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The role of fiscal decentralization in achieving environmental sustainability in developing and emerging economies

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The role of fiscal decentralization in achieving environmental sustainability in developing and emerging economies

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Editorial: The role of fiscal decentralization in achieving environmental sustainability in developing and emerging economies

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Editorial on the Research Topic
The role offiscal decentralization in a chieving environmental sustainability in developing and emerging economies

Global warming and environmental issues have garnered widespread attention, necessitating an immediate global response. Previously, various economic drivers of environmental degradation have been identified in the present literature. However, at the same time, less attention has been paid to non-economic factors while investigating the drivers of environmental degradation. In this context, the role of fiscal decentralization (FD) in sustaining environmental quality requires fresh insights into the Perspective of developing and emerging economies. The FD is a non-economic policy level indicator that may provide the best choice for nations to reshape environment-related policies to sustain environmental quality.

Many nations have recently shown an interest in extending their FD policies to expedite sustainable energy innovation and handle the unique market failure concerns (knowledge spillovers) connected with energy innovation (Smoke, 2017). This reflects governments' shift toward a decentralized fiscal structure to increase the efficiency of supplying ecofriendly public goods since localities can effectively meet people's desires for such public goods (Carley and Konisky, 2020). Although there are opposing perspectives, FD has significant implications for government energy RD&D expenditures. For instance, as stated by (Acemoglu et al., 2005), vertical and horizontal decentralization increases the number of political and economic actors involved in funding and demanding creative activity. This phenomenon will not only enhance R&D activities but will also influence the rate of technological innovation (Robertson and Langlois, 1995; Taylor, 2007). Second, when preferences are diverse, FD provides a better match between people's choices and public goods given by subnational and central governments, according to the "first generation of fiscal federalism" (Oates, 1972). Third, "the second generation of fiscal federalism" contends that competitiveness among local authorities encourages central governments to foster market-oriented growth, which benefits the efficacy of eco-friendly public goods and service supply.

At present, two concepts prevail in the present literature while exploring FD nexus with environmental sustainability; The race to top concept, the believers of this concept support that allocation of power and resources to the sub-level local government will effectively minimize the negative externalities arising from anthropogenic activities (Ahmed Memon et al.; Khan et al., 2021; Tufail et al., 2021; Safi et al., 2022). The rationale behind the race to the top approach, where FD results in environmental sustainability, is the implementation of strict environmental measures to restrict negative externalities arising from human activities (Khan et al., 2021). In the race to the bottom approach, the government relaxes their domestic environment-related policies to attract foreign firms to invest in their economies. In this context, in the absence of stringent environmental measures, the arrival of foreign firms and industries results in environmental degradation.

In this context, a total of 7 articles in the present issues empirically examine the multifaceted linkage of FD with environmental pollution. For example, focusing on provincial-level data of China over the years 2010–2019 (Feng et al.), reports that; (I) the spatial agglomeration impact of China's provincial carbon productivity is apparent, and it is rising, (II) FD have the potential to improve carbon productivity greatly, (III) enhancing FD helps the province's carbon productivity, but it reduces the carbon productivity of surrounding provinces. Finally, the authors make policy recommendations to enhance carbon productivity increase through the channel of FD.

Focusing on the annual data covering the period of 1994–2018. Similarly, (Shi et al.) employed a district based panel data of Beijing and revealed that Beijing's districts had a drop in carbon emission intensity between 2009 and 2020. In all districts, the industrial structure has been upgraded. Beijing's carbon emission intensity exhibits notable positive spatial autocorrelation between 2009 and 2020 and negative spatial autocorrelation between 2015 and 2016. In 2009, 2015, and 2020.

Yuan et al. confirms that fossil fuel-based energy, GDP, and trade liberalization promote carbon emissions in Japan, but FD and green energy help the environment. (Xia et al.; Zhan et al.) discover that FD in eastern China had a substantial positive association with environmental governance performance. Local governments with strong tax autonomy established the finest tax policies for clean production, increasing excitement for firms' green production. (Wang et al.) supports the fact that FD enables local governments to play a significant role in the local economic system and fosters green economic growth. Environmental regulation is an excellent tool for FD to support green economic growth from the standpoint of policy synergy.

The first-order differential dynamic panel econometrics model was used by (Li et al.; Xia et al.), which report that 1) fiscal disparity reduced CO_2 emissions linked to revenue decentralization and 2) spending asymmetry hindered CO_2 emission control. 2) Transfer payments from the central government mitigate the negative repercussions of a fiscal deficit. Furthermore, the impact of FD on carbon dioxide emissions was impacted by the U-Shape effect in industrial structure. Besides, using the SBM-GML model to evaluate green total factor productivity in China (Zhan et al.), proposed that 1) green total factor productivity improves year after year and is better in central and western regions, 2) FD significantly weakens the increase of green total factor productivity in, 3) FD hinders green total factor productivity in central and western regions with provincial diversity, 4) (4)The link between FD and green total factor production is influenced by local government competitiveness. Moreover, (Rehman Khan et al.) suggest that reducing the risk of pandemic illnesses in the industrial and logistics sectors can improve overall international commerce and logistics. Additionally, businesses handle sustainability challenges related to international commerce and operations by employing affordable, renewable, and efficient energy resources.

In this context, a total of 5 papers examine various determinants of carbon emissions as follows; The article by (Li et al.) affirms that provincial carbon emissions have a favorable influence on life happiness and increases in fuel and power use also indicate a better level of life satisfaction. Furthermore, an increase in relative energy consumption has a detrimental impact on the living satisfaction of Chinese households. Focusing on the possible empirical linkages between renewable energy consumption, eco-innovation and trade openness with carbon emissions in G-7 economies (Olanrewaju et al.) revealed that fossil fuel-based energy and trade openness adds to environmental destruction. In contrast, economic development, renewable energy, and eco-innovation improve environmental quality. addition (Fei et al.) conclude that the COVID19 lockdown has resulted in the improvement of air quality based on city level data of Nanjing. Similarly, (Hasnain et al.) employed Prophet Forecasting Model (PFM) to predict both long and short-run air contamination in Jiangsu Province. The authors confirmed that, PFM correctly forecasted PM_{10} and $PM_{2.5}$ with R values of 0.40 and 0.52

respectively, RMSE values of 16.37 and 12.07 g/m3, and MAE values of 11.74 and 8.22 g/m3, respectively. In addition to other contaminants, PFM predicted SO_2, NO_2, CO, and O_3 with R values between 5 and 12 g/m3 and MAE values between 2 and 11 g/m3. To test the effect and mechanism of environmental policy on labor income share in China over the period of 1998–2013, (Huang et al.) confirmed that the EPA-TCZ regulations in China considerably raises the labor income share by 2.6% while lowering sulfur dioxide (SO_2) emissions. To comply with environmental regulations, enterprises typically use source control and end-of-pipe treatments, and labor income share is increased through the factor-substitute effect and the cost impact, according to mechanism studies. Moreover, (Mosleh et al.) explore the association between financial development and environment in developed economies in the year 1990–2019. The study found that renewable energy and globalization reduce while financial development, fossil fuel and economic growth activate carbon emissions in Japan. Considering a panel of middle income and higher income countries, (Galvan et al.) examine the effect of economic development, foreign direct investment and GDP on CO_2 emissions in Latin American economies. The findings revealed that FDI and GDP of higher income economies are detrimental for the environment. However, such effect is not significant in middle income economies. Examining the water resource tax of China, (Xin et al.) report that taxing water resources and water pollution together encourages water conservation and the reduces water pollution, and raising both taxes at once has a less detrimental effect on the economy. (Zhang et al.) study the determinants of bilateral trade in renewable energy for China, Japan and ASEAN economies. The authors conclude that bilateral commerce is strongly promoted by the economic sizes of both the exporting and importing nations, the exporter's economic freedom, trade agreements, and participation in common trade regions, however distance from one another had a significantly negative impact.

In the wake of changing climate and rising global temperature, this special issue advances our understanding of the past and present struggle of various nations in limiting environmental pollution through various measures. Specifically, sustaining environmental quality through policies related to FD, energy consumption, and financial development are well highlighted in the present issue. Based on the evidence from the present literature (Race to the Top Approach), it is rational that the fiscally decentralized nations in the presence of strong institutions and high-income levels perform better than fiscally non-decentralized nations in limiting environmental pollution (Lingyan et al., 2022; Sun and Razzaq, 2022). In contrast, the opposing view of the "Race to the Bottom" approach believes that fiscally decentralization worsens the environment due to various factors, such as attracting foreign direct investment, lack of technological advancement, strong institutions, poor coordination between central and local government and high energy prices (Du and Sun, 2021; Shan et al., 2021).

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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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Nexuses Between Energy Efficiency, Renewable Energy Consumption, Foreign Direct Investment, Energy Consumption, Global Trade, Logistics and Manufacturing Industries of Emerging Economies: In the Era of COVID-19 Pandemic

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This study aims to find the nexuses among energy efficiency, renewable energy consumption, foreign direct investment, logistics industry, manufacturing industry and global trade during the COVID-19 pandemic and their impact on global supply chains in exporting nations of the world. The data for this study has been extracted from the World Development Indicators and Statista 2021 for 13 years ranging from 2007-to 2020 for nine top exporting countries. The fixed effect panel estimation technique was implied to examine and analyze the data. The results of our study revealed that highly risky diseases significantly impact supply chain operations globally. Global supply chains, logistics and manufacturing industries significantly influence global trade operations. Our results implicate that the overall international trade and logistics can be enhanced by improving the manufacturing and logistics industries by coping with the risk of pandemic diseases. Moreover, by utilizing cost-effective, renewable and efficient energy resources companies address sustainability issues of global trade and operations. By exerting further attention to the proficiency of the levies approval process, competence and quality of logistics services, and ease of assembling competitively priced shipments, the governments can significantly enhance the export from the logistics industry. Also, increasing manufacturing and agricultural value-added healthier consequences might be acquired in global supply chain operations from the manufacturing industry.

Keywords: environmental sustainability, developing and emerging economies, energy consumption, sustainability, and development, COVID-19 pandemic

INTRODUCTION

The supply chain is the backbone of every financial and non-financial activity across the world. Due to its immense importance in the operational perspective, supply chain management has always been a delicate deal to perform, especially across borders. Researchers worldwide agree that certain risks are associated with the supply chain, and these risks can mainly be differentiated into operational and disruption-related risks (Tang, 2006; Tomlin, 2006; Choi et al., 2019; Farahani et al., 2020; Xu et al., 2020). The operational risks are related to a day-to-day disturbance in supply chain activities. However, on the other hand, disruption risks are related to rare disturbances in supply chain activities with a higher magnitude of risks (Hosseini et al., 2019; Kinra et al., 2019; Ivanov, 2020a). These risks generally include natural disasters like floods, earthquakes, scarcity of raw materials in the international market, and catastrophic human activities. These risks immediately and adversely affect the supply chain network structures, restricting the suppliers and factories to fulfil the demand in the global market. This restricted performance of suppliers causes the delay and shortage of material in the supply chain stream, which impacts the performance of the organizations and economies in terms of revenue generation, provision of service, and decrease in productivity through ripple effect (Ivanov, 2017; Pavlov et al., 2019; Ivanov, 2020a; Dolgui et al., 2020; Goldbeck et al., 2020; Li and Zobel, 2020). In addition to these risk factors, the outbreak of communicable diseases is a unique risk for global supply chain operations. This risk's spatiality is the prolonged and unpredictable disruption in the supply chain stream and logistics infrastructure, which leads to a disturbance of the supply-demand gap. In contrast to other risk factors, the pandemic outbreak starts with a low scale but propagates fast and spread over many geographic territories. The most common examples of the pandemic outbreak include the Ebolavirus, Swine flu, SARS, MERS, and most recent and the most destructive COVID-19/SARS CoV2.

SARS CoV2, commonly known as COVID-19, is believed as the most horrible pandemic of this century. In the beginning, China's production and exports were severely affected by this deadly virus, which interrupted the world demand due to supply unavailability from China to around the world (Araz et al., 2020). Later on, the spread of COVID-19 across the world resulted in the closure of borders, and all transportation means as the source of the spread of the virus were human beings and surfaces. This stoppage in the movement of goods and humans across the borders severely affected the availability of materials in the international markets and resulted in scarcity and shortages. Due to the leaned and globalized nature of the supply chain, the supply chains of 94% of the fortune 1,000 companies were reported to be affected by the spread of this pandemic (Fortune, 2020). Since China is a leading producer and exporter of products and services, and its supply chains were severely affected by this virus, it interrupted the global supply chains. According to Dun and Bradstreet (2020), 51,000 companies worldwide have one or more than one major direct tier 1 supplier in the city of Wuhan, China, which was the epicentre of this disease. That number increases to 5 million companies globally when second (tier 2) suppliers in the impacted region are included. In addition to it, approximately 938 out of 1,000 fortune companies' suppliers exist in Wuhan city only.

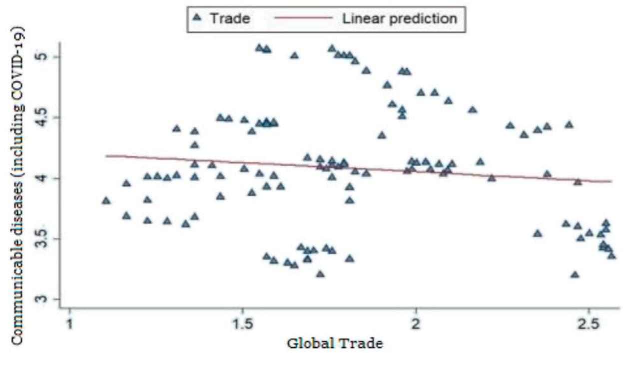

FIGURE 1 | Global trade and communicable diseases (including Covid-19) (Authors own work).

Generally, most significant companies' production exists in different countries of the world to get a competitive advantage. However, after the outbreak of COVID-19, this competitive advantage became a major hurdle in managing supply chains in a globally dynamic environment. There exists a strong nexus between the logistics industry and the manufacturing industry. Hence the global output mainly depends on the smooth and uninterrupted logistics and manufacturing of materials and provision of services. The volume of international production depends strongly on fast and smooth supply chains and production facilities, and therefore, global trade is directly connected with smooth and uninterrupted logistics. The pandemic has influenced the global supply chains and also enhanced the chances of economic collapse (Goel et al., 2021). United Nations trade and development conference has announced that the US $ 3 trillion has been vanished due to the pandemic outbreak and the global trade has reduced to 1.5pp. This pandemic has potentially damaged the logistics of trade across the borders that ultimately compromised the manufacturing industry. The economic growth of the countries mostly relies on their production (Goel et al., 2021). Similarly, the global output depends on the contribution of the nation's production. The outbreak of pandemics has impacted the global supply chains, especially the logistics industry. The world's output mainly depends on the exports of exporting nations. Communicable diseases especially COVID-19 has first and foremost attack on the movement of goods and services. Hence, the requirement of goods across the world was escalating manifold. The pandemic outbreak decreases the supply of goods and services across the borders. Mainly, the supplies of health equipment were shortened in different regions of the world (Qin et al., 2021a). There exists a gap in the literature regarding the evaluation of disruption impact on global logistics, global manufacturing, and supply chains. From the COVID-19 perspective, the impact of the pandemic on logistics and manufacturing industries has not been evaluated properly, especially in the context of exporting countries. Previous literature has empirically evaluated the impact of COVID-19 on these and many other industries (Qin et al., 2021a; Goel et al., 2021; Hilmola and Lähdeaho, 2021; Khan et al., 2021; Sun et al., 2021) but this study evaluated the impact of communicable diseases especially COVID-19 with the help of secondary data of 13 years **Figure 1** depicts the scenario of global trade and communicable diseases.

Moreover, to get a location advantage, companies targeted those areas which are cost-effective, have cheap and skilled labor, and have an abundance of raw material. This trend attracted the geographical and functional integration of production, distribution, and consumption. A complex logistic framework came into existence to fulfil the international needs that involved the flow of commodities, information, parts, and finished goods from one geographical area to another. At the same time, globalization has already increased the interconnection of trade activities that consists of delicate, complex, and interdependent networks of logistics activities. The presence of Global Production Networks (GPN) and Global Commodity Chains (GSS) provided the integrated sets of trade, production, and services in supply chains which involved in the transportation of raw material and finished goods internationally (Dicken et al., 2001; Coe et al., 2004; Grida et al., 2020). According to raw material availability, manufacturing facilities, service provision, and technological aspects, the world has been partitioned into different segments. One geographical territory is favorable in production, and the other is appropriate for the service industry, and some areas are specialized in information technology. Therefore, there is a dire need for multidimensional and strong logistic services that can handle the mobility of raw material, information, services, and finished goods worldwide. Due to this huge network, global trade at different times has been severely affected by various disruption risks, and one of the major disruption risks has been the outbreak of communicable diseases. In the past, the spread of the Ebola virus, Swine flu, MERS, and SARS disrupted the logistics and manufacturing industry and, eventually, the global trade. Presently, the spread of SARS CoV 2 also puts the business activities and especially supply chains to test. The spread of COVID -19 challenged the global movement of goods and blocked the world borders completely. Similar to other communicable diseases, this pandemic has also affected the global supply chains, manufacturing industry, and ultimately the global trade. However, the present study is aimed to analyze the relationship between energy efficiency, renewable energy consumption, foreign direct investment, energy consumption, global trade, logistics and manufacturing industries during the COVID-19 pandemic. Therefore, this study tries to answer the following questions:

1. How have communicable diseases especially the COVID-19 pandemic impacted the logistics industry?
2. How have communicable diseases especially COVID-19 impacted the manufacturing industry?
3. How do the compromised logistics and manufacturing capabilities due to COVID-19 influence global trade?

Economic growth depends on national and global production and smooth supply chain operations. Moreover, addressing the sustainability goals is also a challenge for the countries. This study contributed to the literature by providing comprehensive nexuses among the most debatable variables. This study provides the influence of supply chain disruptions and production on the logistics industry, manufacturing industry and global trade. Moreover, this study also addresses the issues of sustainability among exporting nations. The utilization of cost-effective, renewable and efficient energy resources in business operations during the pandemic provides implications to other nations to address the sustainability concerns. Therefore, this study implicates that the incorporation of eco-friendly operations to enhance economic growth and sustainability are crucial for global trade, global output and logistics across the borders.

