be expressed as Eq. 7:

$$\boldsymbol{IE} = \boldsymbol{V}(\boldsymbol{I} - \boldsymbol{B})^{-1}\boldsymbol{E}' \tag{7}$$

where **IE** is IBE, $\boldsymbol{E}'$ indicates the transpose of the matrix **E.**

2.2 Structural decomposition analysis for driving factors

Since Beijing is a consumption-oriented city, CBE dominates the carbon emission system. It is necessary to decompose the CBE of local and imported products in Beijing from 2002 to 2017 to investigate the driving factors. Based on the SDA and Leontief's IO table, the CBE of local and imported can be further decomposed into multiple components. After referring to previous literature and studying the characteristics of Beijing industries (Chen and Zhu, 2019; Wang and Yang, 2021; Wen et al., 2022), we designed five socioeconomic influencing factors, including carbon emission intensity, production structure, consumption structure, per capita consumption, and population. These socioeconomic factors can explain the mechanisms of carbon emission changes from a macro perspective. In addition, most previous studies focus on overall carbon emissions (Zhai et al., 2020a; Wen et al., 2022), while this paper divides CBE into local and imported components, and decomposes the structure separately. The impact of each socioeconomic factor on CBE can be analyzed in more detail. The calculation formula is as follows:

$$CE^l = \boldsymbol{E}^l\boldsymbol{L}^l\boldsymbol{Y}^l = \boldsymbol{E}^l\boldsymbol{L}^l\boldsymbol{S}^l Q^l P \tag{8}$$

$$CE^{im} = \boldsymbol{E}^{im}\boldsymbol{L}^{im}\boldsymbol{Y}^{im} = \boldsymbol{E}^{im}\boldsymbol{L}^{im}\boldsymbol{S}^{im}Q^{im}P \tag{9}$$

where the symbols l and im denote local and imported products, respectively; CE^l and CE^{im} indicate the local and imported carbon emissions; $\boldsymbol{E}^l$ and $\boldsymbol{E}^{im}$ represent carbon emission intensity; $\boldsymbol{L}^l$ and $\boldsymbol{L}^{im}$ represent the Leontief inverse matrix; $\boldsymbol{S}^l$ and $\boldsymbol{S}^{im}$ are the structure of final demand; Q^l and Q^{im} are the final demand per capita; P is the population. After decomposition, the contributions of five socioeconomic factors to changes in carbon emissions from t0 to t1 (t0 represents the base period, t1 represents the target period) are formulated in Equations 10:

$$\begin{aligned}\Delta CE &= CE_{t1} - CE_{t0} = \boldsymbol{E_{t1}L_{t1}S_{t1}}Q_{t1}P_{t1} - \boldsymbol{E_{t0}L_{t0}S_{t0}}Q_{t0}P_{t0} \\ &= \Delta\boldsymbol{E}\boldsymbol{L_{t1}S_{t1}}Q_{t1}P_{t1} + \boldsymbol{E_{t0}}\Delta\boldsymbol{L}\boldsymbol{S_{t1}}Q_{t1}P_{t1} + \boldsymbol{E_{t0}L_{t0}}\Delta\boldsymbol{S}Q_{t1}P_{t1} \\ &\quad + \boldsymbol{E_{t0}L_{t0}S_{t0}}\Delta QP_{t1} + \boldsymbol{E_{t0}L_{t0}S_{t0}}Q_{t0}\Delta P\end{aligned} \tag{10}$$

The symbols $t0$ and $t1$ correspond to the base period and the target period, respectively. For example, CE_{t0} and CE_{t1} denote the carbon emissions in the base and target periods, respectively, and ΔCE denotes the difference between them. **E**, **L**, **S**, Q and P also follow this pattern. As shown in Eq. 10, ΔCE is composed of the changes in carbon emissions caused by five socioeconomic factors. In addition, this formula can be applied to analyze local and imported carbon emissions respectively. By substituting the relevant parameters of local and imported products into Eq. 10, the socioeconomic factors of changes in $\boldsymbol{CE}^l$ and $\boldsymbol{CE}^{im}$ can be quantified.

2.3 Carbon emission linages analysis

ELA is commonly used to analyze the upstream and downstream relationships of sectors and to identify key consumption-side and supply-side sectors. By calculating FLE and BLE, the interaction between sectors and the transmission mechanism of the industrial chain can be revealed. As shown in Eq. 11 and Eq. 12, key influential sectors with high potential to reduce emissions through industrial chain policies can be discerned.

$$BLE_i = \frac{n\theta_i}{\sum_{i=1}^n \theta_i} \tag{11}$$

$$FLE_j = \frac{n\delta_j}{\sum_{j=1}^n \delta_j} \tag{12}$$

TABLE 1 The 19 aggregated sectors and the corresponding abbreviations.

Code	Abbreviation	Aggregated sector
1	FA	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy
2	MI	Mining Industry
3	FT	Manufacture of Foods and Tobacco
4	TC	Manufacture of Textiles and Clothing
5	WF	Processing of Woods and Furniture
6	PP	Manufacture of Papermaking, Printing, and Paper Products
7	PC	Processing of Petroleum, Coking, and Nuclear Fuel
8	CI	Chemical Industry
9	NM	Manufacture of Nonmetal Mineral Products
10	MP	Manufacture of Metal Products
11	GS	Manufacture of General and Special Machinery
12	TE	Manufacture of Transport Equipment
13	EE	Manufacture of Electric, Electronic and Telecommunications Equipment and Machinery
14	IM	Manufacture of Instruments, Meters and others
15	EP	Electric Power, Gas and Water Production and Supply
16	CO	Construction
17	WR	Wholesale, Retail Trade and Accommodation
18	TS	Transport, Storage, and Post
19	OS	Other Services

where n represents the number of sectors. $\boldsymbol{\theta} = \boldsymbol{EL}$, θ_i denotes the carbon emission intensity of sector i on the production side. $\boldsymbol{\delta} = \boldsymbol{GE}'$, δ_j denotes the carbon emission intensity of sector j on the supply side. In this study, $BLE_i > 1$ means that the carbon emissions caused by a unit increase in the final demand of sector *i* are above the average level. Similarly, $FLE_j > 1$ means that the carbon emission caused by a unit increase in the primary input of sector *j* is above the average level.

2.4 Data sources

The economic and environmental data collected by this research model are currency IO tables, population, and carbon emission inventories. The currency IO tables in 2002, 2007, 2012 and 2017 are released by the Beijing Municipal Bureau of Statistics (Beijing Municipal Bureau of Statistics, 2022). Avoiding the impact of price fluctuations on the monetary IO table is the basis of the research model (Xu et al., 2020; Xu et al., 2021). Therefore, monetary values in all IO tables are adjusted to 2017 prices. Population data are derived from Beijing Statistical Yearbook (Beijing Municipal Bureau of Statistics, 2003; Beijing Municipal Bureau of Statistics, 2008; Beijing Municipal Bureau of Statistics, 2013; Beijing Municipal Bureau of Statistics, 2018). The carbon emission inventories of Beijing are freely available from the China Emission Accounts and Datasets (CEADs) (China Emission Accounts and Datasets, 2022), including fossil fuel consumption and fossil fuel-related carbon emissions. There are significant differences in sectoral classification between the above data. In order to bridge the data differences and simplify the calculation process, sectors need to be integrated. Based on the reference to previous studies (Chen and Zhu, 2019; Mi et al., 2019; Zhai et al., 2020a; Xu et al., 2021), the original 42 sectors were integrated into 19 aggregated sectors according to the characteristics of Beijing sectors, as shown in Table 1.

In summary, the theoretical framework of this study is shown in Figure 1. First, on the basis of previous research, this study collected the IO table and carbon emission inventory of Beijing in 2002, 2007, 2012, and 2017, and integrated the data for the convenience of calculation. Secondly, based on the three-perspective accounting method (i.e., production-based, consumption-based and income-based accounting methods), this study analyzed the differences in carbon emission characteristics of various industries. Thirdly, based on SDA, this study revealed the impact of changes in socioeconomic factors on carbon emissions of urban consumption. Fourth, based on ELA, this study described the evolutionary trajectory of the sector. The research framework of this study is composed of the above data and research methods.

3 Result

3.1 Intersectoral carbon flows in local and import regions

Due to the stark difference in carbon emission intensity and flow direction between local and imported products, the

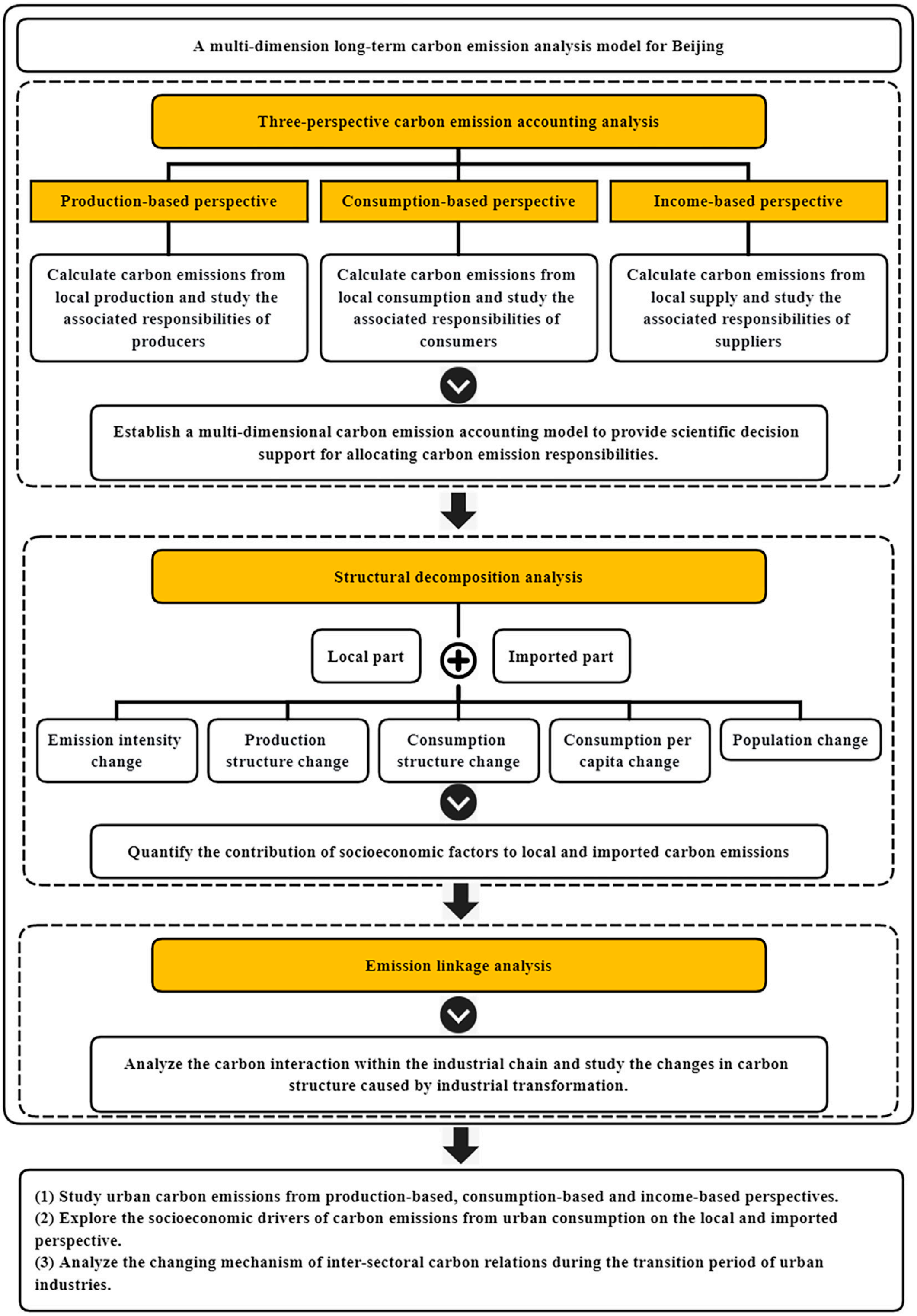

FIGURE 1
Theoretical framework for this study.

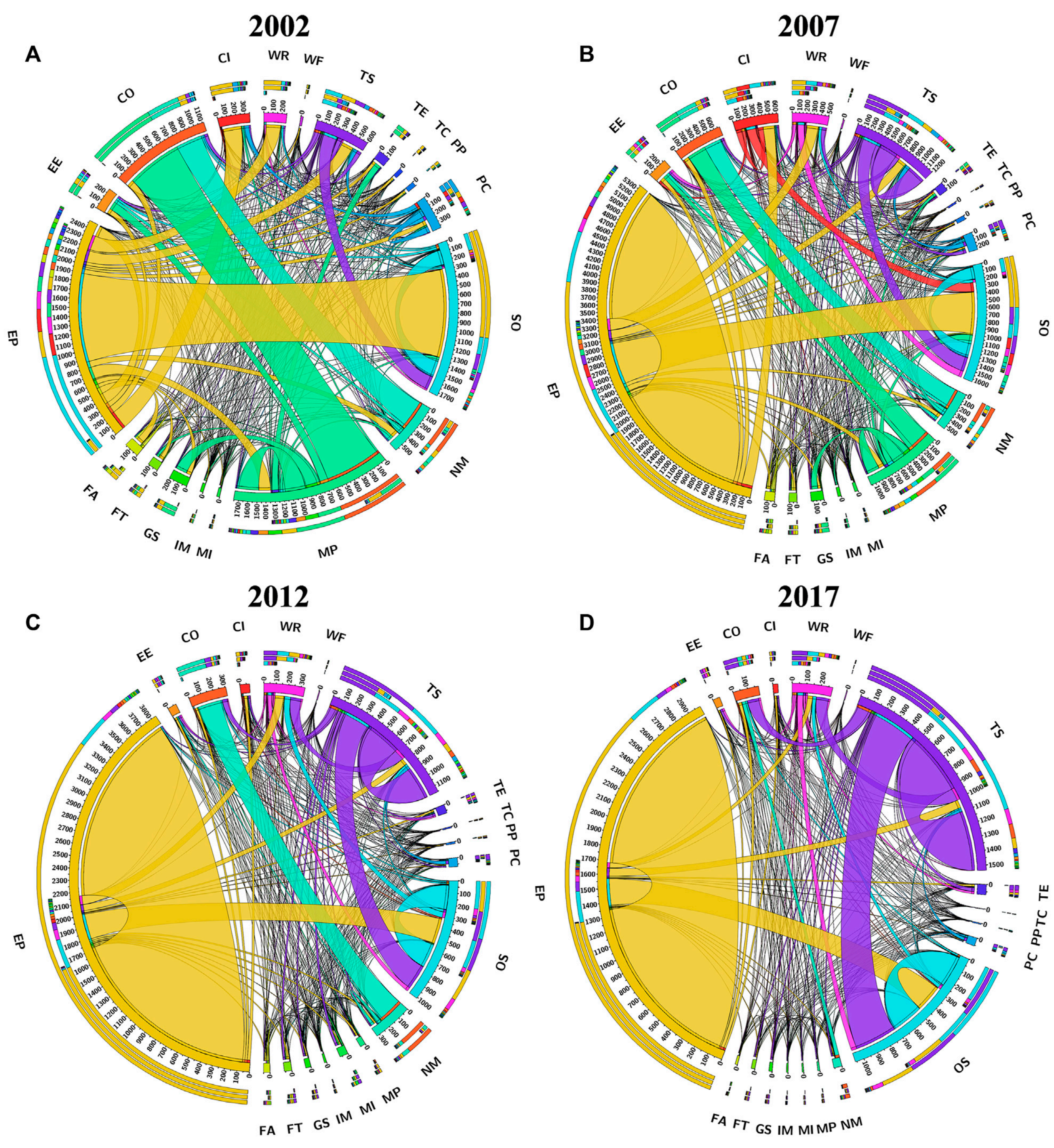

FIGURE 2
Local carbon flows among different sectors from 2002 to 2017. **(A)** 2002 **(B)** 2007 **(C)** 2012 **(D)** 2017.

imported carbon flows are more complex than expected. Thus, the system is fundamentally different when considering the imported carbon flows. The analysis of carbon flows among different sectors is essential to be conducted to further reveal the difference in carbon emissions between local and imported products. The local and imported carbon flows among sectors are shown in Figure 2 and Figure 3, respectively. The values of all carbon flows across sectors are positive. The color of each sector is different. Streamlines between sectors can show the direction of carbon flow. The color of the flow line between industries represents the origin of carbon flow. The width of carbon flow in each sector indicates the amount of carbon flow between this

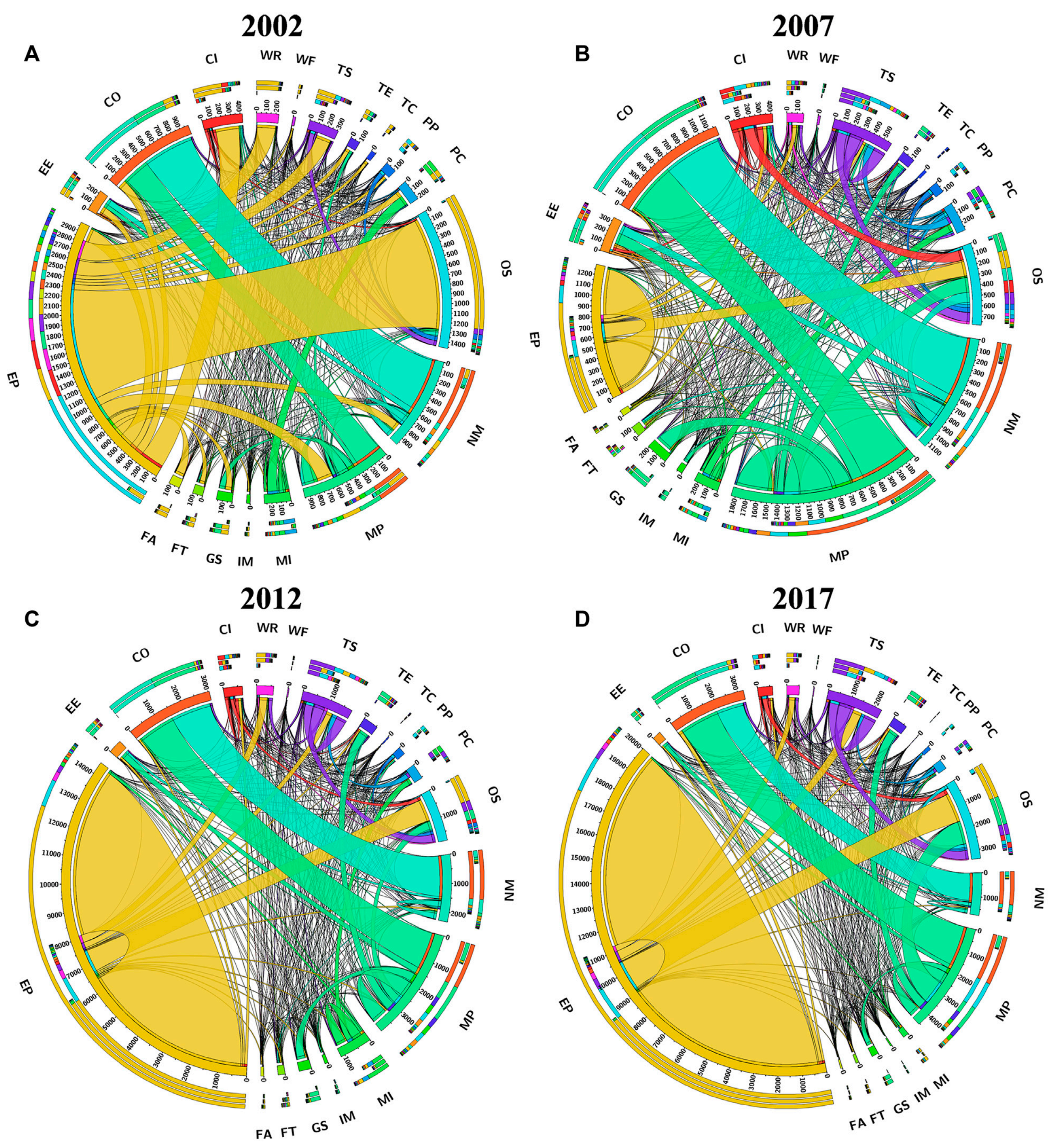

FIGURE 3
Imported carbon flows among different sectors from 2002 to 2017. **(A)** 2002 **(B)** 2007 **(C)** 2012 **(D)** 2017.

sector and others. For example, the yellow flow line between EP and OS in Figure 2A represented the local carbon flow from EP to OS, and the amount of carbon emission was 10.25 million tons (Mt). Compared with Figure 2 and Figure 3, it can be seen that the change in the structure of imported carbon flows was not as large as that of local carbon flows, which indicated that the relationship of imported products among sectors was more stable than that of local products. For instance, the imported carbon flows from NM and MP to CO persisted between 2002 and 2017, while the relationship in local carbon flows disappeared after 2012. It indicated that the local carbon flow of CO was more susceptible than its imported carbon flow. Changing the carbon structure of imported products was more difficult than changing that of local products.

According to Figure 2A, the major contributors of local carbon flows were EP, MP, and NM, which contributed 23.45, 13.44, and 4.37 Mt, respectively. Among them, MP contributed most of its local carbon flow to CO (6.48 Mt) and itself (2.33 Mt), while the rest of local carbon flow mainly contributed to GS (1.29 Mt). Figure 2B–D reveal that TS and OS gradually replaced NM and MP as the main contributors of local carbon flow after 2007. Furthermore, the main contributor to the local carbon flow of EP has always been itself, while the rest of the local carbon mainly flowed to TS and OS. In general, the structure of local carbon flows changed significantly between 2002 and 2017. By contrast, Figure 3A shows that the major contributors of imported carbon flows were EP, MP, and NM with the contribution of 28.24, 8.01, and 6.07 Mt, respectively. Among them, EP contributed a part of the imported carbon flow to OS (12.34 Mt), while the rest evenly contributed to other sectors. According to Figure 3B–D, the structure of imported carbon flows is stable every year, except for EP. The imported carbon flow within EP increased from 4.61 to 86.92 Mt, which reflected Beijing's rapidly increasing demand for imported energy. In summary, imported carbon flows mainly came from EP, NM, and MP sectors and flowed to EP, CO, and OS sectors. This result was in line with the characteristics of the developed tertiary industry in Beijing.

3.2 Carbon emissions analysis from multiple perspectives

3.2.1 Comparison of different perspectives

Based on the carbon emission inventories released by CEADs and the environmentally extended (IO) model constructed in this study, PBE, CBE, and IBE in 2002, 2007, 2012, and 2017 for 19 aggregated sectors were calculated. As shown in Figures 4A–D, embodied carbon emissions differ significantly across the three types of accounting methods, reflecting the different focus on the allocation of various methods. Several major findings were revealed by the overall comparison of three accounting methods.

First, during the study period, the fluctuation trend of PBE and IBE in Beijing was stable, while CBE grew rapidly. Beijing's CBE was the lowest among the three perspectives carbon emission in 2002 and 2007, but it reversed in 2012 and 2017. During the critical period of change (2007–2012), the total amount of PBE and IBE in Beijing decreased by 7.97 Mt (8.73%), while the total amount of CBE increased hugely by 731.52 Mt (924.83%). In 2017, the total amount of CBE was 584.01 Mt, which was significantly higher than that of PBE (68.94 Mt). The result reflected that the carbon emission caused by consumption behavior in Beijing was greater than that caused by the production and supply processes. The industrial transformation and deindustrialization in Beijing were cited as the main reasons. The decline in manufacturing capacity forced Beijing to import products from other regions to meet the local demands of industry and residents.

Second, the key sectors of carbon emissions calculated by the three accounting methods were different. This study defined sectors that once accounted for more than 10% of total carbon emissions as key sectors. Take 2017 as an example, the key sectors of PBE were EP, TS and OS, the key sectors of CBE were MI, MP, and EP, while the key sectors of IBE were EP, TS, and OS. Compared with different accounting methods, it could be found that EP was an important carbon emission contributor from three perspectives. TS and OS had an important position in both PBE and IBE, which indicated that they were both producers and suppliers in the industrial chain. Traditionally, MI was considered to be the supplying sector of raw materials, but in 2012 and 2017, MI was found to be the key sector of CBE. The results showed that the carbon emission characteristics of MI were changed in 2012, and its role in the industrial chain needs to be re-evaluated. Therefore, policymakers should pay more attention to the import process of MI.

Third, the results of PBE, CBE, and IBE vary widely when calculating a specific industry. For example, the IBE of MI was 8.41 Mt in 2007, much higher than its PBE (0.11 Mt) and CBE (0.68 Mt). For TE in 2012, CBE was 15.23MT, PBE and IBE were 0.61 and 1.32 MT. The difference of carbon emission results from three perspectives is significant. Obviously, developing carbon policies based on traditional production-side accounting method cannot achieve a good effect of carbon mitigation for the consumption-oriented cities. Generally, the results imply that the carbon accounting method from single perspective is detrimental to comprehensive evaluate of urban carbon emissions, and formulate of carbon mitigation policies and allocate carbon emission responsibilities. Therefore, it is necessary to evaluate the carbon emissions from different perspectives.

3.2.2 Characteristic analysis of sectoral direct carbon emission

The compositions of direct carbon emission (DCE) for 19 sectors in four statistical years are shown in Figure 5. These compositions varied by year but show certain structural and temporal characteristics. Several results and policy implications are presented in Figure 5. First, EP was the main emitter of DCE in Beijing, which accounted for about 40% of the total DCE with emissions of 26.95, 37.05, 37.35, and 28.5 Mt in 2002, 2007, 2012, and 2017, respectively. In the process of supplying water, electricity and heat to other sectors, a large amount of carbon emission was emitted by EP. The government should promote the development of emerging energy technologies (e.g., hydrogen, wind, solar, and other energy sources) to build a cleaner modern energy system. Second, the structure of DCE differed significantly in

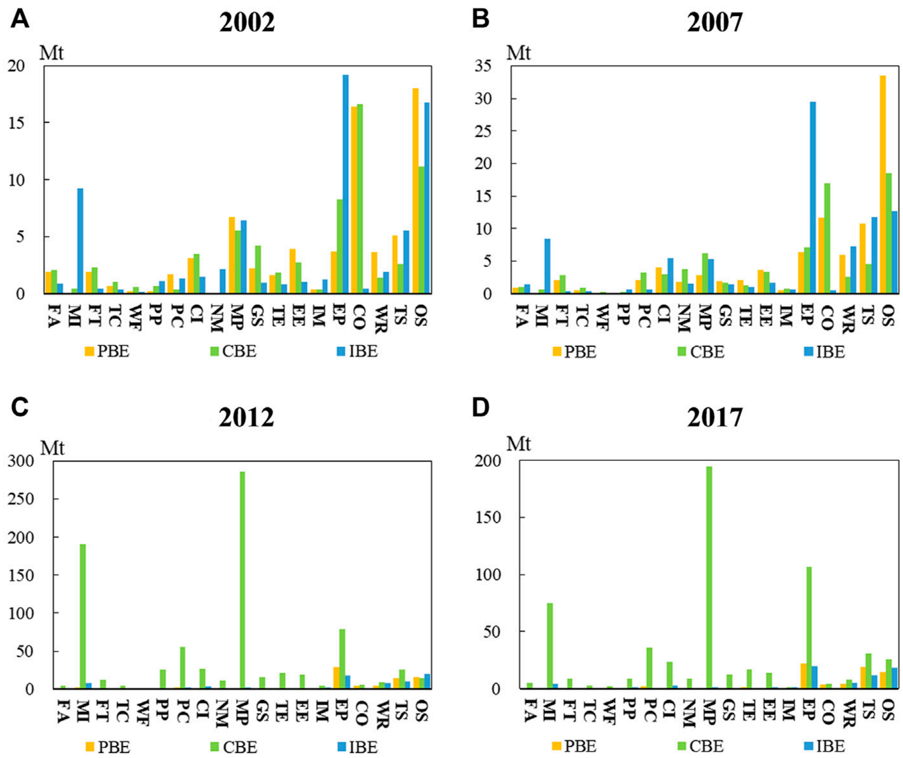

FIGURE 4
Comparison of sectoral PBE, CBE, and IBE in Beijing from 2002 to 2017. **(A)** 2002 **(B)** 2007 **(C)** 2012 **(D)** 2017.

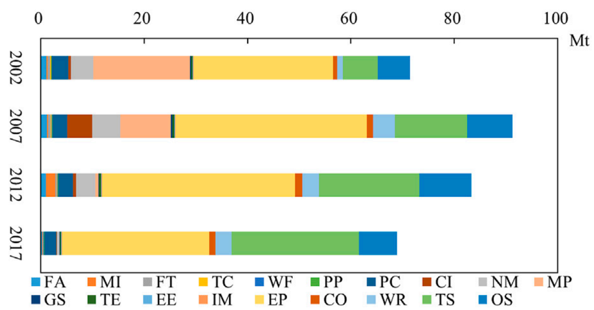

FIGURE 5
Proportion of DCE among different sectors from 2002 to 2017.

different periods. MP contributed 18.65 Mt of DCE and became the second largest DCE emitting sector in 2002, however, its share dropped rapidly from 26.1% to 0.14% between 2002 and 2017. During this period, the total proportion of DCE in the tertiary industry increased rapidly, especially in TS and OS. Therefore, DCE of the tertiary industry should be more concerned by policymakers after the industrial transformation.

3.2.3 Characteristic analysis of sectoral PBE

As shown in Figure 6, compared with the sector clusters of DCE, the main contributors of PBE are partly different. First, the proportion of PBE in EP increased from 5.19% to 31.28% during 2002–2017 and became the largest source of PBE in 2017. This result reflected Beijing's increased demand for energy production. In order to offset the carbon emissions caused by the increase in energy consumption, the development of clean energy technologies (such as wind energy, solar energy, biomass energy, *etc.*) should be encouraged. Second, the PBE of CO in the sample period was 16.42, 11.71, 5.08, and 3.74 Mt, respectively, which were much higher than its DCE. The reason was that the construction process consumed a large number of carbon-enriched products, resulting in more carbon emissions from the production process of the CO sector. The results also showed that the PBE of CO was significantly reduced due to the government's control of carbon-enriched products. Third, the PBE of the manufacturing sector declined rapidly during the 4 years. For example, from 2002 to 2017, the PBE of CI, MP, and EE decreased by 2.64, 6.52, and 3.36 Mt, respectively. This was related to the recession of manufacturing caused by Beijing's industrial transformation. Forth, the PBE of the tertiary industry continued to increase from 2002 to 2017. The proportion of PBE in TS increased rapidly from 7.15% (2002) to 27.27% (2017), and

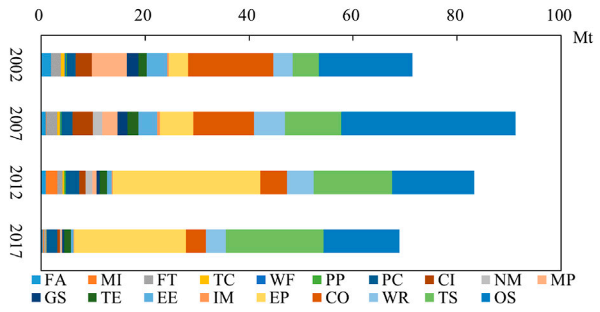

FIGURE 6
Proportion of PBE among different sectors from 2002 to 2017.

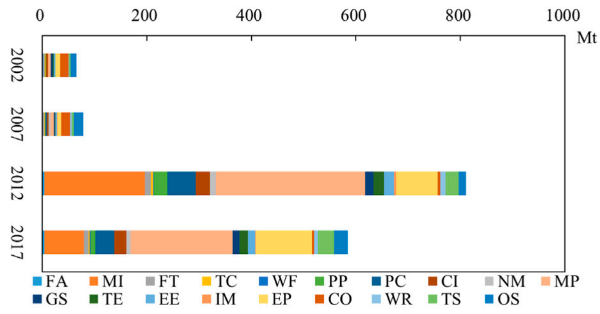

FIGURE 7
Proportion of CBE among different sectors from 2002 to 2017.

emissions increased by 13.69 Mt. The result indicated that the logistics industry played an important role in the urban function of Beijing. For TS sector, the government should continue to promote the transformation of electric vehicles by improving charging infrastructure and subsidizing new energy vehicle companies. OS was the key sector of the service industry, with PBE of 18.00 Mt (2002), 33.53 Mt (2007), 15.84 Mt (2012), and 14.58 Mt (2017), respectively. Public services, infrastructure, scientific research, information services consumed many carbon-intensive products such as electricity, oil, and coal throughout the life cycle of OS. Therefore, despite the low number of DCE, the potential for carbon mitigation in OS was significant from the production perspective. For OS sector, the government should promote the development of low-carbon service industries, introduce policies to support high-tech industries, and strictly limit the use of high-carbon products. Production-based accounting method can help policymakers assess the carbon responsibility and mitigation potential on the production side.

3.2.4 Characteristic analysis of sectoral CBE

Large quantities of goods and services were imported to meet the final demand of local residents. According to Figure 7, the following conclusions can be drawn: first, the total amount of CBE in Beijing varied greatly, ranging from 65.22 Mt (2002), 79.10 Mt (2007), 810.61 Mt (2012), and 584.01 Mt (2017), respectively. The largest increase in CBE occurred in 2012, which was a ten-fold increase compared to 2007. The results showed that the external dependence of Beijing increased significantly from 2007 to 2012, reflecting the growth of consumer capacity of residents and government. Second, the CBE of CO continued to decline over the four sample years, from 16.59 Mt (2002) to 4.35 Mt (2017), which was mainly because of Beijing's strict regulation for carbon emissions in CO. Third, MP replaced OS as the largest source of CBE emissions since 2012. In 2017, the upstream carbon emissions caused by imports in NM were 195.03 Mt, accounting for 33.39% of the total emissions. However, the PBE of NM in 2017 was only 0.18 Mt. Similar to the NM sector, some manufacturing sectors began to import a large number of products from other regions and reduced local production after Beijing's industrial transformation. Interprovincial carbon transfers from commodity trade can be curbed by spreading low-carbon technologies, taxing carbon-rich products, and restricting imports. In addition, the central government should also consider the key role of consumption behavior and comprehensively assess the responsibility of carbon emissions to improve the efficiency of carbon emission reduction. In this case, the development of new carbon emission strategy based on the consumption accounting method is necessary for overall carbon mitigation.

In addition, there is one notable result worth discussing. Beijing's total CBE was 810.6 Mt in 2012, much higher than the total CBE in 2007 (79.1 Mt), and nine times of the total PBE in 2012 (83.29 Mt). There was an order of magnitude gap between CBE and PBE of Beijing during the same period. According to the results, there were two major reasons for this phenomenon.

First, Beijing transformed into a consumption-oriented city, and the frequent activities of import led to a rapid increase in consumption-based carbon emissions. Beijing was a microcosm of China's urban transformation. In the past 2 decades, Beijing experienced a continuous process of deindustrialization due to the macro policies and urban planning. Beijing expelled energy-intensive and high-polluting sectors (such as steel and chemical industries) and developed innovative industries and service sectors. The capability of self-sufficiency of Beijing gradually declined during the process. At the same time, the growth of population and per capita consumption resulted in a rapid increase in the total demand of residents for fundamental products. According to the IO table, the final demand in Beijing (i.e., urban and rural consumption, government consumption and capital formation) increased from RMB 429 billion in 2002 to RMB 2,779 billion in 2017. The capacity of local production cannot meet the growing demand for commodities. Therefore, Beijing began to expand the import volume from 2012, which eventually brought about a rapid rise in CBE.

Second, the headquarters effect of enterprises in Beijing was significant, which increased the CBE in Beijing. Enterprise products required by regions outside the city boundary were uniformly distributed and sold by the headquarters, and most of the income was attributed to the location of headquarters. Headquarters effect existed in many sectors of Beijing, especially in energy-related sectors (such as MI and EP). For example, China National Petroleum Corporation (CNPC), headquartered in Beijing, controlled the allocation and sale of oil and gas through the group's online trading platform. In the past, the sales channels and funds for most products were managed by regional subsidiaries, but now they were in the hands of the headquarters. The separation of upstream and downstream manufacturers caused by the headquarters effect led to a substantial increase in Beijing's domestic and foreign imports. According to the I-O table, from 2002 to 2017, imports from domestic and foreign increased from RMB 422 billion to RMB 8,445 billion, much larger than the increase in final demand. If the consumption-based accounting method is adopted by the policymaker, Beijing will be recorded a large amount of carbon emissions caused by headquarters effect, which is unfair to Beijing. Therefore, the establishment of a multi-dimension assessment mechanism for carbon emissions responsibility is necessary for both cities and decision-makers.

3.2.5 Characteristic analysis of sectoral IBE

The sectoral carbon emissions calculated by the income-based accounting method were different from the previous two methods. Figure 8 shows CO_2 emissions among sectors from the income perspective, and three conclusions can be obtained: first, the primary input of MI, EP, TS and OS enabled a large amount of carbon emissions. The total IBE of these sectors in 2017 was 53.74 Mt, accounting for 77.95% of total emissions. Most IBE were emitted by a few key sectors, which reflected the strong influence of upstream industries on the carbon emissions of downstream industries. Second, sectors related to resource extraction or energy supply such as MI and EP were the major contributors of IBE. In 2012, the carbon emissions caused by the primary input of MI and EP were 8.41 and 18.33 Mt, respectively, accounting for 10.1% and 22.01% of the total IBE. Coal, oil or electricity supplied by these sectors would cause many carbon emissions when used by downstream sectors. This result indicates that more attention should be paid to energy-related sectors when formulating carbon mitigation policies on the supply side. Third, the sectors of the tertiary industry, which were generally regarded as low-carbon industries, were the major contributors to the IBE in Beijing. In 2017, the IBE caused by the primary input of OS and TS were 17.87 and 11.78 Mt. This result reflected that Beijing's tertiary industry was closely linked to carbon-intensive sectors. One possible reason was that the tertiary industry provided a lot of services to carbon-intensive sectors. Generally, the government should introduce more supply-side policies to reduce IBE, such as reducing the use of fossil energy, promoting the development of renewable energy technologies, and limiting the expansion of high-polluting industries, *etc.* Income-based accounting method can discover key sectors on the supply side and provide detailed suggestions for carbon emission reduction at the source of the industrial chain.

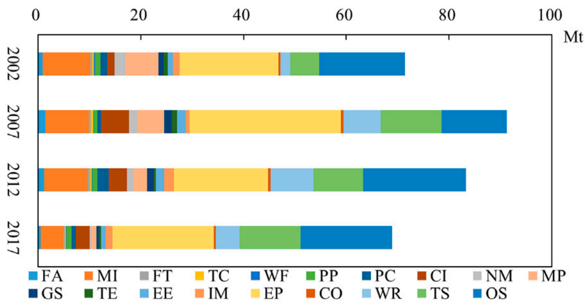

FIGURE 8
Proportion of IBE among different sectors from 2002 to 2017.

3.3 Socioeconomic factors of changes in CBE

As the above results show, it is confirmed that Beijing is a consumption-oriented city and CBE dominated Beijing's carbon emissions after 2012. Therefore, the research on the influencing factors of urban CBE is of great help to the allocation of carbon responsibility and the formulation of related policies. Based on the analysis of five socio-economic factors (e.g., population, per capita consumption, production structure, consumption structure and carbon emission intensity), the impact of macro changes on CBE can be revealed. For example, the carbon emission intensity of manufacturing processes can be reduced through technological advances, thereby reducing CBE. Policy reforms can affect CBE by managing and adjusting the structure of production and consumption. Besides, the growth of the population and spending power can promote the expansion of residents' demand, which will inevitably lead to the growth of CBE. In addition, this paper innovatively distinguishes between local and imported products in SDA, and the difference of their change mechanism can be further studied.

Figure 9 shows the contributions of different socioeconomic factors to Beijing's CBE and decomposed into two parts: local and imported products. It reveals the reason for the variation of CBE from 2002 to 2017. According to Figure 9A, the carbon emission intensity was the main driver of the reduction in CBE over the three periods (period one is from 2002 to 2007, period two is from 2007 to 2012, period three is from 2012 to 2017).

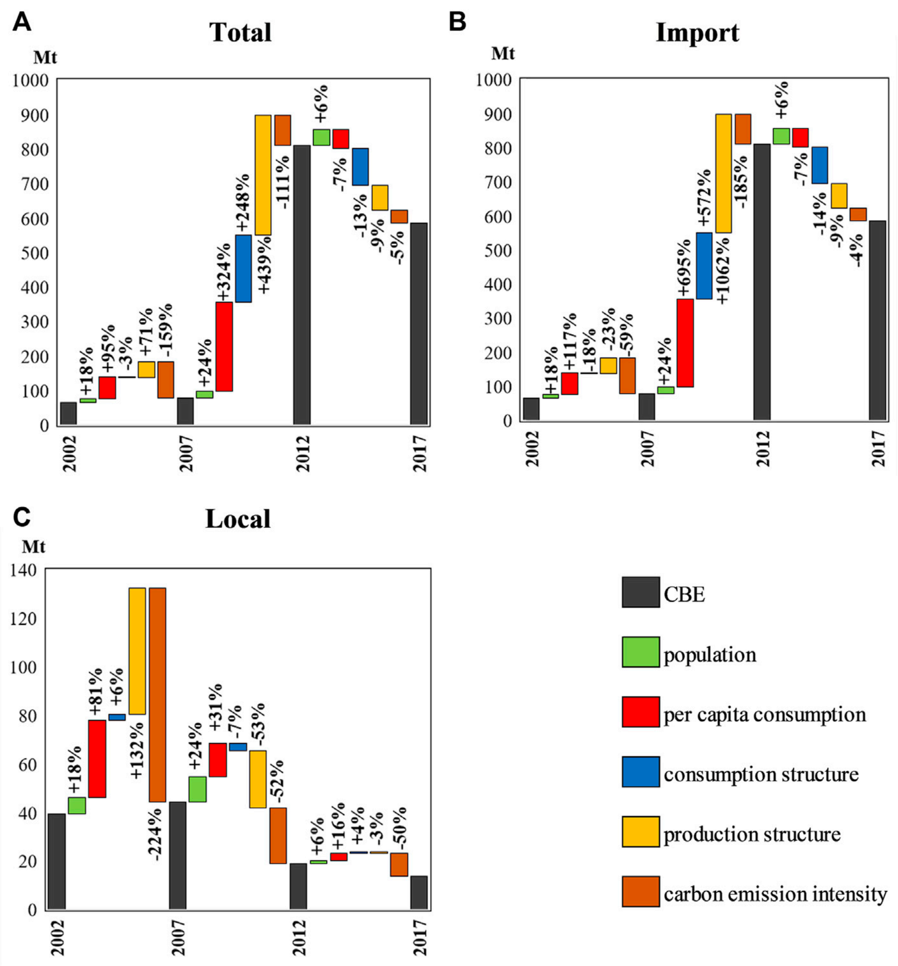

FIGURE 9
Contribution of socioeconomic factors to the change in **(A)** total consumption-based carbon emissions, and decomposed into **(B)** import and **(C)** local components.

