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RESEARCH ARTICLE

The impact of high-tech product export trade on regional carbon performance in China: the mediating roles of industrial structure supererogation, low-carbon technological innovation, and human capital accumulation

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Abstract

The role of expanding the proportion of high-tech products in the export trade of various countries to identify the appropriate export structure has gradually attracted the attention of governments and scholars. While there is some knowledge on how high-tech product exports affect carbon dioxide emissions, the mechanisms involved in that link have not been adequately addressed in previous studies. This study is based on China's inter-provincial panel data from 2006 to 2017 and uses the stepwise regression method and the bootstrap method to systematically investigate the mediating effects of industrial structure supererogation, low-carbon technological innovation, and human capital accumulation, operating in the impact of high-tech product export trade on regional carbon performance. Since the Pesaran's CD test and the P&Y slope homogeneity test confirm the presence of cross-sectional dependence and slope heterogeneity in the panel data, we use the CADF and CIPS unit root tests to verify the stationarity of the variables and therefore employ the CCEMG and DCCE estimators for regression estimation. The research results show that high-tech product exports can help improve regional carbon performance. The mediating variables, industrial structure supererogation, low-carbon technological innovation, and human capital accumulation separately have positive and complete mediating effects on the link between high-tech product export trade and regional carbon performance. The research results highlight the important part of expanding high-tech product exports in improving regional carbon performance and have significance in promoting China's green and low-carbon transition.

Keywords High-tech product export · Regional carbon performance · Industrial structure supererogation · Low-carbon technological innovation · Human capital accumulation · Mediation effect

Introduction

China's rapid economic growth has been accompanied by a strong expansion of exports since its reform and opening up. According to WTO statistics, China reached a new milestone in the development of export trade and was ranked as the world's leader in export trade in 2013. This is a major achievement to China's adherence to trade opening and economic globalization. However, export trade characterized by low added value and low technological content has intensified the growth of China's carbon dioxide emissions, causing China's carbon trade to account for more than 50% of the global carbon trade (Liddle 2017). As a result, China has been recorded as the world's largest carbon dioxide emitter. Yan and Yang (2010) found that 10.03–26.54% of China's annual carbon dioxide emissions are generated when exporting goods, and Liu et al. (2017) found that accumulated carbon dioxide emissions embodied in exports accounted for approximately 30% of the total emissions in China during 2002–2011. By using trade between China and the USA as an example, Xu et al. (2009) demonstrated that carbon dioxide emissions embodied in the exports from China to the USA represented approximately 8–12% of China's carbon dioxide emissions. Zhang et al. (2021) pointed out that the energy intensity of Chinese exports was higher than that

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of domestically consumed products, which further reflected the tendency of China's export trade structure to be highly energy-dependent. Moreover, the signing of the Kyoto Protocol also reflected the pressure on China's international trade competitive position that the rapid growth of greenhouse gas emissions has brought. For this reason, the export trade structure is in urgent need of transformation. The export of technology-intensive, energy-efficient products urgently needs to replace the export of high-energy, high-pollution, and low-tech products (Liu et al. 2020), thereby bringing greater opportunities for improving the country's international status and reducing carbon dioxide emissions.

While the extant literature provides useful insights into the impact of export trade structure on carbon dioxide emissions (Liu et al. 2018, 2020; Tang et al. 2016; Zhang et al. 2021), there has been the generation of limited knowledge on the impact of the expansion of high-tech product exports in a region on the total carbon performance of the region. Since China has officially entered the strategic track of achieving peak carbon dioxide emissions, China's provincial regions will have to consider the issue of achieving peak carbon dioxide emissions. For this reason, this study regards the provincial region as a unit to explore regional carbon dioxide emissions. Although there exists literature on high-tech products and regional carbon performance (Wang and Zhao 2020; Zhang et al. 2008; Su et al. 2020; Dong et al. 2020; Wang et al. 2020), there is still no uniform definition on high-tech products and regional carbon performance. In China, there are basically two definitions of high-tech products in use. The first classifies all products of the high-tech industry as high-tech products. The second combines the characteristics of China's high-tech industry and solicits the opinions of management personnel from relevant ministries, commissions, bureaus, universities, research institutes, and other units and relevant experts. The Ministry of Science and Technology promulgated that high-tech products be divided into nine categories, namely, computer and communication technology, life science technology, electronic technology, computer integrated manufacturing technology, aerospace technology, optoelectronic technology, biotechnology, material technology, and other technologies. This study chooses the second method to define high-tech products. To enhance China's position in the global value chain division of labor and trade competitiveness, promoting the export of high-tech products has become the main direction for upgrading the export structure. The export value of China's high-tech products and their proportion in total merchandise exports in the period 2006–2017 are shown in Fig. 1.

To more accurately understand the regional carbon dioxide emissions and propose corresponding green and low-carbon development suggestions, it is significant to select appropriate regional carbon performance evaluation indicators. This study defines regional carbon performance as the reciprocal of carbon emission intensity. Carbon emission intensity is one of the widely used indicators of carbon dioxide emissions in the world, and is expressed by the carbon dioxide emissions per unit of GDP in a given region. Therefore, the greater the carbon emission intensity, the lower will be the regional carbon performance; conversely, the lower the carbon emission intensity, the higher the regional carbon performance.

To reduce the increase in carbon dioxide emissions caused by export trade, the improvement of energy efficiency has always been considered by scholars as an inevitable choice. Su and Thomson (2016) found that China contributed around 1000 Mt of carbon dioxide emissions each year from 2006 to 2012 through its exports to numerous countries, while the energy efficiency improvements helped reduce emissions by about 2469 Mt of carbon dioxide embodied emissions in exports. During the COVID-19 pandemic, the empirical research of Wang and Wang (2020) concluded that in order to prevent the retaliatory growth of carbon dioxide emissions, expanding trade and increasing energy consumption efficiency are still important driving factors for reducing carbon dioxide emissions. Meanwhile, energy efficiency improvements in certain industries are also