The rest of the paper is organized as follows. In section two, we discuss the literature on communicable diseases (including COVID-19), the logistics industry, the manufacturing industry, and their impact on global trade. In section three, we discuss the methodology of this study. Section four comprised of results and their discussion. The paper is summarized in section five by providing a comprehensive conclusion and policy implications for the supply chain and governments' strategic thinkers.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

The globalization of products and services is a competitive strategy of multinational firms in the current century, and this compels the firms to segregate their operations across the borders to get a competitive advantage through global production. Besides competitive advantages, operating globally has some serious concerns, including the Political, Economic, Social, Technological, and legal (PESTL) environment. Additionally, an approach to achieve more economic growth enhances the utilization of nonrenewable energy resources that causes environmental degradation due to CO_2 emission (Tufail et al., 2021). Recent research showed that technological advancement and exports negatively affect the use of carbon (Wahab, 2021; Wahab et al., 2021). Financial development is a key element of economic growth however, financial growth negatively affects environmental sustainability (Wahab, 2021). More importantly, economic growth largely depends on the availability and abundance of natural resources in a locality or their smooth logistics across the nations. There exists a strong nexus between resource abundance and economic growth (Yang and Ni, 2022). Industrial growth depends mainly on the utilization and availability of affordable and renewable energy resources. The nexuses between the availability, consumption and price of energy resources mainly electricity is crucial for industrial production and global output (Rahim et al., 2021). As the companies are part of delicate and complex supply chains, a robust, eco-friendly, innovative and risk-free global supply chain needs a well-coordinated and structured flow of goods, services, information, and cash within and across the borders (Henderson et al., 2002). To get maximum benefit, companies import raw materials from advantageous location regions or install production plants in cheap labor localities to manufacture and assemble parts. Later on, these products' sales and marketing are made in potentially high-demand regions (Mentzer et al., 2001). Hence, maximization of profit through well-designed supply chain operations has been the main objective of supply chain management for decades (AlHashim, 1980; Hise, 1995).

The supply chain's guiding principle is to maintain a balance between efficiency and effectiveness through the seamless and timely movement of goods, materials, information, and services across borders to expedite profit maximization (Nelson and Toledano, 1979; Schmidt and Wilhelm, 2000). The implementation of effective, well-designed, and well-coordinated supply chain operations globally is a key challenge for the strategic thinkers of supply chains and international trade due to differences in the economic, political, legal, social, and infrastructural environment (Schmidt and Wilhelm, 2000). Besides these operational risks, certain disruption risks have also remained part of supply chain operations throughout history. Natural disasters, floods, earthquakes, and human-created catastrophes had affected supply chain operations many times in previous decades. The most important disruption risk includes SARS, Ebola virus, Swine flu, MERS, and recently the COVID-19 pandemic.

Communicable Diseases and International Trade

A vast body of literature is available on the research conducted to find out the impact of communicable diseases on logistics (2,39–42) but the literature on the impact of the pandemic outbreak on global trade is scarce. This research study focuses on the impact of communicable diseases, including COVID-19, on global trade and supply chain operations. As it is evident global trade is the backbone of the globalized world, but at the same time, global trade is also held responsible for the spread of communicable diseases like H1N1, HIV/AIDS, SARS, MERS, Ebola virus, and swine flu. The transportation of goods, shipping, and humans witnessed the spread of infectious diseases (Gubler and Rosen, 1976; Mack et al., 2011). Fidler (Fidler, 1996) considers the global movement of goods and humans without public health safety a great risk of disease transmission across the borders, and this was evidenced recently in the case of COVID-19 spread, which entirely halted global trade. Similarly, previous literature on the outbreak of SARS in 2002–2003 indicates adverse effects on the airline industry, and the major impact was in Taiwan, where around 30% of the local and international flights were suspended (Chou et al., 2004). Similarly, the Ebola virus spread negatively impacted international supply chain operations (BSI, 2014).

Since globalization was in its initial stages in the early nineties and the distribution of production and networks of supply chain operations was not much flourished in different countries, the SARS effect was negligible on international trade and global supply chain operations as compared to the present decade. Certain studies have been conducted to provide the lessons learned from the Ebola outbreak and suggest the formulation of the decision–support framework that can inhibit the impact of the pandemic outbreak on supply chain operations and provide insight to coordinate the operational and logistics-related policies during and after the pandemic crises (BSI, 2014; Ilbahar et al., 2019). In this scenario Dmitry Ivanov (50) has recently discussed the concept of a viable supply chain and provides a helpful model for the managers in decision making regarding the formulation and recovery of global supply chain operations after disruptions like the COVID-19 pandemic.

The SARC CoV-2, known as COVID-19 was originated from the city of Wuhan, China, in mid of December 2019 and spread throughout the world in a couple of months. This virus threatened the health care system and severely impacted the global supply chain operations and international trade by having closed international borders and domestic manufacturing. Moreover, COVID-19 ceased most business sectors and inhibited the routine flow of goods, humans, services, and capital within and among the nations. This de-globalization of production, manufacturing, supply chains, and international trade continues to date and severely affects global supply chain operations (Chou et al., 2004) as global supply chain operations are performed all over the world but mostly performed by exporting countries like China, Italy, the United States, United Kingdom, and France, etc. The sudden drop in operational performance, shortage of material, and fluctuation in prices caused by this pandemic outbreak were heavily affected by these exporting countries. Coronavirus statistics approve that the German Post declared an EBIT reduction in the range between 60 and 70 million Euro, similarly a 21.9% rise in retail prices in China was reported (BSI, 2014). Apple announced an unexpected drop in quarterly earnings, and at the same time, by the end of February 2020, the pandemic had made 9% of shipping fleets inactive. Due to the suspension of manufacturing activities, the Chinese industry faced its lowest point at the beginning of the COVID-19 outbreak (Ivanov, 2020b).

Moreover, at the start of the COVID-19 pandemic spread, WTO had predicted the drop in global trade by 13–32%, which is worst compared to the financial crises of 2007–2008. The recent data of WTO confirms their claim regarding the drop in global trade by indicating the Goods Trade Barometer at 95 in December 2019, which is lower than in previous months. Therefore, it is confirmed that communicable diseases (including COVID-19) have affected the global supply chain operations worldwide, especially the developing and exporting countries. Previous studies only focused on the effect of natural disasters and financial crises on global trade (Gassebner et al., 2006; Escaith et al., 2011; Ando and Kimura, 2012). However, the impact of communicable diseases (including COVID-19) on global trade has not been adequately addressed. Recent studies regarding the COVID-19 pandemic only focused on the financial markets (Ali et al., 2020; Apergis and Apergis, 2020; Gil-Alana and Monge, 2020; Haroon and Rizvi, 2020; Liu et al., 2020; Phan and Narayan, 2020; Qin et al., 2020). However, one of the aims of this study is to analyze the impact of the communicable diseases including COVID-19 pandemic on global trade. Hence, we proposed a hypothesis that:

H1: Communicable diseases (including COVID-19) negatively and significantly impact global trade.

Logistics Industry and Global Trade

The logistics of materials is the backbone of global production and the literature of various disciplines has shown strong dependence on the supply of raw materials on production activities (Sabel et al., 1987; Slack, 1991; Christopher, 1992; Schonberger, 2008). Especially the manufacturing and logistics of top exporting countries including China, the United States, Germany, the Netherland, Japan, France, Korea, Italy, and the United Kingdom are strongly dependent on the logistics activities of multinational enterprises (Lorenzoni and Ornati, 1988; Womack, 1990; Lamming, 1993). Global logistics is defined as the movement of goods and services across borders with integration to manufacturing industries to provide value addition to the customers (Lin, 2016). Exporting countries play a pivotal role in global trade; for example, China which is the hub of global economic activities for the last 2 decades and owns 60% of the world's GDP in terms of supply and demand, 65% of manufacturing activities, and 41% of exports to the rest of the world (Baldwin and Di Mauro, 2020). And this is the reason that disturbances in Chinese logistics have caused a remarkable impact on the manufacturers of the remaining world (UNCTAD Search, 2020).

Barua, (Barua, 2020), has discussed the likely impact of Chinese logistics disturbances on 13 industries of transitional goods globally, including automobile products, chemicals, machinery, instruments of precision, and information technology. He further explores that only a 2% decrease in Chinese exports due to logistics disruption resulted in a decrease of $ 4 billion in global trade in 34 countries of the world. The shutdown of operational activities by the world's largest companies like General Electric, Volkswagen, Nike, Airbus, and Toyota in exporting countries due to disruption in logistics activities has decreased the global trade among the countries (Author Anonymous, 2020). Besides this, logistics companies like DHL, FedEx, and UPS faced severe disturbances in national and international logistics of goods from exporting countries like China to the rest of the world (Tirschwell, 2020). Moreover, globally, the shipments of containers from 89 ports dropped by 60% since December 2019 and are expected to drop further (Knowler COVID-19, 2020). COVID-19 pandemic affected the logistics of raw material and finished goods, and the logistics of the service industries like tourism and travel industries are among those that were hit the most. WTO predicts a 20–30% decrease in tourism and travel compared to 2019, which will enormously affect the global revenues and the exporting countries like France, Italy, and the United Kingdom especially (Farrer Coronavirus, 2020; ICAO Economic, 2020).

Due to the abrupt rise in cases of COVID-19 in the United Kingdom, United States, Italy, China, and India, production and export of products and services to other countries dropped rapidly in the shape of lockdowns and quarantines. This decrease in production, manufacturing and global trade was mainly caused by disturbances in raw material logistics, finished goods, and services across the borders. According to the World Bank report, the world GDP decreased significantly during the lockdowns. The developed economies shrank by 7% in 2020 whereas; developing economies shrank by 2.5% during the same period. The global trade shrank by more than 13%, the highest after World War II. This reduction in global GDP is caused due to the local and international shutdown of production and manufacturing. Production and manufacturing have a strong relationship with the logistics of raw materials and products. The logistics activities have been severely impacted by operational risks and disruption risks many times in history. The disruption risks are rare but impacted the logistics activities with great magnitudes.

There exists a negative impact of communicable diseases on the logistics industry, and this negative impact leads to a decrease in global trade. The recent disturbance due to COVID-19 in these exporting countries has affected the transfer of raw material and finished goods from one region of the world to another. Recent reports indicate that the global trade of goods and services is getting slow due to the spread of the COVID-19 pandemic. The COVID-19 pandemic has threatened the global logistic industry because previous literature held logistic activities responsible for spreading communicable and infectious diseases such as the Ebola virus, HIV/AIDS, H1N1, MERS, SARS, and Swine flu across the world. This notion immediately affects the logistics industry soon after the outbreak of the COVID-19 pandemic. Hence we propose a hypothesis that:

H2: There is a positive and significant impact of the logistics industry on international trade.

Manufacturing Industry and Global Trade

The manufacturing industry is supposed to be the key element in global production as it helps enhance global trade and economic growth. Several studies have highlighted the role of the manufacturing industry on global trade and economic growth, such as Szirmai (Szirmai, 2012), Thirlwall (Thirlwall, 2006), Tregenna (Tregenna, 2009). Manufacturing includes all those activities associated with the movement of goods, innovation of products and services, planning and management of production, and dissemination of products and services (Martinelli, 1991). These studies suggest that the economic growth of developing and exporting countries mainly depends on the production infrastructure. In addition to it, industrialization is the crucial step towards production, manufacturing, and global trade. Rodrik (Rodrik, 2015) points out that the fast global trade and economic growth happened due to the massive transfer of manufacturing resources to the exporting countries. Industrial activities in developing and exporting countries expedite global trading channels. According to Szirmai (Szirmai, 2012), manufacturing is a vital element of international trade and economic growth, especially in developing and exporting countries. The shift of manufacturing infrastructure in developing countries in the shape of FDI automatically enhanced the production activities. This shift served as a bonus for exporting countries and expedited the international supply chain operations and overall economic growth. Production activities in the manufacturing industry are higher than in any other industry due to abundant resources and technological advancement.

This economic growth and international supply chain operations have been lucrative enough to catch the world's business community's eyes and fulfil the demands of customers across the world. However, the operational and disruption risks in history have many times drowned the dreams of stakeholders. Operational risks and disturbances are usually manageable, and their impact is most of the time measurable and predictable on the manufacturing industry and global trade. On the other hand, disruptions and disturbances caused due to natural disasters and communicable diseases like the Ebola virus, Swine flu, MERS, SARS, and COVID-19 have unpredictable and immeasurable impacts on manufacturing and international trade. Pre COVID-19 analysis of world trade predicts that the global production networks (GPN) were the major portion of world trade that increased industrialization and increased the less developed nations' productivity. Countries like China, India, and Korea have become leaders in the export industry due to GPNs (Vidya et al., 2020). Hence due to competitive advantage in production, manufacturing, distribution, China, Korea, and Japan became the hub of global supply chains. Certain countries among exporting countries, like China and others, are believed to be a hub of industrial goods with a specialization in information and communication technology (Baldwin and Tomiura, 2020).

Dasgupta and Singh (Dasgupta and Singh, 2006) conducted a cross-sectional study for 48 developing nations from 1990 to 2000 and posit that manufacturing still acts as a vital economic growth element. Increased share of manufacturing remarkably contributed to economic growth as compared to the agriculture and services industry. A significant association was established connecting the industrialization level and per capita income in emerging economies. The contribution of manufacturing to GDP and job creation increased due to higher per capita income in emerging economies. The real GDP growth rates on economic development lie in the growth rate of manufacturing (Fagerberg and Verspagen, 1999). Banjoko et al. (2012) posit that the experiences of developed economies and developing economies like India, China, Malaysia, Singapore, and North Korea regarding the manufacturing industry's role exposed a positive relationship between the manufacturing industry and economic development. Similarly, the study of Portugal-Perez and Wilson (Portugal-Perez and Wilson, 2012) revealed that trade improvement not only positively impacted the imports but also increases exports along with the improved provision of inputs related to production and enhanced contribution in international and territorial value chains.

Due to the logistics services' interruptions globally, the production of goods in these countries specialized for production decreased significantly. Hence the negative blow on global logistics disturbed global production, leading to a negative effect on global trade. This disruption in logistics, manufacturing and global trade leads to demand contractions internationally (Baldwin and Freeman, 2020). As per the theory, logistics, manufacturing, and global trade disturbances direct economic fundamentals shifting (Krugman, 1997). Hence, we propose a hypothesis that:

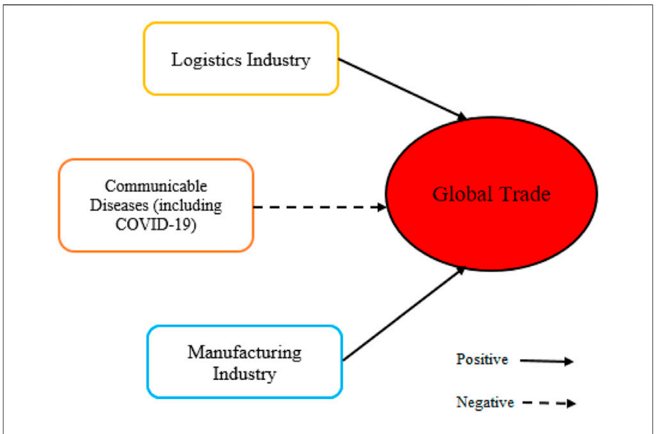

FIGURE 2 | Conceptual framework.

H3: There is a positive and significant impact of the manufacturing industry on global trade.

DATA AND METHODOLOGY

This study uses a fixed effect panel estimation technique to measure the energy efficiency, renewable energy consumption, foreign direct investment, Logistics industry's effect, Communicable diseases (including COVID-19), and manufacturing industry on global trade in top exporting countries naming China, United States, Germany, Netherlands, Japan, France, Korea, Italy and United Kingdom. The data has been extracted from the World Development Indicators and Statista 2020 for 13 years ranging from 2007-to 2020. **Figure 2** shows the conceptual framework of this study. Following is the equation for testing hypotheses:

$$Trade_{it} = \beta_0 + \beta_1 LI_{it} + \beta_2 MI_{it} - \beta_3 CD_{it} + \varepsilon_{it} \quad (1)$$

LI is the logistic industry, MI is the manufacturing industry, and CD is communicable diseases (Including COVID-19), $\beta_{1�2�3}$ depicts the coefficients that are to be determined, ε_{it} and depicts the error term; whereas i is for the country, and t is for time. The dependent variable, global trade, is measured through trade as a percentage of GDP taken from the World Development Indicator (WDI). Additionally, the independent variable, logistics industry, has been measured through the Logistics Performance Index, taken from Statista, which comprises of six further constructs: 1) Capability to trace and track consignments, 2) Proficiency and excellence of logistics services 3) Affluence of assembling competitively priced shipments 4) Proficiency of levies approval process 5) Frequency with which shipments reach consignee within scheduled or expected time 6) Quality of trade and transport-related infrastructure. Simultaneously, data for the manufacturing industry has also been extracted from the WDI, which comprises four further constructs. 1) Industry: Industry value added (% of GDP) 2) Agriculture: Agriculture value added (% of GDP) 3) Manufacturing: Manufacturing

TABLE 1 | Data sources.

Variable	Variable presentation	Period	Source
Proficiency and quality of logistics services	LPI 1	2007–2020	Statista (2021)
The effectiveness of the taxes approval process	LPI 2	2007–2020	Statista (2021)
The affluence of assembling competitively priced shipments	LPI 3	2007–2020	Statista (2021)
Ability to trace and track consignments	LPI 4	2007–2020	Statist (2021)
The frequency with which shipments reach consignee within the scheduled or expected time	LPI 5	2007–2020	Statist (2021)
Quality of trade and transport-related infrastructure	LPI 6	2007–2020	Statista (2021)
Service: Service value added (% of GDP)	SER	2007–2020	WDI (2021)
Trade: Trade (% of GDP)	TR	2007–2020	WDI (2021)
Industry: Industry value added (% of GDP)	IND	2007–2020	WDI (2021)
Agriculture: Agriculture value added (% of GDP)	AGR	2007–2020	WDI (2021)
Manufacturing: Manufacturing value added (%of GDP)	MAN	2007–2020	WDI (2021)
Fossil Fuel (% of total consumption)	FF	2007–2020	WDI (2021)
Energy efficiency	EFF	2007–2020	WDI (2021)
Renewable energy consumption	REC	2007–2020	WDI (2021)
Foreign direct investment inflows	FDI	2007–2020	WDI (2021)
Communicable diseases	CD	2007–2020	WDI (2021)

TABLE 2 | Descriptive statistics.