Specifically, the decrease of carbon emission intensity offset the growth of CBE with the amount of 103.48 Mt (−159%) in period 1, 87.74 Mt (−111%) in period 2 and 38.57 Mt (−5%) in period 3, which suggested that technological progress was an effective way to reduce CBE. On the other hand, the consumption and production structures were the main influencing factors of CBE, which increased CBE by 196.25 Mt (+248%) and 347.45 Mt (439%) in period 2, and decreased CBE by 106.86 Mt (−13%) and 72.03 Mt (−9%) in period 3, respectively. These two factors could be significantly influenced by Beijing's environmental protection and industrial policies (e.g., *Suppress The Second Industry and Develop The Third Industry* and *The Administration of Highly Polluting Fuel Forbidden Zones*). This result showed that Beijing's urban policies had a significant impact on CBE. In addition, growth in population and per capita consumption cumulatively contributed 339.97 Mt of CBE in three periods. This is an inevitable problem in the process of urban development, and policymakers need to develop a series of measures to deal with the above problem. For example, the government can reasonably plan for population growth, guide residents to use carbon-cleaning products, advocate green and low-carbon consumption in daily life.

Figure 9B is the structural decomposition of the local CBE, and the following conclusions can be drawn: first, the carbon emission intensity was the major contributor to the reduction of local CBE, with the carbon emission reduction of 88.06 Mt (−224%) in period 1, 22.99 Mt (−52%) in period 2, and 9.52 Mt (−50%) in period 3, respectively. Second, the local CBE peaked in 2007 with the emission of 44.19 Mt, and it has been on a downward trend since then. In period 1, the local CBE was markedly increased by the production structure (52.02 Mt). But the situation reversed after 2007, the production structure became an inhibition factor of carbon emissions. This was because the exit of high-carbon industries reduced the carbon emissions of the production chain. Therefore, the government should continue to promote the low-carbon technologies and reduce the carbon emission intensity of construction, transportation and industrial sectors. Third, the local CBE increased by the factors of population, per capita consumption and consumption structure in most cases, with a cumulative increase of 66.92 Mt. However, the local CBE was reduced by 3.28 MT by consumption structure in period 2. This is because Beijing's high carbon industry is restricted by the industrial transformation policy, thus reducing the consumption of carbon rich products. According to Figure 9C, the most important factor contributing to the reduction of imported CBE was also carbon emission intensity. However, the impact of carbon emission intensity for imported CBE was weaker than that of local CBE. The major reason was that Beijing was a consumption-oriented city, which had rapidly lowered local CBE by restricting high-carbon sectors. But for production regions, high-carbon sectors were the backbone of the social economy. Restrictions on these sectors might lead to mass unemployment and economic recession. This also showed that carbon mitigation in production-oriented areas mainly relied on technological progress, rather than industrial transformation. In addition, after 2007, CBE induced by imported goods became the largest component of urban carbon emission. This result explained why the trend and influencing factors of imported CBE were similar to that of total CBE. In period 2, the two main drivers of imported CBE were consumption structure and production structure, which contributed 199.53 Mt (+572%) and 370.80 Mt (+1062%) of emissions, respectively. It was worth noting that the production structure increased more carbon emissions than the consumption structure, indicating that the import demand in Beijing was dominated by high-carbon products, which increased the environmental pressure on other regions. In addition, this result was also reflected in the growth of import and export trade in period 2. According to the National Bureau of Statistics of China, the total value of Beijing's import and export trade of goods (by location of business units) increased from US$ 192.9 billion to US$ 408.1 billion during this period. In summary, the reduction of Beijing's CBE requires an entire optimization of the production and consumption structure of the transaction network, and the improvement of the supply structure of production factors and the utilization rate of clean energy.

3.4 The evolutionary path of the sector

Tracking the evolution path of sectors is helpful to study the changing mechanism of carbon emissions in urban sectors, which is a supplement to the urban multi-dimensional carbon emission analysis model. BLE represents the driving force of a sector in the industrial chain, which is used to reflect the impact of the sector's final demand on other sectors in the carbon emissions system. FLE represents the pulling force of a sector in the industrial chain, which is used to reflect the impact of the final demand from other sectors on this sector's carbon emissions.

According to the results of BLE and FLE, all sectors were divided into four categories, as shown in Figure 10. Different zones played different roles in industrial emissions systems. The area within the second quadrant of Figure 10A can be defined as a critical area on the supply side. The MI sector was a typical supplier of raw materials, providing coal, oil, minerals and natural gas to downstream industries. The primary input of MI drove the production of goods and increased carbon emissions of the industrial systems substantially. Carbon mitigation in MI needs to be coordinated with the policies of the supply side.

In contrast, sectors within the fourth quadrant such as TS and NM were considered as the key sectors for consumption, and their demand caused a large amount of emissions from other sectors. Guiding these sectors to use low-carbon products was an important direction of carbon mitigation policies on the consumption side. In addition, there were some "high-weight" sectors (e.g., EP, PC, and MP) in the first quadrant, with high FLE and high BLE. These sectors were integral to both the production and consumption sides. Policymakers need to focus on these "high-weight" sectors and adopt the necessary policies to systematically manage their supply and demand processes.

Notably, the roles of some sectors in the carbon emissions system have changed over time. Take MP as an example, which had high FLE and high BLE in 2002 and was one of the dominators in the industry's emissions system. However, in 2012 and 2017, MP fell into the second quadrant and became a supplier as the sector's driving force weakened. This result was related to Beijing's restrictive policies of the second industry. The production capacity of Beijing's metal products industry was greatly reduced, which was manifested in the reduction of demand for metal products in other industries. This phenomenon was reflected in the decline of the sector's FBL. The results showed that the emission feature of the sector was affected by changes in the policies on the supply and demand side. The analysis of FLE and BLE can help policymakers scientifically evaluate the roles of various sectors, observe the effect of policy implementation, and provide a basis for assigning the responsibility of carbon mitigation.

3.5 Discussion on the calculation method of CBE

The consumption-based accounting method can calculate the embodied carbon emission associated with consumption, target and analyze the key consumption sectors in the industrial chain. The carbon emissions caused by local products and imported products can be calculated separately by

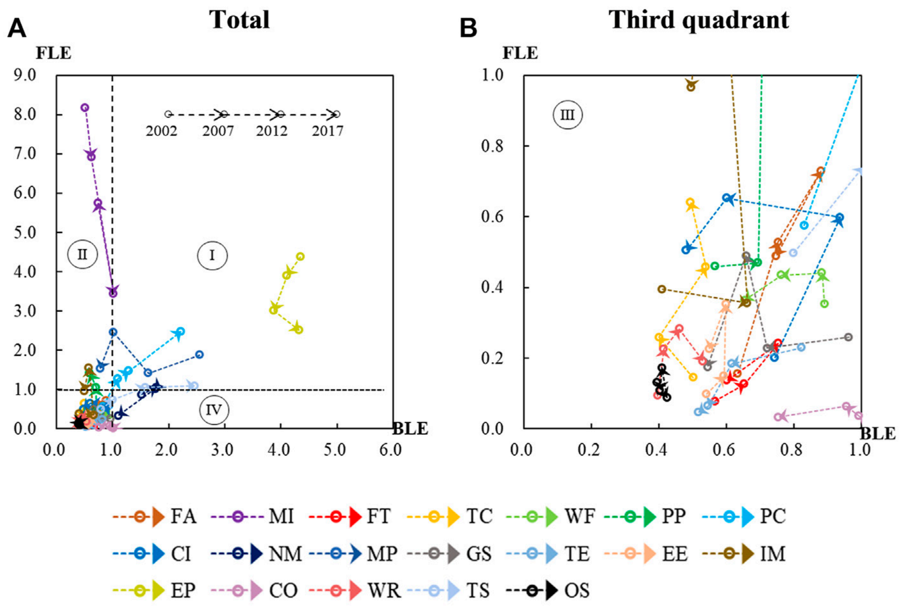

FIGURE 10
Evolutionary trajectories of various sectors during 2002–2017. **(A)** Total **(B)** The third quadrant.

consumption-based accounting method. However, the standards of the calculation process of CBE are ambiguous and inaccurate, and different definitions of parameters will lead to different results. According to previous research, there are three calculation methods for CBE, which are numbered as M1, M2, and M3 (Chen et al., 2019; Mi et al., 2019; Zhai et al., 2020a). The differences in parameter definitions are detailed in Table 2. The main differences are the selection of carbon emission intensity and the statistical scope of final demand. In Table 2, "Local consumption" includes urban and rural residents' consumption, government consumption and capital formation. The CBE calculated by three methods from 2002 to 2007 is shown in Figure 11.

M1 is the calculation method used in this study. The theoretical premise of M1 is that the carbon structure of imported products is different from that of domestic products, which need to be processed separately. When calculating the carbon emission of imported products, the domestic average carbon emission intensity is selected to replace the carbon emission intensity of unknown imported products (Mi et al., 2016; Mi et al., 2019). M1 is characterized by emphasizing the differences between imported and local products, and calculating the carbon emissions of all imported products. Compared to M1, M2 excludes export items from the final demand of the imported portion (Chen and Zhu, 2019). Only local consumption is considered when calculating the final demand of the imported portion. M2 argues that Beijing should not be assigned the responsibility for carbon emissions in the part of "importing products for export". As shown in Figure 11, the CBE for M2 maintained between 50 and 60 Mt. M2 may ignore the actual situation of entrepot trade and underestimates Beijing's carbon emission responsibility on the consumption, so M2 is not adopted in this study. M3 has also been widely used in previous studies (Zhai et al., 2020a; Zhai et al., 2020b; Xu et al., 2020), and the carbon intensity of imported products in this method is considered to be the same as that of local products. However, Beijing is a consumption-oriented city dominated by the service industry, and its carbon intensity is lower than the national average. Therefore, M3 will underestimate the carbon emissions of imported products, as shown in Figure 11. Considering that the technology and process of imported products are different from local products, it is more reasonable to use the national average carbon intensity to estimate the carbon emissions of imported products.

In summary, the main difference between the results of this paper and other scholars' studies is the choice of carbon emission intensity and the range of imported goods. Based on M1, the entrepot trade component (i.e., importing products for export) is found to be the main contributor to CBE in Beijing. Li et al. (2020) studied energy consumption in Beijing between 2002 and 2012 and obtained similar results. The paper points out that the headquarters effect in Beijing is the main cause of energy flows, which is consistent with the findings above. In addition, this paper also verifies the findings using M2 and M3, which are generally consistent with the studies of other scholars (Chen et al., 2019; Chen and Zhu, 2019; Zhai et al., 2020a; Xu et al., 2020).

TABLE 2 Comparison of different parameter definitions, consumption-based accounting method.

Code	Carbon emission intensity	Final demand
M1	Domestic average carbon emission intensity	1. Local consumption 2. Domestic and foreign exports
M2	Domestic average carbon emission intensity	1. Local consumption
M3	Local carbon emission intensity	1. Local consumption 2. Domestic and foreign exports

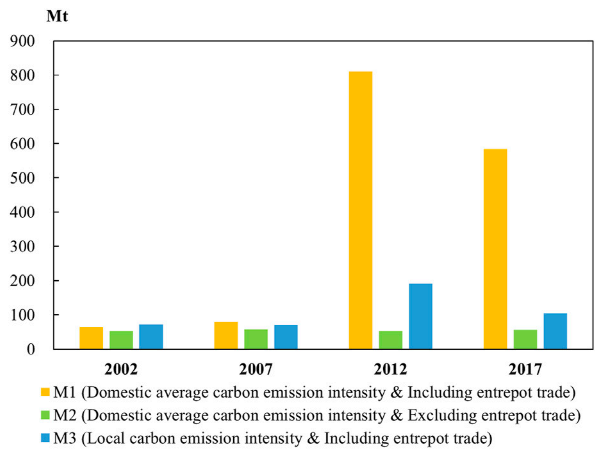

FIGURE 11
Comparison of CBE results of three calculation methods in 2002–2017.

4 Conclusion

In this study, a multi-dimension long-term carbon emission analysis model was established to explore the characteristics and evolution mechanism of carbon emissions from multiple perspectives. In the proposed model, the production-based, consumption-based and income-based carbon emissions of Beijing in 2002, 2007, 2012, and 2017 were calculated, and the roles of various sectors in Beijing's carbon emissions system were identified. Then, SDA was adopted to quantify the contribution of five socioeconomic factors in local and imported carbon emissions. In addition, the transition trajectories of various sectors were further described by ELA, and revealed the interaction between urban economic sectors from the perspectives of consumption and supply. The proposed model has the potential to be applied to more areas or cities, which can provide scientific decision support for policymakers to reasonably formulate carbon mitigation policies and allocate carbon mitigation responsibilities from multiple perspectives.

The results show that there are significant differences in the characteristics of carbon emissions in Beijing from 2002 to 2017, and the choice of accounting methods has a greater impact on the allocation of carbon emissions responsibilities. Based on the above research, the main findings and policy recommendations are summarized as follows:

1) Beijing's PBE and IBE decreased by 3.53% (2.52 Mt) from 2002 to 2017, which is generally stable. During the same period, the CBE increased rapidly by 795.45% (518.79 MT). Along with the process of importing goods from other cities, a large amount of embodied carbon emissions is transferred into Beijing. Therefore, Beijing should change its original production-based management mode and try to reduce CBE by introducing more demand-side policies, such as subsidizing low-carbon products and taxing the consumption of carbon-intensive products.
2) Among the urban sectors, EP is one of the main contributors and has a stable share from production, consumption and supply perspectives. It has a multi-dimension potential for carbon mitigation. Therefore, more carbon emission reduction responsibilities should be undertaken by EP sector, and targeted multiple-dimensional carbon emission governance should be promoted. After Beijing completed its coal-free transformation, the government should try to reduce the proportion of traditional fossil energy in the energy system. In addition, the government should also promote the development of emerging energy technologies (e.g., hydrogen energy, wind power, photovoltaic power, biomass energy, *etc.*), and help establish a modern energy system dominated by renewable energy and clean electricity.
3) There are significant differences in sector-level's carbon emissions from different perspectives. In terms of PBE, the share of traditional manufacturing has gradually declined since 2002, and its share has been replaced by TS and OS sectors. In terms of CBE, the emissions of IM, MP, and EP sectors caused by imports all increased by more than 10 times. In terms of IBE, EP, MI, TS, and OS sectors that provide products and services to downstream industries are the main sources of supply-side emissions. The results imply that the industrial transformation in Beijing has a significant impact on the trend of carbon emission changes in the sector. Therefore, the government should reasonably formulate carbon mitigation and industrial transformation policies, allocate carbon mitigation responsibilities from multiple

perspectives, and prudently plan the future carbon mitigation paths of sectors.

4) Per capita consumption and production structure are important drivers of the increase in total CBE, and carbon emission intensity is the most important factor to offset the increase in total CBE. In addition, carbon emissions caused by the production structure should also be concerned. In local CBE, the effect of carbon emission intensity is more pronounced, while in imported CBE, the effect of per capita consumption and production structure covers the effect of carbon intensity. From an overall perspective, imported CBE maintains a strong growth trend and will continue to dominate in CBE. The government should promote the development of low-carbon technologies in exporting regions and improve energy efficiency in sectors such as buildings, transportation, and industry.
5) According to the results of ELA, industrial transformation has a significant impact on the position of sectors in the industrial structure and changes the development trend of the industry. The government should pay attention to industrial sectors in key positions from a multi-dimensional perspective, anticipate the impact of policies on the sectors, and formulate targeted industrial policies.
6) Beijing's entrepot trade is a major contributor to the city's CBE. Many conglomerates are headquartered in Beijing, which leads to the city becoming a transit point for commodities. For policymakers, the attribution of various types of carbon emission flows should be clarified. This illustrates the necessity of a scientific and reasonable carbon emission accounting method.

In summary, different research tools focus on different priorities, and it is necessary for policymakers to combine multi-dimensional analysis to plan carbon mitigation policies. In addition, the proposed model is expected to help policymakers scientifically allocate carbon emission responsibilities from multiple perspectives.

In future research, some limitations need to be addressed. First, considering the availability of data, carbon emission inventories are used in this study. The effects of other greenhouse gases such as N_2O, CH_4, and HFCs are not considered. This can be calculated from energy consumption and Intergovernmental Panel on Climate Change (IPCC) emission factors. Second, since the preparation of Beijing's IO table takes 5 years as a cycle, this model has a lag in the observation and decomposition of changes in sectors. Gaps between cycles can be filled by using biproportional scaling method. Third, the loss of information caused by the unification of currency prices and the consolidation of 42 sectors will create some uncertainty. In future work, stochastic analysis could be used to deal with the uncertainty caused by information integration. Fourth, the carbon emissions of imported products are calculated without distinguishing the source of imports (i.e., imported from other provinces or abroad). In future studies, the world MRIO table could be tried to calculate carbon emissions of products from different import sources separately.

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

QL: data curation, methodology, writing, visualization. CC: conceptualization, methodology, writing—review and editing, validation, supervision.

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Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.1073167/full#supplementary-material

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Carbon footprint of black tea products under different technological routes and its influencing factors

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Tea industry is considered to have a high energy consumption, due to its complex life cycle system. The global change potential (GWP) of the life cycle of tea, is deserving in-depth discussion. This study conducted a life cycle assessment (LCA) towards the Dianhong black tea products, and evaluated the discharge and mitigation potential, and compared with the results of LCA of other tea to clarify the advantages and disadvantages of Chinese black tea industry. The results showed that the planting stage and packaging stage were the main sources of GWP in the life cycle of black tea, accounting for 43.73% and 39.44% respectively, because of the application of chemical fertilizer and the production of aluminum foil. In the tea processing stage, the GWP has a greater impact on the process of heating and withering, accounting for 8.63%. It is followed by the rolling stage, which accounts for 6.85%, mainly from the consumption of electricity during the process. Finally, the key factors affecting tea production efficiency and quality were analyzed by combining the results of contribution and sensitivity analysis. The research will contribute to the establishment of a more sustainable tea value chain.

KEYWORDS

black tea, carbon footprint, life cycle assessment, process optimization, system efficiency

Highlights

- The cultivation stage is the main source of GWP impact, accounting for 43.73%.
- The contributions of transportation, fermentation and drying processes to GWP are inconspicuous.
- Impacts are mainly from efficiency of picking machines, fertilizer and packaging materials.
- When the equipment power was increased by 10%, the GWP value decreased by 1.3%.

1 Introduction

Almost 14% of global GHG emissions are emitted by the agricultural sector (Cichorowski et al., 2015). The potential to reduce GHG emissions in the agriculture and food sectors is enormous. As a worldwide popular beverage, tea has a long history in China (Xu et al., 2021; Hayat et al., 2015). Black tea is also a plant resource with medicinal function, which has developed rapidly in China in recent years.

According to China's National Bureau of Statistics, black tea production increased from 67,300 ton in 2009 to 258,300 tons in 2019 with an increase of 283.8%. The proportion of black tea in the whole tea industry increased from 4.98% in 2009 to 9.3% in 2019. Given the popularity of tea in the global beverage market, its planting amount and production have risen rapidly. It had been shown that both the planting and production of tea, may be associated with a large amount of greenhouse gas emissions (Cichorowski et al., 2015). The research of Soheili-Fard,et al. showed that machinery and diesel fuel were the most polluting segments in farms and factories, respectively. Compared with other steps in the whole tea life cycle, tea production was identified as a major contributor to the environmental burden, with a 57% share. In addition, two-layer packaging was considered as the most polluted scenario, and stoves were found to be more environmentally friendly than electric kettles. Azapagic et al. (2016) analyzed the global warming potential (GWP) of black tea in Kenya throughout its life cycle "from cradle to grave". The research showed that the total impact of tea was independent of the scale of tea production and that the main contributor was tea consumption. Due to the electricity used for boiling water, tea consumption accounted for 85% of the impact. Kouchaki-Penchah, et al. (2017) used data envelopment analysis (DEA) and life cycle assessment (LCA) to determine the energy efficiency of tea production in Iran's Guilan Province and helped to reduce the environmental burden. Xu, et al. (2019) assessed the carbon footprint and primary energy demand of five Chinese organic tea products using LCA methods. The results indicate that different farming management and processing techniques had a significant impact on the carbon footprint and primary energy demand of different tea products. The study further emphasized the trade-off between high quality tea and low carbon footprint. The whole life cycle of tea, including planting, transportation, production and processing, packaging, had considerable environmental impact.

Fengqing County, Yunnan Province is the "national high-quality tea base county", "national export commodity tea base county", and " national top ten tea producing counties". The tea industry has become an important supporting industry of the local people to raise income, create wealth, develop local economy. Fengqing Yunnan black tea is also the representative of Chinese black tea. Its planting and production technology may represent the highest level in the industry, which is worth further exploration. There are many life cycle assessments of tea, but few studies focus on Yunnan Dianhong tea. For instance, there is almost no study on the potential of climate change in the life cycle. Given the importance of Dianhong tea in China's tea industry, it is essential to study Yunnan Dianhong tea to determine the key factors of climate change at various stages from tea garden to tea to encourage sustainable production strategies. Life cycle assessment (LCA) is the most widely used assessment tool to quantify and systematically analyze the resources consumed and the potential environmental impacts caused by pollutant emissions throughout the production and consumption activities of a product (Lacirignola et al., 2017). Compared with other environmental impact assessment methods, LCA has the advantages of being systematic and objective, and has become a widely used tool for product environmental characteristics analysis and decision support. It is widely used by researchers in the fields of construction (Kim and Tae, 2016; Meex et al., 2018), agriculture (Dijkman et al., 2018; Khoshnevisan et al., 2014; Nabavi-Pelesaraei et al., 2018), new energy (Zackrisson et al., 2010; Deng et al., 2018), and food and beverage (Fusi et al., 2014; Naranjo et al., 2020).

The aim of this study was to assess the emissions and mitigation potential of Fengqing Yunnan black tea in various stages of planting, transportation, processing and packaging. The results of GWP contribution and sensitivity analysis may identify key factors that influence climate change, tea production efficiency and quality. By comparing with other studies, the advantages and disadvantages of Fengqing Yunnan black tea industry can be identified. A more systematic study may contribute to the establishment of a more sustainable value chain of tea and the improvement of the life cycle assessment database of Yunnan black tea. The main data source of the study is the actual research. The missing data is supplemented by literature research and industry consultation.

2 Materials and methods

Yunnan Dianhong tea producing areas includes more than 20 counties in Lincang, Baoshan, Simao, Xishuangbanna, Dehong and Honghe along the Lancang River in Yunnan. According to the geographical location, Yunnan is divided into three tea regions: Western Yunnan, Southern Yunnan and Northeast Yunnan. Yunnan Dianhong tea is produced in western Yunnan and southern Yunnan. The tea area in western Yunnan includes Lincang, Baoshan, Dehong, Dali four states (regions). The tea planting area accounted for 52.2% of the province, and its production accounted for 65.5% of the province's total output. It is the main production area of Dianhong tea, including Fengqing, Yunxian, Shuangjiang, Lincang, Changning and other counties, accounting for more than 90% of the production of Dianhong tea. The tea garden selected for the study was in the southwest of Mengyou Town, Fengqing County, Yunnan, China, with an acreage yield of 543.69 kg. This study assessed the environmental impacts of tea planting and production processes based on the LCA study method of ISO 14040 (2006). The sources of GWP contribution of

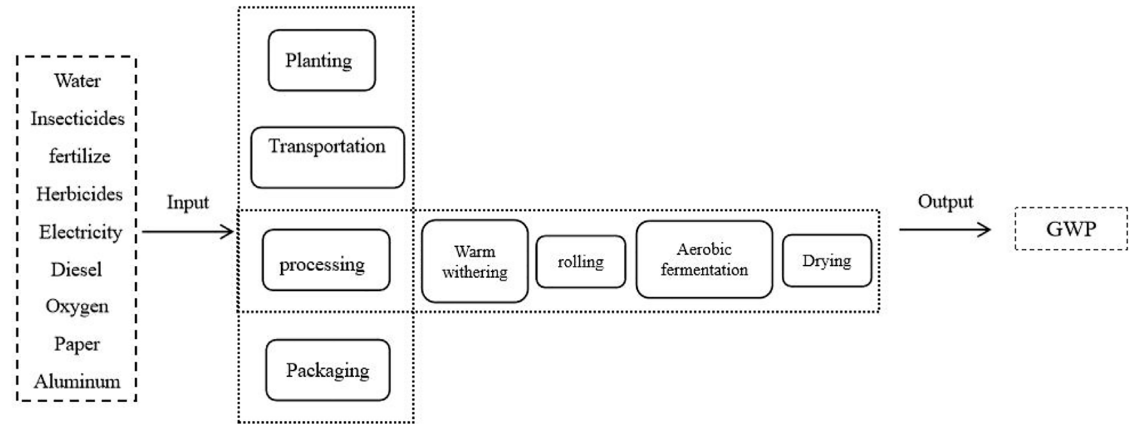

FIGURE 1
Life cycle modeling of Dianhong tea " from cradle to grave"(1999–2017, retrieved on 28 July 2018, Web of Science).

black tea at each stage were studied. Based on the results of the GWP contribution of Dianhong production, the sensitivity analysis of various factors affecting the GWP results was conducted.

2.1 Goal and scope

Climate warming is one of the most significant challenges currently facing the globe and humanity(Zhou et al., 2021). Consequently, it is necessary to assess the climate change impacts of product production processes to support improvement and mitigation strategies.

2.1.1 Functional unit

The analysis was based on the functional unit of "1 kg Yunnan Dianhong tea".

2.1.2 System boundaries

As shown in Figure 1: The system boundary of the study is "from cradle to gate", including the following life cycle stages.

(1)Planting: this includeed the direct and indirect greenhouse gas emissions from the production and application of chemical fertilizers, the application of organic fertilizers, pesticides and herbicides, and the use of diesel engines in the cultivation process, and the transportation of pesticides, herbicides and fertilizers.
(2)Transportation: including the transportation of tea from the tea farm to the factory and the transportation of agricultural materials from the market to the tea farm.
(3)Production: processes water, electricity, and oxygen used in four processes, including warm withering, rolling, aerobic fermentation and drying.
(4)Packaging: the emissions and environmental impact caused by the production process of cardboard and aluminum foil used in packaging, as well as the electricity used in the packaging process.

2.1.3 Data sources and assumptions

The study used field research and actual testing as the main data sources, and the missing data were supplemented by literature research and industry consultation. The study assumed that chemical and organic fertilizers were mainly applied in the cultivation process in a 1:1 ratio. The component content and input amounts of urea, potassium superphosphate, and calcium sulfate were shown in Table 1 below. Assumed all organic fertilizer were conventional farm fertilizer. During the withering and rolling process, besides necessary processing equipments, humidifiers, dehumidifiers, air conditioners, and other equipment were also required to control the temperature and humidity of the processing workshop. The specific process equipment parameters are shown in Table 2. The background database used OpenLCA software and the built-in CLCD-China-ECER 0.8 and Ecoinvent 3.1 databases. In the life cycle inventory data collection, we grouped the transportation process into the cultivation process and the packaging process into the production process.

2.2 Life cycle impact assessment

LCIA is a qualitative or quantitative assessment process for resource consumption and pollution emission in the life cycle inventory. In this section, we selected the following nine impact categories, as shown in Table 3. Nine impact categories were used to examine the life cycle environmental impacts of Dianhong tea, which laid a foundation for the selection of optimization indicators for different fertilization and processing scenarios. Under the green trade barrier, it is very meaningful to focus on the establishment of product life cycle carbon footprint model,

TABLE 1 Fertilizer nutrient composition and input amount.

Chemical fertilizer		
Urea (Mass fraction containing N %)	Calcium superphosphate (Mass fraction containing P_2O_5%)	Potassium sulfate (Mass fraction containing K_2O %)
46	12	50
Organic fertilizer		
Mass fraction containing N %	Mass fraction containing P_2O_5%	Mass fraction containing K_2O %
2.38	0.31	1.12
Total nutrients kg/hm^2		
N	P_2O_5	K_2O
381	86	80

TABLE 2 Process equipment parameters.

Process equipment	Power consumption/kWh	Specific parameters	Data sources
Heating withering			
Withering tank	13.50	Leaf thickness 15–20 cm, time 6–8 h, hot air 35 °C, relative humidity 50–70%, air volume 16,000–20,000 m3/h, wind pressure 3333–4000 Pa, water consumption 1.07 L per kg tea leaves	Jiayou Tea Machinery
Humidifier	0.80		Meihesen Electronics Co. Ltd
Dehumidifier	1.45		Songjing Flagship Store
Rolling			
Air conditioner	1.10	Temperature 20–25 °C, relative humidity 85%–90%, time 90–100 min, water consumption 0.16 L per kg of tea	Yajielan Electrical Flagship Store
Humidifier	0.80		Meihesen Electronics Co. Ltd
Dehumidifier	1.45		Songjing Flagship Store
OT19 Rolling machine	0.55		Shandong Oute Machinery Co. Ltd
Oxygenated fermentation			
HC-01 oxygenated fermentation machine	2.5	Fermentation time 3.5 h, temperature 30 °C, humidity more than 90%, oxygen consumption 2.5 L per kg of tea	Suzhou Jiangkai Machinery Co. Ltd
Drying			
6CH-16 tea drying machine	5.50	120–130 °C, 10–15 min, until the moisture content is 20%–25%; 30–60 min for cooling; 90–100 °C, 15–20 min, until the moisture content is 4%–6%	Chunjiang 6CH-16 Tea Drying Machine

TABLE 3 Environmental impact assessment category.

Impact categories	Symbol	Unit
Climate Change	GWP	kg CO2 eq
Primary Energy Demand	PED	MJ
Abiotic Depletion Potential	ADP	kg Sb eq
Water Usage	WU	kg
Acidification Potential	AP	kg SO2 eq
Eutrophication Potential	EP	kg PO43−eq
Respiratory Inorganics	RI	kg PM2.5 eq
Ozone Depletion Potential	ODP	kg CFC-11 eq
Photochemical Ozone Formation	POFP	kg NMVOC eq

the calculation of carbon emissions and the analysis of emission reduction potential.

2.3 Sensitivity analysis

Sensitivity analysis is used to evaluate the sensitivity of the result change caused by a certain change (Igos et al., 2019). In this study, a single-factor sensitivity analysis was used, in which one factor was selected at a time to vary within a specified range while other factors remianed fixed. Specifically, the sensitivity ratio (SR) (Clavreul et al., 2012) was chosen as a measure, which is the ratio of the relative change between the two, and if SR=2 meant

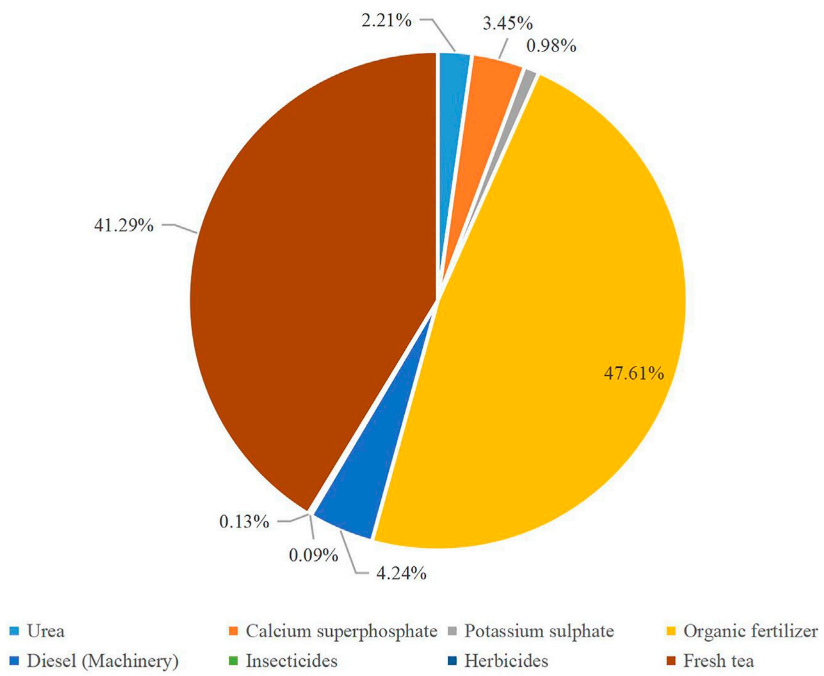

FIGURE 2
Structure of diesel consumption of planting process.

that when a factor increased by 10%, its result would increase by 20%. The formula was as follows:

$$SR = \frac{\frac{\Delta result}{initial\_result}}{\frac{\Delta parameter}{initial\_parameter}}$$

Where, Δresult is the change value of the total GWP; initial_result is the initial value of the total GWP; Δparameter is the change value in the factor; and initial_parameter is the initial value of the factor.

3 Results

This study analyzed the entire life cycle of Yunnan Dianhong tea. The main sources of GWP contribution at different stages were examined. The result of the entire life cycle study of Yunnan Dianhong tea was also compared with other studies to clarify the advantages and disadvantages of Dianhong production technology. Combined with the sensitivity analysis, the key factors affecting the production efficiency and quality of Dianhong were analyzed.

3.1 Life cycle assessment input inventory analysis

3.1.1 List of inputs to the cultivating process

Table 4 showed the life cycle input list of the cultivating process (including planting and transportation process) and Figure 2 analyzed the diesel input structure of this system. Overall, the diesel consumption of this system could be roughly composed of three parts: agricultural materials transportation, tea transportation and agricultural machinery consumption. Among them, the diesel consumption of organic fertilizer transportation accounted for the largest proportion, accounting for 47.61%. It was because the effective nutrients in the organic fertilizer were low (the nitrogen content is only 2.38%). Therefore, to ensure the necessary nutrients of tea plants, the input amount was much higher than that of chemical fertilizer, resulting in a increase of the transportation cost of organic fertilizer. The second was the transportation diesel consumption of fresh leaves, which accounted for 41.29%. The reason for this phenomenon was mainly related to the longer transport distance of fresh tea. It could be seen from the previous section, the transport distance of tea in this study was 29.9 km, while the transport distance of agricultural materials was only 5 km. The diesel consumption of the rest of the sources were smaller, and its total percentage was 11.1%. Meanwhile, a certain amount of nitrous oxide was directly emitted due to the nitrogen loss during the application of nitrogen fertilizer, which was 4.90E-03 kg/kg.

3.1.2 List of production process inputs

Table 5 showed the list of process life cycle inputs (including production and packaging processes). In the processing stage, the heated withering process was used in the withering stage, the aerobic fermentation process was used in the fermentation stage,

TABLE 4 List of life cycle inputs for the planting process.

Input		
Materials (kg/kg)		
Chemical fertilizer	Urea	3.21E-01
	Calcium superphosphate	5.00E-01
	Potassium sulphate	1.42E-01
	Total	9.63E-01
Organic fertilizer		6.89E+00
Insecticides		1.27E-02
Herbicides		1.84E-02
Energy (kWh)		
Diesel	Consumption of machinery	8.65E-05
	Insecticides transportation	1.79E-06
	Herbicides transportation	2.59E-06
	Fertilizer transportation	1.11E-03
	Total	1.20E-03
Diesel (Fertilizer)	Urea	4.52E-05
	Calcium superphosphate	7.04E-05
	Potassium sulphate	2.00E-05
	Organic fertilizer	9.71E-04
Diesel	Fresh tea	8.42E-04
Direct emission (kg/kg)		
N2O		4.90E-03

TABLE 5 List of process life cycle inputs.

Input	
Materials (kg/kg)	
Withering stage	
Water	1.40E-04
Electricity (kWh)	7.35E-01
Rolling stage	
Water	1.60E-01
Electricity (kWh)	5.84E-01
Fermentation stage	
Oxygen	2.86E-03
Electricity (kWh)	5.83E-02
Drying stage	
Electricity (kWh)	5.50E-02
Packing stage	
Paper	6.38E-01
Aluminum	9.20E-02
Electricity (kWh)	3.95E-03

the rolling machine was used in the rolling stage, with a time of 1.5 h, and the dryer was used in the drying stage, with a drying time of 30 min. The whole system covered the material input and power consumption of five stages, including withering, rolling, fermentation, drying and packaging. According to Figure 3, the power of the processing stage system mainly came from the heating withering stage, accounting for 51.17%. The next stage was the rolling stage, which accounted for 40.66%.

3.2 Life cycle inventory analysis

In order to systematically evaluate the environmental impact of the production process of Dianhong tea, this study examined the environmental impacts of nine life cycle evaluation indicators (Climate Chang, GWP, Primary Energy Demang, PED, Abiotic Depletion Potential, ADP, Water Usage, WU, Acidification Potential, AP, Eutrophication Potential, EP, Respiratory

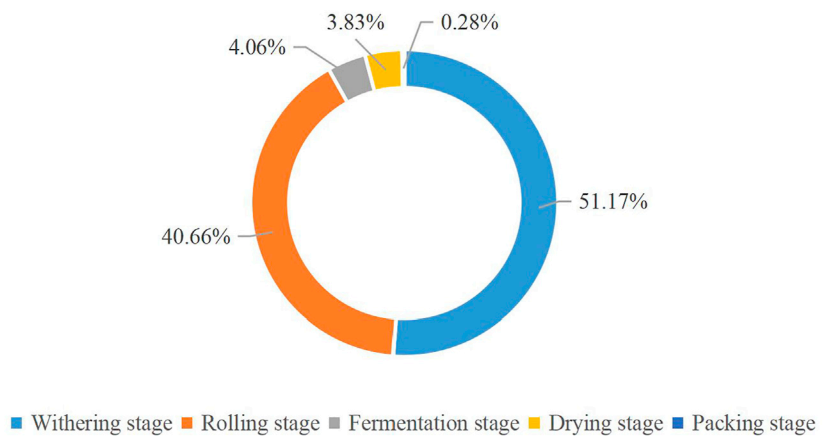

FIGURE 3
Power consumption structure of production process.

TABLE 6 Results of Life Cycle Assessment of the whole production process of 1 kg DianHong tea.

Impact category	Value	Unit
GWP	6.30E+00	kg CO2 eq
PED	1.03E+02	MJ
ADP	2.07E-04	kg Sb eq
WU	9.92E+01	kg
AP	4.00E-02	kg SO2 eq
EP	7.38E-03	kg PO43−eq
RI	8.57E-03	kg PM2.5 eq
ODP	3.70E-07	kg CFC-11 eq
POFP	5.81E-03	kg NMVOC eq

TABLE 7 List and structure of GWP at the packaging process.

Item	Value, kg CO_2 eq	Percentage (%)
Electricity	2.92E-03	0.12
Paper	3.91E-01	15.74
Aluminum	2.09E+00	84.14
Total	2.48E+00	100

3.3 Analysis of GWP results of Dianhong tea in different stages

3.3.1 Contribution analysis of GWP results of the entire system

Figure 4 showed the overall GWP contribution of the system. The cultivating stage had the largest GWP contribution of 43.73%, followed by the packing process with 39.44%. At the stage of tea processing, the sector with great influence of GWP was heating withering, accounting for 8.63%. The second was the rolling stage, accounting for 6.85%. The contribution of transportation, fermentation and drying to GWP was small. To get a clearer picture of the main sources of GWP contribution in each stage, we had made a detailed analysis of the GWP contribution in each stage in the following.

3.3.2 Contribution analysis of GWP results of the planting stage

It could be seen from Figure 5 that the direct emission of nitrous oxide caused by nitrogen fertilizer application would greatly improve the GWP in the cultivating process, with the value of 1.30E+00 kg CO_2 eq, accounting for 47.17%. The second source of GWP contribution was fertilizer production

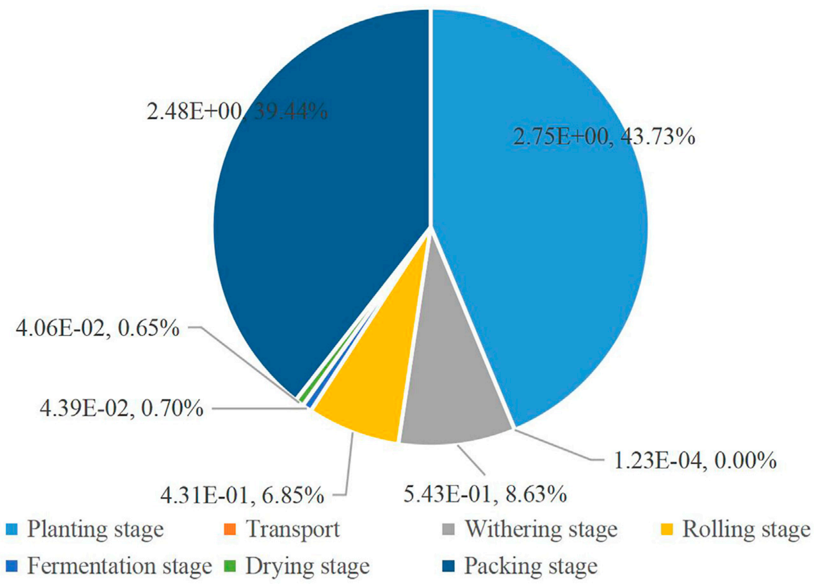

FIGURE 4
GWP contribution of the Overall system of 1 kg Dianhong tea.