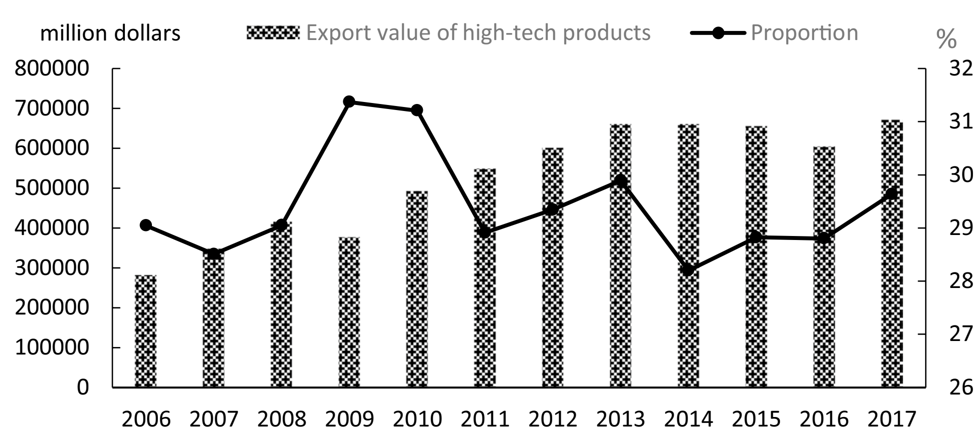

Fig. 1 The export value of China's high-tech products and their proportion in total merchandise exports (2006–2017). Source: The annual data of China Statistical Yearbook of Science and Technology and China Statistical Yearbook

the key to reducing greenhouse gas and air pollution emissions. For instance, China's cement industry is one of the largest energy-consuming, and greenhouse gas and air pollutant emitting industries, Zhang et al. (2015) showed that improving energy efficiency aids a reduction in the emission of carbon dioxide. Other sectors, including agriculture (Shabani et al. 2020), electricity (Babatunde et al. 2020), and transportation (Isik et al. 2021) combined with energy efficiency improvements will also contribute to carbon dioxide reductions.

Although researchers recognize that improving energy efficiency is an important mechanism for reducing the increase in carbon emissions due to export trade (Ren et al. 2014a; Dogan and Inglesi-Lotz 2020; Khan et al. 2020; Yang et al. 2020), limited studies have been conducted to analyze this mechanism. There are two ways that are usually considered to be effective for improving energy efficiency. One way is to improve the position of the industry in the global value chain, that is, to promote the supererogation of the industrial structure (Tian et al. 2019). The supererogation of the industrial structure is an inevitable choice to improve energy efficiency and solve the environmental energy pressure (Hu et al. 2020). Kahrl and Roland-holst (2008) linked exports, industrial structure, and the environment and pointed out the importance of focusing on this linkage for the sustainable development of China's economy. It begs the question, however, whether the export of high-tech products affects carbon dioxide emissions through the supererogation of the industrial structure. Another way of improving energy consumption efficiency is low-carbon technological innovation (Ren et al. 2014b). The growth in exports has led to lower carbon emissions associated with the use of advanced technologies (Khan et al. 2020) and, therefore, will the export trade of high-tech products promote the independent research and development of local technologies and the absorption of international technology spillovers to achieve low-carbon technological innovation? Moreover, technology alone cannot achieve a green economy; skills are the basic conditions for future economic and social development (Sabadie 2014). Therefore, this study considers the impact of industrial structure supererogation and low-carbon technological innovation on regional carbon performance, as well as the impact of human capital accumulation on carbon emissions. In the early stage of its economic development, China's high-tech products were mainly distributed in the eastern coastal areas. Human capital is relatively concentrated in these areas. Then, what is the relationship between the export of high-tech products and the accumulation of human capital? Does the development of high-tech product export trade affect carbon dioxide emissions through human capital?

The answers to these questions will aid the clarification of the impact mechanism of high-tech product export trade on regional carbon performance. This study adds particularly the following novelties to fill the gaps in the extant literature: first, the study uses China's provincial regional panel data to explore the impact of high-tech product export trade on regional carbon performance. This will bring our attention to the effect of structural upgrading of export trade on improving regional carbon performance. Second, this study provides new thinking on the mechanism of the impact of high-tech product exports on regional carbon performance, introducing three dimensions of industrial structure supererogation, low-carbon technological innovation, and human capital accumulation from the perspective of energy efficiency improvement. To investigate whether high-tech product export trade can improve regional carbon performance through industrial structure upgrading, low-carbon technological innovation, and human capital accumulation, we construct a mediating effect model to test the role of transmission in the theoretical mechanism. Last, taking 30 provinces in China as the research object, this study analyzes the nexus between high-tech product export trade and regional carbon performance and puts forward important guidelines for policy makers to achieve China's goal of reaching the peak of carbon dioxide emissions as proposed in the Nationally Determined Contributions.

Literature review

The relationship between the export trade of high-tech products and regional carbon performance

Numerous scholars point out that export trade is an important source of carbon dioxide emissions from emerging economies (Yan and Yang 2010; Liu et al. 2017; Shahzad et al. 2020; Wang et al. 2020; Shao et al. 2020). Based on the comparative advantage theory driven by factor endowments, Cole (2006) indicated that trade increases the per capita energy consumption of exporting countries because the scale effect of export trade exceeds the technical effect. Kahrl and Roland-holst (2008) confirmed that exports are the largest source of China's energy demand growth. They proposed that addressing the economic and environmental challenges created by rapid energy demand growth will require a more comprehensive, supply chain perspective on energy–export linkages. Sadorsky (2011) analyzed the impact of trade growth on the energy demand in the Middle East and showed that a 1% increase in per capita exports increases per capita energy consumption by 0.11%, while a 1% increase in per capita imports increases per capita energy consumption by 0.04%. In addition, export trade will not only increase embodied carbon emissions but also increase total carbon dioxide emissions. According to Weber et al. (2021), trade liberalization may increase global emissions.

Those findings, therefore, highlight the importance of considering trade when designing carbon dioxide reduction strategies. Thus, some scholars analyzed the impact of export trade on carbon dioxide emissions from the perspective of increasing the technical content of export products. For instance, Wang et al. (2020) demonstrated that technological progress in China's high-tech products field is conducive to reducing embodied carbon emissions from China's export trade to developed countries. Waheed et al. (2020) indicated that the Gulf Cooperation Council countries realized that rapid economic growth has an important relationship with a large number of international transactions and energy consumption and found that turning to the export of high-tech products helps reduce total energy demand, energy intensity, and carbon emissions. Based on these arguments and similar economic development models between China and the Gulf Cooperation Council countries, the following hypothesis is proposed:

Hypothesis 1. (H1): Expanding the export trade of high-tech products helps improve regional carbon performance.