Variable	Obs	Mean	Std.Dev	Min	Max
Trade (% of GDP)	117	4.081	0.49	3.198	5.066
Communicable diseases	117	1.815	0.382	1.105	2.565
Manufacturing Value added (% of GDP)	117	2.764	0.419	2.18	3.478
Service Value added (% of GDP)	117	4.167	0.146	3.758	4.369
Agriculture Value Added (% of GDP)	117	0.452	0.723	-0.57	2.327
Fossil Fuel (% of total consumption)	117	4.385	0.186	3.834	4.552
Industry Value added (% of GDP)	117	3.195	0.302	2.827	3.85
LPI 1: Competence and quality of logistics services	117	1.374	0.061	1.215	1.589
LPI 2: Efficiency of the customs clearance process	117	1.353	0.06	1.221	1.461
LPI 3: ease of arranging competitively priced shipments	117	1.283	0.049	1.166	1.472
LPI 4: Ability to track and trace consignments	117	1.291	0.079	1.095	1.417
LPI 5: Frequency with which shipments reach consignee within the scheduled or expected time	117	1.425	0.045	1.303	1.537
LPI 6: Quality of trade and transport-related infrastructure	117	1.382	0.065	1.163	1.491

value added (%of GDP) 4) Fossil Fuel (% of total consumption). Moreover, the communicable diseases (CD) measured inactive cases are also extracted from WDI. **Table 1** contains the details of all the variables and their sources.

ANALYSIS AND RESULTS

The analysis starts with descriptive statistics measuring mean, median, Std. Dev, Min, and Max in **Table 2**. The values of min and max rule out any suspected existence of outliers in the data. The sample mean of trade is 4.081 shows that, on average, sample countries have 4% of GDP attributable to trade. The minimum and maximum values also appear to be not far from the mean, eliminating any risk of an outlier in the data. Communicable diseases have a mean value of 1.815 and a standard deviation value of 0.382. Manufacturing and Service value-added have the mean values of 2.764 and 4.167, respectively, which show the average percentage of a given country's GDP attributable to manufacturing and services value-added. It is also evident that the standard deviations for all of these measures are also very minor.

Table 3 shows the correlation matrix among independent variables and the dependent variable. The correlation coefficient between trade and communicable diseases is (-0.1161), which confirms the negative relationship. At the same time, constructs for the logistics industry are found to be having positive relationships with trade, which depicts the positive link between them.

Table 4 contains the regression output of fixed and random effect models. The Hausman test's probability value confirms that the fixed effect is appropriate for analyzing the effect of the manufacturing industry, logistics, and communicable diseases on global supply chains as it is evident that fixed effects regressions are very useful when the data falls into groups such as countries, industries, companies, etc. Since our data fall into such categories, there might be unobservable factors correlated with the variables used in our model, which will result in omitted variable bias. Since we believe that these unobservable variables are time-invariant, the use of fixed effects regression will remove this omitted variable bias.

TABLE 3 | Correlational matrix.

Variables	Trade	Communicable Diseases	Service	Industry	Manufacturing	Fossil fuel	Agriculture	LPI 1	LPI 2	LPI 3	LPI 4	LPI 5	LPI 6
Trade	1	–	–	–	–	–	–	–	–	–	–	–	–
Communicable diseases	−0.1161*	1	–	–	–	–	–	–	–	–	–	–	–
Service	−0.2171*	−0.1368*	1	–	–	–	–	–	–	–	–	–	–
Industry	−0.0603	−0.0627*	−0.8894	1	–	–	–	–	–	–	–	–	–
Manufacturing	−0.051	−0.0283*	−0.8276	0.972**	1	–	–	–	–	–	–	–	–
Fossil Fuel	0.0167	0.1162**	−0.1826	0.3495**	0.3142***	1	–	–	–	–	–	–	–
Agriculture	0.0136*	−0.297	−0.7772	0.6657*	0.5999	−0.0776*	1	–	–	–	–	–	–
LPI 1	0.2188*	0.1768	0.636**	−0.5206	−0.4756	0.0943*	−0.7681	1	–	–	–	–	–
LPI 2	0.2384**	0.1982	0.6386*	−0.5386	−0.49	0.0351**	−0.7648	0.9565*	1	–	–	–	–
LPI 3	0.35***	−0.0232	0.2975	−0.2966	−0.2894	0.1116*	−0.4052	0.6423	0.603**	1	–	–	–
LPI 4	0.0307	0.2001	0.7533*	−0.6523	−0.6199	−0.0091	−0.832**	0.8533	0.8556*	0.4768	1	–	–
LPI 5	0.2366**	0.1537	0.6612*	−0.6029	−0.5545	−0.0407	−0.8098	0.9182*	0.9279	0.5671*	0.8572	1	–
LPI 6	0.0968*	0.1128	0.6483	−0.4999	−0.4308	−0.0035	−0.6893*	0.8979*	0.9268	0.5222	0.8047	0.8594**	1

***p < *0.01*, **p < *0.05*, *p < *0.1.*

The results show that communicable diseases' coefficient is negative (-0.108) and is significant at 10%, which to some extent shows that communicable diseases may have some adverse effect on trade. Similar findings are reported by Singh et al., (Singh et al., 2020), that confirm how the deadly COVID-19 affected the lives and the economy of millions of people around the globe. They further proved it with a simulation model in their study of how demand and supply were affected severely due to lockdowns and caused shortages due to suspended logistic and manufacturing activities in the food supply chain network. Similarly, the study of Barua (Barua, 2020) also predicts the negative effect of the COVID-19 pandemic on global trade, and it further explains that this dilemma can introduce many new ways of global trade and investment.

Besides this, the coefficients of agriculture value-added, which is (0.334), and manufacturing value-added, which is (0.775), are significant at 1%, confirming that the manufacturing industry has a greater impact on the global supply chains. One unit change in Agriculture value-added and manufacturing value-added will increase the trade by 33.4 and 77.5%, respectively. At the same time, the coefficient of Fossil fuel is also found to be significant at 10% with a coefficient (0.318). Therefore, these findings authenticate that agriculture value-added and manufacturing value-added can play an important role in enhancing trade and economic conditions, which will improve the supply chain globally. In addition to it, the significant and positive coefficient of fossil fuels also validates that the manufacturing industry of a country as a whole can contribute significantly to expanding trade, and this expansion of trade will further contribute to global trade. These findings are consistent with Deshmukh and Haleem (Deshmukh and Haleem, 2020), whose findings confirm that manufacturing industries have been hit severely across the globe due to this COVID-19 pandemic, especially in Europe, the United States, China and India. They suggested that the disruptions caused by COVID-19 can be viewed as an opportunity to enhance improved manufacturing facilities to cope with the new markets internationally. A study conducted by Katuria and Raj (Katuria and Raj, 2009) at the regional level revealed that the more industrialized areas flourish more rapidly than other regions. In association with Katuria and Raj (Katuria and Raj, 2009), research of Chakravarty and Mitra (Banjoko et al., 2012) also explored that manufacturing is a vital and most important factor of overall economic expansion.

At the same time, the logistics industry is also found to have a significant impact on global supply chains as it is evident from the results that three of its constructs are significant at 1 and 10%. The LPI 3 is significant at 1% with a coefficient of (0.973) whereas, LPI 1 and LPI 6 are significant at 10% with a coefficient of (0.131) and (0.517), respectively. According to the findings, the ease of arranging competitively priced shipments (LPI 3) is the most significant variable that implies that slight ease in these shipments will improve the trade dramatically up to 97%. Overall it can be viewed that the logistics industry can play a significant role in supply chain operations internationally by improving its ease of arranging competitively priced shipments and the quality of logistics and infrastructure related to trade.

TABLE 4 | Regression analysis.

Variables	Fixed effect	Random effect
Communicable diseases	−0.108*	−0.414***
	(0.0645)	(0.0722)
Service Value added (% of GDP)	−2.301	−7.762
	(0.551)	(0.499)
Industry Value added (% of GDP)	−1.133	−6.268
	(0.289)	(0.496)
Manufacturing Value added (% of GDP)	0.775***	2.193**
	(0.215)	(0.262)
Agriculture Value Added (% of GDP)	0.334***	0.177***
	(0.106)	(0.0675)
Fossil Fuel (% of total consumption)	0.318*	0.620***
	(0.262)	(0.136)
LPI 1: Competence and quality of logistics services	0.131*	1.198**
	(0.209)	(0.569)
LPI 2: Efficiency of the customs clearance process	−0.0555	-0.729
	(0.316)	(0.840)
LPI 3: ease of arranging competitively priced shipments	0.973***	2.002*
	(0.447)	(1.208)
LPI 4: Ability to track and trace consignments	−0.457	0.638
	(0.567)	(1.456)
LPI 5: Frequency with which shipments reach consignee within the scheduled or expected time	−0.0530	−0.681
	(0.375)	(1.016)
LPI 6: Quality of trade and transport-related infrastructure	0.517*	3.350**
	(0.549)	(1.361)
Constant	14.21***	39.21***
	(2.852)	(3.012)
Observations	117	117
Number of Countries	9	9
Hausman	Prob (0.001)	

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

TABLE 5 | GMM test for robustness.

Variables	One Step difference GMM	One step System GMM
Communicable diseases	−0.107*	−0.332**
Service Value added (% of GDP)	−4.312	−8.642
Industry Value added (% of GDP)	−3.521	−4.237
Manufacturing Value added (% of GDP)	0.632**	0.892**
Agriculture Value Added (% of GDP)	0.258**	0.198***
Fossil Fuel (% of total consumption)	0.315*	0.627**
LPI 1: Competence and quality of logistics services	0.582	0.365*
LPI 2: Efficiency of the customs clearance process	0.014*	0.008**
LPI 3: ease of arranging competitively priced shipments	0.751	0.993*
LPI 4: Ability to track and trace consignments	−0.342	−0.235
LPI 5: Frequency with which shipments reach consignee within the scheduled or expected time	0.032*	0.013*
LPI 6: Quality of trade and transport-related infrastructure	0.461**	0.237**
Renewable energy consumption	0.548*	0.319**
Energy efficiency	0.332**	0.271***
Foreign direct investment	0.712***	0.642***
Constant	21.37***	33.27***
Number of instruments	17	17
AR (2)	0.1894	0.3967
Hansen	0.0922	0.1375

****p < 0.01, **p < 0.05, *p < 0.1.*

Besides these, we also employed the GMM test for robustness and included renewable energy consumption, energy efficiency and foreign direct investment as control variables (see **Table 5**).

The results of the GMM test shows that Communicable disease is negative and significant at a 10% level, which means one per cent change in communicable disease will reduce trade by -0.107%. At the same time, the coefficient of Manufacturing Value added, Agriculture Value Added, and Fossil Fuel is also found to be positive and significant at a 5 per cent level of significance. Additionally, all three control variables are also found to be positive and significant at 5 and 1% respectively which ensures the robustness of our results through GMM.

Szirmai and Verspagen (Szirmai, 2012) have examined the association between the share of service and manufacturing sectors to GDP and development of GDP to per capita income by utilizing panel data for both developed as well as developing nations for three different periods ranging from 1950 to 1970, 1970–1990, and 1990–2005. They realized that manufacturing serves as a backbone of economic growth for low and middle-income nations due to the abundance of human capital in those nations. While aiming at the middle-income economies, Su and Yao (Su et al., 2017) conducted a study and used three methodologies for the long run, i.e., Granger causality tests, cross-sectional regression, and panel regression, to assess the role of the manufacturing sector as a driver of growth for the services sector. Further, Ivanove (Ivanov, 2020b) study substantiates that the timing of the opening and closing of the facilities at various levels might become a major cause that determines the epidemic eruption impact on the supply chain rather than an upstream interruption duration or speed of epidemic spread. The results showed that the manufacturing industry serves as an engine of growth for the services sector. Hence these findings led the researchers to determine that manufacturing serves as a vital element for the growth and flourishing of economies. Besides this, they also concluded that the deindustrialization of premature nature negatively impacts economic growth.

CONCLUSION, POLICY IMPLICATIONS, LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Supply chain complexities grew as the world became interconnected. This global environment offered abundant new opportunities for supply chain diversification and optimization but at the same time exposed the supply chain network to disruptions of higher complexity, uncertainty, and magnitude (Golan et al., 2020). Recently the novel COVID-19 affected all spheres of life, and it has equally affected the supply chain globally. This study attempts to analyze the relationship among energy efficiency, renewable energy consumption, foreign direct investment, energy consumption, global trade, logistics and manufacturing industries during the COVID-19 pandemic in top exporting countries using a fixed-effect panel estimation technique. This study's data has been extracted from the World Development Indicators and Statista 2021 for 13years ranging from 2007to 2020. The results validate the estimated view that high-risk diseases significantly and negatively influence supply chain operations internationally. Simultaneously, manufacturing and logistic industries are also significantly positively influencing global trade operations. Additionally, the utilization of renewable energy resources, efficient electricity use at minimum cost and accommodating the FDI also has significant consideration among developing exporting countries. These factors were also significantly associated with the global output and global sustainability issues during the COVID-19 pandemic.

Practical Implications

These results implicate that improving the manufacturing and logistic industries and coping with the risk of pandemic diseases can prosper the overall international trade and logistics. By paying attention to the affluence of assembling competitively priced shipments, the proficiency of the customs approval process, quality of logistics services, and infrastructure related to trade can significantly expand the export from the logistics industry. Also, enhancing industrial and agricultural value-added healthier consequences might be attained in global supply chain operations from the manufacturing industry.

In addition to it, the supply chain officials should need to address the supply chain disruptions, and these disruptions due to communicable diseases need to be prioritized as it disturbs the supply chains with high and unpredictable magnitudes. Strategic thinkers of supply chains should consider capacity building regarding the storage and transportation of materials for a longer time to fulfil unpredictable situations like communicable diseases outbreak. Sustainability is one of the major issues of this era. Hence the utilization of efficient, renewable and low-price energy resources should be considered to enhance the global output and economic growth of the nations. Managing the foreign direct investment in exporting countries is also a challenging job to address before and during the pandemic. The exporting countries should address only those FDI projects that use sustainable business operations only. Moreover, managers of supply chain management should adopt the recently proposed model of Dmitry Ivanov (Ivanov, 2020b), which introduces the concept of a viable supply chain by integrating resilience and sustainability. The viable supply chain model provides multi-dimensional supply chain structures that help to maintain supply-demand needs and adaptive methods among the transitional structural designs.

Besides this, communicable diseases, especially COVID-19, have brought de-globalization for a certain but meaningful period. As globalization has brought the production shift in one region of the world that leads to the dependency of one entire region to another and in our case, only a few countries contain the major share of the international market. So countries should learn the lesson from this pandemic and increase their domestic production so that they can be able to handle the supply-demand needs of at least their population under challenging times.

Most importantly, the enhancement of technology in logistics and manufacturing is the dire need of time, especially after the

COVID-19 pandemic on global trade. As this virus attacks humans and keeps them away from working in most industries, robotic and other automated machinery in manufacturing and logistics activities should be enhanced to meet the production and logistics needs of at least the life-saving and other necessities of life across the world.

Limitations and Future Research Directions

This study like others has certain limitations. Firstly, this study uses only communicable diseases, especially the COVID-19 pandemic and tried to discuss their impact on the logistics and manufacturing industry that impacted the global trade. Future research can be conducted to adopt some other natural disruptions like floods, earthquakes, and human catastrophes to understand their impact on logistics, manufacturing, and global trade. Secondly, many other areas of the supply chain besides logistics and manufacturing have also been severely affected due to COVID-19 such as lean and agile production, forecasting of material and finished products, and inbound logistics. In future research, tools of future forecasting, SCM sustainability, and technological aspects should be considered to mitigate the impact of such disruptions in global supply chains. Thirdly, literature has been called plenty of time for conceptual and empirical-based research in context to COVID-19. There is a dire need to understand the flexibility, more resilient, and hybrid decision SCM models to overcome the impact of such disruptions in the future. More, importantly this research is quantitative; future research can consider qualitative and mixed-method research to provide further deep understanding. The sample size and target countries of this study are limited hence; future research can consider further counties especially developing countries to measure the impact of COVID-19 on logistics, manufacturing, and national output.

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

Conceptualization SK, DG and SH writing—original draft MT, SK, MAK and MRK writing—review, and editing SH, SK, DG and MT methodology MAK, and MRK project administration SK, MT and DG.

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The Impacts of Carbon Emissions and Energy Consumption on Life Satisfaction: Evidence From China

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This study investigates how carbon emissions and energy consumption related to the life satisfaction of Chinese households over the 2010–2018 period. The China Family Panel Studies (CFPS) data from 25 Chinese provinces shows that the effect of provincial carbon emissions on life satisfaction is positive, and increases in fuel and electricity consumption also predict a higher life satisfaction level. Fuel consumption, especially, has a greater impact on life satisfaction among older people with lower income or education levels. In addition, an increase in relative energy consumption negatively affects Chinese households' life satisfaction. Heterogeneity analysis demonstrates that the relative fuel consumption change has a larger negative life satisfaction effect for younger, less educated or rural people. In developed regions (including Beijing and Shanghai), a strong inverse relationship between carbon emissions and the residents' life satisfaction exists in China, but the effects of residents' own and relative energy consumption are insignificant or slight.

Keywords: carbon emissions, energy consumption, life satisfaction, reference group, relative energy consumption

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INTRODUCTION

In recent decades, carbon emissions have become a vital environmental issue of widespread concern, as excessive carbon emissions have the potential to be sources of both greenhouse effects and depletion of natural resources. Yet, the implications of proposed carbon emissions reduction schemes in developing countries remain a matter of debate, since nations need to extensively rely on fossil energy to fuel their current development demands (Costa et al., 2011). In addition, the carbon emissions dimension is still not well understood in the life satisfaction related literature. Life satisfaction reflects the subjective feelings in our daily lives, which is a vital indicator to measure people's quality of life (Tonon, 2013) and is highly related to social progress (Li and Raine, 2013). With the deepening of reform and opening-up in the past decades, China has undergone remarkable economic growth and societal environment change. At the same time, the Chinese people's requirements for a better life have been gradually increasing, which conflicts with the inadequate development in China (Qiu, 2017; Zhang et al., 2022). Due to higher goals for quality of life, despite the economic prosperity, the Chinese people's life satisfaction is steadily declining (Li and Raine, 2013). Therefore, both carbon emissions and life satisfaction are emerging as public concerns. Understanding how carbon emissions related factors influence people's satisfaction with life can help get a better picture of how to reduce carbon emissions while ensuring the improvement of people's life satisfaction (Li and Chen, 2021), and further promote long-term social development. Recently, studies have called for much closer attention to be given to the role of the carbon emissions in human well-being literature (Fanning and O'Neill, 2019; Sugiawan et al., 2019), as it allows us to have a deeper understanding of how to reconcile a low-carbon lifestyle with a higher level of life satisfaction, which can promote the sustainable implementation of related carbon emissions reduction policies.