Inorganics, RI, Ozone Depletion Potential, ODP, Photochemical Ozone Formation, POFP) for the whole system, and the results were shown in Table 6.

(including urea, calcium superphosphate, potassium sulfate and organic fertilizers), with a total of 1.10E+00 kg CO_2 eq, accounting for 40.00%. From this, it could be found that the

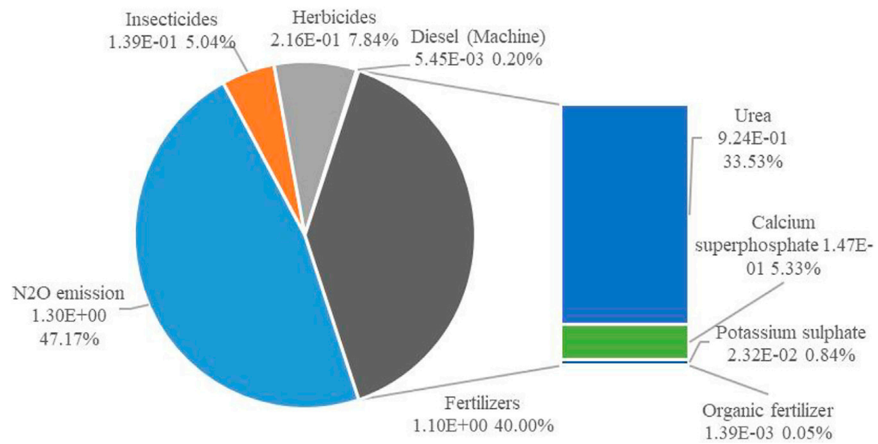

FIGURE 5
GWP contribution of various agricultural inputs in the planting stage of 1 Kg Dianhong tea.

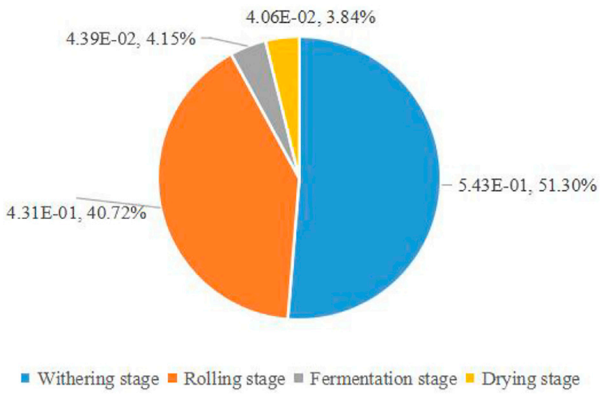

FIGURE 6
GWP contribution of the processing stage of 1 kg Dianhong tea.

cause of the significant increase in GWP at the planting stage was directly related to urea. In this study, the greenhouse gas emissions from urea production were 9.24E-01 kg CO_2 eq., accounting for 33.53%, while the urea application process generated a large amount of nitrogen loss and led to the direct emission of nitrous oxide, accounting for 80.70%. The above results indicated that the production and application of nitrogen fertilizers significantly increased the GWP at the planting stage. Therefore, it was of great importance to improve the efficiency and utilization of nitrogen fertilizers, or to develop slow-release fertilizers and organic fertilizers, and to improve the nitrogen fixation potential of the land to reduce greenhouse gas emissions during the process of crop planting.

3.3.3 Analysis of GWP results during the processing phase

It could be seen from Figure 6 that the main contribution of GWP in the processing stage came from the heating withering stage and the rolling stage, accounting for 51.3% and 40.72% respectively. The drying and fermentation stages accounted for a smaller proportion, accounting for 3.84% and 4.15%. To met the output and quality demands of the market and consumers, the production of Dianhong tea had been gradually upgraded from original pure manual tea production to mechanized tea production, while the efficiency of tea production equipment and tea production quality had been significantly improved (Khanali et al., 2017; Sharma and Dutta, 2018), and the environmental impact of different tea processing technologies had became a key issue. In addition, the optimization of equipment had the same effect (Sari and Velioglu, 2013). In the sensitivity analysis of this study, it was found that withering and rolling time influenced the GWP results, and in Dianhong production, the withering and rolling times were generally 5–7 h and 70–90 min. Therefore, when the withering time was increased by 15%, its GWP decreased by 0.45%, and when the rolling time was increased by 10%, its GWP decreased by 0.7%. Therefore, it was an important measure to promote energy saving and emission reduction in black tea production to develop new withering technology and green rolling equipment.

3.3.4 Analysis of GWP results during the packaging stage

Since the tea packaging process had a great impact on the overall GWP, it was necessary to analyze this stage in detail. The data were shown in Table 7. During the packaging process, the system inputs included electricity, cardboard,

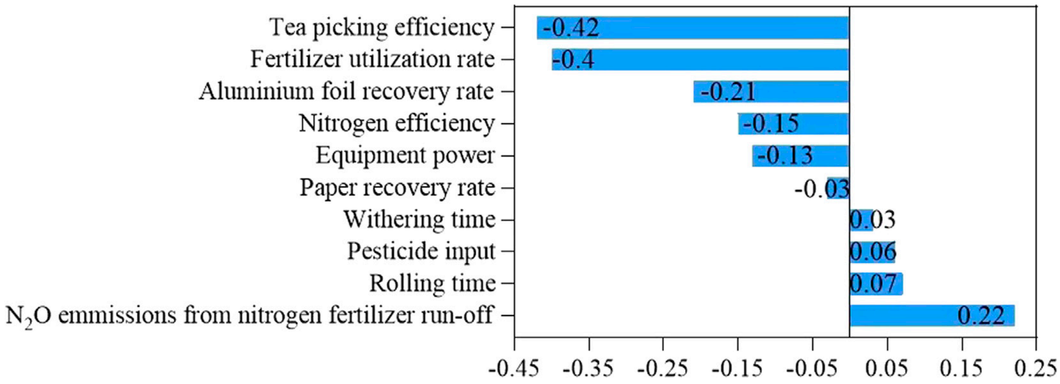

FIGURE 7
Results of GWP sensitivity analysis of the whole production process of 1 kg Dianhong tea.

and aluminum foil with a total GWP of 2.48E+00 kg CO2 eq. Among them, the production process of aluminum foil had the largest GHG emission of 2.09E+00 kg CO2 eq., accounting for 84.14%, followed by the production process of cardboard, with a value of 3.91E-01 kg CO2 eq., accounting for 15.74%. It could be seen from the above results that the production process of aluminum foil had the greatest impact on the GWP of packaging process, while the impact of electricity consumption was very small.

Product packaging plays the role of beautifying and promoting goods, and when these missions were completed, it becomes waste. As the number of goods increases, their packaging waste accumulates in large quantities, causing serious environmental pollution. In this study, the environmental impact generated in the tea packaging process occupies about 40% of the overall, which was mainly affected by the production of two packaging materials, aluminum foil and hard paper. Therefore, how to reduce the emission of packaging materials was of great significance to reduce the environmental impact of Dianhong tea production.

At present, the common methods to reduce packaging costs include using more environmentally friendly alternative materials, avoiding excessive packaging, and recycling packaging materials. This study was only conducted from the perspective of material recycling. According to the research, the average recycling rate of aluminum foil and cardboard in China was about 50% (Zhang et al., 2010; Zhu et al., 2020). Based on this criterion, when material recycling was considered, the GHG of aluminum foil and hard paper could be reduced by 50%, which were 1.05E+00 kg CO2 eq. and 1.96E -01 kg CO2 eq., and the final GWP could be reduced by about 20%. The recycling of packaging materials not only reduces the production cost, but also contributes to the sustainable development of Dianhong tea.

3.3.5 Analysis of GWP results during transportation stage

This study was the LCA from cradle to grave, from the tea production boundary to the packaging, without considering the transportation process of tea from the factory to the sales market and the tea consumption process. Therefore, the transportation stage of this study included the transportation process of agricultural materials from the farmers' market to the tea farm and the transportation process of fresh tea from the tea farm to the processing plant. According to the calculation, the corresponding GWP was 6.99E-05 kg CO2 eq., while the transportation emission of tea was 5.31E-05 kg CO2 eq., and the total GWP was 1.23E-04 kg CO2 eq., which accounted for a small percentage compared to other stages.

4 Discussion

4.1 Sensitivity analysis

Based on the research results of GWP contribution of Dianhong production, sensitivity analysis was conducted on various factors affecting GWP results, including planting, transportation, wilting, rolling, fermentation, drying and packaging, and 10 influencing factors with SR absolute value greater than 0.01 were screened out. The results were shown in Figure 7. The following 10 factors were tea picking efficiency, fertilizer utilization efficiency, aluminum foil recovery rate, nitrogen fertilizer utilization efficiency, equipment power, paper resource recovery efficiency, withering time, pesticide input, rolling time, and loss of nitrous oxide emission due to nitrogen application. Among the 10 factors that had been screened, the absolute values of SR of tea picking efficiency and fertilizer utilization efficiency were relatively high, which were 0.42 and 0.40, respectively, indicating that the final GWP was

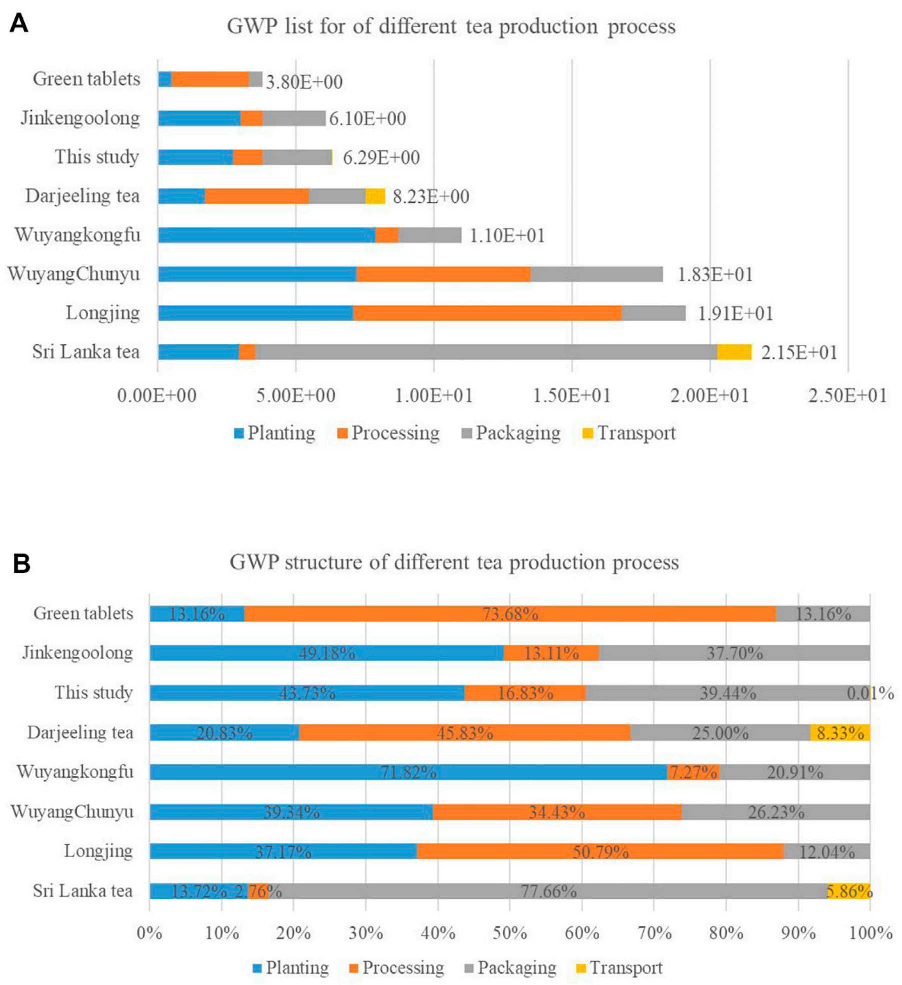

FIGURE 8
Comparison of GWP results and contribution of LCA of different tea with 1 kg tea as the unit.

more sensitive to these two factors. The second was the recovery rate of aluminum foil and the emission of nitrous oxide, with absolute values of SR were 0.21 and 0.22, respectively, which were also sensitive to the results. Among the remaining factors, nitrogen fertilizer utilization efficiency and equipment power had more obvious effects on the GWP results.In Section 4.2, the key influencing factors and the relationship between tea production efficiency and quality were further analyzed by combining sensitivity and contribution results.

4.2 Key influencing factors and relationship between tea production efficiency and quality

According to the results of contribution and sensitivity analysis, the GWP results were more significantly affected by the picking efficiency of tea picking machines, fertilizer utilization rate, packaging materials and equipment power. Since this study used agricultural machinery equipment for tea picking, and the tea bud integrity rate would affect the yield per acre of tea farm, resulting in a decrease in yield. At present, the tea bud integrity rate of tea picking machines in China ranges from 76.5% to 78.0% (Yu et al., 2015). It was found by the results of sensitivity analysis study that when its efficiency increased by 1.5%, the total GWP decreased by 0.63%, and the efficiency and effective picking rate of picking machines could significantly affect the GHG emissions of tea production. Therefore, it is an urgent for China to mechanize tea production to improve the effective picking efficiency and reduce the missed picking rate.

The GWP of the cultivating stage accounted for 43.73% of the total, while the production of fertilizer and the emission of nitrous oxide accounted for more than 80% of the GWP of the cultivating stage. The input of fertilizer had greatly affected the GWP of Dianhong tea production. It was important to improve the quality and efficiency of traditional fertilizer, reduce the input loss, and improve the utilization rate to reduce the greenhouse gas emissions of agricultural production. According to the research, the average utilization rate of N, P and K fertilizers in China is between 30% and 40%, which was much lower than the level of 40%–50% in developed countries (Bingqiang, 2016). In this study, the utilization rate of fertilizers was 45% with SR=-0.40, which meant that when the utilization rate increased by 10%, the total GWP decreased by 4%. This indicated a positive significance for environmental emission reduction in the tea production process. The improvement of nitrogen fertilizer efficiency was more prominent in fertilizer application. When the efficiency of nitrogen fertilizer increased by 10%, the total GWP decreased by 1.5%. In addition, the loss of nitrous oxide caused by the loss of nitrogen fertilizer directly affected the environmental emissions of crop planting. The total nitrogen loss rate in Chinese tea farm was around 20%. In this study, when the nitrogen fertilizer loss increased by 2%, the corresponding total GWP increased by 0.44%. Improving the carbon fixation potential of soil, reducing the loss of nitrogen fertilizer application, and expanding the use of organic fertilizer, slow-release fertilizer, and other green fertilizers could not only improve the production efficiency of tea, but also reduce the environmental impact caused by production.

Reducing the amount of packaging materials and recycling them would significantly reduce the environmental emissions of tea production. When the recycling rate of aluminum foil and cardboard increased by 5%, their corresponding total GWP reduced by 1.05% and 0.15%. Meanwhile, since tea processing uses a variety of processing equipment, the power of the equipment was the main factor affecting its electricity consumption. When the power of all processing equipment increased by 10%, its total GWP reduced by 1.3%.

In addition, the running time, equipment volume, temperature and humidity of tea processing would also affect the greenhouse gas emissions. However, at the same time, these factors would have an impact on the quality of tea. Theaflavin, TFs, Thearubigins, TR, and Teabrown, TB affect the color and taste of tea soup. With the increase of fermentation temperature, the content of TFs and TR increased first and then decreased, while the content of TB continued to increase. The higher the content of TFs and TR, the better the quality of black tea. If the fermentation temperature was set between 22 °C and 28 °C (Li et al., 2013), the quality of black tea was better. Therefore, if we only consider the environmental impact of Dianhong production process and ignore the quality of tea, it will have a serious impact on the economic benefits of Dianhong industry.

4.3 Comparison of yunnan dianhong tea and other tea products

In this section, we compare the results of our own LCA study of Dianhong tea with those of other researchers, and then we used them to discuss the strengths and weaknesses of the Dianhong production process. To be consistent with the functional units and system boundaries of Dianhong production, the GWP results of other tea production were processed in this study, ignoring the drinking stage of tea. The results were shown in Figure 8.

The above tea production mainly included four kinds of black tea (this study, Darjeeling tea (Doublet and Jungbluth, 2010), Wuyangkongfu (Xu et al., 2019), Sri Lanka tea (Munasinghe et al., 2017), three kinds of green tea (Green tables (Xu et al., 2019), WuyangChunyu (Xu et al., 2019), Longjing (Xu et al., 2019) and one kind of Oolong tea (Jinkengoolong (Xu et al., 2019). Among these results, there were significant differences in GWP emissions from different teas. Even the same type of tea produced different results given different backgrounds. For example, among the four kinds of black tea production, the results of this study, Darjeeling tea and Wuyangkongfu were more similar and much lower than those of Sri Lanka tea. It was difficult to show consistency among different production in the cultivation, processing, and packaging stages. For example, in the cultivation process, Wuyangkongfu used the organic planting mode and applied 4500 kg of rapeseed cake per hectare, which caused a large amount of CO_2 emissions, resulting in a significant increase in GWP in the planting stage compared with other black tea production. In addition, the yield of fresh tea would also significantly affect their final GWP results. The yield of Wuyangchunyu, Longjing, Wuyangkungfu, Jinkengoolong and Green tablets were 600 kg/hm^2, 1875 kg/hm^2, 1875 kg/hm2, 6000 kg/hm^2 and 19,875 kg/hm^2. Among these kinds of tea, the yield of Green tablets was significantly higher than that of other teas, thus leading to the smallest results for their GWP. In the packaging process, Sri Lanka tea used many different types of packaging materials (such as polylactic acid, polyethylene, corrugated paper, kraft paper, *etc.*), resulting in a large amount of CO_2 emissions, which seriously aggravated the greenhouse gas emissions of tea production.

Although there were great differences in tea production under different backgrounds, some common contents could still be found. First, it could be clarified that when the drinking process of tea was ignored, the production emissions of tea mentioned above were mainly influenced by three aspects: cultivation, processing and packaging, while the impact of transportation was relatively small. At the cultivation stage, the fertilizer ratio and type, the nitrogen fixation potential of tea farm, the tea yield, and the effective picking rate during harvest (Tang et al., 2011; Han et al., 2014; Mu et al., 2020) could have a significant impact on the final results. At the processing stage, different kinds of tea, different processes of the same kind of tea and different equipment selection of the same process could affect the results. Finally, in the packaging stage, tea manufacturers often adopt different packaging strategies according to the quality of tea, targeted consumers, transportation, storage requirements, and cost budgets, while neglecting the negative environmental benefits generated in the packaging process (Soheili-Fard et al., 2018). This affected the benign development of enterprises. Therefore, balancing economic development and environmental impact was one of the priorities in the current research field.

5 Conclusion

Through the life cycle assessment of Fengqing Yunnan black tea "from cradle to gate", combined with the results of contribution and sensitivity analysis, we could draw the following conclusions:

(1) The planting stage was the main source of GWP of the system, accounting for 43.73%, mainly because of the application of chemical fertilizer and the nitrous oxide emissions generated in the application process;
(2) Packaging process was the second largest source of system GWP, accounting for 39.44%, mainly due to the production of aluminum foil;
(3) During the processing stage, GWP had a greater impact on the heating withering and rolling, accounting for 8.63% and 6.85% respectively;
(4) The results of GWP were more significantly affected by the picking efficiency of tea picking machine, fertilizer utilization, packaging materials and equipment power. When the tea picking efficiency increased by 1.5%, the total GWP decreased by 0.63%; When the fertilizer utilization rate increases by 10%, the total GWP decreased by 4%; When the recovery rate of aluminum foil, cardboard and other packaging materials increases by 5%, the corresponding total GWP decreased by 1.05% and 0.15% respectively; When the power of all processing equipment is increased by 10%, the total GWP decreased by 1.3%.

Therefore, how to produce fertilizers in an energy-efficient way, how to improve the absorption rate of fertilizers in the soil, and how to reduce the loss of nitrogen in the process of fertilizer application and plant growth are still one of the main issues of energy saving and emission reduction in agriculture sector at this stage. The development of more efficient agricultural production, processing equipment, and the establishment of material recycling concepts are also important means to promote energy conservation and emission reduction. Of course, the study ignored the impact of the distribution, drinking and other stages of Fengqing Yunnan black tea, which also made the sustainable evaluation of the entire tea value chain limited. In the future, the carbon footprint evaluation of Fengqing Yunnan black tea products "from cradle to grave" and the sustainable development of its industrial value chain will be our research focus.

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

CZ contributed to the conception of the study; CZ and XY performed the experiment; XW and XY contributed significantly to the analysis and manuscript preparation; XY performed the data analyses and wrote the manuscript; XY helped perform the analysis with constructive discussions.

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Conflict of interest

CZ and XY were employed by Heshan Xinde Biological Products Co., Ltd.

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

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Embodied carbon transfers and employment-economic spillover effects in China's inter-provincial trade

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Understanding the embodied carbon transfer in inter-provincial trade and its employment-economic spillover effects is of crucial value in achieving carbon equity management. Surprisingly, few studies have focused on the intrinsic relationship between embodied carbon, embodied GDP, and embodied employment in iinter-provincial trade and its equity implications. Based on the 2012 and 2017 multi-regional input-output tables, our study of inter-provincial trade in 30 Chinese provinces shows that: 1) net outflows of embodied carbon were concentrated in the Beijing-Tianjin region and the eastern and southern coastal regions, while net inflows were in the central and northwestern regions; 2) embodied carbon, GDP, and employment were characterized by nearby transfer, complementary energy economy, and asymmetric transfers in and out; and 3) western provinces, which relied heavily on traditional energy and heavy chemical industries, gained a competitive disadvantage implying by the internal relationship between net transfers of embodied carbon, GDP, and employment. To mitigate the inequity of inter-provincial carbon trade, top-down climate goals must be aligned with bottom-up socio-economic incentives to achieve balanced regional development and improved public welfare.

KEYWORDS

embodied carbon, employment, equity, GDP, regional difference, trade

1 Introduction

China has pledged that its carbon dioxide emission reduction efforts will peak by 2030, and strives for carbon neutrality by 2060. To achieve rapid emission reductions in high-intensity sectors action must be taken at the provincial level (Liu et al., 2022). The increase in inter-provincial trade poses a challenge for provinces to meet requirements of their carbon emission reduction. This carbon transfer occurs between relatively independent administrative units; primarily from developed to less developed regions (Qi et al., 2013; Mi et al., 2017; Zheng et al., 2020a; Tian et al., 2022). In order to achieve equitable management of carbon emissions, it is vital to investigate the scale and direction of carbon transfers and to understand the potential socio-economic spillover effects of inter-regional trade (Li, 2018).

To date, studies have focused on international carbon transfer and implications for decarbonization (Zhang et al., 2020; Savina et al., 2021). At the global scale, there is skew of indirect transfer of carbon emissions from developed to developing nations due to trade flows in energy-intensive products from developing to developed countries (Feng et al., 2013; Tang et al., 2014; Wiedmann and Lenzen, 2018; Tian et al., 2022). Studies have shown that trade among developing countries (South-South trade) more than doubled between 2004 and 2011, which resulted in some production activities shifting from China and India to other developing countries, especially the production of raw materials and intermediate goods for energy-intensive industries (Meng et al., 2018). Global action on decarbonization must be down-scaled to impacts on national and regional carbon emissions to avoid leakage and enable accountability (Sánchez-Chóliz and Duarte, 2004; Ståhls et al., 2011; Springmann, 2014; Wang et al., 2022).

Inter-regional economic linkages are stronger than international economic linkages, which leads to a wider impact of inter-regional transfer of embodied carbon emissions than international transfer (Davis and Caldeira, 2010; Shi et al., 2012; Liu, et al., 2016; Yu et al., 2021). Within China studies have examined inter-provincial carbon transfers from the perspectives of national internal circulation (Wu et al., 2017; Wang et al., 2018; Wang et al., 2021), between economic regions (Cong et al., 2017; Chen et al., 2019; Du et al., 2020; Yuan et al., 2022), and within province transfers (Huang et al., 2015; Zhong et al., 2017; Zheng et al., 2020b; Yu et al., 2021). The driving factors and mechanisms of inter-regional carbon emission transfer are well understood (Guan et al., 2008; Su and Thomson, 2016; Xue et al., 2023). Based on the inter-regional trade carbon transfer econometric model and the improved log-mean Divisia index decomposition method, the study examined the main factors influencing inter-provincial net carbon transfer, and the results showed that the scale effect and the structural effect increased inter-provincial net carbon transfer, respectively, while the technology effect decreased inter-provincial net carbon transfer. (Wang and Hu, 2020). However, studies accounting for more than single carbon emission transfers and spillover socio-economic effects are rare.

The relationship between energy supply and demand had an impact on the trade in capital and labor (Wiedmann and Lenzen, 2018), facilitating employment mobility and economic growth (Mireku et al., 2017), -likely because the economic benefits of carbon emissions imports were greater than those brought by exports (Sun et al., 2016; Zhu et al., 2022). Studies have shown that the impact of domestic trade on employment growth was three times greater than that of inter-national trade (Feenstra and Wei, 2010). The primary players in inter-regional embodied trade in China were the eastern coastal and central regions (Wang et al., 2017; Yan and Wang, 2021). There is still a lack of comprehensive comparison on the transfer characteristics and resulting effects of embodied carbon, economy and employment in domestic inter-provincial trade.

Embodied carbon transfers in inter-regional trade are also accompanied by compensating gross domestic product (GDP) and employment transfers. The spatial distribution of carbon emissions between provinces in China has been shown to exacerbate inequality due to embodied carbon and embodied GDP transfer in the inter-provincial trade (Guo et al., 2012). Studies showed that there was significant carbon inequality in inter-provincial trade among China's 31 provinces, with some western provinces not only bearing part of the carbon emissions for other provinces, but also exporting net GDP to other provinces. This leaded to a competitive disadvantage in terms of carbon emissions and economic benefits (Zhang et al., 2018; Chen et al., 2020). Therefore, when benefits and costs are spatially separated, how to fairly allocate carbon reduction responsibilities among provinces is worthy of in-depth observation.

To address the abovementioned knowledge gaps, we used a Multiple Regional Input-Output (MRIO) model with data from 30 provinces in China in both 2012 and 2017 to measure the embodied carbon transfer in inter-provincial trade, and analyzed the impact on the GDP and employment. The objectives of this study will present the spatial patterns, intrinsic links and inter-provincial differences of carbon transfer, GDP transfer and employment transfer in inter-provincial trade; and analyze the rationality of the resulting carbon emission reduction and the equity of socio-economic compensation. The study will be beneficial to achieving balanced inter-provincial development and exploring equitable pathways to the carbon peaking and carbon neutrality goals.

2 Methods

2.1 MRIO

The input-output model, developed by Leontief in the 1930s, reflects the quantitative dependence of inputs and outputs among the components of an economic system. It is a useful tool for macroscopic assessment of the amount of resources or pollution contained in goods and services. A single-region input-output model cannot reflect the interrelationships among multiple regions. In practice, the extension of single regional input-output analysis to multiple regional input-output analysis can be used to analyze the interrelationships that exist between sectors in different regions.

The MRIO table can also be divided into competitive input-output tables and non-competitive input-output tables, and the difference between the two lies in the different treatment of imported goods. The competitive input-output table assumes that domestically produced intermediate inputs and imports are fully substitutable, while the non-competitive input-output table is divided into two major parts, domestic intermediate inputs and imported intermediate inputs, reflecting the imperfect substitutability of the two. The non-competitive input-output table used in this paper, excluding exports and other terms can be expressed as:

$$x_i^r = \sum_s \sum_j x_{ij}^{rs} + \sum_s Y_i^{rs}$$

x_i^r represents the total output of the regional division *I*. x_{ij}^{rs} is the intermediate input of region *r* sector *i* to region s sector *j*. y_i^{rs} represents the final demand provided by the region *r* sector *i* to the region *s*.

The consumption factor for each department can be expressed as:

$$a_{ij}^{rs} = x_{ij}^{rs} \big/ x_j^s$$

The direct consumption factor matrix between the region *R* and the region *S* is:

$$A^{rs} = \left(a_{ij}^{rs}\right)$$

Therefore, the above equation is expressed in the form of a matrix:

$$X = (I - A)^{-1}Y$$

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \dots \\ X_m \end{bmatrix} \; Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \dots \\ Y_m \end{bmatrix} \; A = \begin{bmatrix} A^{11} & A^{12} & \dots & A^{1m} \\ A^{21} & A^{22} & \dots & A^{2m} \\ \dots & \dots & \dots & \dots \\ A^{m1} & A^{m2} & \dots & A^{mn} \end{bmatrix}$$

where $X = (X_i^s)$ is the total output matrix. $Y = (Y_i^s)$is the final requirements matrix. I is the identity matrix, and diagonally is 1. The formula can also be written:

$$X = LY$$

$$L = \left(I - \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1m} \\ A^{21} & A^{22} & \cdots & A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & \cdots & A^{mm} \end{bmatrix} \right)^{-1} = \begin{bmatrix} L^{11} & L^{12} & \cdots & L^{1m} \\ L^{21} & L^{22} & \cdots & L^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ L^{m1} & L^{m2} & \cdots & L^{mm} \end{bmatrix}$$

2.2 Embodied carbon transfer in the inter-provincial trade

The inter-provincial carbon emission coefficient is:

$$E = \begin{bmatrix} E^1 & 0 & \dots & 0 \\ 0 & E^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & E^m \end{bmatrix} \; E^r = \begin{bmatrix} e_1^r & 0 & \dots & 0 \\ 0 & e_2^r & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & e_n^r \end{bmatrix}$$

The inter-provincial carbon transfer can be expressed without considering exports (Wang et al., 2018):

$$T = E(I - A)^{-1}Y$$

$$= \begin{bmatrix} E^1 & 0 & \dots & 0 \\ 0 & E^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & E^m \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} & \cdots & L^{1m} \\ L^{21} & L^{22} & \cdots & L^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ L^{m1} & L^{m2} & \cdots & L^{mm} \end{bmatrix} \begin{bmatrix} Y^{11} & Y^{12} & \cdots & Y^{1m} \\ Y^{21} & Y^{22} & \cdots & Y^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ Y^{m1} & Y^{m2} & \cdots & Y^{mm} \end{bmatrix}$$

where T is the amount of carbon transfer, $(I - A)^{-1}$ is the Leontiev inverse matrix; Y is the final requirements matrix between regions.

$$IF^r = \sum_{s,s \neq r} CT^{sr}$$

$$OF^r = \sum_{s,s \neq r} CT^{rs}$$

IF^r indicates the total inflow from other provinces to province r, OF^r indicates the total amount of outflow from province r to other provinces and cities. Thus, the net carbon outflow of region r can be expressed as:

$$CT^r = IF^r - OF^r$$

2.3 Embodied GDP and employment transfer in the inter-provincial trade

Referring to the formula of embodied carbon, the amount of embodied GDP transfer in interregional trade can be expressed as:

$$VT^r = IZ^r - OZ^r$$

where the positive value of VT^r indicates that province r has obtained economic benefits through inter-provincial trade, net transfer of part of GDP from other provinces; A negative value of VT^r indicates that province r has transferred part of its GDP to other provinces, which is a negative contribution for province r in terms of economic growth.

Similarly, the employment transfer caused by inter-provincial trade can be expressed as:

$$\mathrm{L} = \delta(I - A)^{-1}\mathrm{F}$$

$$LT^r = IJ^r - OJ^r$$

δ is the employment factor, a positive value of LT^r means that a large number of employment opportunities are obtained through inter-provincial trade; A negative value indicates that province r has a net transfer of labor to other provinces.

2.4 Data collection and regional division

The multi-regional input-output tables for China and total carbon emissions data for each province in 2012 and 2017 were both accessed from the China Emission Accounts and Datasets (CEADs) (Mi et al., 2018; Zheng et al., 2020a). This paper considers only the impact of domestic inter-provincial trade. In order to avoid data interference, other items and exports are deducted from total output. Due to data unavailability, the study excludes Tibet, Hong Kong, Macau and Taiwan. The provincial GDP in 2012 and 2017 is reported in the *China Statistical Yearbook*, and the employment data is collected from the *2013 and 2018 Provincial Statistical Yearbook*. In order to better analyze the results of the study, we divided the Chinese mainland provinces into eight regions according to the economic, resource and environmental differences, as shown in Table 1.

3 Results

3.1 Inter-regional transfer and difference of embodied carbon

Based on the MRIO tables in 2012 and 2017, this study indicates that the net transfer out of embodied carbon was concentrated in the Beijing-Tianjin region, the eastern coastal region and the southern coastal region, which was basically overlap with the three major economic regions in China (i.e. the Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta economic regions) (Figure 1). For example, the eastern coastal region (e.g., Shanghai, Jiangsu, and Zhejiang) had consistently maintained high embodied carbon net transfer out, 546.31 Mt and 406.64 Mt in 2012 and 2017, respectively. In contrast, the net transfer of embodied carbon was concentrated in the central and northwestern regions. This inter-provincial trade pattern was the embodiment of coal transportation from the north to the south and energy from the west to the east, and reflects the pattern of economic resources after the China's reform and opening up. China's eastern coastal region had a developed economy and a large demand for resources and energy, which needs to be transferred from western China. Complementarily, the industrial level of western China is relatively low, and it relies on the outflows of traditional high carbon, low-value-added products.

Notably, the Southwest has changed from a net transfer-in region in 2012 to a net transfer-out region in 2017 due to the long-term support of the Western Development Strategy launched at the end of the last century (see Figure 1). In 2012, the net transfer in from the Southwest was 12.96 Mt, and in 2017, the net transfer out was

TABLE 1 Thirty provinces in eight regions of China.

Regions (8)	Provinces (30)
Northeastern region	Liaoning, Jilin, Heilongjiang
Beijing-Tianjin region	Beijing, Tianjin
Northern coastal region	Hebei, Shandong
Eastern coastal region	Shanghai, Jiangsu, Zhejiang
Southern coastal region	Fujian, Guangdong, Hainan
Central region	Shanxi, Anhui, Jiangxi, Henan, Hunan, Hubei
Northwestern region	Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
Southwestern region	Guangxi, Sichuan, Chongqing, Guizhou, Yunnan

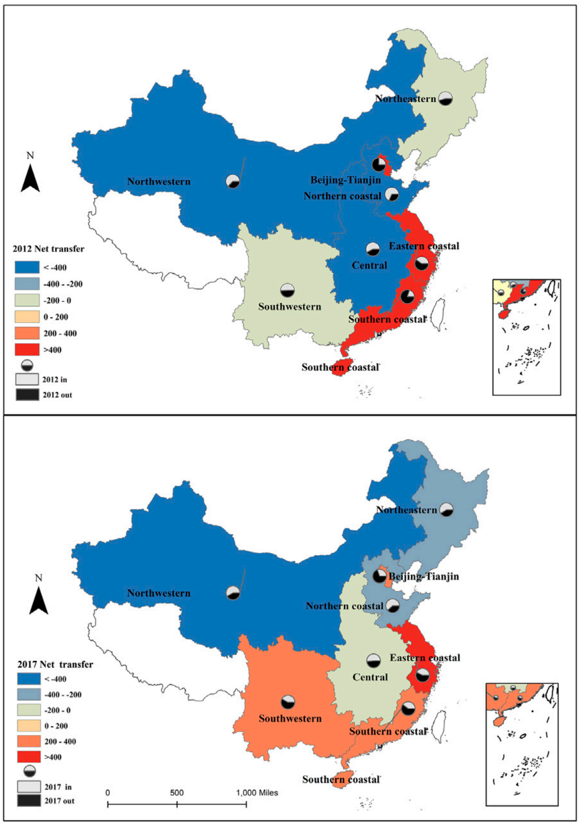

FIGURE 1
Embodied carbon net transfer in inter-provincial trade from 2012 to 2017.

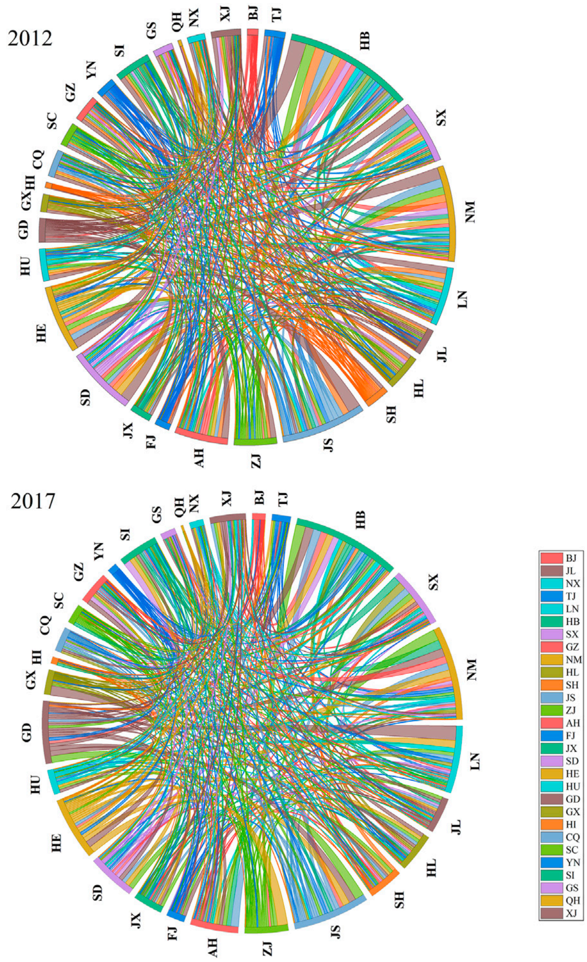

FIGURE 2
Chord chart of embodied carbon transfer by province from 2012 to 2017.

321.99 Mt, which is the opposite of the performance in 2007–2012 (Mi et al., 2017). In addition, since 2007, China has adopted a series of energy transition and emission reduction policies. For example, in 2007 China's National Leading Committee on Climate Change and The National Climate Change Program were established, introducing goals to reduce energy intensity and increase the share of non-fossil energy (Liu et al., 2022). The Nationally Appropriate Mitigation Actions (NAMAs) followed, as did China's Intended Nationally Determined Contributions (INDCs) in 2015, the latter of which aimed to achieve 60%–65% carbon intensity reductions by 2030 (from 2005 levels) and to reach peak emissions around 2030 (Liu et al., 2022). However, these national energy efficiency campaigns and broad industrial low-carbon transitions have not been met with immediate results in the short term. The scale of net transfer-in of embodied carbon in northeastern China, where the proportion of traditional heavy chemical industries was relatively high, had further

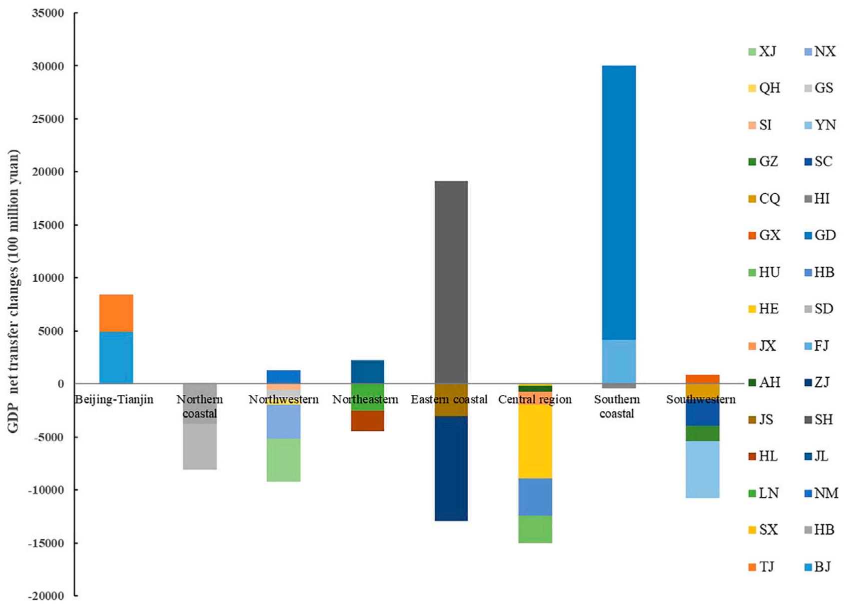

FIGURE 3
Embodied GDP net transfer in inter-provincial trade from 2012 to 2017.

increased, from 148.98 Mt in 2012 to 312.55 Mt in 2017, and the low-carbon transition still remained slow.

The inter-provincial carbon emission transfer between 2012 and 2017 is characterized by neighboring spatial transfer, energy economy complementarity, and transfer-in and -out asymmetry, as shown in Figure 2.