The mediating role of industrial structure supererogation

The supererogation of the industrial structure is based on the rationalization of the industry. It is a process of evolution towards a higher level of comprehensive productivity and technical structure, reflecting the general high-tech process of the industry. In the course of economic development, trade openness has expedited the process of structural upgrading (Jena and Barua 2020). Na (2019) based his research on five countries in Africa and found that expanding the export trade of technological products can help realize the growth of the technology sector and promote the upgrading of existing industries. To achieve sustainable economic development, scholars not only consider the driving role of industrial production technology in economic growth but also incorporate resource and environmental factors into it, emphasizing the importance of industrial green technology. Wang and Xin (2020) used the viewpoint of ecological economics to analyze the positive impact of China's trade with participating countries of the "Belt and Road" initiative on the energy efficiency of China's logistics industry and found that China's exports to these countries are of great significance to the realization of low-carbon industrial transformation and there is room for further release. This is consistent with the view that "Made in China 2025" emphasizes that industrial greening is an important entry point for industrial structure supererogation. Zhao et al. (2019) also showed that the excessive dependence on resource industries will inhibit the progress of the industrial structure, and efforts to transform resource-intensive industries into technology-intensive industries can support sustainable development.

The relationship between industrial structure and regional carbon performance has been extensively researched. Scholars believe that the transformation of industrial structure is an important determinant of reducing industrial carbon dioxide emissions, especially for the situation where China's production and consumption structure has caused upward influences in changes of CO_2 (Wang and Zhou 2020; Tian et al. 2019). Data show that the three major industries and the secondary industry's carbon emission reductions due to structural adjustment accounted for 28.22% and 4.26% of China's total carbon emission reductions, respectively (Zhang et al. 2017). Industry is the main user of energy and an important contributor to global carbon dioxide emissions. From the transformation and upgrading of the internal structure of the industry, Xu et al. (2016) indicated that optimizing the structure of industrial enterprises is the top priority strategy for reducing carbon dioxide emissions in the region. From the perspective of the change of leading industries, Zhang and Ma (2020) stated that with the development of an economy, the transformation of industrial sectors from resource-intensive to labor-intensive and then to technology-intensive and capital-intensive is conducive to the decline of carbon emission intensity. Meanwhile, in the transformation of industrial structure, scholars have also realized the importance of the development of high-tech industries. Li et al. (2019) employed the STRIPAT-Dubin model of spatial panels with data on Chinese provinces to conclude that high-tech industries have an inhibitory effect on carbon emissions in both local and neighboring regions. Taking the comprehensive utilization of resources and environmental protection industries as examples, Xu and Lin (2018) discovered that the rapid development of high-tech industries is beneficial to the application of a plethora of energy-saving equipment and technologies such as waste power generation technology and automobile exhaust gas post-combustion technology. Although scholars have realized the importance of industrial structure transformation and the development of high-tech industries in reducing carbon emissions, they rarely see the impact of industrial structure supererogation in the relationship between high-tech product export trade and regional carbon performance. Therefore, the following hypothesis is proposed:

Hypothesis 2 (H2): The supererogation of the industrial structure mediates the relationship between the export trade of high-tech products and regional carbon performance.

The mediating role of low-carbon technological innovation

With the increasingly fierce global competition, export companies tend to choose to increase productivity through technological progress to obtain international competitiveness and corresponding profits. Perla et al. (2015) indicated that with the increase in export opportunities, the redistributive effect of open trade accelerates the opportunity for enterprises to adopt new technologies and thus accelerates the speed at which exports promote technology diffusion. Some scholars also agree with the existence of learning-by-exporting. Esquivias and Harianto (2020), for example, argued that export activities contribute to promoting technological progress, because export companies need to compete in foreign markets. Mazzi et al. (2020) confirmed that the productivity of export companies has increased after entering the international market. Benkovskis et al. (2020) further stated that corresponding to export activities that generate high value-added in the global value chain, greater productivity increases. In addition, technological progress is not only used to increase productivity. Through reliance on the theory of comparative advantage, Song and Wang (2017) showed that technological progress is also an important technology to improve China's comparative advantage in international competition. Similarly, green technological progress is as essential as productive technological progress to ensure energy security and enhance international competitiveness. Therefore, facing the situation of increasing environmental pollution, scholars indicated that it is necessary to vigorously promote the progress of green technology and increase the technological content of exports.

Numerous scholars have validated the existence of the pollution haven hypothesis and explained why China's large-scale export trade has led to China becoming a "pollution haven" (Sun et al. 2017; Solarin et al. 2017; Shahbaz et al. 2019). In this regard, Ren et al. (2014b) indicated that low-carbon technology development contributes to averting China from being a pollution haven. The development direction of low-carbon technology includes renewable energy technology, energy-saving emission reduction technology, and decarbonization technology. For example, Khan et al. (2020) showed that increasing the proportion of renewable energy consumption to primary energy consumption is one of the effective ways to reduce carbon dioxide emissions. To achieve sustainable development, countries around the world are deploying environment-related innovations, such as renewable energy technologies. Abbasi and Adedoyin (2021) revealed that the development of renewable energy technologies to mitigate CO_2 emissions would be useful for China's environmental sustainability goal. Abbasi et al. (2021a) indicated that using renewable energy and avoiding fossil energy can minimize electricity production cost, alleviate the energy crisis, and be highly beneficial for Pakistan's economic growth. Nathaniel et al. (2020) also recommended that limiting the "dirty" energy sources and substituting them with renewable energy sources can promote environmental sustainability. Moreover, Zang et al. (2021) found that technological progress in production and energy conservation played a significant role in reducing industrial carbon emission intensity. The rapid economic growth in the early stages of the development of emerging economies is closely related to energy consumption, including in China and the Gulf Cooperation Council countries. Therefore, improving energy efficiency is very important. In this regard, Waheed et al. (2020) proposed that the decisive role of technology in improving energy efficiency is very interesting and innovative, allowing the latest technology and high-tech products becoming economic and environmental policy factors. Although the literature proposed the role of technological progress in reducing carbon emissions in many aspects, they did not consider the impact of low-carbon technological innovation between high-tech product export trade and total regional carbon performance. Based on these, the following hypothesis is proposed:

> Hypothesis 3 (H3): Low-carbon technological innovation mediates the relationship between the export trade of high-tech products and regional carbon performance.