Another important issue related to carbon emissions to be addressed is energy consumption. Household energy consumption is largely dominant in the case of per capita carbon dioxide emissions (Sugiawan et al., 2019). In China, the household share of total carbon emissions is increasing (Zheng et al., 2010). Whether and to what extent energy consumption is associated with life satisfaction? And how do individual characteristics moderate the relationship between energy consumption and life satisfaction? Since a household's energy consumption is like the bridge connecting the relationship between human well-being and carbon emissions (Li and Chen, 2021), a better understanding of these questions can help inform policies aimed at carbon emission reduction and enhancing people's well-being. When evaluating life satisfaction, in addition to their own energy consumption level, individuals also draw comparisons with reference groups who share similar characteristics to themselves (Roychowdhury, 2019; Sun and Wang, 2013; Kaus, 2013; Maurer and Meier, 2008). The link between relative consumption and happiness has been one of the most discussed and debated topics in the literature on subjective well-being (Wu, 2019). Studies also shed light on the importance of reference groups and routine behavior for pro-environmental consumption (Welsch and Kühling, 2009; Wolske et al., 2020), however, there has been relatively little research on the impact of reference groups' energy consumption on the well-being literature. Considering relative energy consumption as a potential mechanism may provide a new perspective in explaining people's life satisfaction change, especially in China, a typical "human relationship society" (Zhang et al., 2022). In this context, the reference group's energy consumption patterns are integrated into the framework to explore the mechanism through which the energy consumption of the reference group affects the Chinese households' life satisfaction.

China has a vast territory, and carbon emissions vary from region to region due to discrepancies in climate, infrastructure, and energy consumption structure (Sun and Wang, 2021). Different provinces in China have different resource endowments, energy structures, and economic development levels; for example, the GDP per capita of some cities such as Beijing and Shanghai has reached the level of developed countries, while other regions are still at the level of developing countries (Hong et al., 2021). China provides a natural experiment in which current relationships among provincial carbon emissions, energy use, and household members' life satisfaction; thus, this study is situated in China. With the mainstream goal of "green growth," China has signed up to reduce its carbon emissions and has a plan to peak the carbon emissions within the next decade. The Chinese government began developing a route map that focused on emissions reductions. However, there is still uncertainty regarding the dependence of carbon reductions on people's quality of life. In addition, the Chinese government has made various efforts to improve people's life satisfaction, including implementing some support policies aimed at poverty alleviation. Now that the Chinese government needs to improve people's quality of life and achieve the goal of peaking carbon emissions by 2030, a better understanding of the relationship between carbon emissions, energy consumption, and life satisfaction is needed. This research is among the first to simultaneously evaluate the carbon emission, energy consumption, and relative energy consumption in explaining Chinese people's life satisfaction change.

Correspondingly, this present study makes several contributions. First, this study extends the emerging literature on the relationships among provincial carbon emissions, energy use, and life satisfaction levels within one country covering extended periods. Some research linking greenhouse gases and well-being is often conducted based on the overall index of countries (Apergis and Majeed, 2021). Nevertheless, the effect of environmental factors might vary in broad societal contexts. Focusing on one country makes it possible to test the sensitivity of the effect of carbon emissions and energy consumption on life satisfaction to the choices of geographic factors and control variables (Hou, 2013). Second, as the determinants of life satisfaction involving "internal" factors of personality traits and individuals' socio-demographic characteristics are embedded within "external" factors in individuals' environments, the perspectives of "top-down" and "bottom-up" methods are combined. Not only are macro factors like total provincial carbon emissions and GDP included, but micro factors such as income, socio-economic status, and other demographic characteristics are also examined in the model using a large micro panel data set, which reveals the detailed factors that are related to individuals' life satisfaction and the trade-offs they face. Third, the findings are novel in that the importance of energy consumption comparisons for people's life satisfaction is also underscored, and determine how residents' own and relative energy consumption influence people's life satisfaction in China.

The rest of the paper is organized as follows: **Section 2** comprises a literature review of life satisfaction, carbon emissions, energy consumption, and relative energy consumption studies. **Section 3** presents the data set, variables, and methods. **Section 4** presents the empirical results and estimations. **Section 5** discusses the results and makes policy suggestions.

LITERATURE REVIEW

Life Satisfaction and Carbon Emissions

As a kind of cognitive evaluation individual has regarding their life status, life satisfaction is the most common and reliable measure used in research on individuals' happiness (Hou, 2013; Fanning and O'Neill, 2019). Easterlin (1995) and Hirsch (1976) laid the theoretical foundation for happiness and well-being-related studies. Easterlin (1995) found that more wealth does not guarantee greater happiness, the so-called "happiness paradox." Following-up studies found that other factors ignored in early research may play a vital role in influencing people's life satisfaction, including environment, energy use, health, subjective factors, *etc.* (Betti et al., 2020; Apergis and Majeed, 2021; Kumari et al., 2021). At the same time, scholars have also realized that aspects of the external factors such as the natural environment or ecosystem are vital to people's life satisfaction (Summers et al., 2012; Cuñado and de Gracia, 2013; Zhang et al., 2017; Brereton et al., 2008), including air pollution, noise, and climate. Thus, it is necessary to identify influential environmental and energy-related factors to improve people's life satisfaction.

Most previous studies of life satisfaction are confined to Western countries (Li and Raine, 2013). However, in recent years, some research focused on China, and has found that family characteristic factors such as household income, consumption, housing, and environmental factors such as air pollution are highly related to Chinese people's life satisfaction (Zhang et al., 2022; Zhu et al., 2020; Cheng, et al., 2020; Zhang et al., 2017). Specifically, Zhang et al. (2017) investigated the association between air pollution and well-being using China Family Panel Studies data and found that the increase in the air pollution index reduced happiness and increased depression symptoms.

A large literature has also evolved on the relationship between carbon emissions and life satisfaction, but the results are mixed. Some scholars argue that carbon emissions have a negative effect on people's life satisfaction since it is not only one of the main causes of global warming and pollution (Zhang et al., 2017), but also brings some health risks such as the increased risk of cardiovascular disease and lung cancer (Lelieveld et al., 2019; Betti et al., 2020). Further, an increase in carbon emissions might lead to increased anxiety and concern about the possibility that they will be unable to adapt or otherwise protect themselves in the climate crisis caused by carbon emissions (El Zoghbi and El Ansari, 2014). As household consumption plays a key role in energy use and carbon emissions (Liu et al., 2016; Sun and Wang, 2021; Ivanova, et al., 2016; Kerkhof et al., 2009; Guo et al., 2021), especially in developing countries, some scholars considered the carbon emissions issue from a "bottom-up" perspective, that is, using the method of the basic goods basket to link human well-being and carbon emissions. They argued that the "bottom-up" human well-being index is more appropriate to study the relationship between individuals' lifestyles and carbon emissions (Li and Chen, 2021). Consistent with such predictions, Höysniemi and Salonen (2019) focused on the carbon emission-related behavioral intentions related to Finnish citizens' life satisfaction and found that the limited use of private cars also significantly predicts increased life satisfaction. Vita et al. (2020) compared the carbon footprints of non-members and members of sustainability-oriented grassroots initiatives and found that members show higher life satisfaction compared to non-members.

In contrast, a positive relationship between life satisfaction and carbon emissions has also been found in many studies. Concretely, Rao and Baer (2012) believed that increased use of energy and the accompanying emissions are needed to provide people with a decent living standard. Energy use serves to alleviate extreme temperatures, provide light and shelter, *etc.*, and presently the most readily available sources of energy produce carbon emissions. When its convenience outweighs its costs, increased use of carbon-based energy sources, and the associated emissions, will increase people's life satisfaction.

However, other scholars have noted that carbon emissions and life satisfaction can be decoupled, or can have a non-linear relationship. Sulkowski and White (2015) found that carbon emissions are not correlated perfectly with either development or happiness. Between two clusters with the highest average levels of development, income, and happiness, there was a 43% difference in carbon emissions. A highly developed cluster had roughly the same mean carbon emissions as a cluster with 83% less income, and the least developed cluster had 93% of the happiness level of the most developed cluster, yet 86% fewer carbon emissions. They also reported a happiness Kuznets curve (HKC), implying that average happiness may decrease as countries begin to develop but eventually improves as countries move from being moderately developed to highly developed. In contrast, using panel data on 58 nations, Dietz et al. (2012) examined the environmental intensity of human well-being, that is, the ratio of a nation's per capita ecological footprint to its average life expectancy at birth, and found a U-shaped relationship between gross domestic product per capita and EIWB, not the predicted inverted-U.

Why do previous studies focused on the relationship between carbon emissions and life satisfaction show different results? One potential explanation for this question could be the regional disparities, since carbon emissions are associated with the development and urbanization of a region, people living in developing regions who produce more carbon emissions through driving more and consuming more electricity might be happier than others (Glaeser and Kahn, 2010; Zheng et al., 2010). Some research has employed a "top-down" approach, that is, examining the relationship between macro-level measures of development and energy use from a macro level to expand the research focus of energy use from the economy or technology to society (Li and Chen, 2021). Costa et al. (2011) used the human development index (HDI) as the main indicator to evaluate human well-being and demonstrated the existence of a positive and time-dependent relationship between HDI and CO_2 emissions per capita from fossil fuel combustion. They also proposed that until HDI reached the threshold of 0.8, the developing countries are not suggested to reduce carbon emissions. Using national-level panel data for the 1970–2009 period, Jorgenson (2014) found that economic growth improved human well-being but at the cost of an increasing amount of carbon emissions. The carbon intensity of human well-being (CIWB) indicator, that is, the level of anthropogenic carbon emissions per unit of human well-being, was utilized in this research. For nations in Asia and South and Central America, development increased CIWB throughout the 40 years of the study. Sugiawan et al. (2019) suggested that the commitment to carbon emissions reduction needs to be evaluated and should be different between developed and developing economies because it is important to consider its impact on inter-generational well-being. The developed countries were encouraged to set up a more ambitious target of carbon emissions reduction.

Energy Consumption

In China, the demand for energy consumption and households' share of total carbon emissions is increasing as a result of China's rapid urbanization and transition to being a service economy (Zheng et al., 2010). The corresponding outputs that the energy produces, such as food, heat, industrial objects, or service, are not only related to humans' basic needs and well-being (Jorgenson et al., 2014) but also are a key driver of carbon emissions (Okulicz-Kozaryn and Altman, 2019). To this point, energy consumption is like the bridge connecting the relationship between human well-being and carbon emissions (Li and Chen, 2021); thus, it is necessary to take energy consumption into account in carbon emissions and life satisfaction-related research.

A fundamental trade-off exists in energy consumption between the environmental impact and self-interest at the individual and national levels (Okulicz-Kozaryn and Altman, 2019). It is generally believed that energy use, such as electric power might offer an important material foundation for individuals' happiness and socio-economic development, which brings convenience to their lives and improves their overall quality of life, especially for the rural residents (Guo et al., 2016). Kumari et al. (2021) analyzed the effect of energy consumption and environmental quality on subjective well-being in G20 countries from 2006 to 2019. The findings reveal that renewable energy consumption and environmental quality significantly enhance well-being in G20 countries, while non-renewable energy consumption reduces subjective well-being. Arto et al. (2016) found that the relationship between energy demand and HDI shows a strong positive correlation in 40 developed and developing countries for the period 1995–2008; however, beyond a certain point, HDI is not associated with GDP. Yet, in contrast, some research has also found that subjective well-being and life satisfaction are unrelated to energy use. Okulicz-Kozaryn and Altman (2019) integrated data from multiple sources and found that no evidence of increasing energy consumption substantially increases well-being. Arto et al. (2016) also found that in developed countries, the relationship is decoupled, because international trade enables countries to maintain their development level while goods and services are produced abroad without causing domestic energy consumption to increase. Similarly, Akizu-Gardoki et al. (2020) found that there is a well-being turning point, that is, there is a logarithmic positive relationship between well-being and energy consumption up to a certain point, but a negative correlation between energy consumption and well-being after the well-being turning point has been reached.

Relative Energy Consumption

Relative consumption is defined as consumption in comparison to that of the reference group (Frank, 1985; Sun and Wang, 2013). Individuals live in society and observe others' behaviors; thus, the consumption patterns of others in comparison to oneself are taken into account in individuals' self-reported life satisfaction and well-being (Guillen-Royo, 2011; Wang et al., 2017). The reference group is the social group that consumers compare themselves to and, as a result, make judgments about themselves (Tajfel, 2003). Some research has found that the reference group has a value-expressive influence: it helps consumers express themselves and meets their needs for self-elevation (Hammerl et al., 2016). Through observations and communications with the reference groups, individuals' self-evaluated life satisfaction will be affected accordingly.

Reference groups' spending on different types of commodities might have different externalities. The early work of Veblen (1899) put forward the conspicuous consumption theory, which indicated that people pursued conspicuous consumption to demonstrate that they were better than others, and to help them maintain or raise their position in the social hierarchy. Previous work has also distinguished between positional/status goods and non-positional/non-status goods (Frank, 1985; Hirsch, 1976) to understand the nature of social comparisons regarding consumption behavior. Positional/status goods are the visible things that can signal the owners' place or rank in the society, while non-positional/non-status goods are not used to make such comparisons and are consumed for their utilitarian value. Heffetz (2012) pointed out that different commodities have different degrees of visibility; Strangers notice an individual's expenditures with higher visibility more than other expenditures, such as clothing and cars. Wu (2019) hypothesized that individuals' positional consumption relative to that of others in one's reference group increases their life satisfaction in all income groups, while higher levels of basic expenditures have a negative influence on people in the lowest income quartile.

Energy consumption is a kind of non-positional and basic good. Much of the previous research on energy consumption focuses on how individuals' energy consumption decisions are influenced by the behavior of reference groups (Welsch and Kühling, 2009; Mi et al., 2019; Wolske et al., 2020). Welsch and Kühling (2009) hypothesized that the reference groups' pro-environmental consumption patterns are relevant to consumers' consumption, because social comparison may serve the purpose of encouraging social compatibility within ones' reference group. Wolske et al. (2020) explored two potential ways in which peer effects on energy use and clean technology adoption could occur. The first is interpersonal communication and persuasion. Such communication may raise awareness of pro-environmental behaviors and the potential benefits of new energy technologies, and it may convey important procedural information (Berger, 2014). The second peer effect involves changes in social norms. Some research examined respondents' perceptions of peer influences and found that communicating with peers can reduce uncertainty and confirm peer adopters' beliefs that photovoltaics can work as intended without hassle (Palm, 2017). These two processes represent complementary ways in which social influence may manifest itself in peer effects. Some research has also indicated that a reference group's norms serve as a way to stimulate residents to implement low-carbon consumption behaviors (Mi et al., 2019).

Based on the theory of social interaction and embeddedness, Yin and Shi (2021) found that having a strong relationship with one's reference group can directly promote low carbon consumption behavior among Chinese residents, while network size has an indirect effect through social norms. To date, however, there have been very few empirical studies that consider the relationship between the reference group's energy consumption and life satisfaction directly. This study extends this line of research by investigating whether individuals feel more satisfied when their reference groups engage in more energy consumption.

Most household survey data do not have accurate social interaction variables and lack direct survey questions about the composition of someone's social circles, considering the availability of data, some studies would take reference groups as given exogenous variables. Many scholars assume that people living in the same region constitute a membership reference group (Wang et al., 2017; Cheng, et al., 2020; Roychowdhury, 2019; Sun and Wang, 2013; Kaus, 2013). As argued by Kaus, (2013), consumables are prominently visible in the process of social interaction, and a large proportion of social interactions occur in residential environments. Other researchers assume that individuals primarily compare themselves with others who share certain demographic characteristics (e. g., age, gender, degree, or occupation) (Maurer and Meier, 2008).

To date, although there are mixed findings concerning the impact of carbon emissions and energy consumption on life satisfaction, most research linking carbon emissions and well-being is often conducted based on the overall index of countries (Fanning and O'Neill, 2019; Apergis and Majeed, 2021), few studies test the regional disparities focusing on one country. In addition, little substantive empirical research has addressed the link between reference groups' energy consumption and household members' life satisfaction. To address this research gap, this study analyzes the effects of carbon emissions, as well as consumers', and also underscores the importance of their references groups' energy consumption on life satisfaction in China, using top-down and bottom-up methods.

METHODOLOGY

Model Setting

In this study, for every household member i in year t, life satisfaction is predicted from provincial carbon emissions, household income, energy consumption, and its ratio to the household member's reference group, *etc*. The following model represents this relationship:

$$L_{it} = \gamma_0 + \alpha_1 CE_{it} + \alpha_2 GDP_{it} + \alpha_3 Z_{it} + \beta_1 Inc_{it} + \beta_2 C_{it} + \beta_3 RC_{it} + \beta_4 X_{it} + \varepsilon_0$$

Where L_{it} is life satisfaction level (*Life satisfaction*). γ_0 is the intercept. The notation CE_{it} represents province-level carbon emissions per capita (*Carbon emissions*), which is measured at Mt/capita. GDP_{it} refers to GDP per capita at the province level (*GDP*). Z_{it} is a vector of provincial level control, including provincial population (*Population*). Inc_{it} represents household income per capita (*Income*), and C_{it} represents energy consumption per capita, including electricity consumption (*Electricity expense*) and fuel consumption (*Fuel expense*). To examine whether energy consumption has a positional or non-positional character for the Chinese population, relative energy expenditure factors are added into this model; RC_{it} stands for energy expenditure ratio, the relative electricity expenditure compared to individuals' reference group's level (*Relative electricity consumption*) and the relative fuel expenditure compared to individuals' reference group's level (*Relative fuel consumption*). The vector of variables X_{it} includes individuals' socio-economic and demographic characteristics, such as age (*Age*), education (*Eduyear*), family size (*Family size*), residence (*Residence*), and marital status (*Marital status*). Besides, ε_0 is the province-specific error term.