1) It is obvious that carbon transfers from geographically close provinces. A typical example is the Beijing-Tianjin-Hebei economic region, where close economic and trade ties promote the transportation of products or fuels in close proximity. The embodied carbon emissions borne by Hebei for Beijing and Tianjin in 2012 were 4,726.16 Mt and 2,269.07 Mt. Similar characteristics are also found between Hebei, Shanxi and Inner Mongolia, between Jiangsu and Shanghai, and between Shandong and Henan. 2) Provinces with strong complementary industrial and economic structures have obvious carbon transfer. For example, Guangdong Province is a modern manufacturing-oriented province with strong energy dependency, while Hebei Province is a large producer of traditional energy and has a large energy trade volume between the two provinces. This causes Hebei to bear a large amount of carbon emissions for Guangdong Province. In 2012 and 2017, the embodied carbon emissions borne by Hebei Province for Guangdong Province were 10588.09 Mt and 5,667.74 Mt. Other provinces with similar characteristics include Beijing and Hebei, Guangdong and Liaoning, and Shanxi and Henan. 3) The scale of carbon emission transfer in and out among provinces is found to be asymmetric. The thickness of the lines of the chord diagram indicates the size of the embodied carbon transfer to and from each province, and the asymmetry of the embodied carbon transfer to and from each province can be seen from the thickness of the lines. For example, the embodied carbon transferred to Guangdong Province mainly comes from Beijing, Shanghai, Jiangsu and Zhejiang, with the transferred amounts of 1,013.27 Mt, 1,847.17 Mt, 938.93 Mt and 970.07 Mt, respectively, accounting for 27.3% of the total amount transferred to Guangdong Province. Meanwhile, the embodied carbon transfer out provinces in Guangdong Province mainly include Hebei, Inner Mongolia, Jiangsu and Shandong, with the transferred amounts of 10,588.09 Mt, 8653.96 Mt, 9,255.48 Mt and 7,370.95 Mt, respectively, accounting for 35.25% of the total transferred out amount in Guangdong Province.

3.2 Inter-provincial transfer and difference of embodied GDP

The net transfer of embodied GDP from 2012 to 2017 show that the scale of net transfer in the Beijing-Tianjin region and the southern coastal region had been increasing, with an increase rate of 138.03% and 153.71%, respectively (Figure 3). Meanwhile, the scale of embodied GDP net transfer out of the southwestern, northwestern and central regions was gradually increasing, with 991.31 billion yuan, 789.33 billion yuan and 1,501.87 billion yuan, respectively. The net transfer scale in the northern coastal region has decreased significantly by 66.1% within 5 years. It should be pointed out that the most economically developed and densely populated eastern coastal region and southern coastal region were observed the largest changes in the net transfer of embodied GDP.

The embodied GDP transfer matrix from 2012 to 2017 shows that the impact of inter-provincial trade on the economy of each province varied significantly (see Figure 4). The impact of inter-provincial trade on the embodied GDP in the developing western provinces, e.g., Sichuan and Ningxia, had changed from a positive boost in 2012 to a negative deprivation in 2017. The reason for this may be the rapid economic growth in the western region with the continued support of the targeted poverty alleviation strategy since 2015, and the large amount of energy needs to be transferred and compensated accordingly. On the contrary, the impact on the developed eastern provinces, such as Beijing, Tianjin, Shanghai, and Guangdong, has

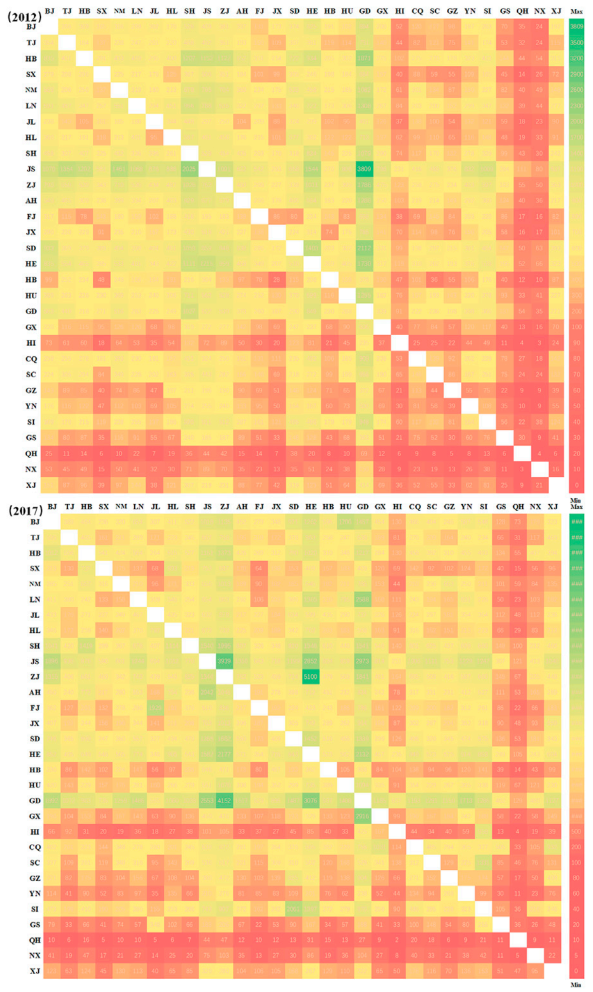

FIGURE 4
Inter-provincial transfer matrix of embodied GDP from 2012 to 2017.

changed from a negative weakening to a positive pulling, which may be related to the local advantages of high-tech, high-value-added industries.

Inter-provincial trade has led to regional economic differences and complementary development, which is closely related to China's environmental and economic policy adjustments over the past decade. For example, the obligatory energy and carbon intensity targets stipulated were included in the Five-Year Plans (FYPs), since 12th FYP (2011–2015) (Liu et al., 2022). Moreover, the *Action Plan for the Prevention and Control of Air Pollution promulgated in 2013* required that, compared with 2012, the concentration of inhalable particulate matter in cities at the prefecture level and above should be reduced by more than 10% by 2017. These targets strictly restricted the development of "two highs and one low (i.e. high energy consumption, high pollution, and low-output level)" industries, shutting down and transferring thousands of small and medium-sized enterprises. Traditionally energy-rich central and western regions (e.g., Hebei, Shanxi, Inner Mongolia, Henan, and Guizhou provinces) have thus been subjected to significant environmental and economic pressures, leading to slower economic growth.

3.3 Inter-provincial net transfer and difference of embodied employment

Changes of embodied employment capacity caused by inter-provincial trade reflect the vitality of regional economy. Unfortunately, this has rarely been mentioned in previous studies. From 2012 to 2017, the provinces with the net transfer out of embodied employment were mainly concentrated in the Beijing-Tianjin region, the eastern coastal region and the southern coastal region, of which the latter two changed the most (see Figure 5). For example, Guangdong Province transferred out 29.27 million workers and 3.97 million workers in 2012 and 2017, respectively, mainly because these provinces consume large amounts of energy transferred from other provinces. Meanwhile, subject to socio-economic factors, the size of the net transfer of embodied labors in northwestern China continued to increase by 82.2% from 2012 to 2017. This suggests that the divergence between labor-intensive industries and technology-intensive and capital-intensive industries was accelerating in eastern and western China. It is worth pointing out that the provinces with the net transfer in of labor were mainly concentrated in the northern coastal region, the central region and the southwest region. Among them, the overall change in the central region was relatively large. From 2012 to 2017, the net employment transfer volume decreased from 45.23 million to 24.42 million, with a reduction rate of 46.0%.

The embodied employment transfer matrix shows that the inter-provincial transfer of embodied employment presented three main characteristics from 2012 to 2017 (see Figure 6). First, the asymmetry of the embodied employment transfer in and out was observed in each province. For example, in 2012, the embodied employment transfer in Hebei Province was relatively large, mainly in Guangdong, Zhejiang, Jiangsu, Shanghai, Shandong and Henan. Meanwhile, the scale of embodied employment transfer out was relatively small, mainly to Jiangsu, Anhui and Henan. In comparison, the scale of embodied employment transfer in Guangdong Province is small, but the scale of transfer out is large. Second, due to the close economic ties and convenient transportation, the embodied employment transfer was observed remarkably between neighboring provinces, for example, between Beijing, Hebei and Tianjin, between Hebei, Shanxi and Inner Mongolia, between Jiangsu and Shanghai, and between Shandong and between Henan. Finally, stimulated by national environmental and climate policies, some provinces presents a reversal between net transfer in and out of the employment. For example, Jiangsu, Shandong, Hubei, Chongqing, Yunnan, and Ningxia changed from net inflows to net outflows of embodied employment, while Jilin, Shanghai, Zhejiang, Fujian, and Hainan performed the opposite.

3.4 Relationships between embodied carbon and embodied GDP

As of 2017, China's GDP has increased more than 30 times compared to the beginning of reform and opening up (National Bureau of Statistics of China, 2018). Meanwhile, China has been actively exploring compatible models of economic transformation and environmental protection in the context of fierce economic competition in international trade (National Bureau of Statistics of China, 2020). These changes in climate economic policy have resulted in making trade-offs between carbon emissions reduction and

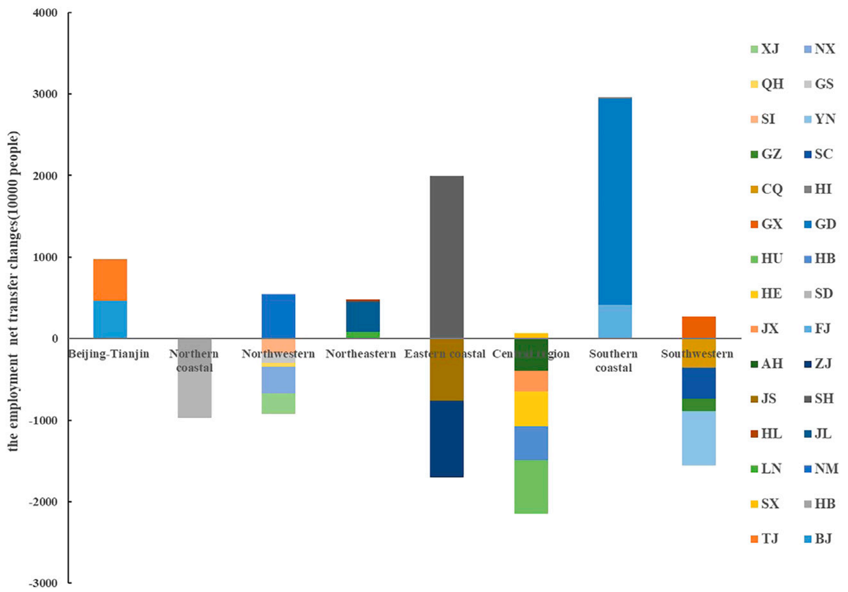

FIGURE 5
Embodied employment net transfer in inter-provincial trade from 2012 to 2017.

economic development in each province. Since 2011, China's economic transition has accelerated with slow growth. Especially, from 2013 to 2016, the growth rate of CO_2 emissions has continued to decline (Green & Stern, 2017; Guan et al., 2018; Zheng et al., 2019).

From 2012 to 2017, the quadrant diagram shows a clear provincial divergence between net transfer of embodied carbon and net transfer of embodied GDP (see Figure 7). First, most provinces were located in the second and fourth quadrants, indicating relatively equitable carbon-economy model in inter-provincial trade. This equitable model of the carbon economy implies that when a province provides energy-intensive or carbon-intensive products to other provinces and bears the pressure of carbon emission reduction for other provinces, it will also receive a net transfer in of embodied GDP from other provinces as compensation, and *vice versa*. Second, some provinces were fixed in a certain quadrant, such as the northern coastal region (Hebei and Shandong) and the central region (Shanxi and Anhui) were always located in the second quadrant; the northwestern region was concentrated in the third quadrant. This suggests that China's climate economy policies will hardly change the trend of carbon economy in these provinces in the short run. Finally, Carbon inequity was observed in inter-provincial trade. For example, from 2012 to 2017, developing provinces in the western region, such as Gansu and Ningxia, moved from the second quadrant to the third quadrant. In inter-provincial trade, these remotely located provinces relied mainly on exporting low-value-added primary products and importing high-value-added products and services from other provinces for their development. The lock-in effect of low-end energy industries made these provinces slow to make the low-carbon transition and at a significant disadvantage in the competition for a low-carbon economy. Inter-provincial equity and central and western support policies of carbon economy has been fully considered in future development plans, e.g., the 13th (2016–2020) and 14th (2021–2025) FYPs.

3.5 Relationships of embodied carbon and embodied employment

After the Copenhagen Climate Conference in 2009, China started three batches (in 2010, 2014 and 2017) of low-carbon provinces and cities successively, and wrote the goal of energy conservation and carbon reduction into the 12th (2011–2015) and 13th (2016–2020) FYPs. These energy-related policies have driven low-carbon actions in the provinces, leading to employment changes following the broad transformation of energy-saving and carbon-reduction industry.

From 2012 to 2017, the net transfer of embodied carbon and employment revealed obvious intrinsic correlation (see Figure 8). First, Most provinces are located in Quadrants 2 and 4, indicating that the net transfer of embodied carbon was accompanied by an equitable compensation for the net transfer of embodied employment. Second, the relationship between the net transfer of embodied carbon and embodied employment in some provinces did not change significantly. For example, the northern coastal region (Hebei and Shandong) were always in the second quadrant, and the northwestern provinces were mainly concentrated in the third quadrant. This indicates that while providing high-carbon products to other provinces and bearing the pressure of carbon emissions, it brings an inflow of employment. Likewise, the central region provinces were largely fixed in the second and fourth quadrants. Finally, the net transfer of embodied carbon is not accompanied by a reasonable compensation for embodied employment in some provinces. For example, provinces in the third quadrant, such as Inner Mongolia and Xinjiang, exhibited a net transfer in of embodied carbon and a net transfer out of embodied employment, and were at a competitive disadvantage; provinces in the first quadrant, on the contrary, including Hunan and Henan, gained a competitive advantage in the carbon economy. The above irrational performances tend to be in the energy-rich provinces of the western region and are the focus of future low-carbon economic equity decision-makings.

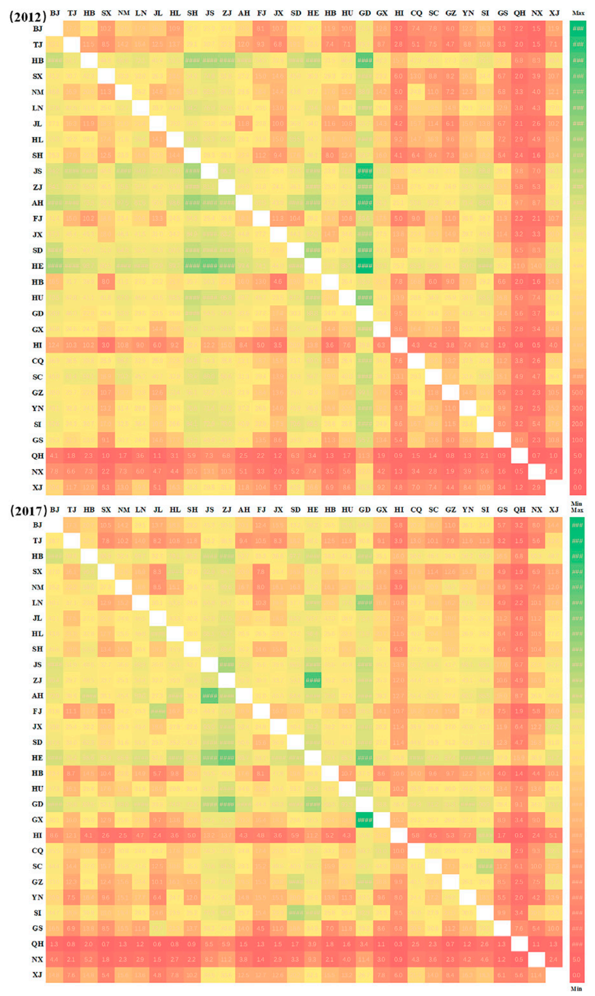

FIGURE 6
Inter-provincial transfer matrix of embodied employment from 2012 to 2017 (In the figure, the block color changing from green to red indicates an increase of the amount of embodied employment transfer.)

4 Discussion

Embodied carbon in trade has received long-term attention in past decades. Surprisingly, the intrinsic correlation between embodied carbon, embodied GDP, and embodied employment in inter-provincial trade and their equitable governance are less well covered in previous research. Undoubtedly, this can not provide effective decision-making support in promoting balanced regional development, achieving common prosperity for residents, and developing a fair carbon compensation mechanism. The evaluation among 30 provinces in mainland China shows that China's embodied carbon transfer is shifting from economically developed regions or less developed regions with imperfect industrial structures to provinces depending on energy-oriented and heavy chemical industries. In some provinces, especially in some central and western provinces, the transfer of embodied carbon is not fairly compensated for GDP and employment. These findings have been partially captured by previous studies (Shi et al., 2012; Mi et al., 2017).

Economic or employment compensation accompanies the embodied carbon transfer in most provinces in inter-provincial trade. However, the less developed western provinces, which rely heavily on high-carbon energy products, are at an absolute disadvantage in the carbon economy era. The welfare inequity caused by this trade in high-carbon products needs to be investigated for achieving balanced regional development (Feng et al., 2013; Liu et al., 2022). In the future, improving resource premium potential and carbon economy competitiveness through low carbon energy transition will be the key challenge to achieve common prosperity.

In response to climate change, China has proposed its INDCs and carbon peaking and carbon neutrality goals, and has decomposed the emission reduction tasks into provinces, industries and enterprises (The Carbon Peaking Action Plan, 2021). This undoubtedly poses an unprecedented challenge to the central and western regions, which need to address both common prosperity and low-carbon transition. Therefore, we can consider developing and introducing low-carbon innovative technologies, and using a combination of government regulation and market regulation to reach economic and employment compensation for achieving a rapid carbon economic transition.

Furthermore, considering the differences in resource endowments and industrial structures, we need to develop complementary policies for top-down carbon reduction targets and bottom-up energy economy transformation. 1) Provinces with high dependence on traditional energy and high proportion of high-carbon industries actively explore low-carbon transformation of energy and introduction of low-carbon technologies to create more jobs; 2) The eastern provinces with developed industrial economies and high energy demand should pay attention to research and development of industrial energy conservation, emission reduction and low-carbon innovative technologies; 3) Considering the differences in industrial structure, trade size, technology availability, and resource endowment across provinces (Guan et al., 2018; Li et al., 2021), appropriate standards, technologies, and policies are needed to mitigate the inequitable effects of embodied carbon transfers in inter-provincial trade.; 4) Adopting a model that combines top-down climate targets and bottom-up socio-economic incentives to obtain reasonable economic and social compensation while reflecting carbon transfer is conducive to achieving the "carbon peaking and carbon neutrality goals."

Top-down national top-level design and bottom-up public participation will be an alternative pathway for China to achieve its long-term climate goals. For example, on 15 March 2021, the ninth meeting of the Central Finance and Economics Commission made an overall plan for China to achieve the "carbon peaking and carbon neutrality goals," and will adopt a "1 + N" climate action strategy in the future (The Communist Party of China Central Committee, 2021). The climate goals are broken down from top to bottom, with all levels of government and the public completing energy saving and carbon reductions in stages. In October 2021, The Carbon Peaking Action Plan (2021) was released, which determined the action goals and specific measures to achieve carbon peaking by 2030. Moreover, the state also announced the energy conservation and emission reduction targets for the coming 14th (2021–2025) and 15th (2026–2030) FYPs. In the current situation where global supply chains are at risk of

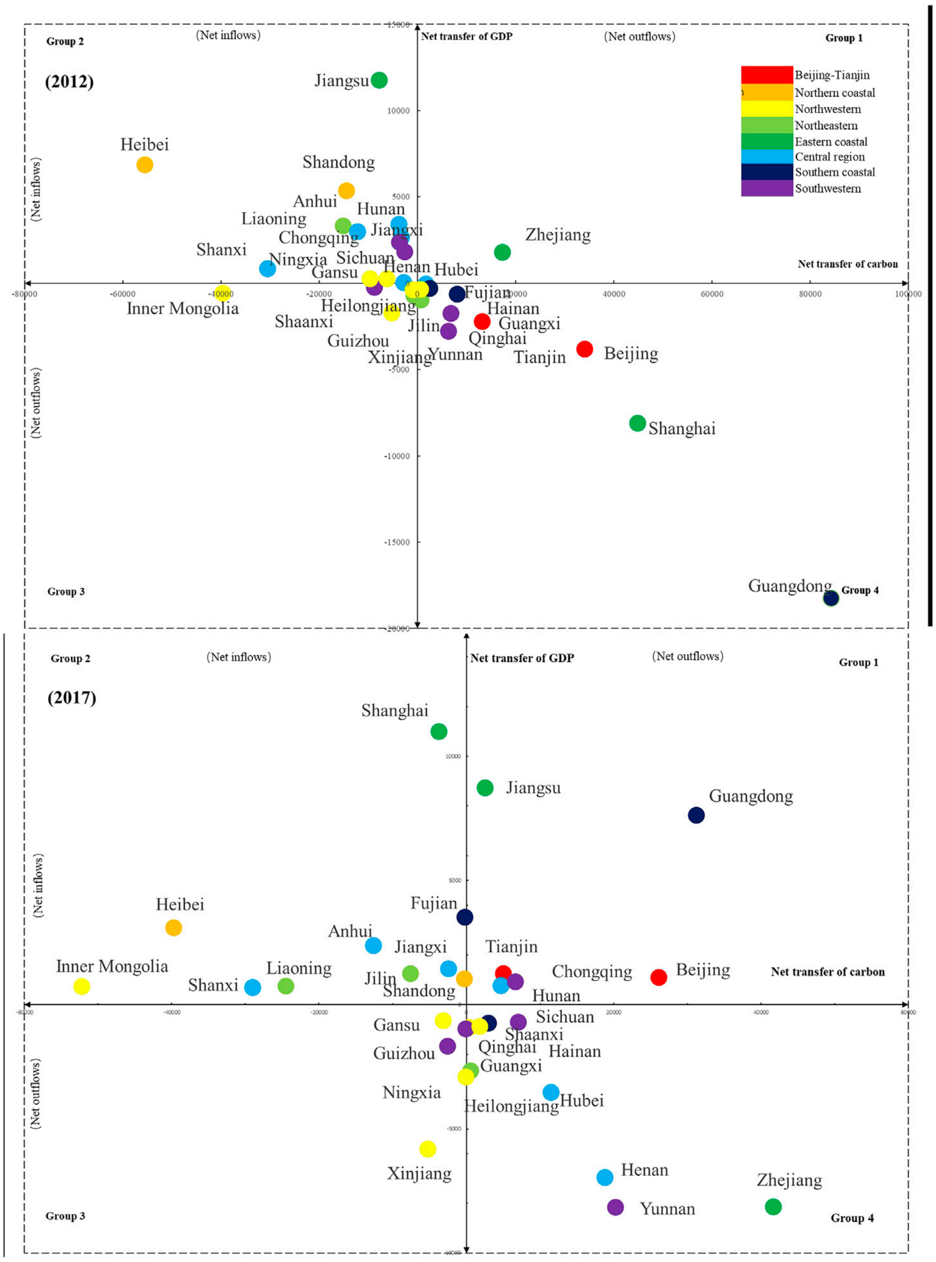

FIGURE 7
Net transfer relationships between embodied carbon and embodied GDP in inter-provincial trade from 2012 to 2017.

disruption, the complementary development of inter-provincial carbon economies will undoubtedly be the key to the realization of China's domestic and foreign "double-loop" development pattern and the climate strategy.

In addition, considering the different distribution of natural resources and industries in each province, there are certain shortcomings in reflecting inter-provincial carbon equity simply by employment or GDP. At present, there is no uniform calculation standard for a reasonable quantification of carbon equity. A small amount of research has introduced pollution trading conditions and carbon Gini coefficients to analyze the rationality of the spatial distribution of carbon emissions and inter-provincial carbon equity in China (Chen et al., 2020). The study shows that some large energy provinces in central and western China even pay a certain economic cost while undertaking net carbon emissions from other regions, and the value of the pollution condition of trading is greater than 1, which is disadvantageous in inter-provincial trading. This is consistent with our findings. The fairness of carbon emissions should be reasonably defined, the inherent factors such as local resource endowment should be fully considered, and the amount of economic employment compensation for carbon transfer in inter-provincial trade should be scientifically quantified. This is of great significance for achieving

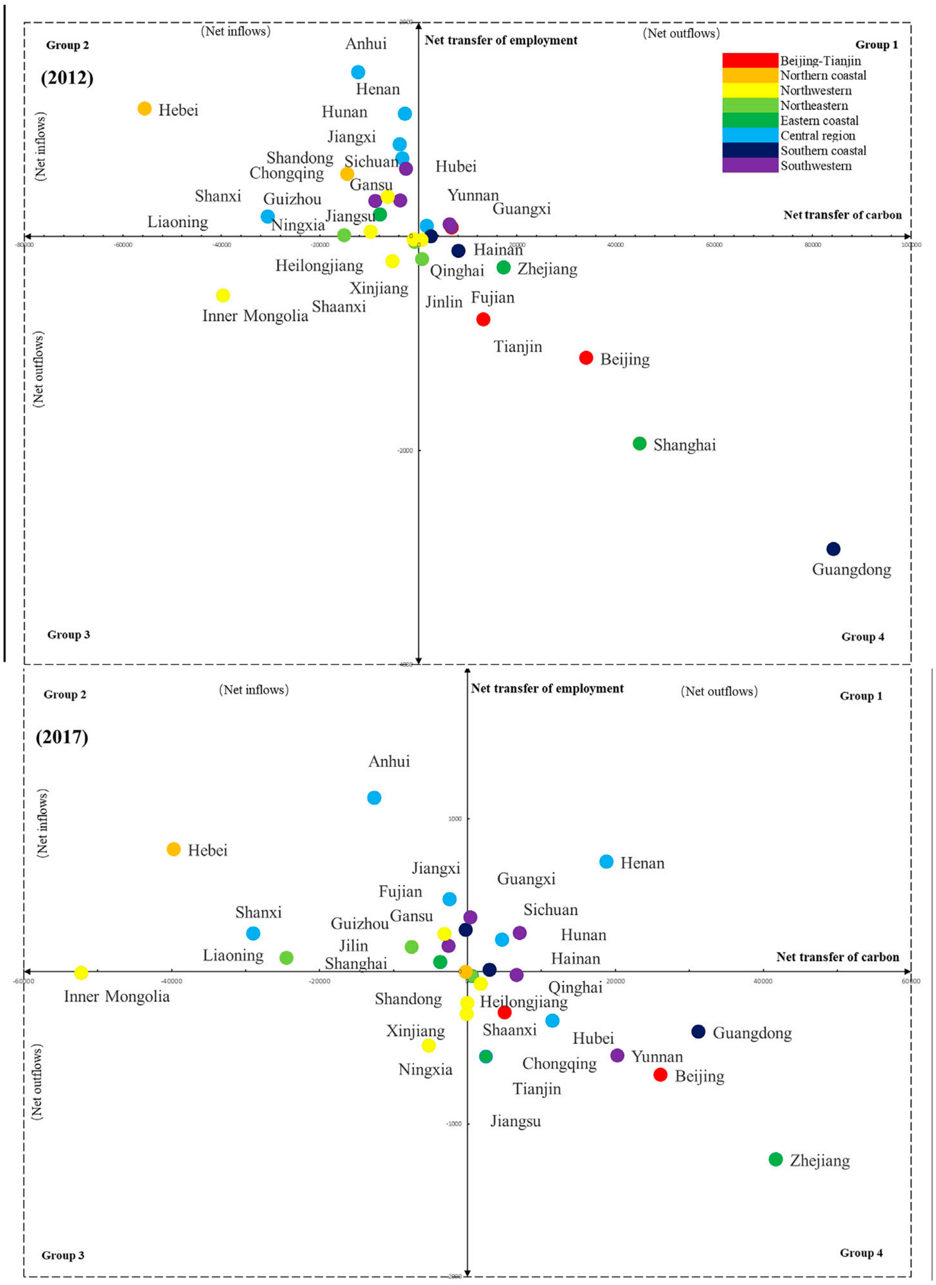

FIGURE 8
Net transfer Relationships between embodied carbon and embodied employment in the inter-provincial trade from 2012 to 2017.

balanced regional economic development and national emission reduction targets.

There are still shortcomings in this study. Due to the lack of first-hand economic and employment data on new energy substitution, we have used the embodied GDP and employment transfer calculated by the MRIO model, which does not adequately take into account the multidimensional drivers of the economy and employment. Moreover, the study only measured the impact of inter-regional trade on spatial embodied carbon transfer and economic employment, without analyzing the potential drivers. Future research should consider the spatial impact of inter-provincial and inter-national trade on the embodied carbon economy, interrelationships and driving factors, which will help to provide a reference for the scientific regulation of regional carbon transfers.

5 Conclusion

Inter-regional trade-induced carbon economic transfers are of importance for achieving balanced regional development and equitable wellbeing. This paper measures the embodied carbon, embodied GDP and embodied employment transfers induced by inter-regional trade in 2012 and 2017 using the MRIO model. The study shows that: 1) The net embodied carbon transfer out provinces are mainly concentrated in Beijing-Tianjin region, eastern and southern coastal regions, while the net embodied carbon transfer in provinces are related to central and western regions; 2) The transfer of embodied carbon, embodied GDP and embodied employment shows the characteristics of proximity transfer, energy economy complementarity, and asymmetry of transfer in and out. 3) Western provinces, such as Gansu, Guizhou, and Ningxia, which relied heavily on traditional energy and heavy chemical industries, gained a competitive disadvantage implying by the internal relationship between net transfers of embodied carbon, GDP, and employment. While these provinces share the pressure of carbon emissions from other provinces, they also suffer the negative economic and employment impacts from the inter-provincial trade.

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

DY, and PO'C: Conceived, redesign and rewrote the manuscript; RG: Performed methodology and wrote the draft; TZ, SZ, HM, and MW: Contributed the data collection; CD and WM: Reviewed 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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Green urbanization efficiency of 18 urban agglomerations in China: Evidence from spatial–temporal evolution

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As a highly developed spatial form of integrated cities, urban agglomeration has become an important fulcrum for promoting economic development and regional growth. Green urban efficiency is the key to achieving green growth in a country. This study propose a slack-based model with undesirable output to evaluate the green urbanization of 18 urban agglomerations in China. Analysis was performed using the integrated barycenter coordinate method, standard deviation ellipses, and the geographic detector model to determine the spatial–temporal characteristics of green urbanization efficiency and the factors that influence urban agglomerations. We found that the green urbanization efficiency of urban agglomerations in China, when plotted, revealed a curve with the shape of "∧," which increased at first and then decreased. The spatial differentiation characteristics were not obvious as the gap was narrowing. The center of green urbanization efficiency in China's urban agglomerations has always been located in the Central Plains, with a small overall span and a relatively fixed position. The barycenter coordinates showed a trend of shifting from east to north, but the transfer speed and rhythm were relatively slow. The explanatory power of the various factors influencing the spatial differentiation of green urbanization efficiency of urban agglomerations differed markedly. The magnitude of importance was in the order of: urban population scale > investment growth > technology level > economic development > industrial structure.

KEYWORDS

green urbanization efficiency, green development, spatial–temporal evolution, influencing factor, urban agglomeration

1 Introduction

Urbanization has promoted the development of social and economic goals and is important as a support for modernization (Yang et al., 2023). China's urbanization process has advanced rapidly, increasing from 17.92% in 1978 to 59.58% in 2020, with an average annual increase of 1.09%. According to the three-stage theory of urbanization, China's urbanization will still be in the accelerating stage in the next 10 to 15 years (Zeng et al., 2022). The rapid development of urbanization has accelerated the solution to the problems of "agriculture, rural areas, and farmers," promoted a balance between urban and rural areas, and promoted overall social progress. However, the driving force in this rapid development has been cheap land and labor, and the extensive development based on high input, high consumption, and high pollution has caused a series of negative impacts on the sustainability of regional development (Zhao et al., 2022). Traditional urbanization has created a significant urban–rural divide, resulting in strong urban growth on the one hand and widespread deflation in rural areas on the other. As a result, urbanization has been a major contributor to China's uneven and inadequate socioeconomic development.

Green development has become a significant trend in the world's urban development with the goal of higher efficiency, higher output level, and greater sustainability. Green urbanization involves a deep integration of urbanization and greening, requiring that the region achieve a low-carbon footprint, and a circular, inclusive development with the goal of seeking a balance between economic growth and environmental protection. China's urbanization rate has reached 50% for the first time in 2011, indicating that the country is no longer a rural society, but instead is transitioning to an urban one. In order to guarantee the stable and healthy development of society as well as the economy, it has become an inescapable choice for future urbanization development to reform the present policies, give attention to green leadership, and support the green urbanization process (Luo et al., 2022).

With the acceleration of green urbanization, urban agglomeration has become an important fulcrum to promote economic development and regional growth (Qian et al., 2022). It can accumulate resources for production, promote the development of industrial clusters, and effectively exploit the agglomeration and radiation effects of central cities (Zhu et al., 2023). Compared with a single city, urban agglomeration produces a highly effective platform for rapid economic growth and national participation in global competition. It is currently the main form of urbanization, and developers must pay more attention to green methods. By 2020, the 18 urban agglomerations recognized in China's planned growth only accounted for 29.1% of the national area, but they produced more than 80% of GDP and actually utilized 92% of total foreign investment, which constitutes absolute support for China's development (Tan et al., 2022). However, the overall development of cities in urban agglomerations in China is quite different from that of other countries, showing an uncoordinated development status. In 2020, the level of urbanization in Wuhan, the central city of the Yangtze River urban agglomeration, was 84.31%, while that of its neighbor city Huanggang was only 47.55%. The urbanization of Xiamen, the urban agglomeration on the west side of the Straits, was 86.99%, while that of Meizhou was only 45% with great regional difference. The regional differences between neighboring cities require us to pay attention to the spatial structure of urban agglomerations. According to the "green development" concept, urban agglomerations are responsible for both economic growth and green development, and carbon peaking and carbon neutrality are the objectives that must be met in the future. Optimizing the spatial structure of urban agglomerations and constructing green barriers become, especially important in planning for green urbanization efficiency. In view of the typical regional spatial differences of urban agglomerations, exploring their green urbanization efficiency from a spatio-temporal perspective is not only conducive to clarifying the current development trend but also to promoting the linkage effect among cities in the region and achieving balanced growth of large, medium, and small towns. It has important theoretical and practical value for optimizing the spatial layout, improving cluster efficiency, and realizing regional coordination.

In consideration of the problems of unbalanced regional development of the 18 typical urban agglomerations in China, this paper utilizes the section data of 2009, 2014, and 2019 to suggest integrating resources and environmental elements into the construction of an urban efficiency index system and applying the SBM (slack-based measure) model, which takes undesirable output into account in measuring efficiency. The spatio-temporal evolution characteristics and green urbanization efficiency of the urban agglomerations were determined using the barycenter coordinate and standard deviation ellipse methods. The geographic detector model was used to determine the impact of specific factors that influenced green urbanization efficiency, providing a reference for the formulation of regional strategies of local governments at all levels.

2 Literature review

Academic research on green urbanization has been accompanied by the rise in green urbanism, highlighting green urban change and transformation, involving research on "green walls" and sustainability. At present, the green urbanization practices in many countries have adopted distinctive models, among which the most representative ones include ecological low-carbon green city construction in the UK, ecological sustainability and urban "smart growth concept" in the US, and the compact model of land use. The formation and development of green concepts provides a logical starting point for the study of green urbanization (Fang and Yu, 2017). At this stage, "green urbanization" is primarily concerned with "ecological civilization" and "new urbanism," and it is seen as a path toward "ecological balance and harmony between man and nature" by combining urban expansion with green concepts (Wang et al., 2023). This new urbanization model incorporates intensive urban development with green practices and harmonizes urban population growth and economics with wise resource use and environmental stewardship. The current development path of green urbanization is constrained by population, resources, economy, ecological environment, etc. The imbalanced growth of metropolitan areas and their excessive structural scale generate a number of problems. With the intense urban expansion, excessive consumption of soil resources, and serious ecological effects of environmental pollution, the efficiency of green urbanization has aroused widespread concern in the academic community (Yu et al., 2020). Excessive energy consumption, land degradation, and environmental damage have always been important factors limiting urban expansion. Green urbanization efficiency has likewise been inseparable from population, land, energy efficiency (Miao et al., 2021), environmental pollution (Yasmeen et al., 2020), economy (Chen et al., 2023), society (Reichenbach et al., 2021), and carbon emissions (Bai et al., 2019; Ma et al., 2019). Wang established an index system to generate an urbanization quality score, including population, economy, society, and space (Wang et al., 2019), while Zhang selected land, capital, and labor as the core elements to evaluate urbanization efficiency (Zhan et al., 2018). Kuang focused on the land, labor, agriculture, machinery, chemical fertilizers, the economy, and society (Kuang et al., 2020). Koroso et al. evaluated the consequences of urban land use and found that rapid urbanization and expansion were key factors in ULUE (Koroso et al., 2021). Green competitiveness and green industrial development were dominant in the green economic development of urban agglomerations (Wang Y. et al., 2021), and resources and environmental factors have become important constraints on high-quality urban development (Zhang and Chen, 2021).

Research on urban agglomeration originated in the early 20th century with Howard's "The Garden City of Tomorrow." He considered the city and surrounding countryside as a whole from the perspective of spatial organization and content dynamics and believed that the manifestation of a city included not only the area occupied by the city but also the garden areas surrounding it (Vasenev et al., 2021). Geddes studied urban agglomerations from the perspective of the aggregation of cities and believed that the rapid suburbanization of cities would produce aggregation patterns in space, emphasizing spatial overlap (Cao et al., 2022). Since then, Cottmann has put forward the concept of a megalopolis, studied the phenomenon of urban spatial agglomeration with New York City as the center, and began to pay attention to the spatial performance of urban agglomerations (Ramos-H et al., 2020). Kipnis linked urban agglomeration with industrialization, arguing that urban agglomeration provided a good regional environment for innovation and entrepreneurship, emphasizing spatial zonal distribution (Kipnis, 1984). Zhu et al. described the zonal distribution of cities around big cities with regional characteristics, gradually forming a consensus on urban agglomeration. Yang explored the multiple effects of urbanization on riverine and terrestrial organisms (Yang et al., 2022). Urban agglomerations are composed of multiple cities, which are increasingly connected with each other and jointly influence regional development. The relevant research on urban agglomeration has gone through four stages: urban, megalopolis, ecumenopolis, and urban agglomeration, focusing on urbanization level, economic growth of urban agglomerations, industrial structure, spatial structure, and land, environment, and ecological problems (Peng et al., 2022; Wang et al., 2022; Xiao et al., 2022).

Environmental concerns in urban development are receiving increasing attention from the government and local officials, and environmental protection has become a major component of urban development. Spatial pattern research has provided important new data, useful in analyzing urban problems. Jiang et al. proposed a novel approach for determining the potential spatio-temporal exposure risk of residents by capturing human behavior patterns from spatio-temporal data on parking lot availability (Jiang et al., 2021). Sun established a spatial econometric model of environmental health to investigate the direction, intensity, and spatio-temporal heterogeneity of the impact of haze pollution and its spillover effects on public health in urban agglomerations (Sun et al., 2022). Jana et al. (2020) analyzed the spatio-temporal pattern of urban expansion and its effects on changes in green space and thermal behavior in the Doon Valley between 2000 and 2019. Urbanization is associated with significant changes in the soil, vegetation, and climate, and it is important to explore its impact on soil function given its spatial–temporal variability (Vasenev et al., 2021). Zhou incorporated spatial analysis with geographical detection, to assess the urban air pollution occurrence in 337 Chinese cities (Zhou et al., 2021). Wang developed an improved method for quantitatively representing urban communities based on multiple periodic spatial–temporal graphs of human mobility (Wang et al., 2018). Wiatkowska analyzed spatial–temporal land use and land cover changes in urban areas using geographic data (Wiatkowska et al., 2021). The spatial analysis method allows scholars to study the internal relationships of cities.

The methods for assessing the evolution of spatial linkages of urban agglomerations have become more diversified and progressively better. From a single process to a combination of approaches, the barycenter coordinate method, standard deviation ellipse, and geographic detector model are the most generally used. Researchers in GCC countries and abroad have carried out comparatively thorough studies on the spatial organization of well-developed urban agglomerations, but they often focus on a single agglomeration. According to the report of the 19th National Congress of China, urban clusters should serve as the main component of a coordinated urban development pattern, and it is crucial to examine the geographical distributions of large, medium, and small urban clusters.

3 Methodology

3.1 Research context

In comparison to other nations, China has experienced industrialization and urbanization at a faster rate and on a larger scale, resulting in the emergence and expansion of several new cities. Urban agglomeration has developed into a crucial fulcrum to support economic development and regional growth as green urbanization has accelerated. Urban agglomerations suffer from a number of inherent difficulties, particularly with regard to the effects of climate change and environmental degradation. How the process of urbanization can strike a balance between increasing the population and preserving the environment is a complex topic that has yet to be thoroughly explored. Based on the National New Urbanization Plan (2014–2020), the thirteenth five-year plan (2016–2020), and related research results on the definition of urban agglomeration (Lu et al., 2022; Wu and Li, 2022; Yu et al., 2023), 18 urban agglomerations including Harbin–Changchun, Central and South Liaoning, Beijing–Tianjin–Hebei, Shandong Peninsula, and the Yangtze River Delta were selected for the study area (Figure 1) because of the availability of data and potential for statistical analysis. The code related to the 18 urban agglomerations (Table 1) is as follows.

3.2 Green urban efficiency

In view of the importance of the impact of resources and environmental factors on green urbanization, this paper constructed a framework (Figure 2), which considered resource consumption as a new input factor along with land, capital, labor and resources, and assumed green urbanization as the output. The output index of green urbanization is the urbanization level of each city. However, urbanization is a comprehensive evolutionary process of population, economy, and society, so this study deconstructs the green urbanization output into the separate elements of population, economic, social, spatial, and environmental urbanization. This division allows the study to characterize the impact of green urbanization in terms of population change, economic development, social inclusion, spatial equity, and environmental consumption status, respectively. In the model, environmental consumption is taken into account as an undesirable outcome, in an effort to reflect the concept of people-oriented green development

TABLE 1 Code of 18 urban agglomerations.