The mediating role of human capital accumulation

Many studies have found evidence that trade liberalization improves enterprise production efficiency by increasing the accumulation of human capital. As an example, Mulliqi et al. (2019) used Tobit and Fractional Logit methods to prove that export companies can increase productivity by hiring more skilled and competent employees and increasing the labor force with higher education will also reduce their relative costs and improve the international competitiveness of the company. Taking into account the needs of export companies for higher levels of human capital, scholars have also studied the relationship between export companies and human capital accumulation from different perspectives. From the perspective of export product structure, Blanchard and Olney (2017) showed that the export of skill-intensive products will increase the education level of the labor force, while the export of agricultural products and low-skill-intensive products will reduce the education level of the labor force. The reason for this phenomenon is that the growth of exports of skill-intensive enterprises will increase the demand for highly skilled talents, thereby promoting the improvement of the average education level of society. From the perspective of resource endowments, Hou and Karayalcin (2019) found that if an economy initially uses a large amount of resources for the production of primary products, the expansion of primary product exports will reduce the accumulation of human capital. From the perspective of different regions, Li (2018) indicated that the level of human capital accumulation in regions dominated by high-tech product exports is higher than that in regions dominated by low-tech product exports and the export shock of high-tech products will increase high school and university enrollment, while the export shock of low-tech products will restrain both. In addition, the scope of human capital is not only the education level of the labor force but also includes the on-the-job training of employees, the work experience of senior managers, and the accumulation of learning-by-doing (Mulliqi et al. 2019; Salim et al. 2017).

Human capital is a key factor in enhancing economic competitiveness and achieving sustainable development. Household energy consumption awareness plays a decisive role in carbon emission reduction. Shahbaz et al. (2019) confirmed that the impact of education on energy demand is negative. They stated that in the USA, school education can increase household energy efficiency awareness, and educated people are willing to use new forms and new energy, thereby reducing energy consumption. Khan et al. (2020) believe that the higher the level of education, the more inclined to adopt a sustainable lifestyle someone would be. This view is consistent with the concept of the "energy culture" framework proposed by Stephenson et al. (2010). When consumers change their values, wishes, understandings, and beliefs about the importance of energy, they will choose to purchase more efficient energy equipment, such as household heating equipment. From a company's internal perspective, company productivity and low-carbon awareness of companies play a key role in reducing carbon emissions. Cieplinski et al. (2021) proved that the reduction in working hours caused by the increase in labor productivity can help reduce carbon emissions. Abdelaziz et al. (2011) indicated that the low-carbon awareness of a company comes from the company's senior management, whether the company's senior management regularly participates in the plan of energy management projects to achieve energy management goals. For example, on the premise of not affecting production output and quality, energy costs and negative environmental impacts can be minimized. Based on the above analysis, it can be found that human capital accumulation is playing an increasingly important role in the development of the green economy and export trade, but the impact of human capital accumulation growth in a region between high-tech product export trade and regional carbon performance has been rarely analyzed. Therefore, the following hypothesis is proposed:

Hypothesis 4 (H4): Human capital accumulation mediates the relationship between the export trade of high-tech products and regional carbon performance.

The theoretical model that underlies these hypotheses as a whole will be tested (see Fig. 2).

Methodology and data

Model specification

To verify hypothesis H1, the impact of high-tech product export trade on carbon emission intensity, this paper constructs the following basic panel data model:

$$CI_{it} = \alpha + \beta_1 H\_ex_{it} + \gamma_j \sum X_{itk} + \varepsilon_{it} \tag{1}$$

Here, the explained variable CI_{it} represents the carbon emission intensity of province i in year t, the explanatory variable $\boldsymbol{H\_ex}_{it}$ indicates the export trade of high-tech products of province i in year t, X_{itk} indicates k control variables, and ε_{it} is a random disturbance item.

To verify hypotheses H2—H4, we explore the role of high-tech product export trade on regional carbon performance, that is, whether high-tech product export trade promotes carbon emission reduction separately through the mechanisms of industrial structure supererogation,

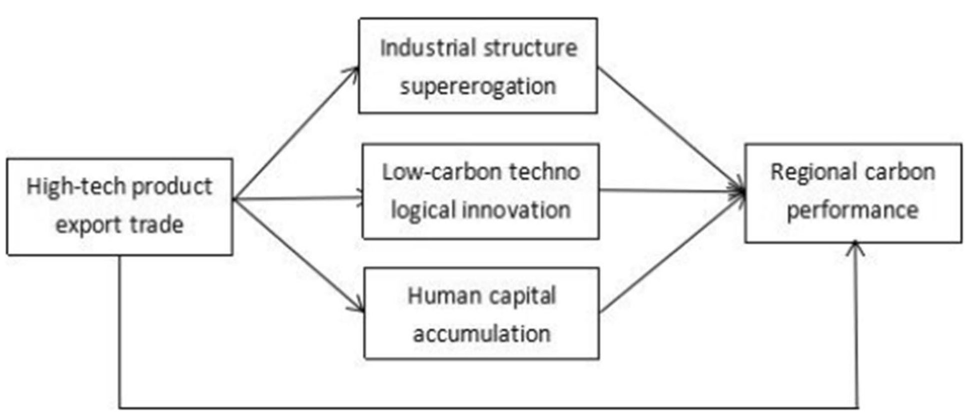

Fig.2 The impact path of high-tech product export trade on regional carbon performance

low-carbon technological innovation, and human capital accumulation mechanism. The investigation determines whether the indirect mechanism is significant in the mediation effect model. The test method is a simple but effective and improved stepwise method. So we introduced the mediating effect model (Baron and Kenny 1986) into the following panel regressions.

$$M_{it} = \alpha + \beta_2 H\_ex_{it} + \gamma_j \sum X_{itk} + \varepsilon_{it} \quad (2)$$

$$CI_{it} = \alpha + \beta_3 H\_ex_{it} + \beta_4 M_{it} + \gamma_j \sum X_{itk} + \varepsilon_{it} \quad (3)$$

Here, M_{it} represents the intermediary variables, which are industrial structure supererogation (IS), low-carbon technological innovation (patent), and human capital accumulation (HC), and β s stands for coefficients.

Data and variable description

Data source

The export trade of high-tech products comes from the China Science and Technology Statistical Yearbook. The data on the education level of employees in each province comes from the China Labor Statistics Yearbook. The investment in environmental pollution control comes from the China Environmental Statistical Yearbook. The data of low-carbon patent applications in each province comes from the incoPat patent database ("CPC = Y02"). The remaining data indicators come from the statistical yearbooks of provinces (autonomous regions and municipalities) from 2007 to 2018. Due to restrictions on the availability of basic data in the Tibet Autonomous Region, Hong Kong, Macau, and Taiwan, in order not to affect the regression results, they were removed from the total sample, and the data of the remaining 30 provincial administrative units in the mainland were retained.