Data

CFPS data administered by the Institute of Social Science Survey at Peking University is used from 2010 to 2018 and the project aims to conduct regular and systematic surveys on the three levels of communities, families, and family members (individuals). CFPS is a nationally representative household survey in China. Up to now, CFPS has released tracking survey data for 2010, 2012, 2014, 2016, and 2018, containing a wide range of detailed economic, social, and demographic information about Chinese households. After data combining and cleaning, 133,204 samples covering 25 provinces and municipalities are obtained.

Some macro-level data such as provincial GDP and provincial population are drawn from the China National Bureau of Statistics Database, and carbon emissions data came from the Carbon Emission Accounts and Datasets (CEADs). CFPS micro-data is also matched with these macro data, which covers 25 provinces in China and spans 2010–2018.

Variables

Dependent Variables

The life satisfaction level of the respondents is measured through self-reported satisfaction levels on a 5-point scale, in response to the question: "Are you satisfied with your life?" Responses ranged from 1 (most dissatisfied) to 5 (most satisfied). Life satisfaction is the most common and reliable measure used in subjective well-being-related literature (Hou, 2013; Fanning and O'Neill, 2019).

Independent Variables

Carbon emissions per capita (in metric tons) are the key independent variable, with data for 25 provinces from 2010 to 2018 from the CEADs. The detailed computation process is available in Shan et al. (2020)'s research. Each province's carbon emissions level is divided by the provincial population to get the carbon emissions per capita variable.

Household energy consumption is also a vital independent variable since it is not only related to well-being (Jorgenson et al., 2014) but also is a key driver of carbon emissions (Okulicz-Kozaryn and Altman 2019). Based on data availability, households' energy consumption mainly contains two parts: electricity expenditures and fuel expenditures, respectively measured through these two questions: "How much does your family spend on electricity?" and "How much does your family spend on fuel (including coal gas, liquefied gas, coal, firewood, charcoal, *etc.*)?" These two questions are only asked starting in 2012. As the expense is monthly and household data, these two variables are multiplied by 12 and divided by family size. For households with no electricity or fuel expenses, the values are replaced with 0.01, then transformed logarithmically.

The relative electricity consumption and relative fuel consumption independent variables are used to measure the positionality of household energy consumption, defined as the ratio between an individual's electricity consumption, fuel consumption, and their reference group's average levels respectively. The reference group is assumed to consist of people of similar age and similar income levels living in the same province. The reference-level energy consumption is first defined at the provincial level as revealed in the literature (Wang et al., 2017; Cheng, et al., 2020). Within each province, further reference groups are constructed along the dimensions of age and household income. Age is divided into six categories: 18–24, 25–34, 35–44, 45–54, 55–65, and 65 or above. Household income is divided into 1–5 quintiles from low to high. Thus, there are 30 reference groups in total within each province in 1 year (5*6 = 30). The electricity consumption ratio is measured by their own electricity expense divided by the average electricity expense of ones' reference group and introduced in logarithmic form. Similarly, the fuel consumption ratio variable is measured by their own fuel expense divided by the average level of reference-group fuel expense and introduced in logarithmic form.

To measure the economic development levels of each province over time, provincial real GDP per capita is selected as the indicator. GDP measures the total market value of all final goods and services purchased within a province. Each province's GDP level is divided by the provincial population to get the GDP per capita. And the natural logarithm form of real GDP per capita is used.

Control Variables

In addition, some key micro-level covariates are also included in the model based on their relevance to life satisfaction as revealed in the literature, including household income and individual demographic variables. Household income is defined as the sum of total money income for all members of the household. Total income includes income from wages and operating income, property income, and transfer income, and is divided by family size, and the natural logarithm calculated. Households with no income are assigned a value of zero. A series of demographic variables are treated as control variables including education, gender, age, marital status, and residence (urban or rural). Among them, the level of education received is calculated according to years of education. Other demographic variables are dummy-coded. For gender, female is 0 and male is 1; for marital status, married or cohabitating is 1, and unmarried, not cohabiting, divorced, or widowed residents are 0; for residence, 1 = living in an urban area and 0 = living in a rural area.

The provincial population (according to the China National Bureau of Statistics Database) is chosen as the macro-level control variable and is log-transformed. The categories of household energy consumption, income, and provincial GDP have been deflated by the consumer price index (CPI), using 2010 as the base year.

Statistical Description

Descriptive statistics for the above variables are presented in **Table 1**. The mean value of life satisfaction increased from 3.652. And the mean value of provincial GDP per capita is 18742.89. However, the standard deviation value of GDP is large, which indicates that China's regional economic development is unbalanced. In addition, reference-group electricity expenditures and reference-group fuel expenditures are defined at the provincial age-income level, and their standard deviation values indicate that residents' energy expenditures are also heterogeneous in different groups or regions.

Methods

In line with previous research, the changes in the coefficients across linear models can be compared, but for logit or probit models, one cannot straightforwardly compare the coefficient changes (Mood, 2009; Hou, 2013). Therefore, life satisfaction was first treated as a continuous variable and employed OLS models. Considering that CFPS data has a multi-level nature, in all OLS models, standard errors are clustered at the province level. The OLS model with cluster-robust standard errors is identical to a random intercept with higher-level predictors and a fixed-slope model with level-1 covariates within the framework of hierarchical linear models (HLM) (Arceneaux and Nickerson, 2017; Hou, 2013). To make the results robust, the results are also replicated in ordered logit models. To test relationship heterogeneity across different regions, the data sample was further segregated into first-tier cities (including Beijing and Shanghai) and other province categories. Finally, a series of heterogeneity analyses across several dimensions: individuals' income, education level, age, and residence type (urban or rural) are conducted.

RESULTS

The Distribution of Life Satisfaction Across Provinces

Life satisfaction and carbon emissions may show heterogeneity in China. Therefore, these two macro variables are plotted in **Figure 1**. The x-axis indicates each province's average carbon emissions per capita, and the y-axis indicates the life satisfaction level. Across these provinces in China, the quadratic fit shows that there is a clear positive association between carbon emissions and life satisfaction. The higher carbon emissions are within a province, the higher life satisfaction is for its households. Still, the variance across provinces is large. Guangxi (GX), Jiangxi (JX), and Guangdong (GD) have both the lowest carbon emissions levels and lowest average life satisfaction. Some provinces, such as Tianjin (TJ), have both higher carbon emissions per capita and higher life satisfaction. Still, there are some exceptions, such as Shanxi (SX) and Liaoning (LN), which have higher carbon emissions per capita, but lower life satisfaction.

TABLE 1 | Descriptive statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
Life satisfaction	133,204	3.652	1.055	1	5
Carbon emission	133,204	0.069	0.026	0.033	0.155
Electricity expense	107,699	265.507	369.051	0.01	14,987.511
Ln(Electricity expense)	107,699	4.379	2.993	−4.605	9.615
Fuel expense	107,699	213.653	837.338	0.01	74,142.725
Ln(Fuel expense)	107,699	1.168	4.987	−4.605	11.214
Relative electricity expense	107,699	1	1.137	0.1	31.174
Ln(Relative electricity expense)	107,699	−1.071	2.811	−11.531	3.44
Relative fuel expense	107,699	0.999	2.696	0.1	174.973
Ln(Relative fuel expense)	107,699	−2.505	4.169	−13.727	5.165
GDP	133,204	18,742.89	12,935.76	3,864.53	53,714.49
Ln(GDP)	133,204	9.597	0.723	8.26	10.891
Income	133,204	12,034.40	18,864.32	0	1,404,276.6
Ln(Income)	133,204	8.757	1.369	−1.684	14.155
Gender (1 for men)	133,204	0.488	0.5	0	1
Registered residence (urban =1)	133,204	0.465	0.499	0	1
Age	133,204	46.51	16.667	16	102
Education	133,204	7.423	4.8	0	22
Marital status (1 for married and cohabitation)	133,204	0.799	0.401	0	1
Family Size	133,204	4.286	1.945	1	26
Population	133,204	5,953.93	3,073.552	1,299	12,348
Ln(Population)	133,204	8.549	0.546	7.169	9.421

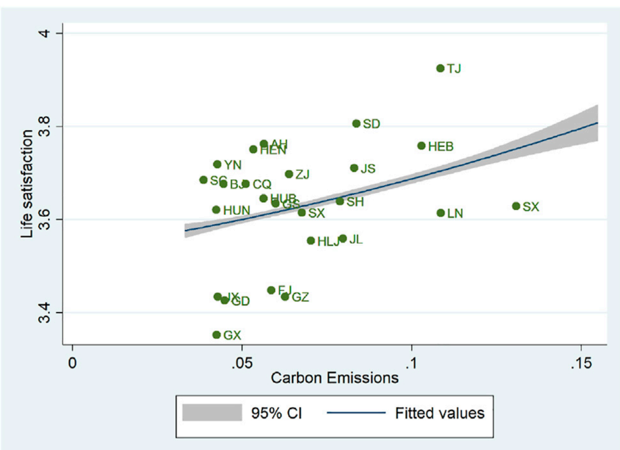

FIGURE 1 | The relationship between carbon emissions and life satisfaction. Notes: Quadratic fit is shown with 95% confidence intervals. All data are averaged over the 2010–2018 period.

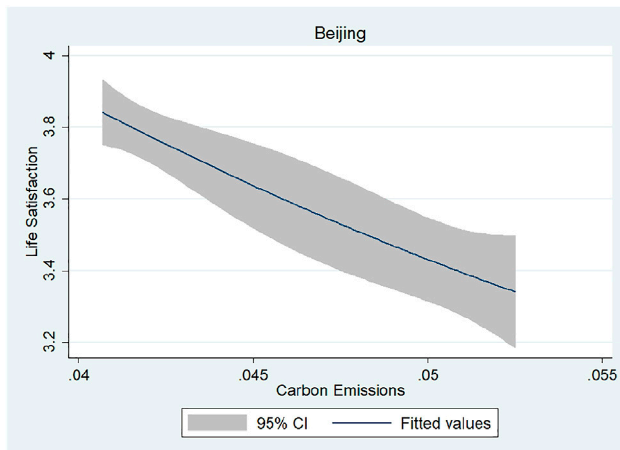

FIGURE 2 | The relationship between carbon emissions and life satisfaction in Beijing.

In addition, Beijing and Shanghai, as two first-tier municipalities of China, are the economic leaders in comparison to other provinces and cities. Thus, these municipalities' carbon emissions and residents' life satisfaction might exhibit unique features that need to be studied. **Figures 2, 3** depict the relationship between carbon emissions and life satisfaction in Beijing and Shanghai respectively. As can be seen in **Figure 2**, contrary to **Figure 1**, the trend in life satisfaction is negatively related to carbon emissions for residents in Beijing, which is somewhat in line with Zhang et al. (2017), who argue for a negative correlation between air pollution and life satisfaction.

The self-reported levels of life satisfaction in Shanghai are shown in **Figure 3**, which illustrates that there is an inverted U-shaped relationship between carbon emissions and life satisfaction levels. Life satisfaction is highest at the intermediate level of carbon emissions per capita, around 0.078–0.079. As carbon emissions increase further, life satisfaction declines. Thus, people who experience the extremes of carbon emissions have the lowest life satisfaction. This is partly in line with Costa et al. (2011), who found that carbon emissions result in more life satisfaction only up to the point that is used to satisfy basic human needs. When essential human needs for energy are met, more carbon emissions will result in decreased life satisfaction.

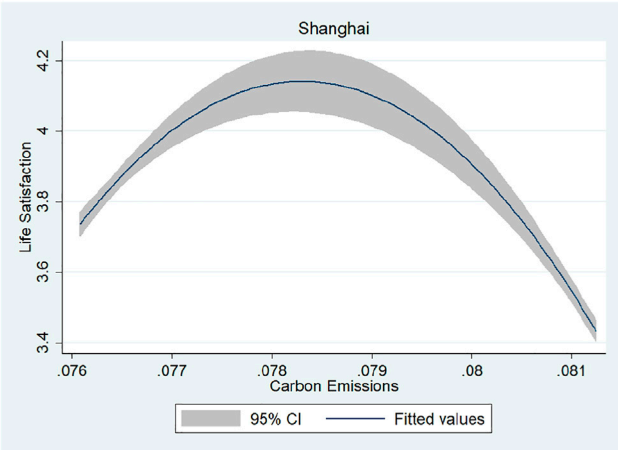

FIGURE 3 | The relationship between carbon emissions and life satisfaction in Shanghai. Note: Quadratic fit is shown with 95% confidence intervals. All data are averaged over the 2010–2018 period.

Empirical Results

In **Table 2**, the results from OLS with life satisfaction as the dependent variable are presented. Column 1 shows whether changes in carbon emissions and other macro variables are relevant to explaining changes in life satisfaction across provinces. The coefficient of carbon emissions implies that a 1% increase in provincial carbon emissions per capita is associated with a 2.122% increase in life satisfaction, and other macro factors such as provincial GDP and population only have some potential insignificant effects on life satisfaction.

In Column 2, alongside other macro determinants of life satisfaction, the model introduces some micro variables, including household income per capita, gender, registered residence condition, age, level of education, marital status, and family size. Among the micro indicators, household income, gender, age, and family size variables have positive and statistically significant coefficients, suggesting that older, female individuals with higher household income and larger family sizes tend to have higher levels of life satisfaction. It can be seen that these findings are consistent with previous research findings (Alesina et al., 2004; Hou, 2013; Zhu et al., 2020). Elders usually have lower expectations for future life and stress compared with younger people, thus having higher life satisfaction. In particular, the coefficient of the provincial population becomes significantly positive when the micro variables are introduced.

TABLE 2 | The impact of carbon emissions and energy consumption on Life satisfaction.

	(1)	(2)	(3)	(4)	(5)
Carbon emissions	2.122**	2.291**	1.886**	1.546*	1.775*
	(0.94)	(0.907)	(0.866)	(0.874)	(0.947)
Ln(GDP)	−0.019	−0.091	−0.08	−0.103	−0.122*
	(0.059)	(0.064)	(0.063)	(0.066)	(0.07)
Ln(Population)	0.075	0.16***	0.139**	0.149**	0.175***
	(0.063)	(0.057)	(0.057)	(0.054)	(0.055)
Ln(Income)	—	0.067***	0.054***	0.038***	0.032***
	—	(0.005)	(0.004)	(0.004)	(0.004)
Gender	—	−0.066***	−0.061***	−0.052***	−0.053***
	—	(0.009)	(0.01)	(0.009)	(0.01)
Residence	—	−0.008	0.009	−0.022	−0.019
	—	(0.028)	(0.028)	(0.028)	(0.027)
Age	—	0.007***	0.007***	0.006***	0.005***
	—	(0)	(0)	(0)	(0.001)
Education	—	0.003	0.002	−0.002	−0.002
	—	(0.002)	(0.003)	(0.002)	(0.002)
Marital status	—	−0.019	−0.009	−0.014	−0.008
	—	(0.013)	(0.012)	(0.013)	(0.014)
Family size	—	0.02***	0.017***	0.017***	0.019***
	—	(0.005)	(0.005)	(0.005)	(0.006)
Ln(Electricity expense)	—	—	—	0.029***	0.102***
	—	—	—	(0.003)	(0.028)
Ln(Fuel expense)	—	—	—	0.024***	0.037***
	—	—	—	(0.003)	(0.002)
Ln(Relative electricity consumption)	—	—	—	—	−0.083**
	—	—	—	—	(0.03)
Ln(Relative fuel consumption)	—	—	—	—	−0.024***
	—	—	—	—	(0.003)
Constant	3.05***	2.05***	2.3***	2.533***	2.054***
	(0.425)	(0.389)	(0.382)	(0.406)	(0.481)
Observations	133,204	133,204	107,699	107,699	107,699
R^2	0.003	0.018	0.016	0.041	0.048

*Cluster robust standard errors are in parentheses. Moreover, ***, ** and * denote 1, 5 and 10% significance level, respectively.*

TABLE 3 | Robust test, with cluster robust standard errors.

	(1)	(2)	(3)
	Ordered logic	**Random effect**	**Fixed effect**
Carbon emissions	3.612**	2.113***	11.327***
	(1.722)	(0.158)	(0.64)
Ln(Electricity expense)	0.182***	0.112***	0.039***
	(0.051)	(0.008)	(0.01)
Ln(Fuel expense)	0.066***	0.038***	0.026***
	(0.004)	(0.001)	(0.001)
Ln(Relative electricity consumption)	−0.149***	−0.094***	−0.027***
	(0.054)	(0.008)	(0.01)
Ln(Relative fuel consumption)	−0.044***	−0.024***	−0.018***
	(0.005)	(0.001)	(0.001)
Observations	107,699	107,699	107,699

****, ** and * denote 1, 5 and 10% significance level, respectively.*

As for the economic factors, the coefficient of lnGDP indicates that provincial GDP, the macro factor, fails to explain people's life satisfaction when incorporating the carbon emissions factor, which is consistent with Easterlin's (1995). However, on a micro-economic level, increased household income is still associated with a higher level of life satisfaction, suggesting that higher income not only satisfies people's requirements of higher-level life quality but provides opportunities for higher relative income level, which is also a positive determinant of life satisfaction, consistent with previous research (Frank, 2012; Yuan, 2015; Wang et al., 2019).

In Columns 4 and 5, the model incorporates the energy consumption factor: electricity expenses and fuel expenses. As these two variables are recorded only for the years 2012, 2014, 2016 and 2018 in CFPS, the sample size has changed. To raise the comparability of the coefficients, all the variables are regressed from the year 2012–2018 in Column 3. The regression of life satisfaction scores on carbon emissions of the variable for carbon emissions is 1.886 in Column 3, but this effect is reduced to 1.546 and 1.775 and becomes less significant in Columns 4 and 5. As for energy consumption, in Column 4, holding other factors fixed, a 1% increase in electricity expenses and fuel expenses are associated with 0.029% and 0.024% increases in life satisfaction, respectively; that is, any reduction of energy expenditures may have a negative effect on people's life satisfaction. Since appliance usage has become a part of daily life, there is usually certain inertia for household appliance usage (Guo, et al., 2016). Using more electric and gas-powered appliances, such as refrigerators, TVs, and cooking appliances, can facilitate people's daily lives, thus improving their life satisfaction. Furthermore, column 5 extends the set of regressors to include the electricity expense ratio and fuel expense ratio. In this case, the coefficients of electricity expense and fuel expense increased to 0.102 and 0.037. As for the referent ratio factors, higher ratio levels tend to be associated with lower life satisfaction levels. The fuel consumption ratio is negative and significant; a 1% increase in fuel consumption ratio leads to about a 0.024% decrease in life satisfaction. Though the electricity consumption ratio is less significant than the fuel consumption ratio, a 1% increase in it is associated with a 0.102% decline in life satisfaction, suggesting that people feel more satisfied or happier if they consume less electricity and fuel than their neighbors or peers.