Number	Urban agglomeration	Number	Urban agglomeration
No. 1	Harbin–Changchun	No. 10	Beibu Gulf
No. 2	Central and South Liaoning	No. 11	Pearl River Delta
No. 3	Beijing–Tianjin–Hebei	No. 12	Central Yunnan
No. 4	Shandong Peninsula	No. 13	Central Guizhou
No. 5	Yangtze River Delta	No. 14	Chengdu Chongqing
No. 6	West Coast of the Straits	No. 15	Guanzhong
No. 7	Jinzhong	No. 16	Lanxi
No. 8	Central Plains	No. 17	Ningxia Yanhuang
No. 9	Middle Reaches of the Yangtze River	No. 18	Hubao Eyu

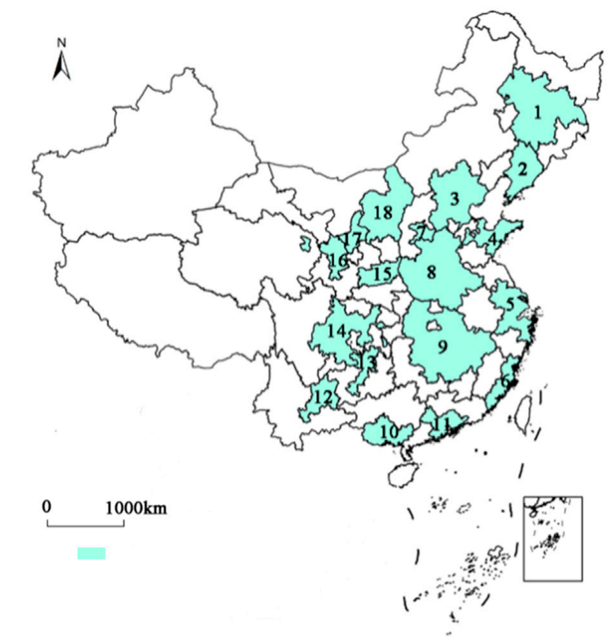

FIGURE 1
Overview of the study area.

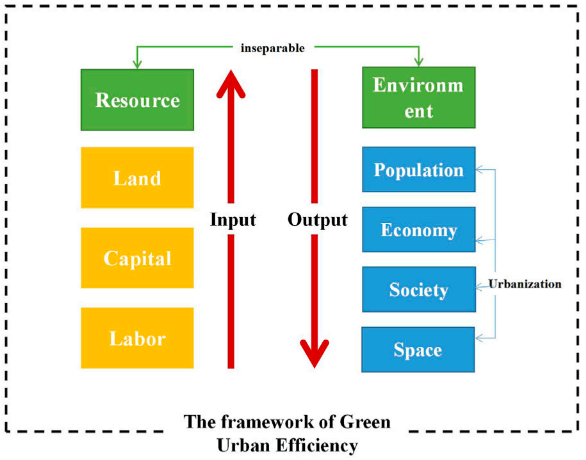

FIGURE 2
The framework of green urban efficiency.

in green urbanization. The details of index selection are shown in Table 2. The data were derived from the China Statistical Yearbook, the China City Statistical Yearbook, and the China Energy Statistical Yearbook in 2010, 2015, and 2020.

3.3 Methodology

3.3.1 SBM model

The SBM model proposed by Tone is introduced to measure the urbanization efficiency of urban agglomerations because it not only resolves the slack problem with input–output variables but also makes use of the non-radial and non-angled processing of undesired outputs resulting in more accurate calculation results (Li et al., 2022; G; Liu S. et al., 2022; S; Liu G. et al., 2022):

$$\rho^{*} = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{r0}^b}\right)}$$

$$s.t.\begin{cases} x_0 = X\lambda + s^- \\ y_0^g = Y^g\lambda + s^g \\ y_0^b = Y^b\lambda + s^b \\ s^- \geq 0, s^g \geq 0, s^b \geq 0, \lambda \geq 0 \end{cases}$$

where ρ^* is the urbanization efficiency of the urban agglomeration, which takes a value between [0, 1]; *s-*, *sg*, and *sb* are the slack variables of factor input, expected output, and undesired output, respectively; and λ is the weight vector.

3.3.2 Barycenter coordinate method

The physical meaning of the term 'barycenter' is the location where the combined forces of gravity operate on an object. It is derived from geometrical mechanics. The barycenter method was first used in a study of population in 1874 by F. Volker and then

TABLE 2 Index system of green urbanization efficiency.

Category	Secondary indexes	Tertiary indexes
Input	Resource	Energy consumption of 10,000 yuan GDP (ton standard coal)
		Per capital water consumption (m^3)
		Per capital electricity consumption (kw·h)
	Land	Proportion of built-up area in total area (%)
	Capital	Investment in fixed assets (100 million yuan)
		Expenditure from the general budget of local finance (100 million yuan)
		Amount of foreign capital actually used (USD 10,000)
	Labor force	Employees (10,000)
Output	Population	Proportion of urban population (%)
	Economy	Proportion of output value of secondary and tertiary industries (%)
	Society	Retail sales of consumer goods (100 million yuan)
	Space	Proportion of built-up area in total area (%)
	Environment	Industrial wastewater discharge (10000 tons)
		Industrial emissions (100 million cubic meters)
		Industrial solid waste production (ten thousand tons)

gradually spread to social economics and other fields. It reflects the mobility of regional factors in the spatial layout, facilitating the exploration of regional development trends over time and laying the foundation for the rational allocation of production factors. The barycenter coordinate method from the field of mathematics was introduced to analyze the spatial changes in urbanization efficiency in urban agglomerations and to describe the agglomeration characteristics and deviation trajectory of spatial attributes (Wang et al., 2021a).

$$X = \frac{\sum_{i-1}^{n} P_i X_i}{\sum_{i-1}^{n} P_i} \quad Y = \frac{\sum_{i-1}^{n} P_i Y_i}{\sum_{i-1}^{n} P_i}$$

In the formula: X and Y are the longitude and latitude of the geographic center coordinates, respectively; p is the score of the urbanization efficiency of urban agglomerations.

3.3.3 Standard deviation ellipse

The standard deviation ellipse proposed by Professor Lefever was introduced to reveal the spatial distribution, spatial movement direction, and discrete characteristics of the urbanization efficiency in urban agglomerations (Liu et al., 2023). The fundamental measurement parameters are rotation angle, major axis standard deviation, and minor axis standard deviation. The direction of the spatial distribution of the factors is represented by the rotation angle, which is a clockwise rotation from true north to the long axis. The direction of the major trend in the spatial distribution of urbanization efficiency in urban agglomerations is represented by the standard deviation of the major axis, whereas the range in the spatial distribution of urbanization efficiency in urban agglomerations is reflected by the standard deviation of the minor axis. The larger the ratio of the major axis to the minor axis, the more concentrated is the centripetal force of the data. A smaller ratio corresponds to a greater degree of dispersion of the data.

$$\tan\theta = \frac{\left(\sum_{i=1}^{n} w_i^2 x_i'^2 - \sum_{i=1}^{n} w_i^2 y_i'^2\right) + \sqrt{\left(\sum_{i=1}^{n} w_i^2 x_i'^2 - \sum_{i=1}^{n} w_i^2 y_i'^2\right)^2 + 4\left(\sum_{i=1}^{n} w_i^2 x_i'^2 y_i'^2\right)^2}}{2\sum_{i=1}^{n} w_i^2 x_i' y_i'},$$

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n} \left(w_i x_i' \cos\theta - w_i y_i' \sin\theta\right)^2}{\sum_{i=1}^{n} w_i^2}}$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n} \left(w_i x_i' \sin\theta - w_i y_i' \cos\theta\right)^2}{\sum_{i=1}^{n} w_i^2}},$$

where tanθ is the rotation angle; σ_x and σ_y are the standard deviation of the *x-axis* and the standard deviation of the *y*-axis, respectively; (x_i, y_i) are the coordinates of the research object *i*; w_i is the weight; x'_i and y'_i are coordinate deviations from different research objects to the average center.

3.3.4 Geographic detector model

The geographic detector model proposed by Wang Jinfeng was introduced to determine the intensity of each factor's effect on the spatial differentiation of urbanization efficiency in urban agglomerations (Song et al., 2020). This method can not only detect numerical data and qualitative data but also explain the interaction of multiple factors.

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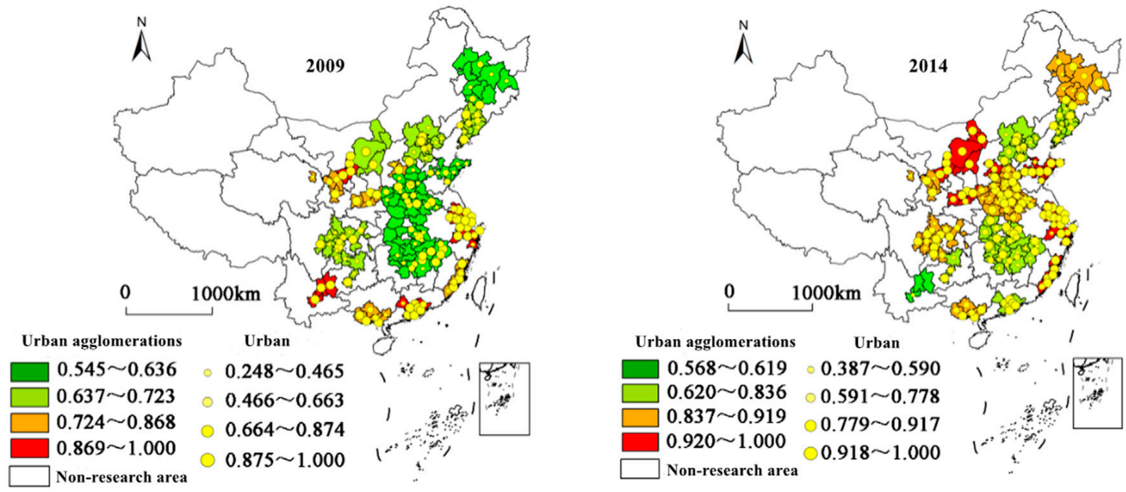

FIGURE 3
Spatial distribution pattern of the urban agglomerations in 2009, 2014.

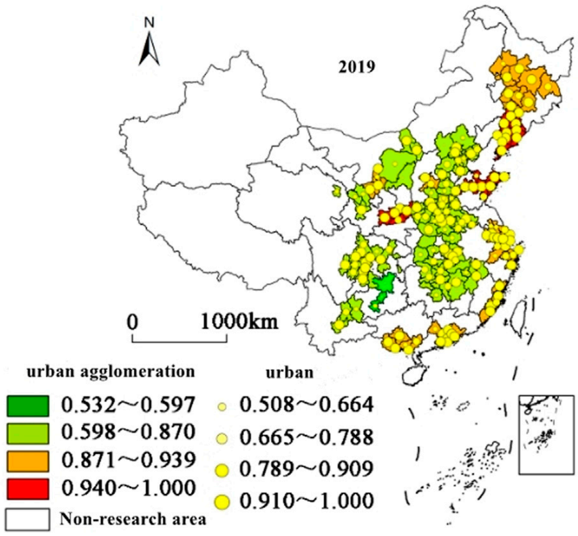

FIGURE 4
Spatial distribution pattern of the urban agglomerations in 2019.

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2},$$

where q is the explanatory power of a certain influencing factor on the spatial differentiation of urbanization efficiency in urban agglomerations, with values between [0, 1]. The smaller the value, the smaller the influence of a certain factor on the urbanization efficiency in urban agglomerations; the larger the value, the greater the influence. When $q = 0$, it means that the influencing factors have nothing to do with the spatial differentiation of urbanization efficiency in urban agglomerations; $q = 0$ indicates that the influencing factors can completely explain the spatial differentiation of urbanization efficiency in urban agglomerations; h is the dependent variable Y or the stratification of influencing factor X; N_h and N are the number of samples in the h layer and the study region, respectively; and $\sigma^2{}_h$ and σ^2 are the variance of the Y-value of the h layer and the Y-value of the study region, respectively.

4 Results and discussion

Figure 3 and Figure 4 show the spatial distribution pattern of green urbanization efficiency of urban agglomerations in 2009, 2014, and 2019. The regional color blocks indicate the green urbanization rates of the city clusters, while the yellow points represent the green urbanization rates of each individual city. The green urbanization rates of the 18 city clusters and the cities inside them were utilized to assess the regional green development.

4.1 Spatial distribution patterns of green urbanization efficiency in urban agglomerations

The graph of the overall green urbanization efficiency of China's urban agglomerations has the shape of a "∧," which indicates a sharp rise followed by a steep fall. The average green urbanization efficiency in the 3 years was 0.777, 0.889, and 0.886 respectively. This represents remarkable progress in urbanization development, continuous improvement in the urban system, and a tendency toward coordination in the development of urban and rural areas after implementation of the eleventh five-year plan, especially since the 2010 National Main Function Zone Plan accepted urban agglomeration as an important carrier for urbanization. However, the high-density urban agglomerations caused high-risk threats to resources and the environment; highly sensitive ecosystems were negatively affected, which diminished the continuous improvement of green urbanization efficiency. A graph of the green urbanization efficiency of the Pearl River Delta and Central Yunnan has the shape of a "∨," with an initial decrease followed by a sharp increase. In contrast, the green urbanization efficiency

TABLE 3 Gravity center evolution of the spatial layout.

Year	Barycentric coordinate	Deflection direction	Corner (θ/°)	Standard deviation along the X-axis/km	Standard deviation along the Y-axis/km
2009	113°55′E, 32°25′N	—	24.98	1,355.26	2,126.23
2014	114°09′E, 33°32′N	Northeast	25.73	1,290.06	2,128.43
2019	114°21′E, 33°52′N	Northeast	26.61	1,276.71	2,193.82

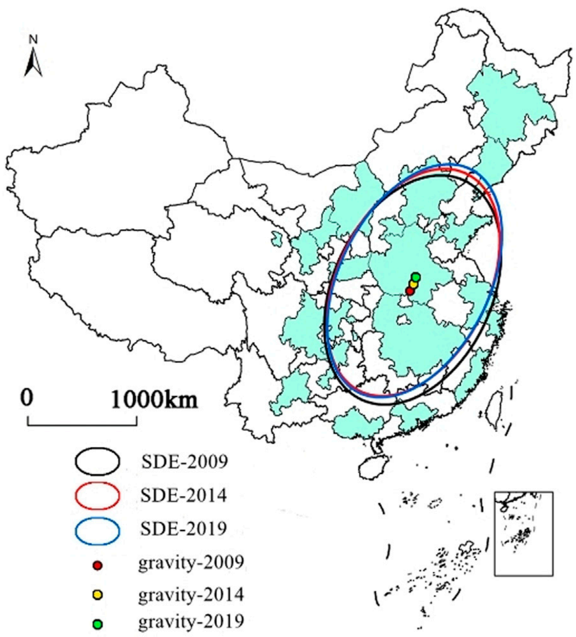

FIGURE 5
Dispersion trends of spatial distribution pattern.

of the five urban agglomerations of Beijing–Tianjin–Hebei, central and southern Liaoning, Shandong Peninsula, the central Shaanxi plain, and Harbin–Changchun showed an upward trend year by year. The green urbanization efficiency increased from 0.656, 0.720, 0.655, 0.563, and 0.563 in 2009 to 0.855, 1.000, 0.965, 0.938, and 0.938 in 2019, respectively. The largest increase was in the Harbin–Changchun urban agglomeration, which has been actively exploring new urbanization paths in major grain producing areas by accelerating the transformation of the development mode, promoting foreign cooperation, overcoming obstacles in the system and mechanism, and fully implementing green ecology in the context of the comprehensive revitalization of the old industrial base.

The spatial differentiation characteristics of green urbanization efficiency in China's urban agglomerations have decreased. The standard deviations of green urbanization efficiency in the 3 years were 0.130, 0.085, and 0.084, respectively. The green urbanization efficiency of the urban agglomeration along the Yellow River in Ningxia (mean 0.981) was the highest. This region covers 43% of Ningxia's land area and accounts for 80% of its cities, 90% of its urban population, and more than 90% of its GDP and fiscal revenue. The region exhibited high land use efficiency and has become a strategic area for regional economic development, along with the six functions of the economic lifeline line, ecological landscape line, characteristic city line and cultural display line, and others still to be built. The green urbanization efficiency of the Yangtze River Delta urban agglomeration (mean 0.931) was the second highest. Its urbanization program developed early, and it has always been in the forefront of China's urbanization development by improving key urban functions, optimizing urban population distribution, and promoting integrated construction. The green urbanization efficiency (mean 0.726) of the urban agglomeration in central Guizhou was the lowest. The backward level of economic development, extensive economic growth mode, fragile ecological environment, and limited development space were the main factors restricting its development. From the perspective of 173 prefecture-level cities, the green urbanization efficiency (mean 1.000) of 26 cities including Beijing, Shanghai, and Nanjing has reached an ideal state, which indicates that under certain input conditions of capital and resources in the process of urbanization, these cities can achieve maximum output. Jiujiang's green urbanization efficiency (mean 0.442) was the lowest among the prefecture-level cities. Its environmental pollution, aging population, and imbalance between consumption in urban and rural areas led to serious inefficiency and waste in its urbanization development (Figures 3, 4).

4.2 The spatial–temporal evolution characteristics of green urbanization efficiency in urban agglomerations

The barycenter coordinate and standard deviation ellipse model were used to obtain the barycenter coordinate and standard deviation ellipse of green urbanization efficiency of China's urban agglomerations in 2009, 2014, and 2019 by using ArcGIS10.2 software for data processing.

From the perspective of the distribution of barycenter Table 3, the centers of green urbanization efficiency of China's urban agglomerations in the 3 years are all located in the Central Plains urban agglomerations, which is between 113°55′E ~ 114°21′E and 32°25′N ~ 33°52′N, showing that the overall span is small and the location is relatively fixed. This is closely related to the location advantage of the Central Plains urban agglomeration linking east to west and north to south, the better urban spatial aggregation form, the strong industrial cluster advantage, and the policy of "1+4" Zhengzhou metropolitan area. In addition, the National New Urbanization Plan (2014–2020) clearly points out that the Central Plains urban agglomeration should be built into an important growth pole that promotes balanced development of land and space and leads regional economic development in the future, so as to provide demonstration samples for promoting urbanization development of urban agglomeration as the main form. All these make the urbanization of Central Plains urban agglomeration present a trend of factors

TABLE 4 Result of the factor detector.

Detector factor	Corresponding influencing factors	*q*-value
Proportion of urban population in total population	Urban population size	.4603
GDP *per capita*	Economic development	.1903
Proportion of output value of the Tertiary industry	Industrial structure	.0906
Proportion of science and technology expenditure in public finance expenditure	Technological level	.2941
Proportion of total investment in fixed assets in GDP	Investment	.3334

aggregation, win–win cooperation, and rapid rise. In general, the barycenter coordinate of green urbanization efficiency in China's urban agglomerations shows a trend of shifting to the east-north. It can be seen that the green urbanization efficiency of urban agglomerations in northeastern China has been improved to a certain extent, but the speed and pace of improvement are relatively slow, which is more restricted by medium-high economic growth, declining demographic dividend and prominent environmental problems.

From the standard deviation ellipse (Figure 5), the green urbanization efficiency of China's urban agglomeration shows a northeast-southwest trend, indicating that urban agglomerations with high green urbanization efficiency are mostly distributed along the northeast-southwest direction. The green urbanization efficiency of urban agglomerations in the southeast of the ellipse axis improved faster than that in the northwest. The rotation angle θ in the 3 years has increased from 24.980 to 26.610, and it rotates counterclockwise to the west. It can be seen that the implementation of the "Belt and Road" Initiative, new urbanization construction, and regional coordinated development strategy have provided strong impetus and new guidance for the urbanization development of the urban agglomeration along the Yellow River in Ningxia, the central Shaanxi plain, and other western regions. The agglomeration capacity of factors has been continuously improved, the urban system has been improved, and the urban connection has been increasingly closed. From 2009 to 2019, the distribution range of the standard deviation ellipse of green urbanization efficiency in urban agglomeration decreased first and then increased, and the standard deviation ellipse areas of the 3 years were $226.32 \times 104\ km^2$, $215.65 \times 104\ km^2$, and $219.98 \times 104\ km^2$, respectively. The standard deviation of the long axis and the short axis changed to varying degrees, among which the long axis has increased from 2,126.23 km in 2009–2,193.82 km in 2019, and the short axis has decreased from 1,355.26 in 2009 to 1,276.71 km in 2019, indicating that although the spatial distribution of green urbanization efficiency in China's urban agglomerations has begun to disperse, its spatial distribution pattern remains stable. The spatial spillover effect is still not obvious, and it is still dominated by the northeast-southwest direction, while the influence of the northwest-southeast direction is weak.

4.3 Analysis of influencing factors of green urbanization efficiency in urban agglomerations

Combined with the urbanization development characteristics of urban agglomerations (Fang and Yu, 2017), this paper believes that urban population size, economic development, industrial structure, technological level, and investment are the main influencing factors of green urbanization efficiency in urban agglomeration (Ningyi Liu, 2022; Tan et al., 2022; Wang Y. et al., 2021). Specific indexes are selected as shown in Table 4. The natural break point method in ArcGIS is used to divide these factors into five levels for data discretization. The effects of these indicators on the regional differentiation of urban agglomeration green urbanization efficiency are analyzed using the geographic detector model. The result shows that the explanatory power of different influencing factors on the spatial differentiation of green urbanization efficiency in urban agglomerations is different, and the order of explanatory power is urban population size > investment > technological level > economic development > industrial structure, and the corresponding detection factor q values are .4603, .3334, .2941, .1903, and .0906, respectively. We can find that:

The size of the urban population is the most important factor affecting the spatial differentiation of green urbanization efficiency in urban agglomerations. Among them, the urban population in the eastern urban agglomerations such as the Pearl River Delta, Beijing–Tianjin–Hebei, Yangtze River Delta, and Shandong Peninsula accounts for more than 65% of the total population. The geographical environment, better economic foundation, supporting public services, and related preferential policies make people from small and medium-sized cities and rural areas continue to gather in these regions on a large scale, thus realizing regional industrial transformation and upgrading and continuously enhancing development vitality. The urban agglomerations of Chengdu–Chongqing, Beibu Gulf, central Guizhou, and central Yunnan account for only about 40% of the urban population, and they are facing the dilemma of population shrinkage. The labor supply has encountered bottlenecks, and the endogenous driving force for economic growth is insufficient. On the basis of improving the soft and hard environment, the attraction of external population should be the focus of their future work.

Investment is a secondary factor affecting the spatial differentiation of green urbanization efficiency in urban agglomerations, which is particularly important when the proportion of fiscal expenditure decreases in high-quality stage of the economy. Among them, the central Guanzhong, Lanxi, and other urban agglomerations are important inter-provincial urban agglomerations in western China. Under the influence of the "Belt and Road" construction and the development of the Yangtze River Economic Belt, fixed asset investment accounts for more than 120% of the regional GDP. It aims to effectively build a new pattern of opening up both internally and externally and to create an important growth pole leading northwest China's development by connecting multi-level transportation network and improving communications and water conservancy facilities guarantee ability. In comparison, the proportion of total investment in fixed assets in GDP in the central and southern Liaoning urban agglomeration is only 31.52%. The fundamental crux is the deep-seated contradiction between system and structure. In the future, we should continue to further promote the reform of "delegate power, improve regulation, and upgrade services," strengthen the construction of convenient service platform, improve the service efficiency, and focus on improving the soft environment for investment.

Technological level, economic development, and industrial structure are important factors influencing the spatial differentiation of green urbanization efficiency in urban agglomerations, mainly manifested in the relatively poorer ability of independent innovation, the lower level of local transformation of achievements, and the failure to effectively integration various scientific research force. Urban function positioning and labor division are unclear, driving and radiation capabilities of the core city are weak, small, and medium-sized cities and towns on the periphery are insufficient, and the polarization phenomena are still readily apparent. Accordingly, the enhancement of innovation driving force based on the construction of collaborative innovation system, the high-quality economic development based on the "five-sphere integrated plan" overall promotion, and the industrial structural transformation based on the construction of modern industrial system should become the focus of improving the green urbanization efficiency of urban agglomeration in the future.

5 Conclusion

In this study, we integrated resources and environment elements, barycenter coordinate method, standard deviation ellipse, and geographic detector model to understand the spatial–temporal characteristics of green urbanization efficiency in 18 urban agglomerations and to study the population size, economic development, industrial structure, technological level, and investment effects on the green urbanization efficiency. Our empirical study in the 18 urban agglomerations demonstrates that the spatial differentiation of urban agglomerations is shrinking, and the specific performance is as follows:

1) The overall green urbanization efficiency of China's urban agglomerations shows a "∧" characteristic. The average green urbanization efficiency of the 3 years is .777, .889, and .886. Only the green urbanization efficiency in the five urban agglomerations of Beijing–Tianjin–Hebei, central and southern Liaoning, Shandong Peninsula, Guanzhong, and Harbin–Changchun is increasing year by year. The spatial differentiation characteristics are not obvious, and the gap is narrowing. The standard deviation of green urbanization efficiency in the 3 years was .130, .085, and .084. The Ningxia Yanhuang was the highest, while that in central Guizhou urban agglomeration was the lowest, with a difference of 1.35 times.
2) The center of green urbanization efficiency in China's urban agglomerations has always been located in the Central Plains urban agglomeration, with a small overall span and a relatively fixed position. The barycenter coordinates of green urbanization efficiency in urban agglomeration show a trend of shifting from east to north, but the transfer speed and rhythm are relatively slow. With the passage of time, the spatial distribution of green urbanization efficiency in urban agglomerations starts to disperse, and the green urbanization efficiency in western urban agglomerations continues to improve, but the spatial distribution pattern is still stable, with the northeast-southwest direction dominating, and the northeast-southeast direction having a weak influence.
3) Different influencing factors have different explanatory powers on the spatial differentiation of green urbanization efficiency in urban agglomerations. The order of explanatory power is urban population size > investment > technological level > economic development > industrial structure. The values of corresponding detection factor q are, respectively, .4603, .3334, .2941, .1903, and .0906. Among them, the urban population size is the most important factor and talent attraction is the most important with the improving environment. The investment is the secondary factor, which is particularly important in the high-quality stage of economic development.

In conclusion, the research on green urbanization efficiency of urban agglomeration under the restrictions of resources and environment involves the scientific construction of the input–output index system, a comprehensive grasp of the connotation of urbanization quality, which is a long-term systematic project and requires gradual progress. The research results of this paper on the spatial–temporal evolution of green urbanization efficiency of urban agglomerations in China and its influencing factors are relatively preliminary, and further research is needed in the future: First, a long time panel data will be used to analyze green urbanization efficiency in urban agglomerations so as to accurately grasp the spatial–temporal evolution rules and systematically summarize problems. Second, we can measure and compare the green urbanization efficiency of different types and grades in urban agglomerations, including national urban agglomerations, regional urban agglomerations, and local urban agglomerations, discussing and proposing different strategies to improve the green urbanization efficiency in urban agglomerations. Third, we can try to build the research framework system of green urbanization efficiency in urban agglomeration from other perspectives such as integration, innovation, and openness and promote all-round improvement of urbanization quality in urban agglomerations.

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found at: https://data.stats.gov.cn/easyquery.htm?cn=C01 https://data.stats.gov.cn/.

Author contributions

XL and LW conceived and designed the experiments; LW analyzed the data; and XL and LW wrote 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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Evolution trend and hot topic measurement of climate migration research under the influence of climate change

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Introduction: Global climate change, which is characterized by climate warming, has become one of the most prominent risk problems in society at present. Climate migration brings many accompanying problems to the environment, economy, politics, society, and culture. It is of great theoretical and practical significance to study the internal relationship between climate change and population migration.

Methods: The data were extracted from the Web of Science core collection database (WOS) and China Knowledge Network database (CNKI). A total of 785 documents and 157 documents in the field of climate migration from 2008 to 2021 were selected as analysis samples. Word frequency analysis, clustering analysis, sudden word detection analysis, and other methods were extensively used to build the evolution trend map of climate migration using CiteSpace visual bibliometric software.

Results: It is concluded that climate migration research has experienced three stages of development: initial exploration stage (2008-2011), development enrichment stage (2012-2017), and system deepening stage (2018).The hot topics of climate migration include: (1) different types of climate migration research; (2) Quantitative model research on climate migration; (3) Climate justice research. Different types of climate migration include 7 main types: (1) migration caused by sea level rise; (2) Resettlement caused by flood disaster; (3) Migration due to worsening drought; (4) Migration caused by extreme climate events; (5) Voluntary migration due to climate change discomfort; (6) Project resettlement caused by climate change response engineering measures; (7) Migrants whose livelihoods are broken due to climate change.

Discussion: The study points out that climate migration research is an interdisciplinary research field, which needs joint research by scholars from different academic backgrounds. In the future climate migration research, 1) strengthen the prediction ability of climate change population migration model; 2) Make use of China's beneficial exploration in the migration fields such as engineering resettlement, ecological resettlement and poverty alleviation resettlement to formulate climate migration policies, regulations and strategic planning; 3) Establish a database cloud platform related to climate change and population migration; 4) Strengthen the exchange and cooperation between Chinese researchers in the field of climate migration and international scientific research institutions.

KEYWORDS

climate migration, evolution trend, hot topics, metrological analysis, climate change

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1. Introduction

Climate change, along with its adverse impacts (Da Silva Espinoza et al., 2023), have triggered many actual or potential climate migrations (Black et al., 2011). Humanitarian crises, refugee flows, regional conflicts, and other issues caused by climate migration are increasingly attracting the attention of governments and the international community. They have become one of the core issues of universal concern to human society at this stage (Ionesco et al., 2016). With the change in the global climate model, the increase in the certainty of global warming has led to a shift in the direction of the Earth's ocean current, which has led to the continuous rise of the tropical ocean surface temperature, the prolongation of the duration and intensity of global ocean storms, the increase in sea levels, the intensification of desertification, and the frequent occurrence of drought and flood (Oliveira et al., 2022). As a result, the climate has become extremely volatile (Morley et al., 2020). An extreme climate has spawned a large number of "climate migrants" who have had to migrate due to climate change, ecological imbalance, geological variation, and environmental pollution (Daoudy et al., 2022). Steve Trent, President of the Environmental Justice Foundation, pointed out that "climate change will affect families, infrastructure, food, water, and human health, and will also lead to unprecedented large-scale population migration"(Trent, 2022).

In 1990, the Intergovernmental Panel on Climate Change (IPCC) pointed out in its report that "one of the most serious consequences of climate change is to affect population mobility (Houghton, 1996). Nicholas Stern put forward a clear message in the "Stern Review on the Economics of Climate Change (2007)": Climate change is a severe problem, and the earth's climate is changing rapidly, mainly due to the increase in greenhouse gases caused by human activities (Stern and Stern, 2007; Da Silva et al., 2023). In addition, the report proposes another view: the poorest countries will be hit hardest by climate change. Some regions are more vulnerable to these adverse factors than others. Generally, mitigation or adaptation is considered the only possible solution to these problems. However, those areas that are already extremely poor and vulnerable before the impact of climate change will not be able to mitigate or adapt to climate change in the usual sense. Therefore, people's only hope is often to move from a habitable area to an area that may give them better living conditions (Stern and Stern, 2007). An increasing number of studies have shown that climate migration caused by climate change is a significant problem that mankind will face in the future (Heltberg et al., 2009; Burrows and Kinney, 2016).

On February 28, 2022, the sixth assessment report released by the IPCC emphasized that the average temperature of the Earth's surface increased by approximately 1°C in the 50 years from 1850 to 1900 (IPCC, 2022). According to the current data, the global temperature will increase by more than 1.5°C in the next 20 years (Pörtner et al., 2022). Mr. Zhai Panmao, cochairman of the IPCC, pointed out that "climate change is affecting all regions in different forms, and this impact will be further intensified with the continuous rise of temperatures"(Wang et al., 2022). When the temperature rises by 1.5°C, the warm season will be prolonged, and the cold season will be shortened. When the temperature rises by 2°C, the incidence of extremely high temperature weather will increase exponentially, reaching the tolerance threshold of agricultural production and human health. Climate change has different combined impacts on different places, and these impacts will be more far-reaching with the increase in temperatures. For example, climate change will intensify the global water cycle, which means that strong rainfall will be generated, resulting in floods, but drought may occur in other regions (Cui et al., 2021). Entering the 21st century, sea levels will continue to rise, devastating island countries and coastal areas (Goodell, 2018).

On March 1, 2022, the "China Climate Bulletin 2021" issued by the China Meteorological Administration showed that China has high precipitation, high temperature, significant warm and humid characteristics, frequent extreme weather events, and a poor climate. The annual average temperature across the country hit a new record high, with the high temperature lasting for a long time and ending late. In 2021, the annual average temperature in China will be 10.5°C, 1.0°C higher than that in 1981–2010, which is the warmest year since 1951. The rising temperature has led to the rise of sea levels, which has changed the land use in China's coastal areas. Climate change may cause significant changes in the occurrence rules of flood and drought disasters in China and increase the frequency of extreme climate disasters. Therefore, it is highly imperative to do an excellent job in coping with climate disasters and overall planning for disaster avoidance and migration. However, the research on climate migration in China is weak, the research results are relatively scarce, the climate migration policy has not been formulated, and the practice of climate migration lacks technical guidance and systematic theoretical guidance (Wickramasinghe and Wimalaratana, 2016). Due to different national conditions and regions, the existing theories, models, and practical experience of climate migration need further comparative research, innovation, and development. Therefore, to discuss the current research situation in the field of climate migration at home and abroad, climate migration-related literature for quantitative analysis was used to analyze the evolutionary path and hot topics in the field.

Global climate change, characterized by climate warming, has become one of the most prominent risk problems in society at present (Bizuneh et al., 2022). Whether people migrate to cope with climate change or climate migration brings many accompanying problems to the environment, economy, politics, society, and culture, it is of great theoretical and practical significance to study the internal relationship between climate change and population migration. How to improve people's understanding of population migration caused by climate risk and analyze the main factors that cause climate migration based on existing research have become urgent issues. Since the 1980s, the international community has gradually paid attention to the issue of population migration related to climate change, while domestic research results on the global environment, climate change, and population migration are relatively few. This paper combs some important issues in the field of climate migration, points out the current research trends in this field, and provides research ideas for scholars in the field of climate migration.

2. Research method

2.1. Data sources

The data used in this study are from the WOS database and CNKI database. CNKI, founded in June 1999, is an authoritative academic platform in China. It is the concept of national knowledge infrastructure, which was proposed by the World Bank in 1998. CNKI project is an information construction project aimed at realizing the dissemination and sharing of knowledge resources in the whole society. CNKI has developed into an international leading online publishing platform integrating journals, doctoral theses, master's theses, conference papers, newspapers, reference books, yearbooks, patents, standards, Chinese studies, and overseas literature resources. The daily updated literature volume of the center website is more than 50,000. The keywords retrieved from the WOS database were "climate change induced migration*," "climate migration*," climate resettlement*, climate refugee*, and "environmental migration*."[1] A total of 807 documents were retrieved, with a time span of 2008–2021. Excluding 12 review papers, six conference papers, two books and two others, and 785 valid documents in WOS database were obtained. The CNKI database searches 274 studies with the subject words "climate migration," "climate refugee," or "environmental migration" (Guo and Shi, 2013; Yan and Shi, 2016, 2017), and the time span was from 2008 to 2021. Excluding 62 dissertations, six conference papers, 17 newspapers, one book, three achievements and 28 characteristic journals, 157 valid documents in CNKI database were obtained.[2]

2.2. Method

The specific research methods include word frequency analysis, cluster analysis, burst word detection analysis, etc. The specific technical software used includes Origin mapping software, CiteSpace visual literature measurement software, SPSS statistical analysis software, etc.

2.2.1. Word frequency analysis

By analyzing the frequency of the subject words in the literature, the hot topics in the discipline or research field were found and the development trend of the research hotspots were transfer through the timeline map.

2.2.2. Cluster analysis

Clustering data based on similar features were used to compare the similarity between different data. It is one of the basic tools for people to recognize the characteristics of unknown things. Following the hierarchical clustering principle, the similarity of subject words was clustered from large to small.

1 The description of the selection of literature search terms. In March 2011, the concept of "climate migration" was first proposed in the report "Climate Change and Migration in Asia and the Pacific" released by the Asian Development Bank (Houghton, 1996; Weir et al., 2017). Thus far, the concept of climate migration has not been widely known. Most researchers at home and abroad use the research topics of ecological resettlement, environmental resettlement, environmental refugees, and climate refugees. Due to the limited number of literature searches based on climate migration keywords, the research is unrepresentative, so this study selects the keywords of "climate migration", "environmental resettlement" and "climate refugees" for literature retrieval. In our literature search, it was found that since 2008 there has been research on climate migration, so the years for the literature search were from 2008–2021.

2 As there are few relevant studies on climate migration in China, the research is in its infancy. So this study conducted in-depth analysis on the evolution trend and hot topics of climate migration research according to relevant documents in the "Web of science core collection" (WOS) database.

2.2.3. Detection and analysis of paroxysmal words

The value of a variable has surged in a short time, suddenly becoming a hot spot, which is a concern for the academic community and can be understood as the "Baidu Index." This variable can be keywords (frequency), authors, institutions, countries (number of documents issued), references (frequency of citations), and other aspects. Through burst detection, it was found that research in a particular field shows an evolutionary trend from macro to micro, and from single to diversified. The aim was to review or predict which key branch technologies have become hot in what period, and even predict which key technologies can continue the burst trend in the future. See Figure 1 for research methods and steps. Burst detection parameter setting: the gamma value range is 0–1. The smaller the value, the greater the number of emergent words will be. The parameter Minimum represents the minimum unit of the emergence time (default: 2 years, minimum: 1 year). Again, the smaller the value is, the more emergent words there will be.

2.2.4. Analysis of keyword co-occurrence

The keywords is are the eyes of the paper and represents a high summary of the research theme of the article. Analyzing the keywords of the paper can provide a quick understanding of the research theme of the paper. There is a certain relationship between keywords in the paper. Usually "cooccurrence frequency" is used to express this relationship. The more keywords appear in the same document, the closer the relationship between the two keywords is. Keyword co-occurrence analysis analyzes the relationship between each topic in the literature set by calculating statistics on the frequency of keyword co-occurrence in the literature.

3. Results

3.1. Statistical analysis of overall literature

3.1.1. Statistical analysis by publishing time

This research is based on the statistical analysis of 785 related documents of WOS source journals and 157 related documents of CNKI source journals (see Table 1). There was significantly more research on climate migration in the WOS database than in the CNKI database, and the research on climate migration in the WOS database shows exponential growth. In contrast, the research on climate migration in the CNKI database tends to grow steadily (see Figure 2). Based on the relevant research literature on climate migration in the WOS database, the number of climate migration research papers can be divided into three stages: (1) From 2008 to 2009, the climate migration research in this stage was stable, with an average annual number of papers of 11. (2) From 2010 to 2016, climate migration research showed an upward trend, with an average annual number of 35 papers. (3) In 2017–2021, climate migration research entered a stage of rapid development, with an average annual number of 102 papers, which has become a focus of academic and social attention.

3.1.2. Statistical analysis by discipline

The discipline classification of relevant literature in the research field plays an important role in scientific research, from which the discipline classification and proportion of the research content can

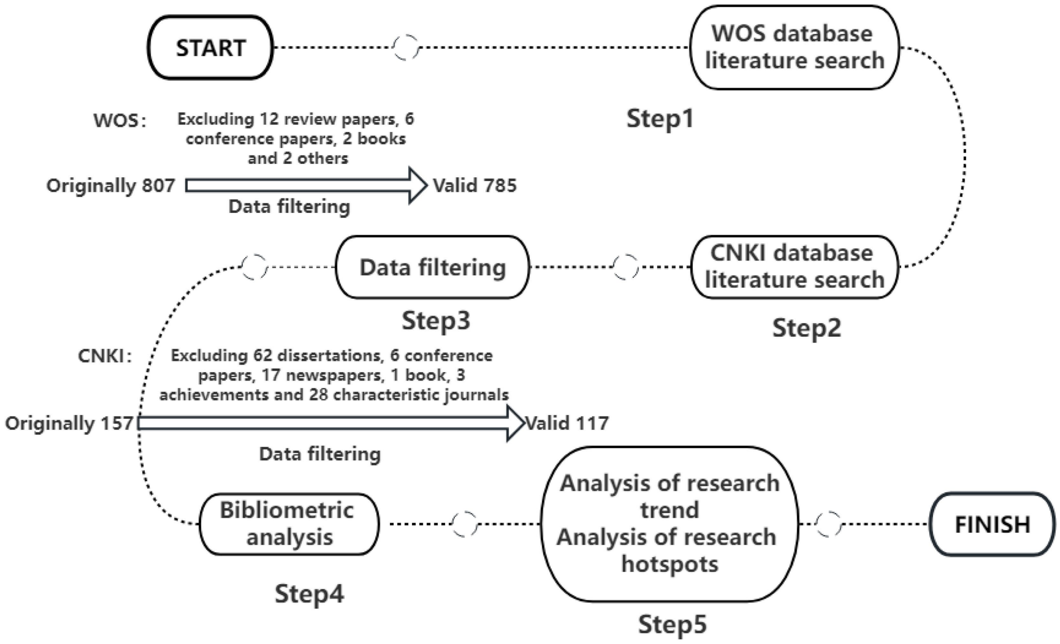

FIGURE 1
Research methods and steps.