China's provincial carbon emissions data is not explicitly given in the statistical yearbook, but the data are obtained through calculations. Previous literature has pointed out that the total regional carbon emissions include emissions from fossil energy, cement manufacturing, steel, and textile industries, among which fossil energy emissions and cement manufacturing emissions account for more than three-quarters of the total carbon emissions. According to international statistical practices, emissions from industries such as steel and textiles are not considered. Therefore, the total carbon emissions in this study only include fossil energy consumption emissions and cement process emissions, and the total carbon emissions are calculated as the sum of the two sources. Regarding the carbon emissions caused by the burning of fossil energy, this paper mainly calculates the carbon emissions generated by the consumption of coal, oil, and natural gas. According to the IPCC formula and its improvements, the formula for calculating carbon emissions from the three primary energy consumption of coal, oil, and natural gas: $CE_{it} = \sum_{j=1}^{3} E_{itj}\theta_j$, where CE_{it} represents the carbon emissions of the i province in year t, E_{itj} represents the physical volume of the j energy consumption in the i province in year t, j = 1, 2, 3, respectively representing coal, oil, and natural gas, and θ_j represents the carbon emission coefficient of j energy. The emission coefficients of various energy sources are shown in Table 1.

Secondly, the calculation formula for CO2 emissions during the cement industry production process: $CC_{it} = P_{it}\delta$, where CC_{it} represents the carbon emissions of i province in year t, P_{it} represents the cement industry production of i province in year t, and δ represents the cement CO_2 emission coefficient; the value is 0.376. Then, $TC_{it} = CE_{it} + CC_{it}$, where TC_{it} is the total carbon emissions of i province in year t.

Explained variable: carbon emission intensity (CI)

Carbon emission intensity is a relative indicator of carbon emission reduction targets, measured by the proportion of total regional carbon emissions in GDP. Carbon emission intensity is an important indicator of low-carbon economic growth, reflecting carbon emissions and carbon source control capabilities from the perspective of economic structure. The smaller the carbon emission intensity, the greater the carbon emission reduction capability and the higher the regional carbon performance.

Core explanatory variable and intermediate variables

The core explanatory variable of this study is the export trade of high-tech products (H_ex), which is measured by the relative indicator of "the ratio of the export value of high-tech products to the total export value" and represents the upgrading of the export trade structure.

Table 1 Carbon emission coefficients of various types of energy

Energy type j	Coal	Oil	Natural gas
Carbon emission coefficient (t carbon/10,000 tons of standard coal) θj	0.7476	0.5825	0.4435

Source: Energy Research Institute of National Development and Reform Commission. China's sustainable development energy and carbon emission scenario analysis [R]0.2003.05

The intermediate variables are the following three: industrial structure supererogation (IS), low-carbon technological innovation (patent), and human capital accumulation (HC). Specifically, the industrial structure supererogation (IS) is expressed by the method of the angle between the vector of the proportion of three industries and the corresponding coordinate axis. Low-carbon technological innovation (patent) is characterized by the number of low-carbon patent applications per 10,000 people in the province that year. The human capital accumulation (HC) is expressed by the product of the education level and the years of education of employees in the province. The average cumulative years of education for various types of education are set to 0 years, 6 years, 9 years, 12 years, and 16 years (Barro and Lee 2001).

Control variables

Foreign direct investment (FDI) is reflected by the proportion of the actual use of foreign direct investment in each province to the regional GDP to measure the impact of foreign capital inflows on the domestic economy under capital internationalization. Renewable energy (RE) is measured by the proportion of renewable energy in total energy consumption. Renewable energy has been considered as an important energy indicator in the low-carbon economic indicator evaluation system. Environmental regulation (ER) is measured by selecting the proportion of environmental pollution control investment in the region's GDP. Greening (green) is measured by the proportion of green coverage area in the built-up area, which characterizes the changing trend of environmental greening.

The variables' descriptive statistics are presented in Table 2.

Empirical Results

Cross-sectional test and slope homogeneity test

Cross-sectional dependence (CD) could arise in econometric methods of panel data due to omitted common effects, spatial effects, or as a result of interactions within socioeconomic networks (Le and Ozturk 2020). To avoid producing biased and inconsistent estimation results, this study conducts CD test proposed by Pesaran on 30 provincial administrative units in the mainland. The results of CD test shown in Table 3 indicate that the null hypothesis of independent cross-sections is rejected and cross-sectional dependence exists as the *p* values of all variables are less than 0.01.

The results of slope homogeneity test of Pesaran and Yamagata (2008) are given in Table 4. The existence of slope heterogeneity in all models as the null of homogeneity is rejected at 1% level.

Panel unit root tests

The data stationarity is the most basic condition required by the econometric model. In the presence of cross-sectional dependence and slope heterogeneity, the cross-sectionally augmented Dickey-Fuller (CADF) and cross-sectionally augmented IPS (CIPS) unit root tests are superior to other unit root tests in assessing the data stationarity according to Pesaran (2007). Therefore, the CADF and CIPS unit root tests were used to test the stationarity of the data in this study. From the results of CADF and CIPS unit root tests in Table 5, we could conclude that the panel data are stationary at first difference, which meets the basic requirements for model.

Table 2 Descriptive statistics of variables

Variable category	Variables	Mean	Std. Dev	Min	Max
Explained variable	CI	0.94	0.651	0.12	4.26
Explanatory variable	H_ex	16.783	16.482	0.21	77.63
Mediating variables	IS	6.613	0.296	6.01	7.64
	patent	0.684	1.021	0.02	6.63
	HC	9.52	1.221	6.56	13.53
Control variables	FDI	2.504	2.198	0.039	13.875
	RE	11.956	11.200	0.07	49.16
	ER	1.372	0.688	0.3	4.24
	green	37.312	4.445	23.45	48.42

Table 3 The results of CD test

Variable	CD test	*p* value
CI	61.217***	0.000
H_ex	5.82***	0.000
IS	59.427***	0.000
patent	69.467***	0.000
HC	65.13***	0.000
FDI	8.132***	0.000
RE	33.648***	0.000
ER	7.235***	0.000
green	46.121***	0.000