Robustness

The robustness of the results is checked and reported in **Table 3**. To explain the possible non-cardinality of life satisfaction data, Column 1 reports the results from estimating the models from Column 5 of **Table 2** using an ordered logit instead of the OLS model. Column 2 presents a full model with fixed effect results, which provide within-person interpretations. And Column 3 shows the random effect results.

Comparing the results, the OLS model, ordered logistic model, fixed-effect model, and random effect model show similar patterns of how life satisfaction is determined. Though the coefficients of carbon emissions in **Table 3** become significant, the other coefficients, including electricity expenses, fuel expenses, relative electricity expenses, and relative fuel expenses are similar in significance and influence direction to that of variables in Column 5 of **Table 2**. These results imply that the model is robust.

Estimation Results for Beijing and Shanghai

For the population as a whole, carbon emissions have a significant positive relationship with life satisfaction. The impact of carbon emissions on people's life satisfaction may vary among different areas, given the significant differences in the economic development levels and natural resource endowments of different provinces. Among all provinces, Beijing and Shanghai are the first-tier municipalities, and the per capita GDP has reached the level of developed countries, while most of the other regions are still at the level of developing countries. As their economic and political resources and people's living conditions are significantly different from other provinces and municipalities, the effects on life satisfaction should also be different.

To test for this, in **Table 4**, split-sample analyses are conducted. OLS models are run separately for the first-tier municipalities (Beijing and Shanghai) and other provinces. Results shown in **Table 4** reveal some significant changes for the regional differences in the effects of provincial carbon emissions, reference groups, and individuals' energy

TABLE 4 | Impact of carbon emissions, energy consumption on Life satisfaction in Beijing and Shanghai.

	(1)	(2)	(3)	(4)
	First-tier cities: Beijing, Shanghai		Other provinces	
Carbon emissions	−22.075*	−8.6**	2.489**	2.302**
	(3.287)	(0.421)	(0.921)	(1.078)
Ln(GDP)	2.504**	2.543**	−0.186	−0.213
	(0.182)	(0.144)	(0.118)	(0.14)
Ln(Population)	3.806	−0.024	0.303*	0.315*
	(0.841)	(0.049)	(0.147)	(0.163)
Ln(Income)	0.042**	0.036*	0.052***	0.032***
	(0.002)	(0.005)	(0.004)	(0.004)
Gender	−0.021	−0.017	−0.064***	−0.055***
	(0.015)	(0.014)	(0.009)	(0.01)
Residence	0.02	0.017	0.006	−0.021
	(0.012)	(0.009)	(0.029)	(0.028)
Age	0.006*	0.005*	0.006***	0.005***
	(0.001)	(0)	(0)	(0.001)
Education	−0.003	−0.005	0.002	−0.002
	(0.002)	(0.002)	(0.003)	(0.002)
Marital status	0.011	0.012	−0.01	−0.01
	(0.042)	(0.042)	(0.013)	(0.015)
Family size	0.039**	0.038***	0.015***	0.017***
	(0.002)	(0.001)	(0.005)	(0.006)
Ln(Electricity expense)	—	0.044	—	0.104***
	—	(0.022)	—	(0.033)
Ln(Fuel expense)	—	0.018	—	0.036***
	—	(0.003)	—	(0.002)
Ln(Relative electricity consumption)	—	−0.027	—	−0.084**
	—	(0.019)	—	(0.034)
Ln(Relative fuel consumption)	—	−0.001	—	−0.024***
	—	(0.004)	—	(0.003)
Constant	−49.794	−21.512*	1.882***	1.676***
	(8.093)	(1.905)	(0.403)	(0.489)
Observations	7,902	7,902	99,797	99,797
R-squared	0.059	0.062	0.017	0.048

*Cluster robust standard errors are in parentheses. Moreover, ***, ** and * denote 1, 5 and 10% significance level, respectively.*

consumption. The first-tier municipalities' sample results are reported in Columns 1–2, and those of other provinces in Columns 3–4. For individuals living in the first-tier municipalities, the carbon emissions variable is negatively related to their life satisfaction, which has also confirmed the conclusion from **Figure 2**, that carbon emissions have a significant negative coefficient. As Beijing and Shanghai are the most developed first-tier cities in China, the results presented so far suggest that how the changes in carbon emissions explain changes in life satisfaction across provinces depends on the degree of development of the region, which reinforces the conclusion of the previous research (Dietz et al., 2012). In addition, the effects of relative and individual energy consumption for Beijing and Shanghai are statistically different from the effect for other provinces. While the coefficients significantly influence life satisfaction levels in other provinces, they are not statistically significant for residents in Beijing and Shanghai.

Heterogeneity Analysis

Some individuals, depending on their characteristics, might be more prone than others to respond to carbon emissions or energy consumption. To obtain a better understanding of how these characteristics correlate with it, a series of heterogeneity analyses across several dimensions are conducted: individuals' income, education level, age, and residence type (urban or rural).

In the heterogeneity analysis, main independent variables, including carbon emissions, electricity consumption, fuel consumption, relative electricity consumption, and relative fuel consumption, are interacted with individual characteristic variables. In **Table 5**, the results show that the carbon emissions variable does not exhibit different effects across an individual's income, education level, age, and residence type.

For electricity, fuel consumption, and relative consumption, their interactions with individuals' income are first assessed, the results of which are shown in Column 1. Among all the interaction terms, only the coefficient of the interaction term of fuel expense is negative and significant. This suggests that fuel expenditures have significantly positive effects on life satisfaction for all people, but the effects for higher-income individuals are less than for others.

A similar heterogeneity analysis is conducted as above for the interaction of carbon emissions, electricity consumption, fuel consumption, relative electricity consumption, and relative fuel consumption with individuals' education level, the results of

TABLE 5 | Heterogeneity analysis.

	(1)	(2)	(3)	(4)
	Income	*Education*	*Age*	*Residence*
Carbon emissions	0.486	1.812	2.073**	2.191**
	(1.874)	(1.59)	(0.957)	(1.042)
Carbon emissions × Ln(Income)	0.148	—	—	—
	(0.158)	—	—	—
Carbon emissions × education	—	−0.005	—	—
		(0.097)		
Carbon emissions × Age	—	—	−0.007	—
	—	—	(0.024)	—
Carbon emissions × Residence	—	—	—	−0.887
	—	—	—	(0.831)
Ln(Electricity expense)	0.057	0.101**	0.035	0.083***
	(0.069)	(0.037)	(0.043)	(0.029)
Ln(Electricity expense) × Ln(Income)	0.005	—	—	—
	(0.008)	—	—	—
Ln(Electricity expense) × education	—	0.001	—	—
	—	(0.003)	—	—
Ln(Electricity expense) × Age	—	—	0.002**	—
	—	—	(0.001)	—
Ln(Electricity expense) × Residence	—	—	—	0.034
	—	—	—	(0.024)
Ln(Fuel expense)	0.062***	0.046***	0.024***	0.037***
	(0.01)	(0.004)	(0.003)	(0.003)
Ln(Fuel expense) × Ln(Income)	−0.003**	—	—	—
	(0.001)	—	—	—
Ln(Fuel expense) × education	—	−0.001***	—	—
	—	(0)	—	—
Ln(Fuel expense) × Age	—	—	0.0003***	—
	—	—	(0)	—
Ln(Fuel expense) × Residence	—	—	—	−0.001
	—	—	—	(0.004)
Ln(Relative electricity consumption)	−0.028	−0.078**	−0.017	−0.063*
	(0.07)	(0.037)	(0.045)	(0.031)
Ln(Relative electricity consumption) × Ln(Income)	−0.007	—	—	—
	(0.008)	—	—	—
Ln(Relative electricity consumption) × education	—	−0.002	—	—
	—	(0.003)	—	—
Ln(Relative electricity consumption) × Age	—	—	−0.002**	—
	—	—	(0.001)	—
Ln(Relative electricity consumption) × Residence (urban = 1)	—	—	—	−0.036
	—	—	—	(0.024)
Ln(Relative fuel consumption)	−0.045***	−0.032***	−0.014***	−0.028***
	(0.014)	(0.004)	(0.005)	(0.003)
Ln(Relative fuel consumption) × Ln(Income)	0.002	—	—	—
	(0.002)	—	—	—
Ln(Relative fuel consumption) × education	—	0.001***	—	—
	—	(0)	—	—
Ln(Relative fuel consumption) × Age	—	—	0.0002***	—
	—	—	(0)	—
Ln(Relative fuel consumption) × Residence (urban = 1)	—	—	—	0.009**
	—	—	—	(0.004)
Ln(Income)	0	—	—	—
	(0.043)	—	—	—
Education	—	−0.003	—	—
	—	(0.015)	—	—
Age	—	—	−0.004	—
	—	—	(0.004)	—
Residence (urban = 1)	—	—	—	−0.121
	—	—	—	(0.121)
Constant	2.318***	2.041***	2.437***	2.437***
	(0.685)	(0.532)	(0.525)	(0.525)
Observations	107,699	107,699	107,699	107,699
R-squared	0.048	0.048	0.048	0.048

*Cluster robust standard errors are in parentheses. Moreover, ***, ** and * denote 1, 5 and 10% significance level, respectively.*

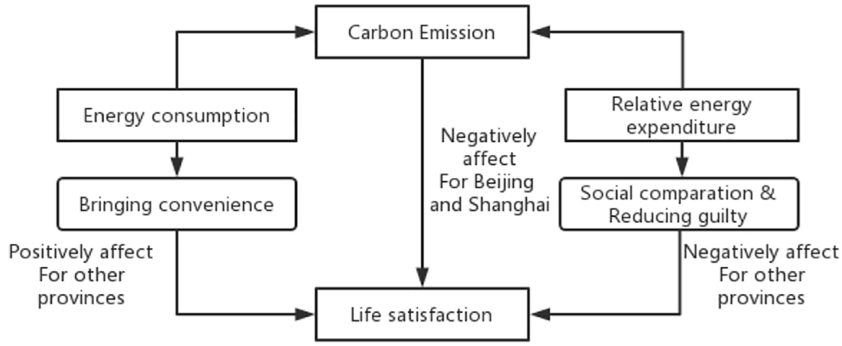

FIGURE 4 | Summary of the main findings.

which are shown in Column 2. The fuel interaction term and relative fuel consumption interaction term have significant effects, and the other relevant interaction terms did not have a significant influence. Thus, for individuals who have higher educational attainment, increased fuel expenses will bring less increase in their life satisfaction than for others, and they are also less likely to compare themselves to their reference groups on fuel consumption.

People's reactions to energy consumption could vary with their age. In Column 3, electricity, fuel consumption and relative consumption regressors by themselves have significant influences. The fuel consumption interaction and electricity consumption interaction terms have significant and positive effects, which means that older individuals are more sensitive to their energy consumption than younger individuals when evaluating their life satisfaction. And the relative electricity consumption interaction shows a significant negative influence, and relative fuel consumption interaction terms are significantly positive. The results indicate that older people care more about their relative electricity consumption, but care less about their relative fuel consumption than younger ones.

To check for residence type differences in the relationship between life satisfaction and energy consumption, the interactions with residence dummies are computed and are shown in Column 4. In this regression, the relative fuel consumption interaction term has a significant and positive effect, and the other three relevant interaction terms are not significant. This suggests that if urban people consume more fuel than their reference group, the negative effect is less on life satisfaction than it is for rural people.

CONCLUSIONS AND IMPLICATIONS

This study is conducted to expand the body of knowledge by simultaneously extrapolating the carbon emissions, energy consumption, and relative energy consumption factors in the life satisfaction literature. Using CFPS data from 2010 to 2018, we find that the increase in provincial carbon emissions over time predicts increased household life satisfaction, but when the model adds energy consumption-related factors, the effect of carbon emissions becomes less significant. As for energy consumption, increased household energy consumption can proportionally increase life satisfaction. In addition, the results also present that energy consumption is subject to positional concerns, indicating that having more electricity and fuel expenditures than their reference group decreases people's life satisfaction.

Therefore, the possible reason for the positive relationship between people's self-reported life satisfaction and carbon emissions is partly due to the demand for more energy consumption. Higher energy consumption brings a higher-carbon form of lifestyle, because some direct and indirect energy consumption, such as lighting, heating, cooling, *etc*., are major sources of carbon emissions (Lamb and Steinberger, 2017), and these behaviors facilitate individuals' daily life and enable them to obtain higher life satisfaction (Guo et al., 2016). Thus, the result is in line with previous research indicating that the relationship between life satisfaction and energy consumption reflects the relationship between people's life satisfaction and carbon emissions (Li and Chen, 2021). In heterogeneity analyses, it is also found that the electricity consumption change has a larger life satisfaction effect for older people. Since fuel is a kind of cheap energy resource (Zheng et al., 2010), for people with lower income, lower education, or older age, fuel consumption increase has a higher life satisfaction effect.

The ratios of individuals' and references groups' energy consumption might have social and ethical impacts on people's life satisfaction, which indicates that the effects of reference energy behaviors are mostly external and relevant to group affiliation characteristics (Chen and Peng, 2014; Mi et al., 2019). The heterogeneity analysis results demonstrate that the relative fuel consumption change has a larger negative effect on life satisfaction for younger, less educated, or rural people. And older people have a higher relative electricity consumption effect on life satisfaction. Therefore, social comparison with the reference group can effectively elicit Chinese residents' attention to the energy consumption of others, and further influence their life satisfaction. Fuel and electricity expenditures can be categorized as non-positional or basic expenditures, and excess levels of energy consumption might also bring excess carbon emissions and resource depletion. Especially, fuel consumption (such as coal, firewood, charcoal, *etc*.) also represents traditional energy use and relatively backward lifestyles. Compared to electricity use, this kind of expenditure is not environmentally friendly and produces more carbon emissions (Huang et al., 2021). Therefore, possible explanations of this finding are as follows: first, the explanation of the social comparison, which means people often observe and compare themselves to their reference group, by gathering information or accidentally witnessing other's lives (Heffetz, 2012), due to their aspiration to be evaluated positively by others and themselves. Fuel and electricity expenditures are kinds of basic consumption, which have not been tied to social status and showing off to others. Veblen's conspicuous consumption (Veblen, 2005) also indicates that superfluous consumption might not satisfy human needs but simply only demonstrate that one consumes more than others, which does not make people any happier (Okulicz-Kozaryn and Altman 2019). On the contrary, spending more on energy might squeeze on other household expenditures tied to higher social status, such as clothing or cars, especially for lower-income households. Hence, unlike the positional commodities, spending on more energy consumption than others might decrease people's life satisfaction. The results are in line with Wu (2019), who found that increases in basic consumption expenditures have a negative influence on people's life satisfaction. Second, the guilty explanation states that a higher level of reference groups' fuel and electricity expenditure brings happiness to the people because they feel less guilty about the impact of their actions on the environment. According to Burger et al. (2022), people's behaviors influenced by climate change largely result from feelings of guilt, an ecological worldview, and a desire to play a positive role in society. Regarding the mechanism of a guilty conscience, consuming more energy than the reference group might lead people to feel guilty about their higher energy consumption. But if an individual observes an increase in the reference group's fuel consumption compared to their own, this might generate lower pressure to reduce their use of energy, and thus increased spending on fuels might lead higher level of life satisfaction. Thus, the experienced guilt about the reference group's energy consumption can be a crucial influence on people's life satisfaction. These two explanations demonstrate the potential mechanisms of relative energy consumption effects in addition to the other mechanisms discussed in this context.

Given that different regions may exhibit different resource endowments, energy structures, and economic development levels in China, samples in first-tier municipalities are separated from other provinces. According to Guo et al. (2021), as economically developed cities, Beijing and Shanghai have transitioned to service sector-oriented economics, the producer service industries can lead to relatively low carbon emissions. In addition, the energy resources in Beijing and Shanghai are highly reliant on domestic and foreign imports, Beijing also implements local restrictions on enterprises with heavy energy consumption and emissions, which result in a notable energy cost to other provinces. The results show that people living in Beijing and Shanghai have reduced life satisfaction when carbon emissions increase, which reinforces the conclusions of previous research (Dietz et al., 2012), indicating that for developed regions, there is a strong inverse relationship between carbon emissions and individuals' life satisfactions. In these cities, the energy consumption of themselves and others is less relevant to people's life satisfaction, since the basic needs for energy consumption in these areas have already been met to a large extent. But for other provinces, energy consumption still plays an important role in bringing about convenience and improving people's quality of life despite a high level of carbon emissions. This result for these provinces is consistent with Rao and Baer (2012), who indicated that energy and the accompanying emissions are needed to provide people with a decent living standard. Therefore, low-carbon forms of lifestyle should first meet people's demand for convenience and higher quality of life, and the regional development should be viewed as a necessary condition for adopting a low-carbon policy.

The results for the links and pathways are illustrated in **Figure 4**.

Future policies should attempt to reconcile environmental and well-being agendas. First, carbon emissions reduction and energy policies should focus on their impact on residents' life satisfaction, since environmental factors such as carbon emissions, and energy consumption are playing the prescribed roles in people's quality of life as well. Second, carbon reduction and energy policies should address the regional synergy and the characteristics of different regions across China. For Beijing and Shanghai, a more ambitious target of carbon emissions reduction should be encouraged, since reducing carbon emission meet people's requirement for higher life quality in these cities. For other provinces, as the increased energy consumption can increase life satisfaction and carbon emissions, the economic structure needs to shift to renewable energy (Huang et al., 2021), to keep life satisfaction unchanged or increasing, while reducing carbon emissions. Third, as life satisfaction is highly influenced by relative energy consumption, to take advantage of energy consumption externalities, advanced publicity can be used to make people believe that low-carbon and energy-saving lifestyles are becoming more and more popular among their reference groups, especially for rural and less educated people, as they are more sensitive to others' energy consumption. Such policies can enhance residents' endogenous motivation to save energy and live a low carbon life.