TABLE 1 Annual statistics of literature related to climate migration research (2008–2021).

Years	2008	2009	2010	2011	2012	2013	2014
WOS	11	11	30	26	30	34	38
CNKI	10	16	10	10	11	17	18
Years	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
WOS	47	46	80	82	94	130	126
CNKI	12	14	9	9	8	9	4

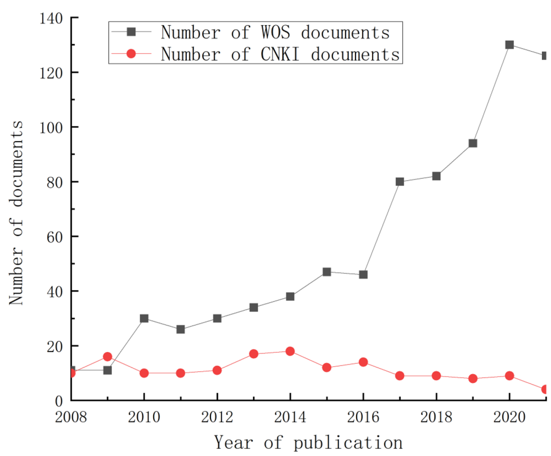

FIGURE 2
Annual statistical chart of literature related to climate migration research (2008–2021).

be analyzed. In this study, the top 10 disciplines from the climate migration literature database were selected (Table 2). The WOS database accounts for a relatively high proportion of disciplines, including Environmental Sciences and Ecology and Geography; Environmental science, resource utilization, and meteorology account for a high proportion in the CNKI database. In addition, the subjects involved in the literature in the two databases were administration, demography, and macroeconomic management. Climate migration is an interdisciplinary research field involving both natural science and social science, which puts forward higher academic level requirements for researchers.

3.1.3. Statistical analysis by core authors

Core authors play a significant role in scientific research, reflecting the level of the research field, to a certain extent, and driving research forward. In this study, CiteSpace measurement software was used to analyze the literature in the two databases (Tables 3, 4). The analysis found that the scholars Farbotko C (Farbotko, 2010, 2019; Farbotko and Lazrus, 2012; Farbotko et al., 2016, 2020; Boas et al., 2019), Kelman I (Mercer et al., 2010; Watts et al., 2015, 2017, 2018, 2019, 2021), and McNamara KE (McNamara, 2007; McNamara and Gibson, 2009; McNamara and Des Combes, 2015; Farbotko et al., 2020; McNamara et al., 2020) published more than 10 papers on climate migration research in the WOS database in the target period, belonging to high-yield scholars in the field of climate migration. In the China CNKI database, scholars Shi Guoqing, Chen Shaojun, and Cao Zhijie have published more than five articles on climate migration research in the target period. They are leading scholars in the field of climate migration

TABLE 2 Statistics of relevant literature on climate migration by discipline (2008–2021).

Serial no	Database of WOS			Database of CNKI		
	Discipline	Number of records	Proportion (%)	Discipline	Number of records	Proportion (%)
1	Environmental Sciences ecology	306	38	Environmental science and resource utilization	46	27
2	Geography	119	15	Meteorology	27	16
3	Science technology other topics	69	9	Administration and state administration	25	15
4	Government law	67	8	International law	22	13
5	Meteorology atmospheric sciences	56	7	Chinese politics and international politics	22	13
6	Social sciences other topics	44	5	Demography	11	6
7	Geology	42	5	Building science and engineering	5	3
8	Demography	40	5	Economic system reform	5	3
9	Business economics	33	4	Macroeconomic management	4	2
10	Water resources	31	4	Industrial economy	4	2

research in China. Professor Shi Guoqing is not only one of the scholars who jointly published climate migration papers in Science on January 28, 2011, but also one of the Chinese scholars who published the most papers in both Chinese and English. At the same time, he also published many papers on various resettlement policies, theories, and applications, such as projects, disasters, ecology, poverty alleviation, mines, etc. (Shi, 2005; Guo and Shi, 2010). Professor Chen Shaojun has made many achievements in the field of climate migration research, systematically defined the concept and type of climate migration, performed an in-depth analysis of the migration mechanism, current situation, and countermeasures of climate migration, and creatively combed the formation mechanism and evolution trend of climate poverty (Cao and Chen, 2013, 2016; Cao et al., 2014).

3.1.4. Statistical analysis by leading research institutions

In this study, Cite space measurement software was used to analyze the cooperation network of scientific research institutions and generate corresponding maps (Figures 3, 4). The scientific research cooperation network was measured by jointly publishing papers in bibliometrics. In the cooperation network map of scientific research institutions in the WOS database, there were 341 network nodes and 281 connecting lines between nodes. Among them, the color of network nodes represents the time distribution of published literature by institutions, and the color of connecting points represents the year of the first cooperation of scientific research institutions. Chinese Acad Sci, Univ Melbourne, Australian NatlUniv, Univ Queensland, and UCL are high-yield scientific research institutions in the field of climate migration research internationally. The National Research Center of Resettlement of Hohai University is a high-yield scientific research institution in the field of climate migration research in China. These scientific research institutions have strong leadership and authority in the field of climate migration research. From the perspective of network map density, the node density of the cooperative network map in Figure 3 was 0.0048, and the density of the cooperative network map in Figure 4 was 0, indicating that scientific research institutions lack cooperation in the field of climate migration. Climate migration will become a hot research topic. China can introduce scientific research talent from the above scientific research institutions to strengthen China's scientific climate migration research.

3.2. Analysis of keyword co-occurrence

Due to space constraints, this study selected the top 40 keywords (Table 5). The size of centrality reflects the co-occurrence of this keyword and other keywords. The top three in terms of centrality are an environmental refugee (0.34), exposure (0.34), exposure (0.34), and risk (0.31).

3.3. Analysis of keyword cluster

Keyword clustering analysis is based on keyword co-occurrence analysis. This study uses measurement software to cluster keywords and obtains a keyword clustering atlas (Figure 5). In the keyword clustering map, two values determine whether the clustering effect is ideal. One is the Q value of the clustering module, and the other is the S value of the average clustering contour. When $Q > 0.3$, the clustering structure is significant; when $S > 0.5$, the clustering is more reasonable, and when $S > 0.7$, the clustering effect is satisfactory. In Figure 4, the Q value is 0.7921, and the S value is 0.9216, indicating that the keyword clustering structure is very significant and the clustering effect is satisfactory.

In this study, the log likelihood ratio (LLR) is used to extract the clustering label words of keywords. The larger the LLR value is the

TABLE 3 Statistics of more than five core authors (WOS 2008–2021).

Number of documents issued	Core author				
12 or more	Farbotko C (12)	Kelman I (12)			
7–11	Mcnamara KE (10)	Fang XQ (8)	Mcmichael C (8)	Boas I (7)	Stojanov R (7)
5–6	Arnall A (6)	Bettini G (6)	Lazrus H (6)	Coley D (5)	Oppenheimer M (5)
	Upadhyay H (5)	Warner K (5)	Xiao LB (5)	Ye Y (5)	

TABLE 4 Statistics of more than two core authors (CNKI 2008–2021).

Number of documents issued	Core author			
7 or more	Shi Guoqing (10)	Chen Shaojun (9)		
5–6	Cao Zhijie (5)			
3–4	Wang Kelin (4)	Shi Mingyu (3)	Chen Hongsong (3)	
2	Zeng Fuping (2)	Yu Qingnian (2)	Wang Yijie (2)	Zheng Yan (2)
	Xi Penghui (2)	Yan Dengcai (2)	Cai Lin (2)	Guo Jianping (2)
	Yu Yizun (2)	Fan Liangshu	Liu Haijian (2)	Mao Yingjie (2)

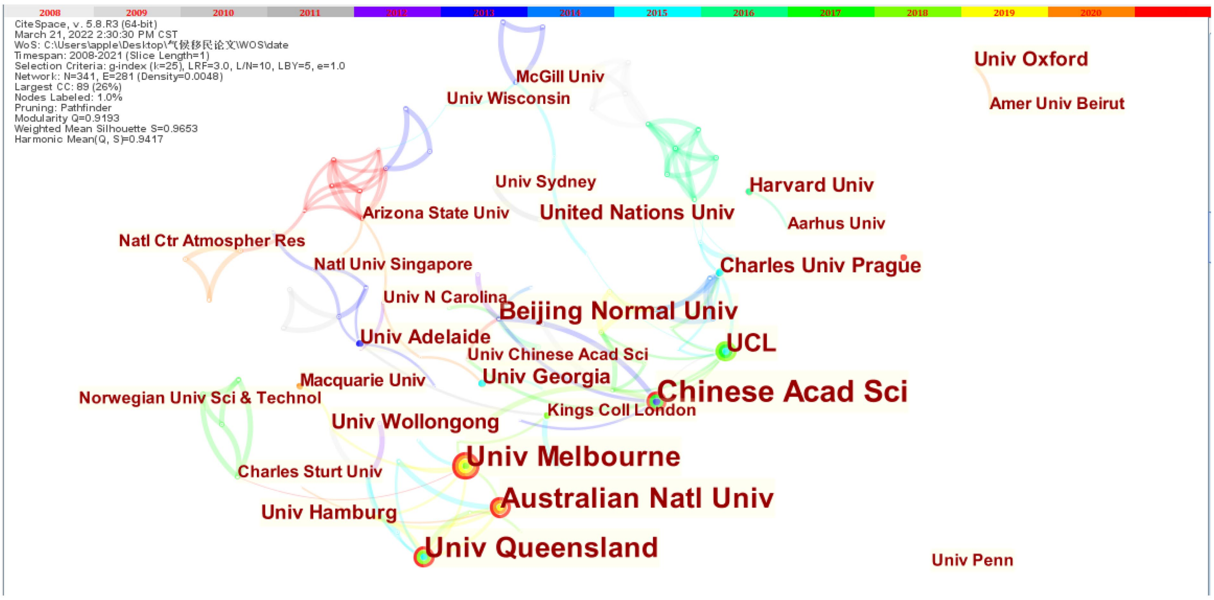

FIGURE 3
Map of the cooperation network of research institutions (WOS 2008–2021).

more representative the clustering label words are. The number of keywords in keyword clustering is greater than 10 indicating that the clustering is meaningful. According to the LLR algorithm, a total of 18 clusters are obtained. Since the number of keywords in cluster # 16 and cluster # 17 is only 8 which is less than 10 they are eliminated without analysis so that we can obtain a total of 16 effective clusters (Table 6). The number of clusters represents the total number of keywords contained in the cluster. The degree of clustering represents the similarity between the members of the cluster. The larger the number the more similar it is. For example for cluster # 0, the number of clusters is 48 indicating 48 keywords and the compactness is 0.931 indicating substantial similarity among cluster members. The keywords of cluster members in the top three clusters with LLR values are defection LLR value is 9.74; anthropological activities LLR value is 5.73; and migration flyway LLR value is 4.67.

3.4. Analysis of the timeline map

The timeline atlas is \ generated on the basis of clustering. Cluster members are arranged on the same line according to the order of the timeline. Due to space constraints, this study selects the timeline atlas of the top 10 keyword clusters (Figure 6). The timeline map is mainly interpreted from the four dimensions of “first appearance,” “hot

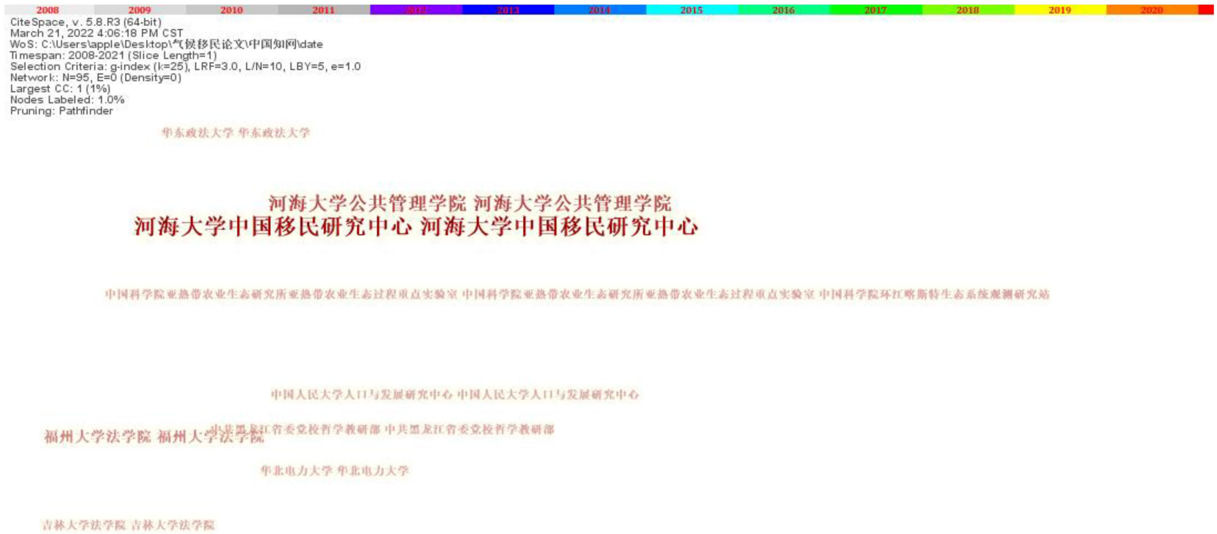

FIGURE 4
Map of the cooperation network of research institutions (CNKI2008–2021).

TABLE 5 Statistics of high-frequency keywords in the field of climate migration research (WOS 2008–2021).

Serial no	High frequency keywords	Frequency	Centrality	Serial no	High frequency keywords	Frequency	Centrality
1	Climate change	159	0.04	21	Management	17	0.28
2	Refugee	129	0.06	22	Migrant	17	0.07
3	Migration	99	0.25	23	Sea level rise	17	0.06
4	Adaptation	99	0.14	24	Conservation	16	0.15
5	Impact	88	0.07	25	Variability	16	0.04
6	Vulnerability	68	0.01	26	Conflict	15	0.22
7	Resettlement	54	0.14	27	Security	15	0.04
8	Politics	40	0.09	28	Framework	15	0.03
9	Climate	38	0.13	29	Model	15	0.02
10	Risk	36	0.31	30	Crisis	15	0.06
11	Displacement	33	0.00	31	Environmental change	14	0.00
12	Policy	28	0.02	32	Africa	14	0.21
13	Community	26	0.10	33	Immigrant	13	0.10
14	Resilience	26	0.04	34	Biodiversity	13	0.09
15	Environmental refugee	24	0.34	35	Mental health	13	0.08
16	Population	19	0.04	36	Experience	13	0.06
17	Discourse	19	0.02	37	Livelihood	13	0.05
18	Governance	19	0.01	38	Disaster	13	0.00
19	Drought	18	0.16	39	Island	13	0.02
20	Context	17	0.01	40	Out migration	13	0.01

trend," "cold trend," and "landmark research." Taking cluster # 0 deformation as an example, the keyword "climate" with the highest frequency among its cluster members first appeared in 2009 (Figure 7). As shown in Figure 7, the frequency of the keyword appeared to fluctuate and increase, becoming a research hotspot. Figure 6 shows that the core keywords in cluster # 0, the deforestation cluster, are densely distributed, and the research is hot. Scholars have paid more attention to them. The distribution of core words in cluster # 8 metal is relatively small, indicating that this cluster's research is cooling down and attention has decreased since 2011. Iconic keywords generally refer to words with high intermediary centrality. The purple keyword in the outermost circle of the key word tree ring chart is a

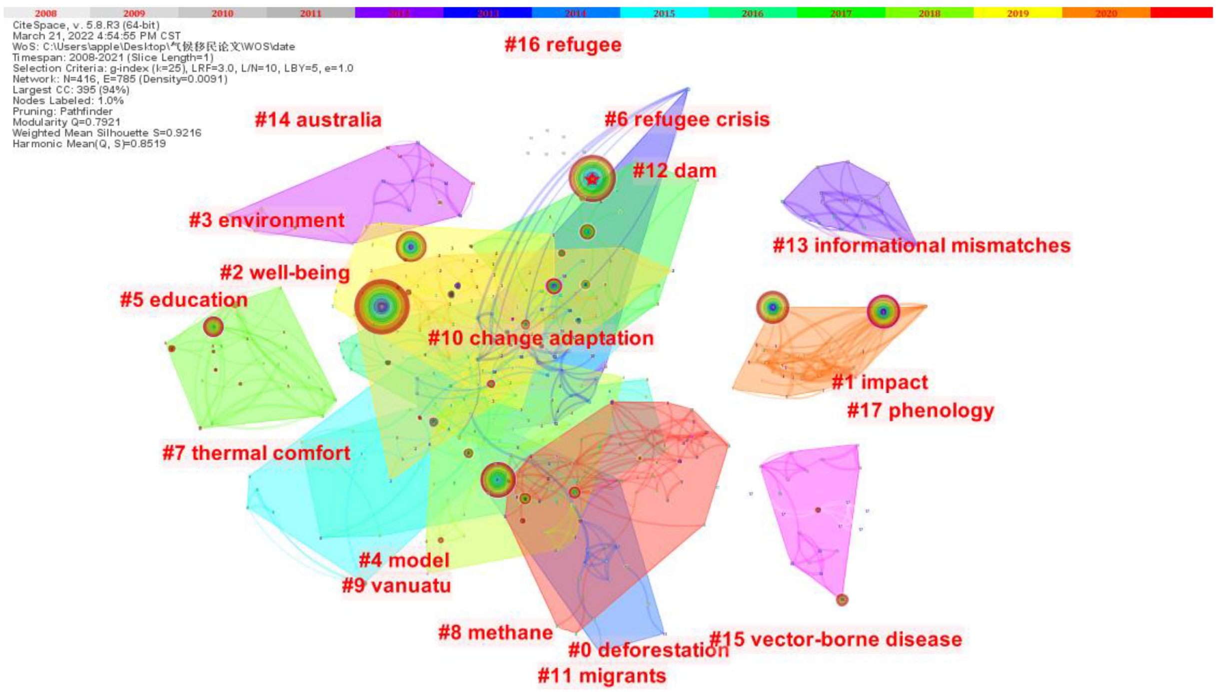

FIGURE 5
Keyword clustering map (WOS 2008–2021).

TABLE 6 Keyword clustering table (WOS 2008–2021).

Cluster no	Clustering number	Clustering degree	Keywords of the top three LLR values in cluster		
#0	48	0.931	Deforestation (9.74)	Anthropocentric activities (5.73)	Migration flyway (4.67)
#1	34	0.924	Impact (14.69)	Pattern (12.7)	Survival (8.46)
#2	31	0.854	Well-being (12.8)	Africa (9.07)	Flight (6.39)
#3	30	0.864	Environment (10.66)	Risk (10.66)	Ethiopia (10.47)
#4	27	0.935	Model (8.64)	Environmental refugee (8.64)	Flood (6.36)
#5	24	0.953	Education (10.98)	Just transition (10.98)	Political economy (10.03)
#6	21	0.875	Refugee crisis (11.17)	Politics (8.83)	Security (8.83)
#7	21	0.864	Thermal comfort (16.02)	Environmental migrants (13.61)	Refugee shelters (9.86)
#8	20	0.925	Methane (7.56)	Malawi (7.56)	Precarity (7.56)
#9	19	0.908	Vanuatu (14.08)	Samoa (14.08)	Fiji (10.32)
#10	19	0.947	Change adaptation (10.86)	Maldives (9.12) 马	Kiribati(8.4)
#11	18	0.909	Migrants (12.12)	Acculturation (9.49)	Climate change (8.28)
#12	18	0.945	Dam (14.87)	Investment (7.42)	Public health response (7.42) 公
#13	17	0.956	Informational mismatches (8.24)	Atlantic oscillation (8.24)	Annual survival (8.24)
#14	17	0.982	Australia (9.36)	Collective deprivation (7.39)	Tradable quotas (7.39)
#15	15	1	Vector-borne disease (6.97)	Sensitivity to climate (6.97)	Middle miocene climatic optimum (6.97)

symbolic keyword, such as impact, resilience, adaptation, etc. The evolutionary relationship of the intermediate core words between clusters over time can be clearly seen according to the evolution map of the relationship between keyword clusters. The color of the line indicates the corresponding year. Due to space limitations, Figure 8 shows the evolution map of the relationship between climate migration keyword clusters in 2021.

3.5. Detection and analysis of paroxysmal words

Here, the gamma value of the parameter is 1, and the minimum value of the parameter is 2. The keyword emergence map in the climate migration research field is obtained (Figure 9), where "Begin" refers to the year when the keyword first appeared; "End" refers to the

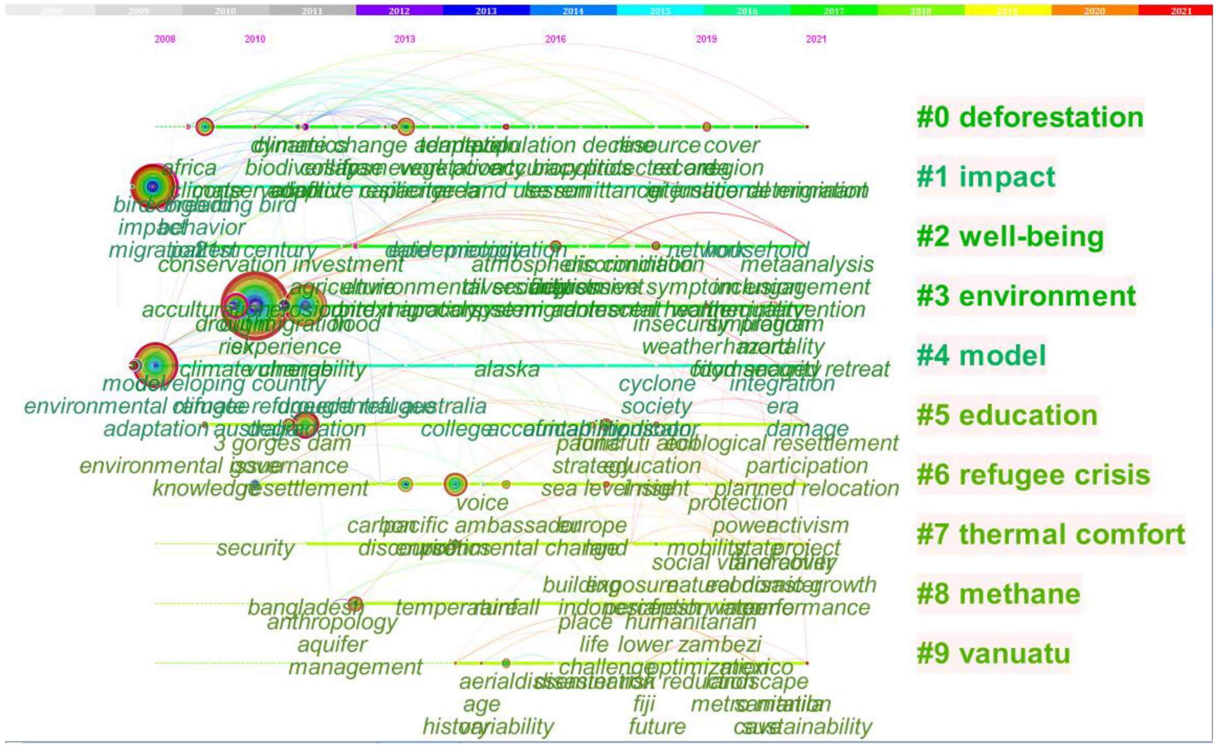

FIGURE 6
Keyword timeline map of climate migration (WOS 2008–2021).

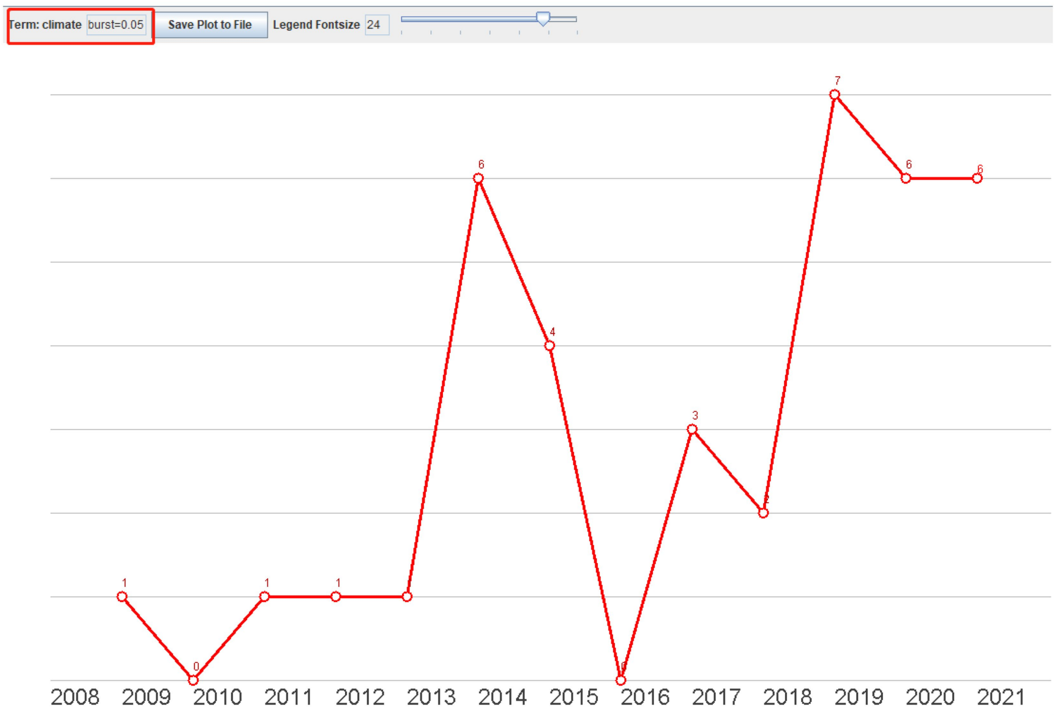

FIGURE 7
Year of the first keyword in the #0 Cluster group (WOS 2008–2021).

year when the keyword disappeared; and "Strength" refers to the strength of keyword emergence. The larger the value, the more important it is. The red line indicates the duration of the keyword highlighting.

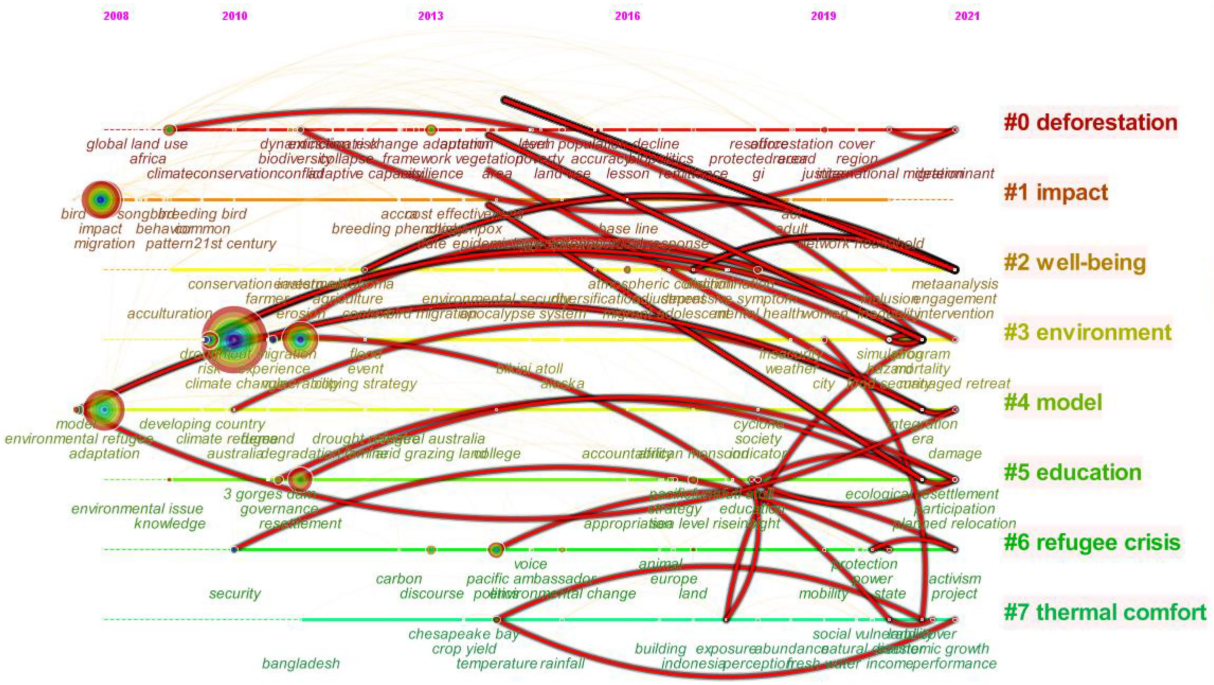

FIGURE 8
Evolution map of the relationship between keywords of climate migration (WOS 2008–2021).

Keywords	Year	Strength	Begin	End	2008 - 2021
drought	2008	4.09	**2010**	2016	
out migration	2008	4.96	**2011**	2013	
dynamics	2008	3.09	**2011**	2014	
environmental refugee	2008	2.95	**2011**	2013	
dam	2008	2.78	**2011**	2015	
narrative	2008	2.88	**2014**	2017	
island	2008	2.76	**2015**	2018	
sea level rise	2008	3.84	**2017**	2018	
pacific	2008	2.82	**2017**	2018	
justice	2008	3.1	**2019**	2021	
network	2008	2.88	**2019**	2021	

FIGURE 9
Burst detection keyword map of climate migration (WOS 2008–2021).

4. Discussion

4.1. Division of research stages

Based on the above analysis of the detection of unexpected words, the unexpected words in the key words can be identified within a certain period of time. Combined with their evolution and changes on the timeline, the first 11 unexpected words can be obtained. Combined with relevant literature research and expert opinions, the development trend of climate migration research was divided into three stages.

4.1.1. Initial exploration stage (2008–2011)

This stage is mainly in the preliminary exploration stage of climate migration research. It can be seen from the mutation core words "drought," "out migration," "dynamics," "environmental refugee," and "dam" in Figure 7 during this period that the concept of climate migration has not been put forward at this stage. Foreign scholars pay more attention to the study of "environmental refugees" and have carried out a series of fruitful studies on "environmental refugees" through multiple dimensions.

4.1.2. Rich development stage (2012–2017)

In 2011, the Asian Development Bank put forward the expression of "climate migration" for the first time. Since then, there has been much research on "climate migration." The research results mainly focus on the factors of population migration induced by climate change, migration patterns caused by different climate types, prediction models of climate change and population migration, and the impact of climate change and population migration on health. It can be seen from the sudden changes in the core words "narrative," "island," "sea level rise," and "pacific" in Figure 7 that scholars pay special attention to the migration and reconstruction of cities, rural areas, and enterprises, the inundation of islands, and the resettlement from disasters planned in advance due to land use changes in coastal areas caused by sea level rise.

4.1.3. System deepening research stage (2018)

It can be seen from the mutation core words "justice" and "network" in Figure 7 during this period that the research on climate migration has extended to the level of climate justice. With the signing of the Paris Agreement, international scholars have gradually deepened their research on climate justice. The Lauterlich Handbook on Climate Justice (2019) prepared by Jia Fuli, a scholar, systematically summarized the relevant scientific research achievements of international climate justice; the Stanford Encyclopedia of Philosophy launched the term "climate justice" written by Carney, a scholar, in 2020. At this stage, scholars from different disciplines also successively joined in the study of climate justice. Second, the research on the restoration of the livelihood network of climate migrants has been deepened. When climate migrants flow into the immigration area, they may compete with the residents of the immigration area for scarce natural resources, economic resources and social resources, resulting in sharp conflicts. Many scholars have begun to study the construction of a sustainable development network for livelihood restoration (Figure 10).

4.2. Discussion on hot research topics in the field of climate migration

According to the previous quantitative analysis of relevant documents in the field of climate migration and the views of experts and scholars in the field of climate migration, the research focuses mainly include the following three points.

4.2.1. Research on different types of climate migration

4.2.1.1. Climate migration caused by sea level rise

The potential land inundation, immersion, and erosion impact of islands and mainland coastal areas due to sea level rise will restrict the land use of sea areas, move residents and enterprises in urban and rural areas in a planned way and rebuild the production and life of migrants. As sea level rise is a slow change process, it provides time for formulating and implementing resettlement plans, and disaster avoidance resettlement plans can be carried out in advance. Compared with sudden climate disasters, such as hurricanes, floods, and tsunamis, sea level rise is difficult to stop. For people in island countries and coastal areas, migration is the only option (Bohra-Mishra et al., 2017). At present, island countries threatened by sea level rise include some Pacific countries, such as Kiribati and Tuvalu. The residents of these countries will have to choose to relocate to other countries to find another way to live (Constable, 2017). According to a study of Dhaka immigrants, the rise in sea level has impacted domestic population migration (Ahsan et al., 2014). In Kiribati, the local government has begun implementing the national policy of "dignified migration," allowing citizens to master technology and migrate abroad through technology (Wyett, 2014). Scientists predict that if the government does not take effective measures, the water level in Venice, Italy, will rise by 54 cm by 2,100 compared with 2009, meaning that Venice may be immersed in water daily.

4.2.1.2. Climate migration caused by flood disasters

Due to the temporal and spatial variation in rainfall, the probability of external floods and local rainfall waterlogging is increased, and flood disasters are aggravated. As a result, urban and rural residents temporarily or permanently lose the conditions for settlement and production. They choose to relocate and rebuild their production and life. When rainfall increases sharply, it is easy to distinguish the population migration caused by rainstorms and floods, and most affected people are in poor countries with low mobility (Lonergan, 1998). Globally, population migration caused by floods or rainstorms is only temporary. They want to return to their original location to rebuild their homes (Thiede et al., 2016). The current case study also notes that most migrants choose to return to their original place of residence due to temporary internal migration caused by floods (Martin et al., 2014). For example, in the flood disaster in Pakistan in 2010, approximately 7 million victims returned to their homes to continue production and life after the flood (Lom, 2010).

4.2.1.3. Climate migration caused by drought deterioration

Climate change will reduce rainfall in areas with severe ecological vulnerability, which will become a long-term trend (Dantas et al., 2020). It will lead to the rapid reduction of groundwater level, soil degradation, reduction of agricultural land use value, decline of farmers' livelihoods and income, and the attraction of development opportunities in different places, which may lead to the migration of the rural population to other villages

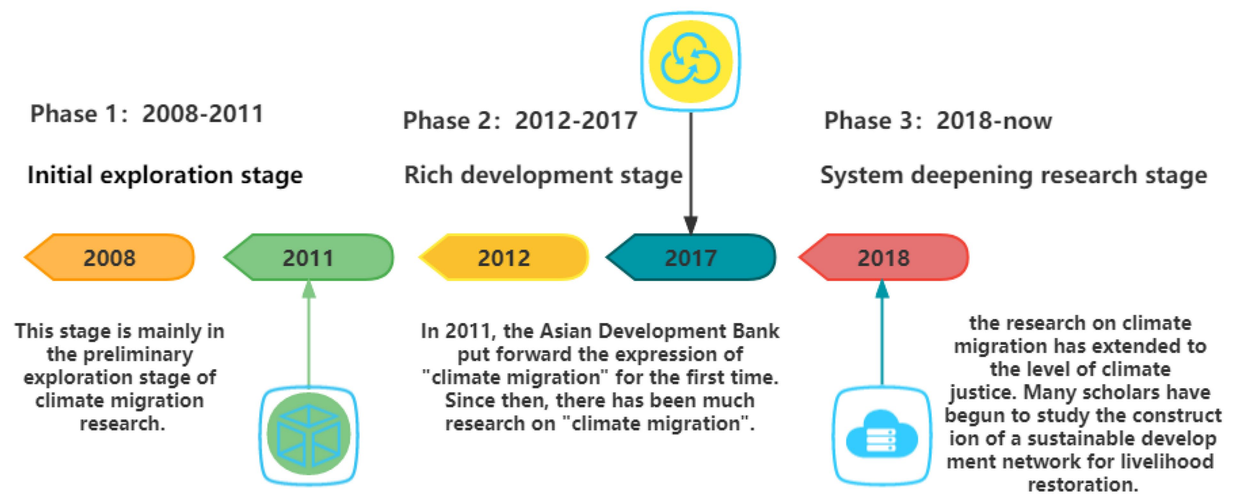

FIGURE 10
Division of research stages.

or cities to make a living (Brasil Neto et al., 2022). The study found that the increase in the number of domestic migrants in Tanzania (Afifi et al., 2014), the rise in the number of migrants in Burkina Faso and Mali, and the intensification of urban migration in sub-Saharan Africa are all related to the reduction in local rainfall (Findley, 1994; Barrios et al., 2006). When precipitation decreases, the drought cycle will be prolonged, the soil quality will decline, and it is unsuitable for farming. Farmers will move from rural areas to cities (McLeman and Ploeger, 2012). Based on the comparative analysis of three villages in Tanzania, the results show that after considering other important demographic and socioeconomic factors, such as age, wealth, and education, there is a positive correlation between rainfall shortage and outward migration (Hossain et al., 2021). In the study of Ethiopian migration, more than half of the respondents said drought had aggravated the migration of the rural population. In addition, villge conflict, food supply, land quality, livestock quantity, and other factors also influence migration (Ezra, 2001). Gray and other researchers have shown that during a particularly severe drought, the number of long-distance population movements related to labor will double, especially for men who go out to work due to a lack of land resources (Gray and Mueller, 2012). This is the same as the research conclusion of Mersha et al., in the extreme drought period, the mobility of the male labor force in Ethiopia is much higher than that of the female labor force (Mersha and Van Laerhoven, 2016). In Guizhou, Shaanxi, Gansu, and other western regions of China, the majority of the 8.63 million migrants relocated from 2016 to 2020 are also from ecologically vulnerable areas with severe drought and land degradation caused by climate change. The core issue considered by the migrants in Zhijin County, Guizhou Province, is how to improve the environment through relocation, effectively reduce family risks, maintain their livelihoods and original social network, and obtain housing subsidies from the government. Environmental and non-environmental factors affect their choices differently (Shi et al., 2019). The "Massive Scale Shangnan Migration Plan (MSSMP)" in Shangnan County, Shaanxi Province, Northwest China, was launched to cope with the impacts related to climate change. The results show that MSSMP helps local residents better adapt to the environment (Lei et al., 2017). Through research on the migration willingness of immigrants in southern Shaanxi Province, it was found that policy factors, psychological expectation factors, and environmental factors significantly impact migration willingness (Shi and Zhou, 2018). Yu Qingnian, a scholar, analyzed the characteristics of rural population migration under an extremely arid climate through his field survey in Xundian County, Kunming City (Yu and Shi, 2010; Yu et al., 2011).

4.2.1.4. Climate migration caused by extreme climate events

Population migration activities caused by extreme weather, such as storm surges, hurricanes, tsunamis, hail, and freezing rain, often occur in coastal areas. In terms of extreme weather events, South America is often affected by floods, and the Caribbean is often affected by hurricanes. Researcher Dasgupta et al. noted that Puerto Rico, the Bahamas, and Belize were the countries that suffered the most from coastal storms (Dasgupta et al., 2009). Academician Saldana studied the relationship between climate disasters, such as storms, floods, and frost, in Mexico and population mobility. Under the same conditions, the migration rate of the population will increase by 5–13% for every 10% increase in the frequency of climate disasters (Saldaña-Zorrilla and Sandberg, 2009).

4.2.1.5. Climate migration due to climate change discomfort

Fluctuating and extreme temperatures, humidity, air pollution, and other factors have a negative impact on the production and living conditions of residential areas. To avoid risks, local residents choose to migrate voluntarily to other areas to live. The temperature rise has affected grain production in the United States, which has led local people to move to places more suitable for crop production (Feng et al., 2012). The continuous increase in temperature has increased the number of Indonesian people migrating across provinces (Bohra-Mishra et al., 2014). The temperature difference between the immigration and emigration places plays an important role in interstate population migration in the United States (Poston et al., 2009). Temperature and air pollution affect population migration in various ways, such as air pollution in chemical industry parks and the reduction of household income (DeWaard et al., 2016). Among many possible ways, climate change causes farmers to migrate through its impact on agricultural mechanisms (Kubik and Maurel, 2016). Under such conditions, climate change will have a negative impact on the livelihood of farmers and eventually lead to migration activities by affecting agricultural production activities.

4.2.1.6. Climate migration caused by climate change response projects

To actively respond to climate change, hydropower, wind power, solar energy, and other power generation engineering facilities in renewable energy sources will be used to replace fossil energy power generation. In addition, dikes and sluice projects will be built in coastal areas and river sea intersections to avoid seawater intrusion. Reservoirs will be built in rivers to regulate water volume to address floods and waterlogging drought disasters caused by climate change. Flood storage and detention areas will be set up in low-lying areas of rivers to retain floods, or flood channels will be opened manually. In addition to the migration of various polluting enterprises that reduce carbon emissions, the abandonment and transformation of thermal power plants will result in population migration. In addition, socioeconomic recovery activities occur in response to climate change projects due to the permanent or temporary occupation of land for project construction. When climate change negatively impacts local social stability and economic development, local residents will spontaneously seek more suitable places to live to adapt to climate change (Warner et al., 2010). The government usually makes policies to require people living in places where the environment is extremely fragile to relocate. For example, the Kiribati government has developed a relocation plan to address climate change (Barnett and McMichael, 2018). The Chinese government has removed the residents in the flood storage and detention area of the Huaihe River basin. It has enacted attractive policies and measures to guide the voluntary migration of migrants. The research results show that resettlement location, resettlement subsidies, and policy rationality have the most significant positive effect on population migration. The government should encourage farmers to resettle to speed up the resettlement process (Wang et al., 2020). In the lower reaches of the Yellow River basin, residents in the beach area will be relocated to residential areas to cope with the possible floods caused by climate change.