***Represents significance at 1% level

Table 4 The results of slope homogeneity

Models	Statistics	Values
Model 1	$\tilde{\Delta}$	6.790***
	$\tilde{\Delta}_{adj}$	10.519***
Model 2	$\tilde{\Delta}$	6.892***
	$\tilde{\Delta}_{adj}$	10.677***
Model 3	$\tilde{\Delta}$	3.220***
	$\tilde{\Delta}_{adj}$	4.989***
Model 4	$\tilde{\Delta}$	4.993***
	$\tilde{\Delta}_{adj}$	7.735***
Model 5	$\tilde{\Delta}$	3.189***
	$\tilde{\Delta}_{adj}$	5.523***
Model 6	$\tilde{\Delta}$	5.207***
	$\tilde{\Delta}_{adj}$	9.019***
Model 7	$\tilde{\Delta}$	4.195***
	$\tilde{\Delta}_{adj}$	7.266***

***Represents significance at 1% level

Table 5 Panel unit root tests results

Variables	CADF test statistic		CIPS test statistic	
	Level	First difference	Level	First difference
CI	−1.843	−2.192***	−2.360	−3.603***
H_ex	−0.593	−2.233***	−2.046	−2.891***
IS	−1.904	−2.088**	−2.199	−2.861**
patent	−1.285	−2.119**	−2.234	−3.348***
HC	−1.138	−2.438***	−2.303	−3.027***
FDI	−1.212	−2.509***	−2.083	−3.167***
RE	−1.682	−3.494***	−1.071	−3.541***
ER	−1.781	−2.208***	−2.600	−3.597***
green	−1.322	−2.205***	−2.421	−3.157***

***, **, and * denote $p<0.01$, $p<0.05$, and $p<0.1$, respectively

Panel cointegration tests

As it has been confirmed that the variables in the panel data are integrated of order 1, the panel cointegration tests should be done to examine whether there are long-run equilibrium cointegration relationships among the variables. The outcomes shown in Table 6 indicate that there exists cointegration among the variables in each model.

Estimations of heterogeneity parameters

Given the presence of cross-sectional dependency and slope heterogeneity in the data, the popularly used OLS, fixed-effects, and random-effects models are not suitable for this study. Thus, we employ the CCEMG estimator introduced by Pesaran (2006), as its estimates remain unbiased and efficient in the case of CD and parameter heterogeneity.

Table 6 Cointegration results using Westerlund (2007)

Models	Statistics	Values
Model 1	5.695***	0.000
Model 2	6.144***	0.000
Model 3	5.805***	0.000
Model 4	5.860***	0.000
Model 5	5.682***	0.000
Model 6	6.332***	0.000
Model 7	5.793***	0.000

***Represents significance at 1% level

The regression analysis results of the CCEMG estimator are shown in Table 7. Model 1 in the table examines the impact of high-tech product export trade on carbon emissions intensity. The regression coefficient of high-tech product export trade is −0.488 and is significant at 5%, indicating that high-tech product export trade has the effect of reducing carbon emission intensity, thus supporting Hypothesis 1. This finding is supported by Cole (2006), who explained that trade improves environmental quality when the technique effect of export trade dominates the scale effect. This result is similar to Liu et al. (2017), who suggested in optimizing the structure of the export and supply side to reduce the total carbon dioxide emission intensity. Model 2 examines the impact of high-tech product export trade on the supererogation of the industrial structure. The regression coefficient of high-tech product export trade is 0.838 and is significant at the 5% level, indicating that high-tech product export trade promotes the supererogation of the industrial structure. The regression coefficient of the industrial structure supererogation in Model 5 is −0.210 and is significant at the level of 5%, indicating that the industrial structure supererogation can reduce the carbon emission intensity; industrial structure supererogation is conducive to improving regional carbon performance. This finding is consistent with Wang and Zhou (2020) and Su et al. (2020), who showed that adjusting the production structure by promoting industrial upgrading contributes to carbon dioxide emission reduction because the inhibition effect of structural change on carbon emissions presents an increasing marginal trend. The regression coefficient of high-tech product export trade in Model 5 is −0.003 but insignificant. After the introduction of industrial structure supererogation, the coefficient of the effect of high-tech product exports on carbon emission intensity changes from significantly negative to negatively insignificant, indicating that the supererogation of the industrial structure has a complete mediating effect between high-tech product export trade and regional carbon performance. Model 3 examines

Table 7 The results of CCEMG estimation

Explained variable	Model 1 CI	Model 2 IS	Model 3 patent	Model 4 HC	Model 5 CI	Model 6 CI	Model 7 CI
H_ex	−0.488**	0.838**	0.021**	0.340***	−0.003	−0.008	−0.118
	(0.233)	(0.395)	(0.011)	(0.124)	(0.027)	(0.012)	(0.149)
IS					−0.210**		
					(0.102)		
patent						−0.170**	
						(0.075)	
HC							−0.348**
							(0.176)
lagged H_ex			0.004				
			(0.021)				
FDI	0.091	−2.536	−0.085*	0.093	0.071	0.027	−0.042
	(0.099)	(2.51)	(0.052)	(0.066)	(0.087)	(0.064)	(0.049)
RE	−0.231	0.894	−0.173	0.385	0.013	0.036	0.145
	(0.321)	(0.672)	(0.181)	(0.260)	(0.011)	(0.040)	(0.125)
ER	−0.177	0.574	0.070*	0.086**	−0.092	−0.051	−0.024
	(0.147)	(0.527)	(0.044)	(0.038)	(0.059)	(0.042)	(0.037)
green	0.001	0.053	−0.515**	−0.099	0.111	−0.007	0.287**
	(0.001)	(0.052)	(0.224)	(0.197)	(0.140)	(0.032)	(0.130)

Coefficient standard errors are shown in parentheses; ***, **, and * denote $p<0.01$, $p<0.05$, and $p<0.1$,respectively