There are some limitations to this research. First, in CFPS data, some psychological factors (such as people's environmental attitudes, *etc*.) that might impact the relationship between carbon emissions, energy consumption, and life satisfaction were not included in the analysis, and this may have led to some deviations in the research results. Second, it is assumed that the reference group consists of people with similar ages and similar income levels living in the same province, but this method is to some extent post-inference, although most studies have used the same post-inference strategy (Hou, 2013; Quintana-Domeque and Wohlfart, 2016). For this reason, future research should collect reference group data about respondents' subjective judgments, environmental attitudes, or other psychological factors, to elaborate more precisely on the mechanisms of influence of relative energy consumption on life satisfaction. Third, the conclusions drawn from this research focusing on China might not be applicable to other countries. In future studies, the sample can include other countries to test the relationship between carbon emissions, energy expenditures, and life satisfaction in other developed countries and developing countries, and a comparative study can be conducted.

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

JL contributed to conceptualization and writing. FC contributed to formal analysis and methodology. All authors contributed to the article and approved the submitted version.

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The Nexus Between Fiscal Decentralization and Environmental Sustainability in Japan

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This paper adds to the existing body of knowledge by incorporating the role of fiscal decentralization (FD) in influencing CO_2 emissions. Therefore, this study looked at the effect of FD on CO_2 emissions in the presence of nonrenewable energy consumption (NRE), renewable energy consumption (REN), gross domestic product (GDP), and trade openness (TOP) for the period 1994–2018 in Japan. Thus, the current work intends to fill this knowledge gap by employing econometric techniques such as Bayer and Hanck cointegration, dynamic ordinary least squares (DOLS), fully modified ordinary least squares (FMOLS), and canonical cointegration regression (CCR). Additionally, the frequency domain causality analysis is used in the investigation to determine the causal impact of FD, NRE, REN, GDP, and TOP on CO2 emissions. The novelty of the frequency-domain approach is that it can differentiate between nonlinearity and causality levels and show causality among parameters with different frequencies. The DOLS, FMOLS, and CCR results reveal that NRE, GDP, and TOP augment CO_2 emissions in Japan, whereas FD and REN increase the quality of the atmosphere. Furthermore, the frequency causality test results show that FD, REN, GDP, and TOP have implications for CO_2 emissions in the long run, while NRE raises CO_2 emissions in the medium run. As a policy direction, the current study suggests expanding renewable energy consumption in Japan by emphasizing more on Sustainable Development Goals (7, 8, and 13).

Keywords: fiscal decentralization, CO_2 emissions, FMOLS, DOLS, Japan

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1 INTRODUCTION

Climate transformation and global temperature increase have recently emerged as two of the world's most serious and contentious issues, and there is expanding agreement that these issues must be discussed expeditiously (Ma et al., 2019). As per World Bank (2020) statistics, carbon dioxide (CO_2) emissions have increased rapidly over the last few decades, with a significant increase from 22,149.4 million tonnes in 1990 to 36,390.3 million tonnes in 2018. As a result, the global society has begun to pay interest to environmental issues caused by rising CO_2 emissions. In this prospect, many countries all over the globe have put in place a slew of initiatives to combat global climate transformation (Dong et al., 2020). On 31 October 2021, global leaders will met in Glasgow for the 26th Conference of the Parties (COP26). The procedure is governed by reaching an agreement, and the intensity is established by the nations that are least keen to participate. A sound verbal commitment was made at similar gatherings in Kyoto in 1997, Copenhagen in 2009, and Paris in 2015, but the output is not noticeable. Nations committed in Paris in 2015 to maintain the global temperature rise well below 2°C (Christoff, 2016). The United Kingdom is urging for an agreement to "relegate coal power to history," the United States intends a net-zero agreement, and the Association of Small Island States (AOSIS) has insisted that the Earth's temperature increase be kept well below the 1.5°C threshold. Least developing nations expect climate emitters to give billions in damages, while Like-Minded developing economies expect $100 billion in climate funding and carbon storage (Suresh, 2021).

Furthermore, environmentalists and energy activists shift their focus and strive to establish democracy for energy, which is an indication of grassroots decentralized patterns (Hager, 1992; Burke and Stephens, 2018). Worldwide, central governments have agreed to delegate responsibilities to lower-level authorities, a phenomenon known as fiscal decentralization (Hao et al., 2021). Fiscal decentralization in environmental viewpoints provides power over ecological resources between federal and provincial authorities, i.e., the proportion of revenues and expenditures is distributed by local authorities to promote the environment's performance (Liang and Yang, 2019). Nations can effectively enact initiatives designed to improve environmental performance by authorizing the lower unit of country. As a result, there is a robust link between FD and CO_2 emissions. To obtain the low CO_2 emissions benchmark and the energy-saving roles of fiscal expenses, it is critical to specify commitments at various stages of administration (Cheng, 2019).

In the current literature, there are two different views regarding the relationship between fiscal decentralization (FD) and CO_2 emissions. According to several academics, FD degrades environmental quality because some sectors set poor environmental standards in order to enhance their environment-related business at the expense of environmental loss (Kunce and Shogren, 2008; He, 2015; Yang et al., 2020a). Other perspectives contend that some sectors inhibit contaminating activities by enforcing strict environmental regulations, and in this situation, FD has been shown to restore the atmosphere (Millimet, 2003; Chen and Chang, 2020; Cheng et al., 2020). As a result, the relationship between FD and CO_2 emissions is unclear. Climate activists are still attempting to investigate the association between FD and environmental performance (Romero Molina 2018). Though it is critical to probe the approaches and institutes that aid in the recovery of environmental quality, aspects that lead to lower CO_2 emissions must also be investigated.

These contradictory shards of evidence motivate researchers to dig deeper into the FD topic with diverse ideas. The vast portion of existing research on the association between FD and environmental quality has been undertaken from the standpoint of advanced or emerging economies. To the best of our insight, no significant attempt has ever been made with a developed economy like Japan in mind. Similarly, in view of carbon output, the United States and the European Union are the second and third biggest emitters, respectively, though Japan is not an outlier. It is the world's fifth-highest polluter of greenhouse gases, with a 26 percent decrease in emissions intended between 2013 and 2030, contrasted to an 18–20 percent decrease in the United States and a 24% reduction in the European Union (Shahbaz et al., 2018). Japan intends to use nuclear energy for 20–22% of its electricity mix by 2030, up from 30% before the Fukushima nuclear disaster. It has set renewable energy priorities of 22–24% of the electricity mix, liquefied natural gas at 27%, and coal at 26% (Shahbaz et al., 2018).

As a result, it is critical to study the role of FD in decreasing CO_2 emissions. Therefore the main objective of this paper is to explore the importance of FD on CO_2 emissions in the case of Japan, this paper fills a gap in the current literature. Moreover, this study also incorporates nonrenewable energy consumption (NRE), renewable energy consumption (REN), economic growth (GDP), and trade openness (TOP) for the period 1994-to 2018 as significant factors of CO_2 emissions. Furthermore, by incorporating advanced time-series estimation techniques to investigate the influence of FD on environmental quality, this paper empirically extends the literature. The study's outcomes can aid in the development of FD and environmental policies in Japan.

The next section includes a summary of relevant work. The third section goes over the data and methods employed. The fourth section includes outcomes based on the approaches used. The fifth section describes the conclusion and future policy agenda.

2 LITERATURE REVIEW

2.1 Fiscal Decentralization and Environmental Sustainability

FD is the process of allocating mandate or command over regional economic exercise to regional or provincial authorities (Liu et al., 2019; Hao et al., 2020). As a result, FD has been identified as a worldwide trend over the last few decades (Wang & Lei, 2016). Furthermore, researches show that FD can have an impact on environmental performance both directly and indirectly (Li et al., 2021). According to the studies, FD has an effect on economic development and progression, which in turn has an effect on environmental performance and environmental deterioration. As a result, there is an indirect link between environmental efficiency and FD. On the contrary, the research shows that FD has a direct influence on environmental preservation and performance. The literature in this setting can be classified into two main groups of research findings.

In the first group, Fredriksson and Millimet (2002), Levinson (2003), Konisky (2007), and Cheng (2019) are among those who believe that FD has a positive impact on environmental performance. According to Konisky (2007), a high standard of FD is required for environmental improvement. Furthermore, Cheng (2019) asserted that it is critical to specify roles and responsibilities at various levels of government in order to effectively accomplish the benchmark of minimal CO_2 emissions and energy-saving aspects of fiscal spending. Recently, Khan et al. (2021) used a balanced panel data of seven Organisation for Economic Co-operation and Development (OECD) nations for 1990 and 2018 and examined the influence of FD on CO_2 emissions. According to the empirical findings, FD enhances the quality of the environment. Furthermore, advancements in institutional quality and human capital improvement enhance the connection between FD and ecological sustainability. Likewise, Ji et al. (2021) utilized data from seven extremely fiscally decentralized nations, namely Australia, Austria, Belgium, Canada, Germany, Spain, and Switzerland, between 1990 and 2018. Enhanced panel data econometric instruments that could cope with both heterogeneity and cross-sectional dependence issues were utilized for econometric investigation. The outcomes affirm that FD improves the atmosphere by lowering CO_2 emissions in both linear and nonlinear aspects. In the case of China, Cheng et al. (2021) investigated the influence of FD on CO_2 emissions from 2005Q1 to 2018Q4. They discovered that environmental quality improves as a result of an increase in FD. From 1990 to 2018, Tufail et al. (2021) examined panel data from seven highly fiscally decentralized OECD) nations. They utilized the cross-sectional autoregressive distributive lag model for their econometric investigation. The long-term outcomes show that FD reduces CO_2 emissions, which is good for the environment. Besides, Shan et al. (2021) looked into the impact of non-linear FD on CO_2 emissions. They used innovative econometric panel methods to analyse data for the top seven fiscally decentralised OECD countries between 1990 and 2018. The findings disclosed that the linear term of FD increases carbon emissions, whereas the non-linear term reduces them. The inverted U-shaped curve between FD and CO_2 emissions was confirmed.

The second set of research findings, which includes Millimet (2003), and Fell and Kaffine (2014), is more defeatist about FD's role in influencing environmental durability. Millimet (2003), for example, contended that in the phase of decentralization, nations sacrifice environmental performance due to the inadequate local atmosphere as a result of enhanced consent of the lower unit of the country. Likewise, Sigman (2014) postulated that free behavior among localities degrades environmental effectiveness as the level of FD increases. Zhang et al. (2017) examined the influence of FD on the useful mechanisms of environmental policy while adjusting for spatial correlations of CO_2 emissions utilizing panel data from 29 Chinese provinces from 1995 to 2012. The empirical findings suggest that environmental policy alone cannot attain the goal of lowering CO_2 emissions. Moreover, FD considerably stimulates CO_2 emissions, resulting in a green paradox.

2.2 Studies on Other Factors Affecting Environmental Sustainability

In addition to the fiscal decentralization, other elements, such as renewable energy, nonrenewable energy, economic development, and trade can affect CO_2 emissions. In particular, Adebayo et al. (2022a) analyzed the effect of nonrenewable energy, renewable energy and COVID 19 on carbon emission in United Kingdom by applying the Fourier ADL cointegration test, Markov switching regression, non-linear ARDL and Breitung and Candelon causality test. According to the findings of the study, renewable energy and COVID -19 cases were negatively associated while fossil fuel energy was positively associated with carbon emissions. Moreover, unidirectional causality was found to be present in all of the variables in the United Kingdom. Awosusi et al. (2022a) examined the impact of technological innovations, political risk, globalization, economic growth and nonrenewable energy on ecological footprints in BRICS countries. They found that nonrenewable energy, economic growth, political risk and technological innovations increased pollution levels, whereas globalization reduced pollution. For another study for Brazil, Russia, India, China, and South Africa (BRICS), Awosusi et al. (2022b) considered the impact of biomass energy consumption on ecological footprints controlling for the role of natural resources, globalization and gross capital formation. According to their findings, biomass energy consumption and globalization had a negative relationship with ecological footprints at all quantiles, while natural resources, gross capital formation and economic growth enhanced ecological footprints. Nawaz et al. (2021) analyzed the effect of nonrenewable energy, renewable energy, economic growth, and trade openness in BRICS economies. They found the negative effect of economic growth, positive effect of nonrenewable energy and insignificant impact of trade openness on carbon emission. For a study of ten Asian countries, Chien et al. (2021) investigated the nexus between renewable energy, nonrenewable energy, innovations, environmental taxes and environmental quality and observed that renewable energy, innovations and environmental taxation mitigated environmental deterioration but nonrenewable energy enhanced CO_2 emission.

In continuation, the study of Adebayo et al. (2022b) attempted to estimate the effect of tourist arrivals on CO_2 emission by controlling energy consumption, economic growth and globalization through Quantile on Quantile Regression. Globalization, economic growth, energy consumption and tourist arrivals increased CO_2 emission at different quantiles. Similarly, Adebayo (2022c) scrutinized the data for Spain to estimate the association between renewable energy, fossil fuels, economic complexity and FDI on load capacity factor (a measure for environmental degradation) by applying Wavelet Coherence Approach. The authors found that renewable energy improved, but fossil fuel energy deteriorated the environmental quality in the medium and short run. FDI improved the environmental quality at all frequencies, and economic complexity deteriorated environmental quality in the medium, short and long run. Fareed et al. (2022) attempted to estimate the moderating effect of innovations on financial inclusion on environmental quality relationship controlling for economic growth and renewable energy in 27 European countries. According to their findings, financial inclusion deteriorated the environmental quality, but innovations significantly reduced this negative association between financial inclusion and environmental degradation. According to their analysis, renewable energy was found to mitigate environmental pollution, whereas economic growth enhanced environmental degradation in studied countries. Adebayo et al. (2022d) scrutinized the data for Sweden and analyzed the role of renewable energy, trade openness and economic growth on CO_2 emission by applying Quantile on

Quantile regression. Trade openness and renewable energy were found to be negatively associated with CO_2 emission at low and medium Quantile and low and high Quantile, respectively. Economic growth also had a negative impact on CO_2 emission at many Quantiles.

Despite the fact that an expanding body of research has probed the environmental consequences of FD, a certain research gap is still present. Although several scholars have begun to concentrate on the influence of FD on CO_2 emissions, understanding of the effect of such decentralization on CO_2 emissions remains limited, especially in Japan. The current study provides a deeper understanding of the role of FD as a significant factor of CO_2 emissions.

3 THEORETICAL MODEL AND EMPIRICAL METHODOLOGY

3.1 Theoretical Model

To examine the effect of FD on CO_2 emissions in the existence of control variables such as NRE, REN, GDP, and TOP for the period 1994–2018, the empirical equation is displayed as:

$$\ln CO_{2t} = \alpha_0 + \alpha_1 \ln FD_t + \alpha_2 \ln NRE_t + \alpha_3 \ln REN_t + \alpha_4 \ln GDP_t + \alpha_5 \ln TOP_t + u_t \quad (1)$$

where CO_2 signifies carbon dioxide emissions, FD stands for fiscal decentralization, NRE is nonrenewable energy consumption, REN denotes renewable energy consumption, GDP is a gross domestic product, and TOP is trade openness. ln is the natural log, μ represents the error term, and t is the time period.

Following Cheng et al. (2021), Lingyan et al. (2021), and Tufail et al. (2021), FD is involved in the regression as a critical parameter. The research on the sign of the FD coefficient is uncertain. The theoretical justification for the negative relationship between FD and CO_2 emissions is that nations can effectively incorporate policies aimed at enhancing environmental efficiency by allowing the lower unit of government. FD, on the other hand, raises emissions due to the free-rider challenge between states, i.e., the higher the fiscal expenditure power given to lower units of the nation, the bigger the likelihood of degradation in environmental performance (Cheng, 2019). FD increases environmental performance if $\alpha 1 < 0$, otherwise the environment is ruined by a rise in FD. In addition, the model takes into account nonrenewable energy use. An increase in NRE due to the unnecessary usage of fossil fuels for the development process raises the level of emissions, resulting in a reduction in environmental quality (Yang et al., 2022; Yu and Qayyum, 2022). Therefore, we posit $\alpha_2 > 0$ if the relationship between NRE and CO_2 emissions is positive. Renewable energy can have a favorable impact on environmental efficiency by integrating alternate methods for growth and energy-efficient innovation (Qayyum et al., 2021a). So, we speculate $\alpha_3 < 0$ if REN and CO_2 emissions are negative. Increased economic activity leads to increased energy consumption, which has an adverse impact on environmental performance (Yang et al., 2020b; 2020c; Chunling et al., 2021; Qayyum et al., 2021b; Qayyum et al., 2022). We presume $\alpha_4 > 0$ if the association between GDP and CO_2 emissions is positive, if not, $\alpha_4 < 0$. Similarly, trade could have both favorable and unfavorable consequences. Detrimental effects include substantial amounts of carbon-emitting competence, extensive transportation utilization, and so on (Antweiler et al., 2001). The accusation that trade will boost revenue and facilitate cross-border green energy is well-founded. Developed economies can then afford renewable energy advancements, which will favor the environment for future generations run (Antweiler et al., 2001). So, we expect $\alpha_5 > 0$ if the association between TOP and CO_2 emissions is positive, if not, $\alpha_5 < 0$. **Table 1** shows the data sources, definitions, and variable units utilized in **Eq. 1**. **Figure 1** depicts the flow chart of the estimation performed in this research.

3.2 Empirical Methodology

3.2.1 Unit Root Test

The order of the integration should always be confirmed by analyzing the unit root tests until a cointegration test is conducted. Our period of study contains global transformation that results in structural breaks. Conventional unit root measures, such as ADF, KPSS, and DF-GLS, do not account for structural breaks and may yield insufficient results. As a result, we employ the Zivot and Andrews (2002) unit root method to assess the stationary properties of the factors and single structural breaks. The Zivot-Andrews unit root method is advantageous over others because it accounts for structural breaks when determining the series' stationarity level (Kirikkaleli and Athari, 2020; Özbay et al., 2022).