4.2.1.7. Climate migration due to disruption of fishermen's livelihood caused by climate change

Climate change has led to changes in natural conditions, such as ocean temperature and ocean currents (Falco et al., 2018), which have a negative impact on the supply of fishery products and the livelihood of migrants (McMichael et al., 2012). Many scholars have studied and are concerned about the impact of climate change on fishery security and the livelihood of fishermen. Fishery production needs to rely on stable and good marine environmental conditions. The standard development process of catches also needs appropriate sea water density, temperature, climate, and other conditions. The continuous deterioration of the marine environment, sea level rise, marine disasters, and other adverse factors have affected the original accumulation of fishermen's livelihood capital, which may also destroy the fishermen's livelihood system (Xu and Shi, 2017). Therefore, climate change will have a negative impact on fishery security in many places, and people will migrate to places where fishery access and agricultural livelihoods are more secure, increasing the speed of population mobility.

4.2.2. Study on quantitative models of climate migration

The research on quantitative models related to climate migration started from spatial vulnerability modeling, which is a set of vulnerability impact assessment and development technologies caused by natural disasters (Cutter et al., 2012). The general cycle model or regional climate model is built by using geographic information system (GIS) and remote sensing technology (RS) to combine many resource data, population data, and agricultural economic data to calculate which places and populations will suffer from the negative impact of climate change (McGranahan et al., 2007). For example, McLeman established a geographic population information simulation model through regional climate data and population census data to study the truth of population migration caused by climate change in western Canada in the 1930s (McLeman et al., 2010). Academician Feng calculated the semi-elasticity between population migration and crop yield in each state by using Mexican census data and crop yield data over the years and calculated the impact of future climate change on crop yield and population migration (Feng et al., 2010). Barbieri, a scholar, measured the impact of changes in crop yields on the future population migration pattern in northeastern Brazil. It is anticipated that as scholars' interest in climate change and population migration models grows, more and more breakthroughs in modeling research will be produced (Silva et al., 2022), advancing the study and advancement of the relationship between climate change and population migration (Barbieri et al., 2010).

4.2.3. Climate justice research

Climate justice, on the one hand, has been analyzed from the macro perspective of developed and developing countries. People around the world are experiencing climate change in different forms. The truth is that rich developed countries have burned many fossil fuels for economic development in the past few 100 years and benefited most from the carbon emissions that have led to climate change. However, they are not the biggest victims of climate change. The largest victims are those in poor or developing countries. Indigenous people, people with disabilities, women and children, and other groups are most vulnerable to the damage caused by climate change, which has formed the "injustice" of the current climate. In addition, there is "intergenerational injustice": older generations benefiting from fossil fuels, but young generations facing the serious consequences of climate change. On the other hand, from the micro perspective of transnational migration. Diane C. Bates' research shows that many countries usually regard climate migration as a burden rather than an opportunity. As there is no uniform provision and recognition for "climate refugees," they are not protected by international refugee law. Shi Xueying, a scholar, studied two legal cases of climate migration: citizens of Kiribati failed to apply to New Zealand for residence through the status of "climate refugee," while citizens of Tuvalu successfully applied. Whether the international community can recognize climate migrants and whether they can enjoy the rights of "refugees" has attracted everyone's attention.

5. Conclusion

The migration problem caused by climate change has become an unavoidable and prominent problem in the 21st century. Many island countries have faced the risk of national subjugation due to rising sea levels triggered by climate change. The island countries that will disappear due to the increase in sea levels include but are not limited to Tuvalu, Nauru, the Maldives, Kiribati, Palau, Western Samoa, etc. China has conducted a large number of characteristic studies on ecological resettlement, relocation for poverty alleviation, and disaster resettlement in response to climate change. Nevertheless, research on the theory and practice of climate migration caused by climate change, in reality, is seriously insufficient. The international research on climate migration is also limited to the perspective of the origin of the problem, and specific cases are analyzed, lacking systematic and comprehensive research on theories, methods, policies, and strategies. Moreover, climate migration research is an interdisciplinary research field integrating multiple disciplines (atmospheric science, meteorology, hydrology, oceanography, geography, demography, economics, management, sociology, psychology, agronomy, water conservancy engineering, etc.), which requires the participation of scholars from different academic backgrounds.

For future research on climate migration, the following is suggested: (1) Strengthen the research on the prediction ability of climate change and population migration models. Focus on strengthening the prediction of urban, rural and enterprise migration and reconstruction caused by land change in coastal areas due to sea level rise and research on population migration due to flood, waterlogging and drought disaster risks caused by meteorological and hydrological changes. (2) Make use of China's beneficial exploration in the fields of engineering resettlement, ecological resettlement, poverty alleviation resettlement, etc., to formulate climate migration policies, regulations and strategic planning; apply them to the preparation, planning, and implementation management of climate migration policies in a planned way; and explore sustainable livelihood restoration based on the migration mechanism of creating a harmonious society (De Sherbinin et al., 2011; Xu and Shi, 2020; Downing et al., 2021). (3) Establish a database cloud platform related to climate change and population migration. Classify different climate types, import climate-related data and population migration data generated by climate change into the database, and implement dynamic monitoring and management. (4) Climate refugia, defined as the regions can help species buffer the impact of climate change, has been a hot research in biodiversity conservation planning

(Hua et al., 2022). This term also has important reference value for climate migration. Although it is currently only for species protection, it could improve the resilience of communities to climate change. The study points out that climate migration research is an interdisciplinary field that needs joint research by scholars from different academic backgrounds. We should strengthen the exchange and cooperation between Chinese researchers in the field of climate migration and international scientific research institutions.

Through a literature review, this study summarized the research hotspots in the field of climate change and population migration and pointed out the research direction for researchers entering the field of climate migration. However, this study did not conduct in-depth research on specific cases, which is also the main research aspect of our future research.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements.

Author contributions

BL full text writing. GS paper framework construction. ZS method guidance. HB paper modification and embellishment. MZ revision and improvement of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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

Publisher’s note

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The development of green finance under the goal of carbon neutrality: A review from China's perspective

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Extreme environmental and climate problems have been ravaging the world, causing serious economic losses and hindering human development, so that carbon neutrality has become a global undertaking related to the survival of human civilization. To ensure climate change mitigation and carbon emission reduction, this paper finds that green finance as an important and efficient tool has become a legislative priority for many countries and have been embedded in the path to achieve carbon neutrality. On the basis of in-depth analysis of the evolution and development of global green finance, this paper reviews and summarizes the development of green finance in China through literature analysis and horizontal comparison, and explores concrete recommendations and feasible tools that can be tailored to China's carbon neutrality goal and stage of development. It is concluded that China needs to improve the green finance operation mechanism and flexible policy framework, to formulate a more accurate timetable and roadmap, to strengthen the modernization of the governance system and governance capacity and to promote the global green finance cooperation.

KEYWORDS

climate change, carbon neutrality goals, green finance evolution, international cooperation, incentive and constraint mechanisms

1 Introduction

On 9 August 2021, the United Nations Intergovernmental Panel on Climate Change (IPCC) held a press conference in Geneva, Switzerland, to officially release the IPCC Sixth Assessment Report Working Group I report "Natural Science Basis of Climate Change 2021". The report points out that with global warming, more weather events such as droughts and heavy rainfall will occur. For example, the high temperature weather in the northwest of the United States in June 2021 and the heavy precipitation in Zhengzhou, China, in July. Extreme environmental problems have been ravaging the world, encroaching on human life safety, causing serious economic losses and hindering human development, so carbon neutrality has become a global undertaking related to the survival of human civilization. At present, 136 countries and regions around the world have made major strategic commitments to achieve carbon neutrality around the middle of this century.

China has been committed to mitigating climate change. On 22 September 2020, at the general debate of the 75th session of the United Nations General Assembly, China clearly stated that "carbon dioxide emissions should peak before 2030 and achieve carbon neutrality before 2060" (Cao et al., 2021), but China's coal-dominated energy consumption structure has put tremendous pressure on carbon emission reduction (Solarin et al., 2013). In this context, the development of green economy has become a necessary path to achieve the goal of carbon neutrality (Feng and Ma, 2017; Chai, 2018). In the report of the 19th National Congress, General Secretary Xi Jinping proposed that China should "establish a sound economic system of green, low-carbon and circular development and develop green finance" (Xi, 2017).

The concept of "green finance" is derived from "environmental finance", which was proposed by White (White, 1996). As early as 1974, Germany established the world's first policy-based environmental bank to provide preferential loans for environmental projects (Hu et al., 2017). In the United States, the Comprehensive Environmental Response Compensation and Liability Act was enacted in 1980, which recognized the traceability of environmental liability (Guo and Cai, 2015; Jiang and Zhang, 2017). Salazar believes that green finance is the product of combining the financial industry with the green industry and incorporating environmental benefits into financial innovation (Salazar, 1998). In 2002, Japan promulgated the Enforcement Order of the New Energy Utilization Measures Act, which can be regarded as the legal basis for Japan to achieve the goal of carbon neutrality (Du and Li, 2021). In 2008, the South Korean government launched the Low-Carbon Green Growth Strategy, which provides a strong and favorable policy to ensure the smooth development of green finance (Xi, 2011). The European Commission released a policy document "Net Zero Emissions by 2050" in November 2018 (Zhang et al., 2021). In China, in 2005, the State Council issued the Decision on Implementing the Scientific Outlook on Development to Strengthen Environmental Protection, emphasizing the importance of environmental protection (Li et al., 2019). In 2016, green finance was included in the G20 summit for the first time (Chen and Tao, 2021). In the same year, seven ministries and commissions, including People's Bank of China, jointly issued the Guiding Opinions on Building a Green Financial System, formally establishing a top-level framework for China's green finance (Bai, 2022). The guidance states that green finance is an economic activity that supports environmental improvement, climate change, conservation and efficient use of resources. Green finance is an important tool to achieve the goal of carbon neutrality. Based on the perspective of carbon emission reduction: green finance can guide the flow of social funds to production activities conducive to green development, and promote more resources to be allocated in the field of pollution control and environmental protection, which will reduce carbon emissions per unit of output and enhance regional carbon removal capacity, thereby promoting carbon neutrality. Based on the perspective of carbon absorption: Green finance can encourage talents and funds to invest in the research of carbon capture, utilization and storage technology (CCUS) to promote carbon neutrality.

At present, China has basically formed a multi-level green financial products and market system such as green credit, green bonds, green funds, etc. The proportion of loans invested by green finance in projects with direct or indirect carbon emission reduction benefits has reached 67%, and has successfully promoted the implementation of green low-carbon transformation projects in China's energy structure, industrial structure, production and lifestyle." China's carbon emission trading market has also been officially launched, which means that carbon finance has become an important part of green finance. Fan Yaping proposed that the establishment of a sound green financial system needs to learn from the development experience of green finance in developed countries (Xia, 2021). Zhang Zhongxiang believed that achieving the goal of carbon neutrality requires accelerating the construction of green finance (Lin et al., 2022).

In summary, although China started to develop green finance slightly late, the issuance of the Guidance on Building a Green Financial System means that China became the first country in the world to formulate a top-level design for green finance (Writing Group of China Green Finance Progress Report, 2021). Understanding and grasping the international green finance development situation is conducive to strengthening the communication and cooperation between China and the international community in the field of green finance development, continuously improving the green finance development system in light of China's objective and actual conditions, and exploring effective paths for China's green finance development to promote the achievement of carbon neutrality.

2 Analysis and judgment of current global carbon neutrality goals

The Paris Agreement, which is the main goal of the global green and low-carbon transition, is a major trend to actively address climate change. In line with the Paris Agreement's goal of limiting temperature rise to 1.5°C (Savaresi, 2016), countries have put forward carbon neutrality visions. As of December 2021, 136 countries and regions have proposed "zero carbon" or carbon neutral climate goals, in which 2 countries have achieved carbon neutrality, the European Union and 11 other countries have legislated, and 4 countries in the legislative state, according to the Energy and Climate Intelligence Unit. In addition, more than 30 countries have issued formal policy documents, and nearly 100 countries and regions have proposed targets but are still under discussion (Nelson and Allwood, 2021), as detailed in Table 1.

2.1 Carbon neutrality target status

There are two countries that have achieved carbon neutrality - Suriname and Bhutan, which were announced in 2014 and 2018, respectively. Due to their small size, extremely high forest cover and low level of economic development, the two countries are of little relevance to other countries that are still in the process of achieving carbon neutrality.

In order to achieve the target of carbon neutrality, different countries and regions have issued key guidance documents and taken specific measures according to their specific conditions, as summarized in Figure 1.

Among the countries and economies that the carbon neutrality target is in legislation, the EU, as a leader in the fight against climate change, first set out its vision of achieving carbon neutrality by 2050 in November 2018. On this basis, the EU has successively published a draft "European Green Deal" and the European Climate Law, which was adopted in June 2021, becoming Europe's first

TABLE 1 Development of carbon neutrality targets of countries and regions.

Target stage	Country & region*
Carbon neutrality has been achieved	Suriname, Bhutan
In legislation	European Union, Germany, Sweden (2045), United Kingdom, France, Japan, Canada, Spain, Denmark, New Zealand, Hungary, Luxembourg
At the stage of legislative discussion	South Korea, Ireland, Chile, Fiji
Official policy document has been issued	China (2060), United States, Finland (2035), Austria (2040), Iceland (2040), South Africa, Italy, Brazil, Switzerland, Argentina, Norway, Portugal, Panama, Costa Rica, Uruguay, Slovenia, Nepal, Laos, Vatican, Indonesia (2060)etc.
At the stage of policy discussion	Mexico, Netherlands, Belgium, Pakistan, Peru, Greece, Ecuador, Ethiopia, Myanmar, Bulgaria, Tanzania, Lebanon, Lithuania, Congo, Sudan, Uganda, Zambia, Cambodia, Namibia, Madagascar, Nicaragua, Guinea, Dominicaetc.

Note: * represents the target year of carbon neutrality, specifically marked in parentheses, and for the unmarked country and region, the target year is 2050.

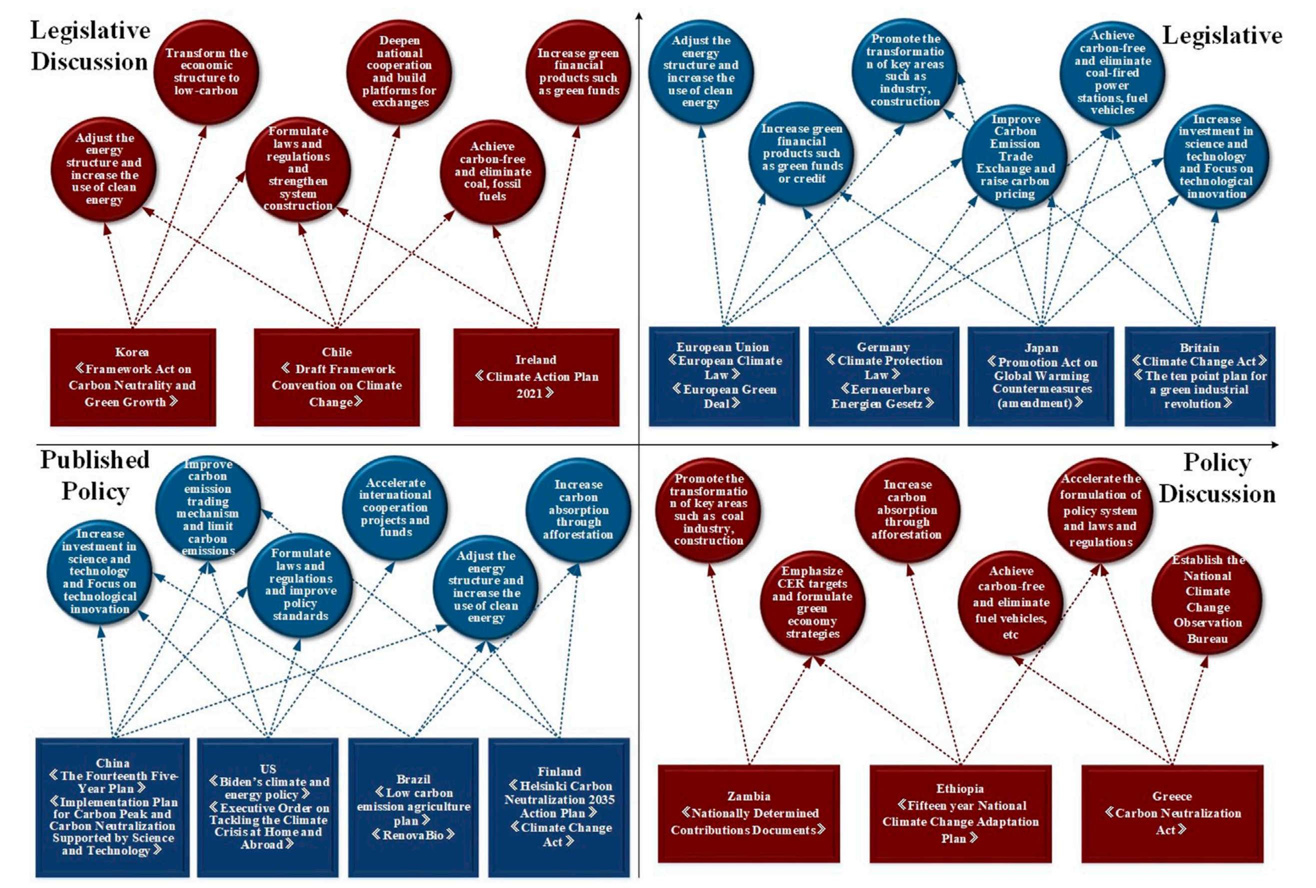

FIGURE 1
Specific measures taken by different countries and regions to achieve carbon neutrality.

climate law, which restricts carbon emissions in 27 member states (European Commission, 2020). In the process of achieving carbon neutrality, the EU uses the European Green Deal as the key guiding document (Claeys et al., 2019), controlling carbon emissions from four aspects, supplemented by financial support (Wang Y et al., 2021), the specific measures are shown in Figure 1. Germany and France responded positively to the bill, and Germany introduced the Climate Protection Plan 2050 before the legislation, on the basis of which it enhanced the binding force with laws and regulations such as the Federal Climate Legislation and the Renewable Energy Act, focusing on investments in renewable energy and phasing out coal-fired power plants with a view to achieving carbon neutrality by 2050 (Wang H Y et al., 2021). In April 2020, France issued a decree to adopt "National Low-Carbon Strategy", which not only accelerates the country's energy transition and green development, but also focuses on "green diplomacy" with Africa and Latin America, and helps countries in the region to cope with climate change by providing funds and other means.

In addition to European countries, Japan, as the only Asian country that has enacted legislation, promulgated the "Green Growth Strategy for Achieving Carbon Neutrality by 2050" at the end of 2020, mobilizing more than 240 trillion yen for green investment in the private sector through incentives such as regulations and subsidies, and proposing specific development targets for 14 industries such as offshore wind power, nuclear energy, and hydrogen energy (Ozawa et al., 2022).

Currently, there are four countries in the legislative state, and South Korea is the third Asian country to announce carbon neutrality goals after Japan and China. In December 2020, the South Korean government announced the "Carbon Neutrality Promotion Strategy", in which relevant departments of the central government should carry out long-term planning, such as the Financial Commission to formulate green investment guidelines for the financial sector, and the government to reduce residential energy consumption and encourage waste sorting through publicity and incentives (Phillips, 2021). In addition, Chile is carrying out two activities to achieve carbon neutrality by 2050: afforestation and the development of electric vehicles. Chile, a developing country with China, proposed in October 2020 to achieve carbon neutrality through Sino-Chilean cooperation, encouraging Chinese capital to enter Chile and help it modernize its energy production and industry (Li, 2020). Achieving carbon neutrality through international cooperation is gradually becoming a major development trend in the future. In addition to the above-mentioned countries, most countries, including China, are at the stage of policy document release or policy discussion.

2.2 Specific measures to achieve carbon neutrality

Among the countries that have set carbon neutrality targets, a few have achieved, legislated or proposed legislation, but most are still in the stage of policy release or policy discussion. More than 30 countries have issued official policy documents on carbon neutrality, including developing countries such as China, South Africa and Indonesia, and developed countries such as the United States, Italy and Brazil. In the process of achieving carbon neutrality, developed countries use their advanced production technology to provide certain reference and help to developing countries. For example, the United States returned to the Paris Agreement after Biden took office and pledged to achieve carbon-free power generation by 2035 and carbon neutrality by 2050. The "Biden New Deal" he promulgated can be summarized in three aspects (Wei, 2021; Williams et al., 2021), and the specific measures are shown in Figure 1. Similarly, Brazil has issued nine measures in line with its carbon neutrality goal, completely banning illegal deforestation, increasing forest cover and the proportion of renewable energy, and making specific plans for annual carbon emissions (Chen, 2021). Finland put forward its vision of carbon neutrality in February 2020, aiming to fully offset Finland's carbon dioxide emissions by planting trees, using renewable energy, and purchasing carbon sinks, so as to achieve carbon neutrality by 2035.

Compared with developed countries, developing countries such as China have not yet achieved carbon peaking, and achieving the goal of carbon neutrality in the short term requires leapfrog development. In March 2021, China included climate change mitigation actions in its 14th Five-Year Plan, with the goal of "peaking carbon emissions by 2030 and achieving carbon neutrality by 2060". Combined with the Guidance on Accelerating the Establishment of a Sound Economic System for Green, Low-Carbon and Circular Development (The State Council of the People's Republic of China, 2021) issued in February 2021, China's climate action is based on the principle of controlling carbon intensity, supplemented by the total amount of carbon, supporting conditional localities and key industries to take the lead in reaching peak carbon emissions, promoting low-carbon and safe and efficient use of energy, and advancing low-carbon transformation in industry, construction, transportation, and other fields.

In addition to China, Indonesia, after announcing its goal of achieving carbon neutrality by 2060, quickly took various actions, such as stopping the construction of new coal-fired power plants after 2023. Governments such as South Africa and Costa Rica have issued green transportation decrees to harmonize vehicle purchase standards and encourage the use of electric or zero-emission vehicles.

At present, there are nearly 100 countries under policy discussion, generally distributed in Africa and the Middle East. In April 2021, for example, Israel announced a plan to reduce greenhouse gas emissions by 85% by 2050 compared to 2015, and set specific targets to reduce the number of coal-fired power plants and expand the use of renewable energy. Zambia set important targets on carbon reduction in 2020, aiming to reduce greenhouse gas emissions by 25%–47% compared to 2010, while including some highly polluting areas in the scope of reduction (Turcotte and Dusyk, 2021). As a major African country, Ethiopia has established a 15-year national climate change adaptation plan. It is worth noting that in the next few years, countries from Africa, the Middle East and other regions are expected to rise head-on in the field of carbon neutrality, proposing policy documents or bills on carbon neutrality, thus bringing about 75% of global emissions under strict regulation for emission reduction.

By comparing the measures of countries and regions in different carbon neutrality status in Figure 1, the measures to promote the process of carbon neutrality can be grouped into five aspects: First, the formulation of climate change laws and regulations. For example, EU member states, the United Kingdom, Japan and other countries have formed a relatively complete regulatory system for low-carbon development, and some developing countries such as China are in the process of carbon neutrality legislation (Zhai et al., 2021). The second is to optimize the energy structure and reduce dependence on fossil energy. For example, Germany, Denmark and Hungary have proposed to accelerate the withdrawal of coal-fired power stations and reduce the use of fuel vehicles, increasing the proportion of overall consumption of green and clean energy. The third is to attach importance to the research and development of low-carbon technologies and promote the use of renewable energy. For example, Austria, Ireland and other countries support the development of renewable energy by increasing allocations and reducing the tax of renewable energy. The fourth is to improve the carbon emission trading market and improve the green financial system (Zhao et al., 2022). For example, China opened its national carbon emissions trading market in 2021, and there have been eight carbon trading pilots so far. The

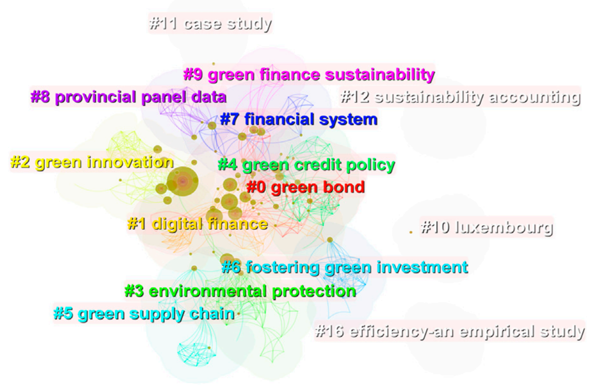

FIGURE 2
Co-occurrence map of green finance research keywords.

European ETS reasonably stipulates the carbon emissions of enterprises, making a great contribution to reducing carbon emissions in the world. Fifth, encourage green consumption, cultivate citizens' green production methods, and reduce carbon emissions from life. With the support of various national policies, green transportation such as new energy vehicles is gradually becoming the main tool for citizens to travel.

According to the 2019 world ranking of carbon emissions (Friedlingstein et al., 2020), China, the United States, Japan, Germany, the United Kingdom, and South Korea are in the top 10 and are also at the forefront of the push to achieve carbon neutrality. Japan, Germany, the United Kingdom and South Korea are already in the stage of legislation or legislative discussion. Although China and the United States have not legislated, they are also actively promoting the promulgation of relevant laws and regulations, China has written carbon neutrality into the 14th Five-Year Plan and proposed to enact the Carbon Neutrality Promotion Law as soon as possible at the National Two Sessions, although the United States has not legislated at the national level, but six states have passed legislation at the state level to set targets, both of which have mature legislative opportunities and conditions. The positive response of these major countries will not only have a positive impact on reducing global carbon emissions, but also increase the enthusiasm of other countries to achieve carbon neutrality.

3 The development situation of international green finance under the goal of carbon neutrality

3.1 The development situation of green finance-related research

As an organic combination of financial and environmental issues, green finance is an important contribution to achieving the goal of carbon neutrality and has become an important global issue (Xu, 2020). In order to explore the research focus of green finance by scholars at home and abroad, and to find out the research themes and development trends of green finance-related research, this paper uses CiteSpace software and Web of science literature retrieval tool to co-appear the keywords of the literature related to green finance, as shown in Figure 2.

Through keyword visualization, it is found that green bonds, green innovation, digital finance, environmental protection, and green credit policies are keywords with more common frequency, from which it can be seen that green bonds, digital finance, and green credit, as important components of the green financial system, are closely related topics for the further research and improvement of the green financial system. The research on green innovation and environmental protection is mainly discussed from the perspective of research purpose, and whether the establishment of green financial system improves the level of green innovation and environmental protection in countries or regions is a research theme that scholars at home and abroad are more concerned about. For other keywords such as accelerating green investment and green supply chain, the co-emergence reflects the further refinement of scholars' research on green finance.

3.2 International development trend of green financial system

The relevant research on green finance theory by scholars at home and abroad is finally reflected in the construction of the national financial system, and at the specific construction level of the green financial system, the green finance practice of various countries is mainly reflected in the green finance standard system, information disclosure requirements, incentive and constraint mechanisms, green financial product tools, and international cooperation in green finance. The summary is as follows:

3.2.1 Green finance standard system

Internationally, some countries have established standards in related fields, including the Equator Principles (Principles, 2013), the Green Bond Principles (Ehlers and Packer, 2017), and the Climate Bond Standards (Climate Bond Initiative, 2011). Robert F. Lawrence & William L. Thomas briefly describe the sustainability of the Equator Principles in long-term practice (Lawrence and Thomas, 2004). Kariyawasam has found that better adherence to green bond principles has had a significant positive impact on investor demand, contributing to the development of green finance (Nanayakkara and Colombage, 2021). The Climate Bonds Initiative calls the Climate Bonds Standard is the key to sustainable development (Palleschi, 2016). CEIBS has taken the lead in publishing the Common Taxonomy of Sustainable Finance. China has issued the Green Industry Guidance Catalogue and updated standard documents such as the Catalogue of Green Bond-Backed Projects, which has effectively promoted the rapid development of green finance in China. Green finance requires that all funds raised must be used for the construction of green projects that meet the criteria, however, the study found that some of the current international standards are consistent, but there are also more differences. Different standards across countries may have implications for financial products based on such industries and even cross-border capital flows, and may even create "greenwashing" or arbitrage risks (Kong, 2022). Therefore, sound policy support is the foundation of China's green financial standards system. For example, the Guiding Opinions on Building a Green Financial System, issued in August 2016, provides an overall plan for the green finance standard system at the national level. The Overall Plan for the Construction of a Green Finance Reform and Innovation Pilot Zone in Guangzhou, Guangdong Province, released in July 2017, provides in-depth practice of the green finance standard system at the local level.

3.2.2 Financial institution regulation and information disclosure

Some countries in the world have been relatively mature in the formulation of information disclosure systems, information disclosure content and frameworks. In 2018, Japan issued the latest Environmental Reporting Guidelines, which further set detailed requirements for information such as reporting enterprises and reporting standards for environmental reports (Islam et al., 2020). The Regulations on the Content and Format of Financial Information Disclosure and the Regulations on the Content and Format of Non-Financial Information Disclosure, which have been used in the United States, stipulate the content of corporate environmental disclosure (Manes-Rossi et al., 2020). Moalla M clarified that the establishment of an environmental information committee in France and environmental external guarantees are conducive to the timeliness of environmental reporting (Moalla et al., 2020). China has initially established an environmental information disclosure system and issued documents such as the Guidelines for Environmental Information Disclosure (Youth Research Group of the International Department of the People's Bank of China, 2021).

Under the current legal system in China, information disclosure is still not transparent enough compared to foreign countries, the current mandatory disclosure of environmental information covers key pollutant dischargers, listed companies and green finance bond issuers. Due to the late involvement of environmental information disclosure, China's green finance information disclosure system is still imperfect at this stage, especially the lack of disclosure system and detailed implementation standards for environmental benefits and high-carbon asset information. Due to the large number of subjects and contents involved in information disclosure, the existing information disclosure capacity cannot fully meet the needs for carbon emission collection, calculation and assessment, and needs to be further strengthened.

3.2.3 Incentive and constraint mechanisms

Some countries and regions have carried out relatively sound incentive and constraint mechanisms earlier, and the implementation path is clearer, providing inspiration for other countries to develop green financial incentive and constraint mechanisms. The EU actively operates government funds to promote the development of green finance. For example, the German government gives certain interest discounts and interest rates to green project loans, and makes full use of policy-based financial tools such as policy banks to drive private capital into the green economy. The United Kingdom invested 3 billion to establish the United Kingdom's first green investment bank. The EU Classification Regulation, which comes into force in 2020, provides further incentives for investors to invest in financing transformational projects (Larsen, 2022). The United States has established a special government procurement agency for green financial products to stimulate public interest in green projects (Meltzer and Shenai, 2019). Relatively speaking, the incentive mechanism of green finance in some countries is relatively perfect, which can meet the financing needs of long-term development of green finance.

For green finance and its product system, China has introduced a variety of green finance assessment and incentive mechanisms from the perspective of fiscal, monetary and regulatory aspects, including positive reward mechanisms and negative punishment mechanisms (Qin et al., 2022). In 2020, the Guiding Opinions on Promoting Investment and Financing to Address Climate Change was issued, strengthening the use of refinancing and MPA assessment to encourage financial institutions to promote green credit (Zhang, 2022). Ma Jun believes that in order to change the polluting industrial structure, it is necessary to establish and improve the incentive mechanism to encourage green investment, but compared with the specific implementation measures such as interest discounts and guarantees adopted by other countries for green finance, China's incentives for green projects are not deep enough and the focus of constraints is not prominent enough, which makes the green financial market lack endogenous power and affects the development of green finance under the goal of carbon neutrality (Ma, 2018).

3.2.4 Products and market systems of green finance

After decades of development, many developed countries have leveraged the market with relatively perfect policy systems and abundant financial tools, making green financial products more abundant.

The United States has always been dominated by mandatory environmental liability insurance, with government intervention and the use of various economic incentives, and has rich experience in green insurance practices (Richardson, 2001). As for China, the balance of green credit at the end of 2021 was 15.9 trillion yuan, an increase of 33% year-on-year. By the end of 2021, China's green bond stock reached 1.16 trillion yuan. And in terms of carbon trading, the national carbon emission trading market operated for 114 trading days, with a cumulative trading volume of 179 million tons of carbon emission allowances (CEAs) and a cumulative turnover of 7.661 billion yuan. In 2021, the issuance of green investment-related thematic funds exceeded 50, and the scale of green funds was close to 800 billion yuan. China has seen steady growth in the scale of green credit business and rapid development of the green bond market in recent years, further promoting the development of environmental pollution liability insurance and studying the establishment of a compulsory liability insurance system for environmental pollution in high-risk areas of the environment (Zhao et al., 2021), but there is still much room for development.

The mismatch of green finance policies leads to the mismatch of the maturity of green financial products, which cannot fundamentally solve the financing needs of green projects, and the funding gap still exists. In addition, a complete green financial system on which green finance can be effectively relied on for a long time has not yet been formed, there is still a big gap in product diversification and liquidity compared with developed markets, many green financial products have not been linked to carbon footprints, the role of carbon markets and carbon financial products in the allocation of financial resources is still very limited, and the openness of carbon markets to the outside world is still very low.

3.2.5 International cooperation in green finance

More than 120 countries worldwide have already committed to achieve carbon neutral by the mid-21st century, covering 68% of global GDP and 56% of global population, and accounting for 61% of global GHG emissions (Lin et al., 2022). Countries around the world are sparing no effort to promote the green transformation of their economies and should strengthen cooperation to jointly build a community of human destiny (Lee et al., 2022).

The Joint Statement of Chinese and European Leaders on Climate Change and Clean Energy, signed in 2018, in which both sides emphasize the highest political commitment to the full and effective implementation of the Paris Agreement (Gurol and Starkmann, 2021). In 2019, the European Banking Authority (EBA) published the Sustainable Finance Action Plan. In order to promote sustainable and green development across the EU, in December 2019, the European Commission announced the "European Green Deal", which proposed a series of green development goals, such as Europe taking the lead in achieving carbon neutrality globally by 2050 (Zhuang and Zhu, 2021). In November 2020, the Italian Presidency of the G20 co-hosted with the United Kingdom the 26th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change, and Italy has proposed to reactivate the work of the Sustainable Finance Research Working Group, focusing on green finance development. The United Kingdom government and the City of London have jointly established the Green Finance Institute, which aims to promote collaboration between the United Kingdom's public and private sectors to help investors pursue opportunities. After taking office, Biden announced his rejoining of the Paris Agreement on 19 February 2021. The Sino-US Green Fund, established in 2016 and with an investment of more than 10 billion yuan, will be further promoted (Michaelowa, 2022).

China has made great efforts to promote green finance as a global consensus, promoting green finance cooperation and international exchanges by participating in the initiation of multilateral cooperation platforms and establishing bilateral cooperation mechanisms, and actively publicizing China's progress and practice in green finance to the world. Deeper cooperation with other countries, including continuing to steadily promote Sino-United Kingdom green finance cooperation, covering topics such as green investment principles, climate and environmental disclosure, ESG investment, and green technology incubators. China and France will discuss in depth the risk weight of green assets, environmental information disclosure, green investment and other topics, and will carry out in-depth cooperation in promoting the unification of green finance standards and exploring green finance incentive mechanisms. China and Germany will cooperate closely on a range of issues related to the promotion of joint development of green finance (Wei et al., 2022). In the process of building a new "double-cycle" development pattern, green finance should become a priority area for financial opening to the outside world. China should further participate in international cooperation in green finance, encourage cross-border capital to carry out green investment, strengthen international cooperation in the construction of the green "the Belt and Road", enhance international recognition of China's green finance policies, standards, products and markets, and continuously improve China's discourse and leadership in this field.

4 Conclusion and outlook

It has become an international consensus to move towards carbon neutrality, and more than 130 countries have proposed carbon neutrality targets so far, many of which have already achieved and legislated. It is worth mentioning that in the next few years, some countries in Africa and the Middle East are expected to join the initiative to achieve carbon neutrality, when most of the world's carbon emissions will be under effective regulation.

Green finance is an important means to achieve the goal of carbon neutrality, the "Equator Principles" have been internationally recognized green finance related standards, some countries have also established green finance standard systems, while strengthening the supervision of financial institutions and improving the information disclosure system, using incentives and constraints to promote the iterative upgrading of financial products and services, and injecting vitality into the development of green finance into society.

China, as a major energy-consuming country, plays a crucial role in the process of achieving carbon neutrality. Although the relevant theoretical and practical research started slightly later than some developed countries, it has made outstanding contributions in the top-level design framework and international cooperation on low carbon emissions. With the concept of building a community of human destiny, China has been striving to achieve carbon neutrality in four major areas: formulating carbon neutral laws and regulations, optimizing energy consumption structure, developing low-carbon technologies, and improving carbon emission trading market. In terms of green finance, China has more room for improvement. Specifically, compared with developed countries, green finance is not strongly connected with the goal of carbon neutrality and high-quality development of low-carbon transformation. A green finance standard system has not yet been formed. On the one hand, unified standards have not been established for green funds and green insurance, etc. On the other hand, the statistics of green credit and green bonds are affected by factors such as statistical caliber, and there are problems such as ambiguous flow of funds. The environmental information disclosure system of green finance is still imperfect, there is a lack of disclosure of environmental benefits and high-carbon asset information, and the level of environmental information disclosure does not meet the requirements of carbon neutrality target. At present, most Chinese regulators have not yet made it mandatory for companies to disclose carbon emissions and other information, and there is a lack of uniform criteria for identifying green companies, which has led to the phenomenon of "drifting green". The incentive and constraint mechanism of green finance needs to be strengthened, the incentive and constraint mechanism is not detailed enough, and the focus of incentives and constraints is not prominent, resulting in a lack of enthusiasm for green investment among social investors. And SMEs, as an important market force, lack targeted preferential policies.

In view of the above problems, the next research needs to effectively connect green finance with the goal of carbon neutrality and the high-quality development of low-carbon transformation, to learn from its lessons on the basis of in-depth analysis of the evolution and development status of global green finance, to improve the operation mechanism and policy system, to formulate a more accurate timetable and roadmap, to strengthen the modernization of the governance system and governance capacity of the green financial system embedded in the goal of carbon neutrality, to promote the integration of China's green finance and lead the process of a new round of globalization, to build a unified domestic green finance standard system that is in line with international standards, to improve the relevant standards for green credit and green bonds, establish in-sector standards such as green funds and green insurance under the goal of carbon neutrality, and determine the identification standards for green enterprises, and strengthen the supervision of green capital flows, to clarify the scope and content of information disclosure, issue targeted information disclosure guidelines for different industries, and use new technologies such as big data to intelligently supervise corporate carbon emissions, to improve incentive and constraint mechanisms, establish carbon neutral performance assessment mechanisms for green projects, financial institutions to guide the flow of green funds to low-carbon and zero-carbon projects, and introduce targeted policies to support SMEs in green transformation.

Author contributions

The manuscript was approved by all authors for publication. YX and YM conceived and designed the study; YX, TM, and TZ did the literature analysis and collected and analyzed the data; All authors wrote the paper. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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Research on the risk evaluation of enterprises' carbon compliance failure

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In order to mitigate global warming and help the country achieve its carbon peaking and carbon neutrality targets at the earliest possible time, the emission-control companies should accomplish the carbon compliance in accordance with relevant national policies and regulations. However, these companies frequently face the failure risk of carbon compliance subjected to various factors, including the national carbon quota policy, local carbon market situation, the verification of carbon offset projects, as well as the effectiveness of carbon reduction technologies. To help the enterprises avoid the risk of carbon-compliance failure and design rational carbon asset management strategy, in this research, the innovative combination of interpretive structural modeling (ISM), Bayesian network model, risk calculation and sensitivity analysis method was formulated. Firstly, the ISM method was used to establish a hierarchical relationship of risk factors that contribute to the failure of carbon compliance. Secondly, the probability prediction model of carbon-compliance failure risk based on the Bayesian network model was established by aid of the Netica software. Thirdly, the risk value of enterprise's carbon compliance failure was quantitatively calculated based on its production operation and carbon asset management. Finally, the sensitivity analysis method was used to identify critical risk factors and design risk control measures for six well-known domestic enterprises, laying good foundation for improving the success rate of carbon compliance and facilitating low-carbon green transformation. Compared to traditional qualitative risk assessment method, this combined approach is capable of realizing the quantitative evaluation of failure risk based on comprehensive investigation and analysis of the production and operational situation, which provides effective technical support to enhance enterprise's compliance awareness and improve low carbon competitiveness.

KEYWORDS

carbon compliance, risk evaluation, ISM method, Bayesian network, sensitivity analysis method

1. Introduction

Global warming is a pressing issue that profoundly affects the development and progress of human society. Developing a low-carbon economy characterized by low energy consumption and low GHG (greenhouse gas) emissions and establishing a low-carbon society have become a basic consensus and critical strategy for countries around the world in order to mitigate climate change and achieve sustainable development (Trotter et al., 2022; Pentz and Klenk, 2023). In the 75th session of the United Nations General Assembly, President Xi Jinping announced the strategic goal that 'China will improve its independent national contribution, adopt more vigorous policies and measures, strive to reach the peak CO_2 emission by 2030, and achieve the carbon neutrality by 2060'. This announcement shows the direction for the next phase of national energy structure adjustment and green development (Zhu et al., 2018). Under the context of energy conservation, carbon emission reduction, and low-carbon development, the emission permits trade market of carbon (abbreviated to the carbon market) of China was established in 2021. The market mechanism and trading rules are capable of regulating and adjusting the carbon asset management strategies of participating parties, significantly improving the flexibility of carbon reduction strategies. This way helps high-emission companies to establish a conception of low-carbon development and realize the goals of carbon peaking and carbon neutrality. Overall, the establishment of the carbon market in China is a crucial step toward the country's green development and transition (Nie, 2022).