the impact of high-tech product export trade on low-carbon technological innovation. According to Song and Wang (2017) and Khan et al. (2020), there may exist a bidirectional causality between high-tech product export trade (H_ex) and low-carbon technological innovation (patent). Drawing on Groves et al. (1994), we use a 1-year lagged explanatory variable (lagged H_ex) as an instrumental variable to filter out the opposite causality. The regression coefficient of high-tech product export trade is 0.021 and is significant at 5%, indicating that high-tech product export trade promotes low-carbon technological innovation. The regression coefficient of low-carbon technological innovation in Model 6 is − 0.170 and is significant at the 5% level, indicating that low-carbon technological innovation can reduce carbon emission intensity; low-carbon technological innovation is conducive to improving regional carbon performance. This result is consistent with the findings of Gu et al. (2020) that technological progress can effectively reduce carbon emission intensity and strengthening the development of energy conservation and emission reduction technology patents will be conductive to achieving China's low-carbon development strategy. The regression coefficient of high-tech product export trade in Model 6 is − 0.008 but insignificant. The coefficient of the effect of high-tech product exports on carbon emission intensity changes from significantly negative to negatively insignificant after the introduction of low-carbon technological innovation, indicating that low-carbon technological innovation plays a completion in the mediating effect between high-tech product export trade and regional carbon performance. Model 4 examines the impact of high-tech product export trade on human capital accumulation. The regression coefficient of high-tech product export trade is 0.340 and is significant at 1%, indicating that high-tech product export trade promotes human capital accumulation. This finding is consistent with that of Matyushenko et al. (2020), who showed that the ratio of the number of scientific and technical staff to the working population of the country is most influenced by high-tech exports of the country. The regression coefficient of human capital accumulation in Model 7 is − 0.348 and is significant at the 5% level, indicating that human capital accumulation can reduce carbon emission intensity; human capital accumulation is conducive to improving regional carbon performance. The regression coefficient of high-tech product export trade in Model 7 is − 0.118 but insignificant. Introducing human capital accumulation, the coefficient of the effect of high-tech product exports on carbon emission intensity changes from significantly negative to negatively insignificant, indicating that human capital accumulation has a complete mediating effect between high-tech product export trade and regional carbon performance.

Based on the aforementioned analysis, it is concluded that the export trade of high-tech products affects performance through three parallel paths of industrial structure supererogation, low-carbon technological innovation, and human capital accumulation. For the sake of improving the credibility of the statistical results, the following will verify the effect of multiple intermediaries through the bootstrap repeated sampling method. The bootstrap process samples the sample 5000 times, and the results are shown in Table 8.

According to the results displayed in Table 8, the effect of industrial structure supererogation on the relationship between high-tech product export trade and regional carbon performance is − 0.369 (95% confidence interval does not include 0). Therefore, the mediating role of industrial structure supererogation between the export trade of high-tech products and regional carbon performance is established, and Hypothesis 2 has been verified. In the same way, the mediating role of low-carbon technological innovation between the export trade of high-tech products and regional carbon performance is established, and Hypothesis 3 is verified. The found the important role of technology in the process of analyzing the impact of trade on the environment. Ali et al. (2017) revealed that the trade opening has led to a unidirectional increase in carbon emissions, while changes in trade patterns and energy-saving economic activities can help reduce carbon emissions. Therefore, governments and policy makers will need to focus on export-oriented trade and the upgrading of energy-related policies to ensure the use of new energy-efficient technologies. The mediating role of human capital accumulation between the export trade of high-tech products and regional carbon performance is established, and Hypothesis 4 is verified.

Robustness test

Endogenous issues are important issues that should be considered in regression analysis. However, because it is impossible to put all the factors that affect regional carbon performance into the control variables, some variables will be omitted. At the same time, there may be a bidirectional causality between variables, which will lead to the emergence of endogenous problems. Therefore, to avoid differences in regression results due to different regression methods, method replacement will be used for robustness testing. Based on the basic regression in this study, the static panel data CCEMG estimator is used for regression. The dynamic panel data regression system Dynamic Common Correlated Effects (DCCE) estimator provided by Chudik and Pesaran (2015) will be used to estimate the impact of high-tech product export trade on regional carbon performance. The estimated results are shown in Table 9.

The results confirm that the hypotheses H1–H4 are established, meaning that the research results are not affected by the research methods. Also, in the first-order lagged term of the explained variable, the carbon emission intensity of the lagging period is significant at the level of 5%. This indicates that the issue of regional carbon performance improvement is not a short-term temporary problem but has a certain law of inertia. Therefore, strong measures should be taken to improve regional carbon performance.

In summary, we conclude that (1) the export trade of high-tech products has a significant positive impact on local carbon performance, and (2) in the intermediary effect test, the export trade of high-tech products has a positive effect on industrial structure supererogation, low-carbon technological innovation, and human capital accumulation, and industrial structure supererogation, low-carbon technological innovation, and human capital accumulation have positive effects on local carbon performance. Therefore, high-tech product export trade indirectly improves local carbon performance through industrial structure supererogation, low-carbon technological innovation, and human capital accumulation.

Conclusions and policy implications

This research innovatively analyzes the mechanisms of expanding the export of high-tech products to improve regional carbon performance and came to the conclusion that expanding the export trade of high-tech products reduces total regional carbon emissions through industrial structure supererogation, low-carbon technological innovation, and human capital accumulation. Understanding the mechanisms by which the export trade of high-tech products affects regional carbon performance has important theoretical and practical significance. On the one hand, it expands the endogenous power of the impact of high-tech product exports on regional carbon performance and provides theoretical support for further expansion of high-tech product exports, industrial structure supererogation, low-carbon technological innovation, and human capital accumulation. On the other hand, it helps to reduce the negative environmental impact and energy resource loss caused by

Table 8 Bootstrap test of the mediating effects

Mediating variables	Coef	Std. Err	95% Conf. Interval	
			Lower limit	Upper limit
Industrial structure supererogation	− 0.369	0.078	− 0.522	− 0.216
Low-carbon technological innovation	− 0.309	0.068	− 0.442	− 0.176
Human capital accumulation	− 0.214	0.084	− 0.379	− 0.049

Table 9 Robustness test results of method replacement

Explained Variable	Model 1 CI	Model 2 IS	Model 3 patent	Model 4 HC	Model 5 CI	Model 6 CI	Model 7 CI
Lagged CI	−0.556**				0.996**	0.390**	−0.628**
	(0.269)				(0.473)	(0.170)	(0.258)
Lagged IS		0.610***					
		(0.099)					
Lagged patent			0.918***				
			(0.257)				
Lagged HC				0.725**			
				(0.285)			
H_ex	−0.100**	0.107**	0.117**	0.029**	−0.011	−0.004	−0.586
	(0.425)	(0.044)	(0.052)	(0.014)	(0.018)	(0.02)	(0.724)
Lagged H_ex			1.022				
			(0.719)				
IS					−0.866***		
					(0.303)		
Patent						−0.242***	
						(0.089)	
HC							−0.655***
							(0.158)
FDI	−0.15	11.275	−0.138	0.073	−0.031	0.100	−0.045
	(0.153)	(7.018)	(2.587)	(0.175)	(0.219)	(0.104)	(0.041)
RE	2.640**	29.60**	2.380	0.485	0.003	0.174	0.144
	(1.322)	(14.503)	(2.466)	(0.519)	(0.004)	(0.157)	(0.145)
ER	0.037	-1.739	1.379	−0.007	−0.142*	−0.129**	−0.006
	(0.034)	(3.232)	(1.713)	(0.035)	(0.083)	(0.061)	(0.062)
Green	0.003***	3.626	0.285	0.625	0.009	0.008	0.050*
	(0.001)	(6.449)	(0.533)	(0.491)	(0.008)	(0.006)	(0.029)

Coefficient standard errors are shown in parentheses; ***, **, and * denote $p<0.01$, $p<0.05$, and $p<0.1$, respectively

the long-term export trade of high-energy consumption and low-tech products, improve China's position in the global value chain division of labor, and promote China's low-carbon economic transformation. These findings are similar to those of Hu et al. (2020) and Li (2018), who indicated that reducing energy consumption-intensive but low value-added exports and developing high-tech industries, promoting cleaner production technology, are important for promoting sustainable development. The green transformation of export trade and the realization of China's provincial sustainable development goals can, therefore, be improved by expanding the proportion of high-tech product export trade in the total regional export trade, thereby improving industrial structure supererogation, low-carbon technological innovation, human capital accumulation, and regional carbon performance. Moreover, since China could be regarded as a model for developing countries, the conclusions of our study are helpful for other developing countries to get rid of becoming "pollution havens."

To expand the impact of high-tech product export trade on improving regional carbon performance, this study proposes policy recommendations. First, while vigorously developing the export trade of high-tech products, the export of high-tech products should be developed diversely and comprehensively. Enhancing the technical make-up of high-tech products will not only help expand the technique effect of export trade to exceed the scale effect and improve regional carbon performance but also improve China's position in the division of labor in the global value chain, promote the transformation of export trade from quantity to quality, and accelerate the upgrading of the export trade structure. In addition, the long-standing imbalance in China's high-tech product export structure may become a bottleneck in the vigorous development of high-tech product exports. Therefore, high-tech product exports should be developed in a diversified and comprehensive manner. Meanwhile, to increase the enthusiasm of export enterprises to comprehensively develop the export of high-tech products, governments at all levels should set up special funds to guide and encourage export enterprises to invest in the export trade of high-tech products. Second, giving a constructive play to the intermediary role of industrial structure supererogation, local governments should focus on the part of advanced industrial structure for low-carbon economic development, vigorously develop high-tech industries and modern service industries and promote their structural optimization. Localities should combine their own resource endowments to enhance the competitiveness of embodied high-tech industries, thereby playing an essential part in the development of low-carbon economy through the advanced industrial structure. Industrial structure supererogation promote environmentally friendly behaviors throughout the economy, as Dogan and Inglesi-Lotz (2020) confirmed, taking seven European countries as examples, that higher levels of industrial structure contribute to reductions in the emission levels. Third, giving a major play to the intermediary role of low-carbon technological innovation, the government should encourage and subsidize enterprises, scientific research institutes, colleges, and universities to conduct research and development of low-carbon technology innovation to accelerate the development and universal application of low-carbon technology. Ben Youssef (2020) also proposed that local governments should provide administrative facilities and R&D grants for the creation and use of technological patents. The advanced low-carbon technologies from developed countries should be introduced through the increase in export trade of high-tech products. Low-carbon technologies are more efficient and cleaner than traditional production methods, the same products can, therefore, be produced with less pollution emissions (Ren et al. 2014b). Fourth, the role of human capital shall be brought into full play. Local governments and schools should increase investments in education to improve the level of human capital since it was shown in this study that educated people are beneficial in improving carbon performance. Human capital significantly influences environmental sustainability through awareness related to environment and abilities to innovate with high-tech products (Soomro et al. 2021). Furthermore, colleges should expand the enrollment and training of higher technical majors, strengthen the construction of industry-university-research cooperation bases with local governments and enterprises to boost technological innovation capabilities, and give priority to the role of talents, knowledge, technology, and industry in the development of the green economy. Besides, to prevent the "drain of minds," governments need to develop incentive measures to retain specialists at home (Matyushenko et al. 2020). Fifth, learning from the advanced experience of international export trade development, governments at all levels should incorporate energy efficiency and other factors affecting carbon emissions consumption into the design stage of technical products and promote environmentally friendly investments. Governments should improve the energy tax system. A sound energy tax system is conducive in mitigating the impact of energy on the environment by giving companies the ability to choose and adopt economic methods that meet environmental requirements (Abbasi et al. 2021b). Also, an environment-related tax is assumed to change the investment and consumption behavior by bringing economic-effective and environmentally friendly means of production (Hao et al. 2021). This forces the industry to adopt advanced environmental protection technologies and renewable energy technologies and accelerate industrial upgrading and transformation as well as the systematic training of human capital to enhance national competitiveness and sustainable economic development.

There are still deficiencies in this study. First, limited by the unavailability of data, the sample period is relatively short. The supplement of the sample can be used to test the stability of the impact of the development of high-tech product export trade on regional carbon emissions. Second, due to the limitation of the length of the article, there is no comparative analysis of the impact of carbon emissions reduction in the three major economic regions of the East, Central, and West and highlighting their different stages of industrialization. Further research can be done in these areas. Finally, the environmental effect of trade is described by the ratio of the export value of high-tech products to the total export value as an environmental influence factor. Indeed, the environmental effects of high-tech product export trade should also be considered in terms of its scale, technique, and composition effects in further studies.

Nomenclature CO_2: Carbon dioxide; GDP: Gross domestic product; CI: Carbon emission intensity; H_ex: High-tech product export trade; IS: Industrial structure supererogation; HC: Human capital accumulation; FDI: Foreign direct investment; RE: Renewable energy; ER: Environmental regulation; R&D: Research and development; WTO: World Trade Organization; P&Y: Pesaran and Yamagata; USA: United States of America; OLS: Ordinary least square; CD: Cross-sectional dependence; CADF: Cross-sectionally augmented Dickey-Fuller; CIPS: Cross-Sectionally Augmented IPS; CCEMG: Common Correlated Effect Mean Group; DCCE: Dynamic Common Correlated Effects; COVID-19: Corona Virus Disease 2019; 'i': *i*Th province; 't': *t*Th period; 'j': *j*Th energy; 'k': *k*Th control variable; βs: Slope coefficients; ε: Random disturbance item

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Declarations

Ethical Approval This manuscript is original and is neither under consideration elsewhere nor has it been published previously in whole or in part.

The results are presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation.
No data, text, or theories by others are presented as if they were the author's own.

Consent to participate We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

Consent to publish The authors agree to publish this article in the Environmental Science and Pollution Research.

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