Emission control enterprises are a crucial part of the carbon market and are driven by carbon compliance to participate in carbon emission trading, which is the only way for them to complete low-carbon transformation and realize green development. With the rapid development of the carbon market, emission control companies with high GHG emissions will face a bigger challenge. On the one hand, the approaching deadline of the 'carbon peaking and carbon neutrality goals' has imposed more stringent carbon reduction requirements on these enterprises, leading to tremendous pressure on their production and operation. On the other hand, these enterprises are affected by various factors such as policies, markets, and technologies in fulfilling their compliance and emission reduction obligations, resulting in the failure risk of carbon compliance. Therefore, the accurate evaluation of the carbon compliance failure risk and effective regulation of risk factors are beneficial to enhance enterprises' compliance awareness, increase their enthusiasm to participate in a market transaction, and ultimately realize their green and low-carbon transformation while maintaining sustainable and healthy development. To assist enterprises in completing carbon compliance and avoiding the compliance failure risk, many scholars and experts have conducted extensive and in-depth research on the risk evaluation of enterprises' carbon compliance (Blanco and Rodrigues, 2008; Chevallier et al., 2009; Fan and Wang, 2014; Chen, 2015; Zhao et al., 2017; Liang, 2018; Guan et al., 2019; Wang et al., 2020; Xu, 2020a; Guerin, 2021; Hang and Tan, 2021; Gao and Gao, 2022; Zhu and Hou, 2022; Tian et al., 2023). For example, Chen (2015) summarized the problems associated with the carbon compliance risk management process of enterprises, including the failure to incorporate carbon management into strategic planning, the lack of a unified carbon management information platform, the lack of a carbon compliance risk pre-warning mechanism, and weak carbon asset management capabilities. Xu (2020a) established an integrated evaluation index system of carbon compliance risk coupling the political, market, and operational risk and completed the risk evaluation of carbon compliance based on the multi-attribute evaluation method. Guan et al. (2019) analyzed four types of factors affecting carbon compliance under the carbon trading mechanism, which included policy factors, market factors, industry factors, and enterprise factors, and they also examined the influence of carbon price, carbon quota, and carbon emission levels on enterprises' carbon asset management. Blanco and Rodrigues (2008) considered the impact of incentive effects caused by the carbon trading mechanism on the carbon compliance cost of enterprises and proposed a market operation scheme for driving emission control enterprises to participate in the carbon trading market. Chevallier et al. (2009) investigated the interaction between low-carbon technologies and compliance costs and proved that the successful implementation of energy-saving technologies was capable of reducing the cost and contributing to the successful possibility of enterprises' carbon compliance. Liang (2018) proposed the optimal carbon management strategy based on the production and emission characteristics of iron and steel enterprises for ensuring carbon compliance on schedule. Meanwhile, Hang and Tan (2021) examined the low-carbon transformation path of a petrochemical enterprise and pointed out the challenges encountered by the enterprise during the carbon compliance process.

As in the research findings mentioned above, it is concluded that most of the existing evaluations of carbon compliance risk are based on a macro-analysis approach, which examines the impact of various factors on an enterprise's carbon compliance, such as market fluctuation, policy development, and carbon reduction technologies. Although these qualitative assessments facilitate the increase in the success probability of carbon compliance, however, the inability to accurately identify the risk-causing effects of the abovementioned factors and quantitatively evaluate the compliance failure probability will lead to weak crisis awareness, inaccurate risk evaluation, and ineffective carbon asset management of the enterprise. This will directly affect healthy development and low-carbon transformation in the future. In other fields, the interpretive structural model (ISM) has been used to display the structural relationships of a complex system by using minimal directed topological diagrams without compromising the system's functionality (Huang et al., 2022; Li et al., 2022; Qian et al., 2022; Zhao et al., 2022). Similarly, the Bayesian network model can be used to calculate and display the occurrence probability of non-specified events by using the pictorial form, where statistical analysis techniques are employed to infer unknown variables based on certain known variable values (Sacchi and Swallow, 2021; Joffard et al., 2022; Ren et al., 2022; Wang and Xu, 2022; Yao et al., 2022). Therefore, the combination of these two methods is suitable for calculating the occurrence probability of carbon compliance failure risk in an enterprise. However, there is little research on their application in the evaluation of carbon compliance failure risk.

Therefore, the aim of this research was to fill this gap and propose a novel combination method for evaluating the carbon compliance failure risk of six prominent domestic enterprises in China, namely, steel, power, cement, petrochemical, aviation, and electrolytic aluminum, which were also the first batch of companies included in the carbon market management (Bin and Zhang, 2022; Wang et al., 2023). This research involved several tasks: (i) the determination of the carbon quota of each enterprise by using the baseline method; (ii) the hierarchical division of risk factors causing carbon compliance failure with the aid of the interpretive structure model; (iii) the establishment of a probability prediction

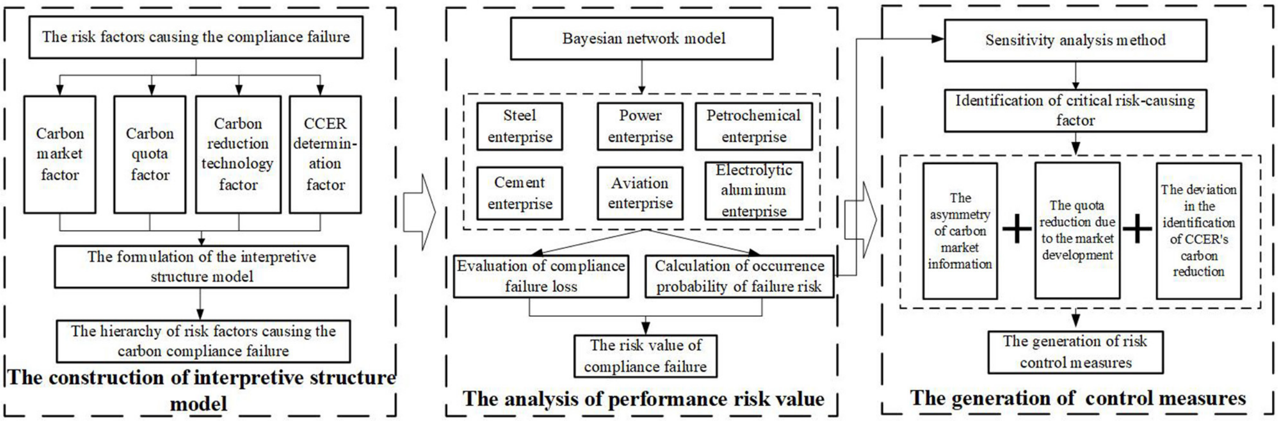

FIGURE 1
Technological roadmap.

model of carbon compliance failure risk based on the Bayesian network model; (iv) the calculation of the risk value of carbon compliance failure of six enterprises based on the risk definition; and (v) the identification of major risk factors using the sensitivity analysis method, which is beneficial in generating specific risk control measures. On the whole, the aforementioned research achievements provide excellent technical support for high-emission enterprises to avoid carbon compliance failure risk and improve their low-carbon competitiveness.

2. Methodology

2.1. Overall technical route

Figure 1 shows the overall technology roadmap. The interpretive structure model was first used to determine the hierarchical relationship of risk factors causing carbon compliance failure. Then, the occurrence probability of enterprises' carbon compliance failure risk was calculated based on the Bayesian network model. Next, the risk was quantitatively evaluated by incorporating the losses caused by compliance failure into the computational process. Finally, the critical risk-causing factors were identified with the aid of the sensitivity analysis method; correspondingly, the risk control measures were proposed, which provide the technical support for reducing the risk of compliance failure and promoting the green low-carbon transformation of target enterprises.

2.2. Risk calculation of enterprises' carbon compliance failure

As a crucial mechanism in China, the carbon compliance process regulates that the targeted enterprise needs to adjust its carbon emission behavior in order to ensure its annual carbon emission magnitude is less than or equal to the initial carbon quota allocated by the local authority. The enterprise's failure to comply with these regulations will result in a penalty or fine and reputational damage (Tian and Xu, 2020; Xu, 2020b; Yang, 2021a). The carbon compliance failure risk of the enterprise consists of of compliance risk factors, compliance failure risk incidents, and compliance failure loss. Among them, compliance risk factors are the conditions that cause or increase the chance of compliance failure or enlarge the loss magnitude, which are the potential reason for compliance failure. The compliance failure risk incidents are the episodic events that lead to carbon compliance failure, which are the important medium of default loss. The compliance failure loss is the loss due to the failure of carbon compliance tasks, such as a financial penalty, credit damage, and reduction of free carbon quota (Yang, 2021b). The

TABLE 1 The summary of risk factors causing carbon compliance failure.

Category	Specific risk-causing indicators
Carbon market factors	The over-high price of carbon quota
	The asymmetric market information
Carbon quota factor	The reduction of free initial quota due to the market development
	The reduction of free initial quota caused by the variation in government policy
	The reduction of free initial quota subjected to the change in its allocation method
Technical factors of carbon reduction	The improper operation of personnel
	The equipment loss
	The difficulty in production technology transformation of enterprise
Identification factor of CCER project	The reduction of CCER's offset proportion
	The offset magnitude reduction due to the inaccurate identification of CCER project
	The decrease in the number of CCER project

TABLE 2 The adjacency matrix of risk factors.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
X_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
X_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
X_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
X_4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
X_5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
X_6	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1
X_7	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
X_8	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
X_9	1	0	0	0	0	0	0	0	0	1	1	1	0	0	1
X_{10}	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1
X_{11}	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1
X_{12}	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1
X_{13}	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1
X_{14}	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1
X_{15}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: X_1 represents the high price of free carbon quota; X_2 represents the decrease in the carbon reduction amounts of enterprise; X_3 represents the reduction of free carbon quota of enterprise; X_4 represents the reduction of CCER offset magnitude; X_5 represents the asymmetry of carbon market information; X_6 represents the improper operation of personnel; X_7 represents the equipment loss; X_8 represents the difficulty in production technology transformation of enterprise; X_9 represents the reduction of free initial quota due to the market development; X_{10} represents the reduction of free quota caused by the variation in government policy; X_{11} represents the reduction of free initial quota subjected to the change in its allocation method; X_{12} represents the reduction of CCER offset ratio; X_{13} represents the offset magnitude reduction due to the inaccurate identification of CCER project; X_{14} represents the decrease in the number of CCER project; X_{15} represents the failure of enterprise's carbon compliance.

TABLE 3 The reachability matrix of risk factors.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
X_1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
X_2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
X_3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
X_4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
X_5	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1
X_6	0	1	0	0	0	1	1	0	0	0	0	0	0	0	1
X_7	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1
X_8	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1
X_9	1	0	1	1	0	0	0	0	1	1	1	1	0	0	1
X_{10}	1	0	1	1	0	0	0	0	0	1	0	0	0	0	1
X_{11}	1	0	1	1	0	0	0	0	0	0	1	0	0	0	1
X_{12}	1	0	0	1	0	0	0	0	0	0	0	1	0	0	1
X_{13}	1	0	0	1	0	0	0	0	0	0	0	0	1	0	1
X_{14}	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1
X_{15}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

risk evaluation of carbon compliance failure is to quantitatively assess the risk value of carbon compliance failure by measuring the occurrence probability of compliance failure and default loss caused by risk factors, which lays the theoretical foundation for subsequent risk control measures and compliance strategies. The risk value of compliance failure was calculated based on the following equation:

$$R = P \times C, \quad (1)$$

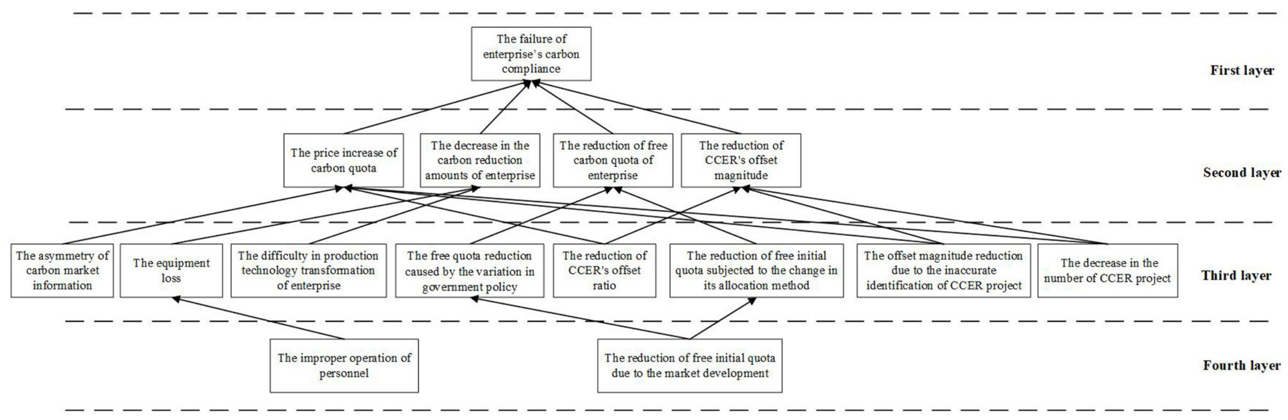

FIGURE 2
Hierarchical relationship among risk factors based on the ISM method.

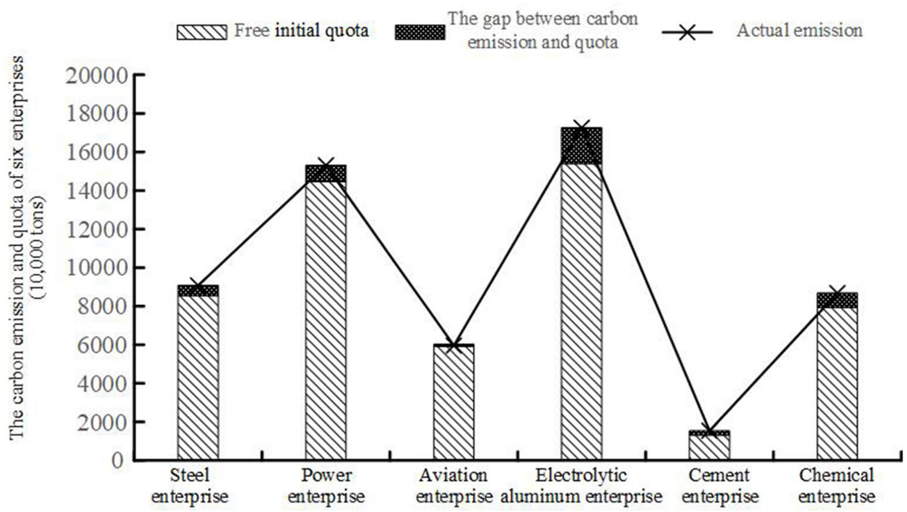

FIGURE 3
Occurrence probability prediction model of the enterprises' carbon compliance failure risk.

where R is the risk value of compliance failure; P is the probability of compliance failure, %; and C is the economic loss caused by the enterprise's compliance failure, million yuan.

2.3. Hierarchical division of risk factors based on the ISM method

There are many risk factors with a complex interactive relationship that lead to the failure of an enterprise's carbon compliance; it is, thus, extremely difficult to calculate the failure probability of carbon compliance. The first task of failure risk evaluation is to identify the autocorrelation and portray the hierarchical relationship among the affected factors. As a typical system structure analysis method, the ISM (interpretive structural modeling) method is capable of illustrating the intricate relationship among the system factors and formulating a clear hierarchical structure, which is suitable for completing the internal analysis of the system with many elements and unclear relationships. The basic process of the model formulation was as follows:

(i) Through the combined utilization of the data collection, literature review, and expert consultation, the relationship among the influencing factors was identified based on the association rule; the initial determination of the relationship among the affected factors was completed; the adjacency matrix containing 0 and 1 variables was formulated as follows:

$$a_{ij} = \begin{cases} 1, & X_i has\ an\ effect\ on X_j \\ 0, & X_i has\ no\ effect\ on X_j, \end{cases} \quad (2)$$

where X_i and X_j are the different influencing factors; and a_{ij} is the [0,1] element of the adjacency matrix.

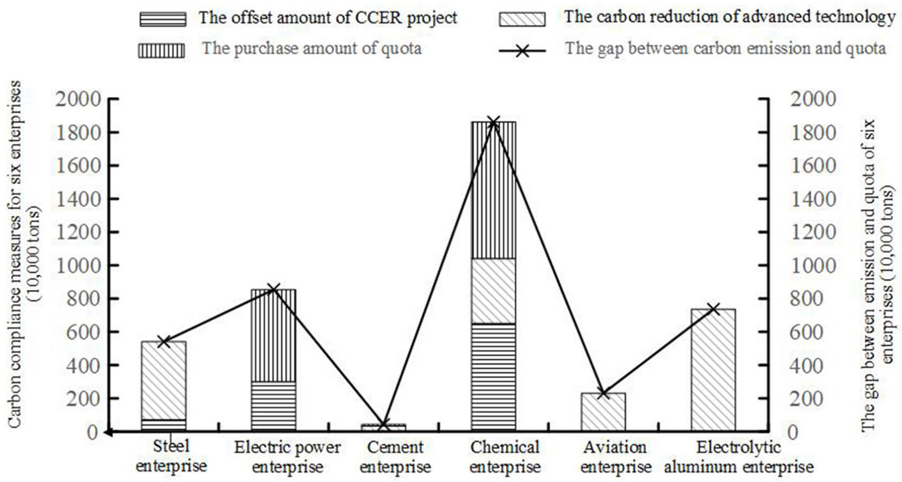

FIGURE 4
Free carbon quota and the difference between a quota and the actual emissions of the six enterprises.

TABLE 4 The carbon asset management of six enterprises.

Type	The management measures		
	The carbon market	The technology of carbon emission reduction	The certification of CCER project
Steel enterprise	Active participation in carbon market	The promotion of low-carbon metallurgical technology	Active participation in the trading of CCER project
Electric power enterprise	Five carbon trading pilot projects were implemented.	The active research and development of green technologies such as CCUS and microalgae carbon sequestration.	The rapid development of CCER project
Cement enterprise	Active participation in the pilot activities of the national carbon market construction	The active research and development of CCUS technology	/
Chemical enterprise	Active participation in carbon market	The active development of carbon reduction technologies such as molecular oil and green hydrogen refinement	The carbon emission has been offset through purchasing the CCER projects.
Aviation enterprise	/	The fuel saving of operation and the optimization of the energy structure	/
Electrolytic aluminum enterprise	Active research on carbon trading	The research and development of low-carbon technologies	The development of forestry carbon sequestration

(ii) Based on the formulated adjacency matrix, the Boolean logic operation rule was used to generate the reachable matrix, which is written as follows:

$$M = (A+I)^{K+1} = (A+I)^{K} \neq (A+I)^{K-1}, \quad (3)$$

where A is the adjacency matrix; I is the unitary matrix; and M is the reachability matrix.

(iii) The hierarchical division method was exploited to decompose the structure of the reachable matrix. As a result, the interpretive structure model was formulated, and the hierarchical relationship diagram of the influencing factors was plotted.

2.4. Probability calculation of the enterprise's carbon compliance failure risk with the aid of the Bayesian network model

The Bayesian network with N nodes is described as follows:

$$N = \langle DAG, P \rangle = \langle \langle V, E \rangle, P \rangle \quad (4)$$

$$V = \{v_1, v_2, \cdots v_i\} \quad (5)$$

$$E = \{e_1, e_2, \cdots e_i\}, \quad (6)$$

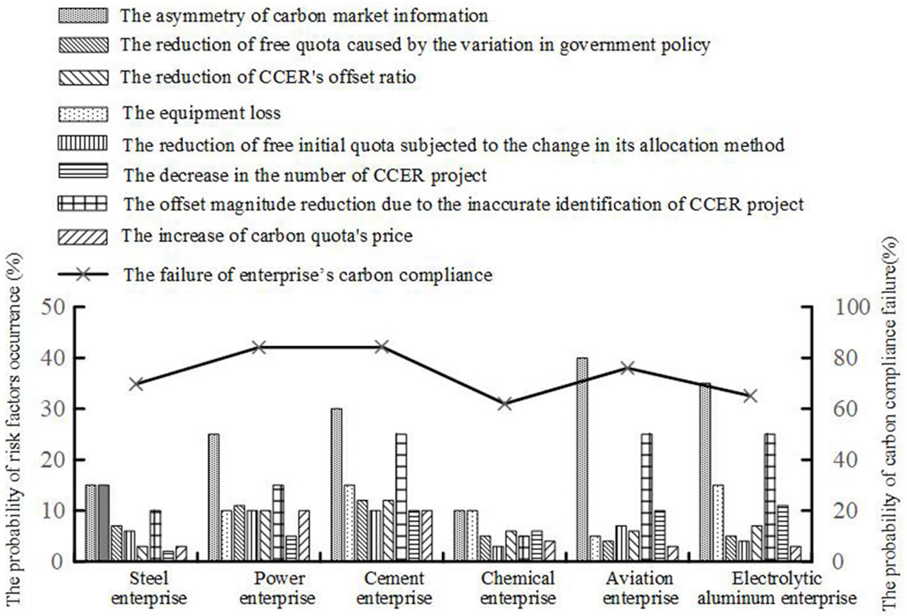

FIGURE 5
Implementation of the enterprises' carbon compliance measures.

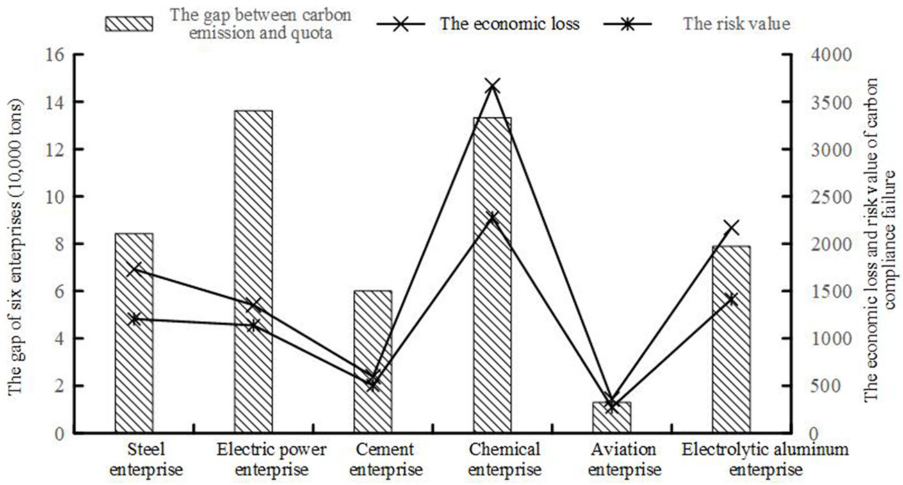

FIGURE 6
Occurrence probability of risk factors and carbon compliance failure.

where *DAG* is the structure of the network; *V* is the set of node variables in the network; v_i is the node variables in the network; *E* is the set of directed edges with links in the nodes; *P* is the set of conditional probability distributions, which is described as follows:

$$P(X|Y,Z) = P(X|Z), \quad (7)$$

where *X*, *Y*, and *Z* are the disjoint subsets in the set of variables; $U = \{x_1, x_2, \ldots, x_i\}$; $P(Y,Z)>0$. It is assumed that *X* and *Y* are independent with respect to *P(U)* under the condition that *Z* is known, which is denoted as $X \perp Y|Z$.

The joint probability can be decomposed into equation (8) based on equation (7), indicating that the introduction of the Bayesian network reduces the complexity of joint probability calculation and facilitates the smooth realization of Bayesian inference.

$$P(V) = \prod_{i=1}^{n} P(X_i|X_1, X_2 \cdots X_{i-1}) = \prod_{i=1}^{n} P\left(X_i|parent(X_i)\right) \quad (8)$$

$$P(V_i) = \sum\nolimits_{except V_i} P(V), \quad (9)$$

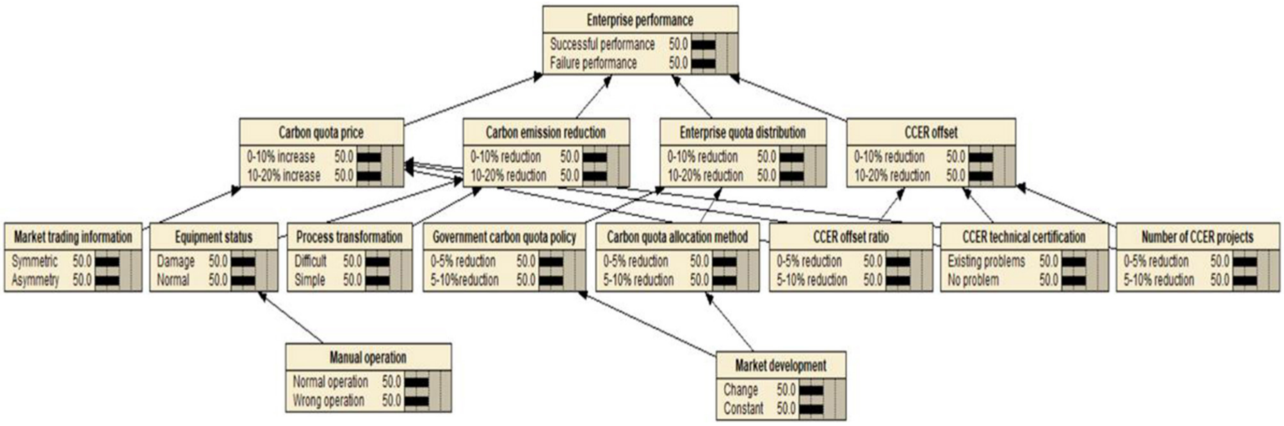

FIGURE 7
Risk value of the enterprises' carbon compliance failure.

TABLE 5 The identification of critical risk factors for enterprise's carbon compliance failure.

Risk factors	The occurrence probability of carbon compliance failure			Sensitivity degree
	0%	50%	100%	
The improper operation of personnel	25.1%	24.1%	23.1%	2%
The reduction of free initial quota due to the market development	27.2%	23.9%	20.6%	6.6%
The asymmetry of carbon market information	26%	19.7%	16.6%	9.4%
The equipment loss	25.4%	24%	22.6%	2.8%
The difficulty in production technology transformation of enterprise	24.8%	24.7%	24.5%	0.3%
The reduction of free quota caused by the variation in government policy	23%	21.6%	20.1%	2.9%
The reduction of free initial quota subjected to the change in its allocation method	25%	22%	20.9%	4.1%
The reduction of CCER offset ratio	25.7%	23.6%	21.6%	4.1%
The offset magnitude reduction due to the inaccurate identification of CCER project	23.6%	21%	18.4%	5.2%
The decrease in the number of CCER project	25.1%	22.8%	20.4%	4.7%

where $P(V)$ is the joint distribution of the network; $parent(X_i)$ is the parent of node X_i; and $P(V)$ is the edge probability of node X_i.

According to the Bayesian theorem, when the occurrence probability of an event is known, the occurrence probability of other relevant nodes is deduced. It is assumed that the event e is given, and the probability of $P(V|e)$ is calculated as follows:

$$P(V|e) = \frac{P(V,e)}{P(e)} = \frac{P(V|e)}{\sum_v P(V,e)}. \quad (10)$$

3. Formulation of the probability prediction model for enterprises' carbon compliance failure risk

3.1. Identification of risk factors causing carbon compliance failure

In order to realize carbon compliance on schedule, the emission control enterprises first utilize the historical method to estimate their possible free emission quota based on historical carbon emission amount, then calculate their clearance volume, which is equal to the gap between actual carbon emission and emission quota, and finally, they generate a rational carbon asset management pattern, including appropriate carbon reduction measures, optimal market participation strategies, and suitable China Certified Emission Reduction (CCER) projects. In terms of carbon reduction, enterprises can achieve carbon emission reduction through the advancement of the production technology and implementation of emission reduction technology or the development of CCER projects. Additionally, enterprises with insufficient quotas can purchase the carbon quota in the carbon market for realizing carbon compliance. It is summarized that three types of measures help assist enterprises to realize carbon compliance on schedule, which include appropriate carbon reduction measures, optimal market participation strategies, and suitable CCER projects. Therefore, this study classified the risk factors leading to compliance failure into four categories of factors, namely, carbon market, carbon quota, carbon emission reduction technology, and CCER recognition, respectively. Table 1 provides the specific risk-causing indicators based on the factor identification process, which lays the foundation for subsequent quantitative evaluation of carbon compliance failure risk.

3.2. Hierarchical division of risk factors causing carbon compliance failure based on the ISM method

Based on the identified results of the risk factors in Section 3.1, the adjacency matrix (as shown in Table 2) and reachability matrix (as shown in Table 3) of the influencing factors of carbon compliance failure were generated; correspondingly, Figure 2 shows the hierarchical diagram of a risk factor with the aid of the interpretation structure model.

As shown in Figure 2, the risk factors leading to the failure of enterprises' carbon compliance were divided into four levels, where the division results conformed to the actual situation. It was found that low-level factors will affect high-level factors. For example, the improper operation of personnel at the fourth level may lead to equipment loss at the third level. In addition, the decrease in the free initial quota due to market development exerts an influence on the free quota provided by the government and its allocated way. Moreover, third-level factors, such as asymmetric market information, the change in CCER offset ratio, the deviation in identified CCER's carbon reduction amounts, and the decrease in the number of CCER projects, will force the emission control enterprise to passively enter the carbon market for purchasing the carbon quota in order to complete the quota settlement and payment. This will lead to the over-high carbon quota price. Similarly, the equipment loss and the difficulty in the production technology transformation of the enterprise will impair the implementation of the carbon reduction technology, which is adverse to the realization of the expected carbon reduction.

3.3. Probability prediction model of enterprises' carbon compliance failure risk based on the Bayesian network model

Based on the aforementioned determined hierarchical relationship among risk factors, and considering the advantages of the Bayesian network with its low data requirement and intuitive and great inferential capabilities based on existing information, in this research, the Bayesian network model was adopted to establish the risk probability prediction model of enterprise's carbon compliance failure. The Netica software is a Bayesian network tool with a user-friendly interface, which offers a range of practical features, such as parameter learning, Bayesian inference, and sensitivity analysis. Compared with other software, it is capable of realizing a visual display of the posterior probability and occurrence probability calculation of specific events. Therefore, the Netica software was first chosen to establish the preliminary Bayesian network based on the aforementioned hierarchical diagram of risk factors. Second, combined with an on-site survey and literature review, the risk factors causing the carbon compliance failure of the enterprise were collected and organized, such as the government policy, carbon market fluctuation, carbon reduction situation of the enterprise, and the identification of the CCER offset magnitude. Finally, the Bayesian network-based probability prediction model of the enterprise's carbon compliance failure risk was formulated by using the self-learning process of the Netica software (as shown in Figure 3), which is capable of calculating the occurrence probability of the enterprises' carbon compliance failure risk under various risk factors.

4. Case study

4.1. Determination of targeted enterprise

In order to better reflect the accuracy and rationality of the interpretive structure model and Bayesian network model in the risk evaluation of carbon compliance failure, in this study, the first batch of six wellknown domestic enterprises, including in the carbon market management, was selected as the research objects, i.e., steel, electric power, petrochemical, cement, aviation, and electrolytic aluminum. Referring to the annual reports and social responsibility reports in the last 5 years released by six enterprises, the production and operation situation, carbon emission, and carbon asset management of these six enterprises were analyzed and evaluated. Finally, the risk evaluation of carbon compliance failure for six enterprises was accomplished based on the aforementioned methods.

4.2. Risk probability prediction of enterprises' carbon compliance failure

Based on the production and operation status and actual carbon emission amounts of the six enterprises, combined with the relevant policies of free carbon quota in the region, the free carbon emission quota and the quota gap to be paid were calculated (as shown in Figure 4). As shown in Figure 4, the pressure of quota clearance and the difficulty of carbon compliance were found to be significantly different among the six enterprises. For example, although the chemical enterprise owns the largest free allowance of 153.945 million tons, its quota gap is relatively large due to the high carbon emissions during their production and operation processes, at 18.615 million tons. Conversely, the airline enterprise has the smallest free quota of 13.127 million tons; correspondingly, its quota clearance pressure is also small due to the low annual carbon emission at 15.442 million tons.

With the background of the 'dual carbon goals', the amount of free basic quota for enterprises will be reduced. In order to ensure the smooth realization of carbon compliance, enterprises need to design and execute reasonable and effective quota settlement measures based on their own carbon asset management and external carbon market environment. Table 4 shows the carbon asset management of these six enterprises. Among them, the chemical enterprise pays attention to carbon asset management and widely participates in various fields, since it has the greatest pressure on quota clearance. Conversely, the aviation enterprise attaches importance to its own emission reduction potential due to the small quota gap, leading to the inactive participation of the carbon market and CCER market.

Figure 5 shows the implementation of three types of measures for the six enterprises. In order to effectively reduce the carbon compliance cost, all six enterprises chose to clear the quota gap without the reserve space, resulting in inelasticity in carbon asset management and limited ability to resist the compliance failure risk. Among them, the steel and electrolytic aluminum enterprises adopted production technology innovation for realizing carbon compliance due to a large number of quotas that needed to be cleared and the obvious progress of production technology. Their carbon reduction amounts were 4.70 million tons and 7.36 million tons, respectively. Conversely, electric power and chemical enterprises filled the quota gap by purchasing the quota. This is because the local carbon market was improved with transparent trading, where the purchase amounts reached 5.54 million tons and 8.22 million tons, respectively. In addition, the steel, electric power, and chemical enterprises finished the part of quota settlement by developing CCER projects due to the limited number of CCER projects and the controversy in the identification of carbon reduction, where the offset amounts were 70, 300, and 6.5 million tons, respectively.

Based on the aforementioned carbon asset management measures of the six target enterprises, combined with the carbon quota policy, carbon market price, carbon reduction technology implementation, and CCER project situation of the local region, the occurrence probability of various risk factors corresponding to six enterprises was first predetermined. Next, they were inputted into the probability prediction model of the enterprise's carbon compliance failure risk based on the Bayesian network model. Finally, the probability of enterprises' carbon compliance failure was calculated, which is shown in Figure 6.

As depicted in Figure 6, the compliance failure probability of steel, electric power, cement, chemical, aviation, and electrolytic aluminum is 69.7, 84.1, 84.4, 62, 76, and 65.1%, respectively. As mentioned above, their clearance volume is equal to the gap between the carbon emission and quota, without the reserved space. This leads to the limited ability to resist the compliance failure risk, which is also the main reason why the compliance failure probability of the six enterprises is generally high. In addition, it is concluded that the limited carbon asset management measures may also result in carbon compliance failure. For example, the cement and aviation enterprises have a high probability of failure due to their excessive reliance on their own technological innovation, although their gap is small. Conversely, the chemical enterprise has a large clearance pressure; however, its compliance failure probability is the lowest because it actively participates in the carbon market and develops CCER projects; meanwhile, its carbon reduction technologies are relatively mature.

4.3. Risk evaluation of the enterprise's carbon compliance failure

The compliance failure risk evaluation of the enterprise is not only affected by the probability of compliance failure but also the loss caused by compliance failure. Currently, the penalty institution for an enterprise's carbon compliance failure is slightly different across the country, including two forms: economic punishment and non-economic punishment. Among them, economic punishment means penalties of 3–5 times the average carbon price based on the gap value. The non-economic punishment includes the inclusion of credit history, the cancelation of financial assistance, and the reduction of the free carbon quota in the next year. In order to realize the quantitative failure risk assessment of the six enterprises, it was assumed that the non-economic penalty can be converted into an economic penalty. The economic loss caused by the carbon compliance failure of six enterprises was calculated based on the gap value. Figure 7 demonstrates the economic loss and risk value of the six enterprises.

As shown in Figure 7, the chemical enterprise has the highest risk value of compliance failure, at 2,276.06; correspondingly, the aviation enterprise has the lowest risk value, at only 273.05. Although the chemical enterprise has the most comprehensive carbon asset management measures and the strongest ability to resist the failure risk, leading to the lowest failure probability, its economic cost caused by compliance failure is the highest (36.7107 million yuan) due to the largest gap, resulting in the highest risk value. As for the aviation enterprise, its carbon quota gap is the smallest, leading to a low economic penalty and risk value, although its failure risk probability is higher.

5. Risk control measures generation for carbon compliance failure

5.1. Identification of major risk factors based on the sensitivity analysis method

Considering that various risk factors exert different influences on the carbon compliance failure of an enterprise, the quantitative evaluation of the impact caused by risk factors on carbon compliance and the accurate identification of critical risk factors are of great importance for enterprises in order to design subsequent risk control measures and execute low-carbon rectification. The occurrence probability of risk factors was designed as three levels: 0, 50, and 100%; moreover, the difference between the maximum and minimum occurrence

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probability of carbon compliance failure was defined as the sensitivity degree. Based on the risk probability prediction model formulated in section 3.3, the sensitivity degree was calculated for reflecting the influence of risk factors on the occurrence probability of the enterprises' compliance failure. Table 5 provides the occurrence probability of carbon compliance failure and factor sensitivity degree of the six enterprises under the fluctuation of risk factors.

As shown in Table 5, the occurrence probability of an enterprise's compliance failure will change with the variation in the occurrence probability of the risk factors. For example, at three probability levels of CCER offset reduction, the occurrence probability of carbon compliance failure is 25.7, 23.6, and 21.6%, respectively. Similarly, accompanied by the change in the occurrence probability of initial carbon quota reduction caused by varying allocation methods, the occurrence probability of compliance failure reaches 25, 22, and 20.9%, respectively. The comparison results of the sensitivity degree among all the risk factors demonstrated that three risk factors, including the asymmetry of trading information, the free quota reduction caused by the carbon market development, and the deviation in the identification of carbon reduction of CCER projects, exert a significant influence on carbon compliance, with the sensitivity degrees of 9.4, 6.6, and 5.2%, respectively. Therefore, they have been identified as critical risk factors causing carbon compliance failure; correspondingly, effective countermeasures are needed to be generated in order to raise the success rate of the enterprises' carbon compliance.

5.2. Risk control measures for carbon compliance failure of enterprises

To reduce the failure risk of enterprises' carbon compliance, three types of control measures have been proposed corresponding to the three critical risk factors identified in section 5.1, which are as follows: (i) For the asymmetry of carbon market information, on the one hand, the enterprise should comprehensively investigate and analyze the current situation of the local carbon market; moreover, combined with the fluctuation of the carbon price, the enterprise should own enough quota reserve under the low-carbon price. On the other hand, the daily monitoring of the local carbon market should be strengthened, and the daily trading information list of the carbon market should be established in order to generate suitable trading strategies. (ii) In view of the reduction of the free quota caused by the carbon market development, first, enterprises should pay attention to the research and application of CCUS technology and promote the realization of major breakthroughs in green and low-carbon technology. Second, a clean and low-carbon energy supply system should be established, and the energy utilization efficiency of the equipment should be improved. Finally, the enterprise needs to activate the carbon sink projects and participate in the carbon market for generating additional carbon asset value. (iii) With regard to the deviation in the identification of CCER's carbon reduction, based on actively participating in the CCER market and thoroughly understanding the trading rules and the supply and demand situation of the CCER projects, the enterprise should complete the accurate measurement of the CCER emission reduction through the CCER technology management and in-depth research of the CCER methodology. In addition, the combination utilization of the CCER purchase, agreement transfer, listing transaction, and auction should obtain more concerns.

6. Conclusion

In this study, an innovative combination of interpretive structural modeling and Bayesian network algorithm was used to quantitatively evaluate the occurrence probability and risk value of certain enterprises' carbon compliance failure. The obtained results demonstrated that the compliance failure probability of steel, electric power, cement, chemical, aviation, and electrolytic aluminum is generally high, at 69.7, 84.1, 84.4, 62, 76, and 65.1%, respectively. This is because their clearance volume is equal to the gap between the carbon emission and quota, without the reserved space, leading to the limited ability to resist the compliance failure risk. Moreover, the critical risk-causing factors were identified based on the sensitivity analysis method, which is beneficial to help the enterprise design the risk control measures and raise the success rate of carbon compliance. Finally, three risk factors, including the asymmetry of trading information, the free quota reduction caused by the carbon market development, and the deviation in the identification of carbon reduction of CCER projects, were found to exert a large influence on carbon compliance, with sensitivity degrees of 9.4, 6.6, and 5.2%, respectively. Compared to the traditional qualitative risk assessment method, the proposed evaluation model is capable of realizing the quantitative evaluation of failure risk based on the comprehensive investigation and analysis of the production and operational situation and the carbon asset management of the enterprise, which provides effective technical support to enhance an enterprise's compliance awareness and improve low-carbon competitiveness. However, this model still faces some issues that require further improvement. First, as the national carbon quota clearance is still in its infancy, the information on relevant enterprises involved in carbon compliance is limited. There is a serious lack of relevant cases on enterprise compliance failure, which affects the rationality of the ISM method and Netica software. Second, the limited availability of data and information on carbon asset management and the participation situation in the carbon market of the target enterprise is not conducive to quantitative evaluation of the impact of risk factors on the carbon quota clearance. Therefore, it is crucial to accomplish a more thorough investigation of enterprises to improve the accuracy of compliance failure risk assessment. Finally, the model mainly focuses on the risk evaluation of the enterprises' compliance failure and neglects how to improve their compliance performance by designing a rational carbon asset management strategy. In the future, it needs to select the appropriate carbon reduction measures, design optimal market participation strategies based on an accurate prediction of the carbon price, and implement suitable CCER projects.

Data availability statement

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

Author contributions

XW: software, formal analysis, and writing—original draft. YX: supervision, conceptualization, and methodology. WL: validation. All authors contributed to the article and approved the submitted version.

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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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