3.2.2 Cointegration Test

Following the stationarity confirmation, Bayer and Hanck's (2013) method is used to probe the cointegration association between the interest factors. This newly modified technique for cointegration provides a more appropriate finding by integrating many different test outcomes, such as those of Engle and Granger (1987), Johansen (1991), Peter Boswijk (1994), and Banerjee et al. (1998). The Fishers' equations for the Bayer-Hanck approach are as follows:

$$EG - JO = -2\left[\ln\left(P_{EG}\right) + \ln\left(P_{JO}\right)\right] \quad (2)$$

$$EG - JO - BO - BDM = -2\left[\ln\left(P_{EG}\right)\right] + \ln\left(P_{JO}\right) + \ln\left(P_{BO}\right) + \ln\left(P_{BDM}\right] \quad (3)$$

P_{EG}, P_{JO}, P_{BO}, and P_{BDM} are the possibility values for each of the above-mentioned cointegration tests. The cointegration of the underpinning parameters is determined by the formation of Fisher statistics.

3.2.3 Long Run Estimates

The current study also uses the fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS), and canonical cointegration regression (CCR) methods, respectively, to identify the long-run effects of FD on CO_2 emissions in Japan, with NRE, REN, GDP and TOP employ as

TABLE 1 | Data description.

Variables	Description	Units	Source
CO2	Carbon emissions	Metric tons	Global Carbon Atlas, 2019 http://www.globalcarbonatlas.org/en/CO2-emissions
FD	Fiscal decentralization	An index is computed relying on the ratio of own revenues/expenditure to general government revenues/expenditures utilizing principal component analysis	International Monetary Fund, 2019 https://data.imf.org/?sk=1C28EBFB-62B3-4B0C-AED3-048EEEBB684F
NRE	Nonrenewable energy	kg of oil equivalent per capita	Word Development Indicators, 2019 https://databank.worldbank.org/source/world-development-indicators#advancedDownloadOptions
REN	Renewable energy	Percentage of total final energy consumption	Word Development Indicators, 2019 https://databank.worldbank.org/source/world-development-indicators#advancedDownloadOptions
GDP	Gross domestic product	Constant 2010 US Dollars	Word Development Indicators, 2019 https://databank.worldbank.org/source/world-development-indicators#advancedDownloadOptions
TOP	Trade openness	% of GDP	Word Development Indicators, 2019 https://databank.worldbank.org/source/world-development-indicators#advancedDownloadOptions

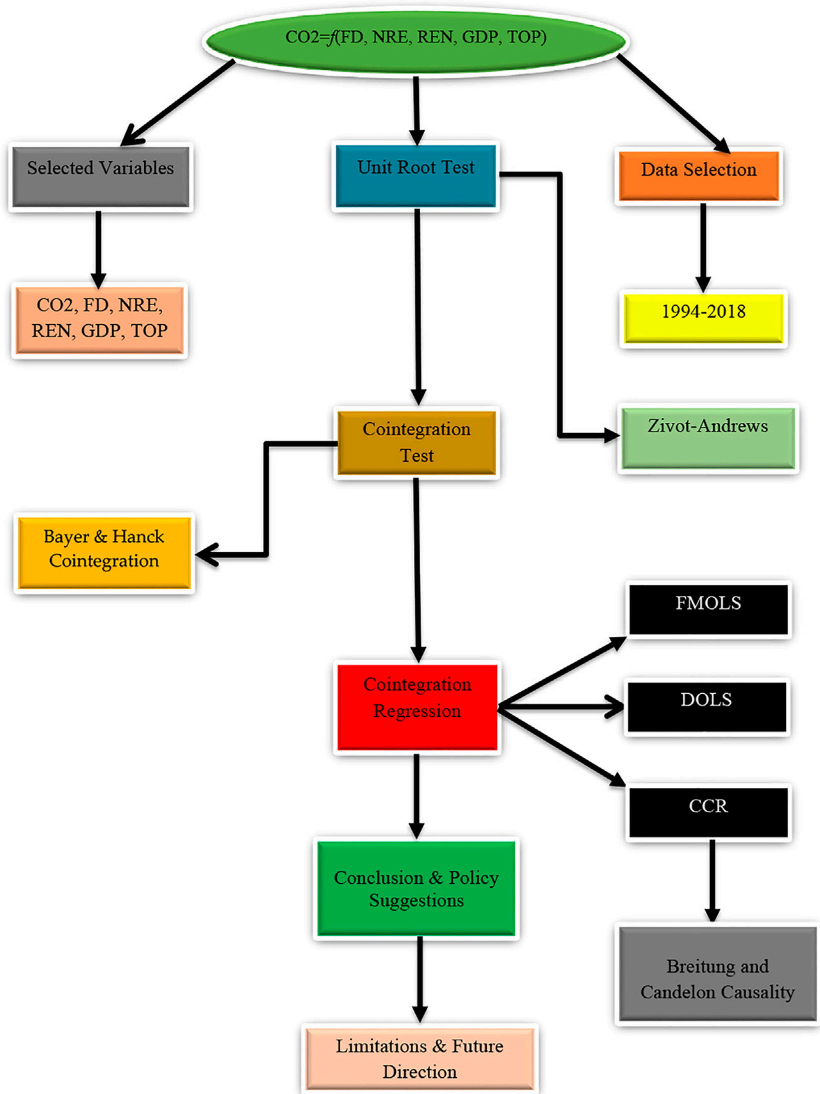

FIGURE 1 | Flow chart of the analysis.

TABLE 2 | Descriptive statistics.

	CO_2	FD	NRE	REN	GDP	TOP
Mean	3.034658	0.560293	3.531540	−1.041482	12.63558	1.376554
Median	3.048319	0.421852	3.544582	−0.801312	12.70443	1.381233
Maximum	3.121714	0.683467	3.612227	0.072894	12.79215	1.577717
Minimum	2.901830	−0.942951	3.393930	−2.629585	12.28614	1.199674
Std. Dev	0.460559	0.294171	0.562411	0.774850	0.949991	0.710919

controlled variables. To prevent the correlation concern, Phillips and Hansen (1990) formed the semi-parametric methodology FMOLS, emphasizing that the technique is asymptotically free of bias and accurate. CCR, a procedure comparable to FMOLS formed by Park (1992), is used to investigate cointegration sequences in a pattern where the order of the stationarity of time series variables is I(1). The biggest distinction between the FMOLS and CCR estimation methods is that the FMOLS focuses on both data and variable conversion, while the CCR only emphasizes data alteration (Wu et al., 2018). To counter simultaneity and small sample bigotries, the DOLS technique contains leads and lags. By dealing with disorderly variables, both DOLS and FMOLS estimation methods handle the concern of endogeneity and serial correlation (Yildirim and Orman, 2018; Kirikkaleli et al., 2021).

3.2.4 Breitung and Candelon Causality

Furthermore, while controlling for NRE, REN, GDP, and TOP, this paper investigates the causal effects of FD on Japan's CO_2 emissions at multiple frequencies. In this study, the frequency domain causality strategy of Breitung and Candelon (2006) is used. This strategy is based on Geweke's (1982) and Hosoya's (1991) preliminary research. According to Odugbesan and Adebayo (2020), the critical gap between time domain and frequency domain techniques is that the time domain methodology locates a particular transition within a time series, while the frequency domain methodology constitutes the intensity of specific changes within a time series.

TABLE 3 | Unit root test results.

Variables	At level		At first difference	
	Test statistic	Time break	Test statistic	Time break
Level				
CO_2	−1.5311	1989Q2	−5.7195***	1983Q2
FD	−1.3889	2002Q2	−4.8576*	2000Q2
NRE	−3.7634	1987Q2	−6.0762***	1983Q2
REN	−1.1656	1981Q2	−6.2025***	1984Q1
GDP	−2.7517	1983Q2	−5.7068***	1991Q2
TOP	−4.4029	1985Q2	−5.7325***	1994Q4
Critical value				
1%	—	−5.34	—	—
5%	—	−4.93	—	—
10%	—	−4.58	—	—

** and *** show significance at 10 and 1% levels, correspondingly.*

4 RESULTS AND DISCUSSIONS

Table 2 reports the descriptive statistics of the variables employed in the current investigation. The natural logarithm of the CO_2 emissions, FD, REN, REN, GDP, and TOP was utilized. CO_2 emissions fluctuated from 2.90 to 3.12, FD ranged from -0.94 to 0.68, NRE varied from 3.39 to 3.61, REN ranged from -2.63 to 0.07, GDP fluctuated from 12.29 to 12.79, and TOP reached from 1.19 to 1.57.

The next process is to investigate the variables' stationary properties. In order to identify a set of stationary attributes in the likeness of a structural break, we used the Zivot-Andrews unit root technique. The unit root method demonstrates that none of the parameters is stationary at the level, as shown in **Table 3**. Furthermore, all of the factors become stationary after the first difference is made.

The present research investigates the cointegration characteristics of variables using the composite Bayer-Hanck technique for cointegration. **Table 4** articulates the results of the Bayer-Hanck methodology. The findings show that long-term cointegration persists between CO_2 emissions, FD, NRE, REN, GDP, and TOP at the 5% level of significance.

After founding cointegration between the parameters, we explored the long-term relationships between CO_2 emissions and FD, NRE, REN GDP, and TOP. As a result, we employed FMOLS, DOLS, and CCR methods to investigate the long-run impact of FD, NRE, REN, GDP, and TOP on CO_2 emissions (**Table 5**). Throughout all three methods, the indication, direction, and significance of coefficients are almost or considerably similar. According to **Table 5**, FD decreases CO_2 emissions by 0.283% in FMOLS, 0.240% in DOLS, and 0.3027% in CCR, respectively. It implies that numerous environmental prevention guidelines, such as fiscal expenses and environmental costs, are also imposed *via* fiscal decentralization. According to the findings, FD is connected with more efficient and comprehensive financial and monetary reforms, which may enhance environmental sustainability through accountable governance. These findings are comparable to those of Fredriksson and Millimet (2002), Cheng et al. (2021), and Tufail et al. (2021). A greater degree of FD is required for environmental improvement. As a result, it is critical to specify duties at various levels of authority in order to effectively attain the goal of reduced CO_2 emissions and energy-saving mechanisms of fiscal expenses.

As per our findings, a 1% raise in NRE results in a 0.546, 0.511, and 0.548% boost in CO_2 emissions, respectively. The NRE findings support the commonly held belief that NRE is the

TABLE 4 | Results of bayer-hanck cointegration.

	Fisher statistics	Fisher statistics	Cointegration
$CO_2 = f$ (FD, NRE, REN, GDP, TOP)	EG-JO 15.4213	EG-JO-BO-BDM 26.0567	Yes
5%	Critical value 10.576	Critical value 20.143	—

TABLE 5 | Long-run results.

Variables	FMOLS	DOLS	CCR
FD	−0.2832*** (−2.4651) [0.0001]	−0.2401*** (−2.7631) [0.0009]	-0.3027*** (−2.9782) [0.0471]
NRE	0.5461*** (4.1038) [0.0001]	0.5114** (2.5284) [0.0124]	0.5484*** (4.2107) [0.0000]
REN	−0.0549*** (-4.0507) [0.0001]	-0.0571*** (−4.9796) [0.0033]	−0.0565*** (−4.2184) [0.0000]
GDP	0.3507*** (2.6769) [0.0081]	0.3273* (1.8898) [0.0605]	0.3476*** (2.7784) [0.0060]
TOP	0.3597*** (3.7431) [0.0003]	0.3326*** (2.8369) [0.0065]	0.3656*** (4.2172) [0.0007]
Constant	−4.1959*** (−4.1959) [0.0001]	−4.3099*** (−2.9988) [0.0031]	−4.1947*** (−4.1947) [0.0000]
R^2	0.9441	0.9525	0.9441
Adjusted R^2	0.9426	0.9439	0.9427

, **, and * show significance at 10, 5, and 1% levels, correspondingly.*

primary root of environmental pollutants. So, our findings corroborate empirical facts presented by Shabir et al. (2022) and Saud et al. (2019). The empirical findings also indicate that the studied economy consumes a lot of energy, which is bad for the atmosphere. It is suggested that Japan should enhance energy performance by increasing the use of alternative energy sources, which will cut pollution. Hence, the Japanese government must focus on developing approaches that can boost energy utilization. When referring to the connection between REN and CO_2 emissions, we can see that the REN has a negative and substantial impact. A 1% augment in REN diminishes CO_2 emissions by 0.054, 0.057, and 0.056%, respectively. It contends that renewable energy is a coherent and important factor in boosting the effectiveness of the atmosphere. Our findings on REN are familiar with those of other studies, which show that utilizing REN increases environmental performance (Dogan and Seker, 2016; Wolde-Rufael and Weldemeskel, 2020; Shah et al., 2021; Hanif et al., 2022). Our results propose that increasing the use of renewable energy could be a useful strategy framework for improving Japan's environmental sustainability.

GDP results indicate that it has a favorable and significant impact on CO_2 emissions. It suggests that a 1% upsurge in GDP will contribute to 0.350, 0.327, and 0.347% spikes in CO_2 emissions, respectively. It must be acknowledged that an upsurge in a nation's GDP has a strong impact on the ecosystem, and prolonged and irregular use of a country's resources further degrades the performance of the atmosphere. As a result, the level of CO_2 emissions will eventually increase. This signifies that as the gross domestic product rises, nations will shift their focus to more industries, further raising demand for greater levels of energy usage. The outcomes corroborate those of Salahuddin et al. (2018), Umar et al. (2020), and Kirikkaleli et al. (2022). Likewise, TOP has a substantial favourable influence on CO_2 emissions. It insinuates that TOP adds to the deterioration of the environment. A 1% raise in TOP boost CO_2 by 0.359, 0.332, and 0.365%, respectively. Because of the spike in export sales, this result may be justified; however, the scale effect may have aided in contamination by raising the growth of the economy. This conclusion also suggests that future studies must look into imported advanced technology in the aspect of ecological issues. Finally, the composition effect could as well be the

TABLE 6 | Results of Frequency domain causality test.

Direction of Causality	Long-term		Medium-term		Short-term	
	$\omega_i = 0.01$	$\omega_i = 0.05$	$\omega_i = 1.00$	$\omega_i = 1.50$	$\omega_i = 2.00$	$\omega_i = 2.50$
FD →CO_2	5.7999* (0.0550)	5.8058* (0.0549)	0.1947 (0.9073)	0.1695 (0.9188)	0.1797 (0.9141)	0.1865 (0.9110)
NRE →CO_2	0.3831 (0.5611)	0.3281 (0.9321)	6.2921** (0.0211)	6.4941** (0.0731)	2.7233 (0.5914)	3.0649 (0.4100)
REN→CO_2	6.4268** (0.0137)	6.7621** (0.0235)	0.2513 (0.1777)	0.2173 (0.1935)	0.4183 (0.4497)	0.1657 (0.5295)
GDP→CO_2	6.856** (0.0237)	6.0521** (0.0430)	5.5686 * (0.0758)	6.8754** (0.0353)	0.3142 (0.2266)	0.2853 (0.3715)
TOP→CO_2	6.8562** (0.0529)	6.4472** (0.0242)	0.2093 (0.9007)	0.1646 (0.9210)	0.1506 (0.9274)	0.1451 (0.9300)

*The values within () indicate p-value. → Indicates the direction of causality. * and ** indicate significance at 10 and 5% levels, respectively. SIC, determines the lag lengths for the VAR models.*

rationale for the favorable impact of international trade on carbon emissions. These outcomes are akin to the conclusion of Fan et al. (2020), Nawab et al. (2021), and Yang et al. (2021).

A frequency-domain causality method is used in this research to evaluate the causal connection between parameters (**Table 6**). The frequency value of 0.01–0.05 for the long, 1.00–1.50 for the medium, and 2.00–2.50 for the short-run to test the causal association between variables. The results indicate that FD, REN, and TOP emit CO_2 in the long term. However, NRE only contributes to CO_2 emissions in the medium term. Likewise, GDP causes CO_2 in the medium to long-term. As a result, any strategy change in FD, REN, or TOP has repercussions for CO_2 emissions in the long term. Likewise, any strategy adjustment in NRE affects CO_2 in the medium term. Furthermore, any policy change in GDP affects CO_2 in the medium to long term.

5 CONCLUSION AND POLICY RECOMMENDATIONS

The rapid rising CO_2 emissions have piqued the interest of scholars who are attempting to identify the aspects that influence CO_2 emissions. Several research works have been performed in order to determine the primary issue of environmental deterioration. Nevertheless, apart from foreign direct investment, globalization, and technological innovation, researchers frequently ignore a nation's political structure because of its indirect, difficult-to-measure impact on carbon minimization. In the case of Japan, this study looked at the effect of FD on CO_2 emissions in the presence of NRE, REN, GDP, and TOP. When developing strategies to acquire sustainable development, it is critical to acknowledge the relationship between FD and CO_2 emissions. The empirical analysis yields reliable outcomes: a) CO_2 emissions, FD, NRE, REN, GDP, and TOP are long-run cointegrated variables; b) FD, NRE, REN, GDP, and TOP are prominent components in understanding CO_2 emissions in Japan; c) FD and REN are useful in decreasing CO_2 emissions in Japan; d) NRE, GDP, and TOP are detrimental to environmental performance; e) any plan change in FD, REN, GDP, and TOP has repercussions for CO_2 emissions in the long-term.

The research's conclusions can aid in the development of FD and environmental reforms in Japan. Japan must develop solutions to combat emissions in order to control declining environmental performance. Encouraging energy-efficient schemes to modify the industries to renewable energies is essential. Furthermore, to ease the process, it is critical to specify tasks at various tiers of authority in order to effectively reach the benchmark of reduced pollution and energy-saving fiscal expense systems. It is necessary to concentrate on environmentally friendly advanced technologies that shift economic expansion contributors away from nonrenewable energies to renewable and sustainable sources of energy. These environmentally friendly advancements have far-reaching impacts on the ecosystem and global warming. Furthermore, in order to encourage innovations, Japanese economic structures must be altered.

However, this research only offers introductory empirical support and some constraints are still. One such constraint is associated with the control parameters utilized in this research; in future studies, it would be informative to incorporate additional control parameters into our model. Another difference is that we only used Japan as a case study. The study's findings can be expanded to other nations or groups of countries.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/ Supplementary Material.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Does Fiscal Decentralization Promote or Inhibit the Improvement of Carbon Productivity? Empirical Analysis Based on China's Data

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Based on the panel data of 30 provinces in China from 2010 to 2019, this study empirically analyzes the relationship between fiscal decentralization and carbon productivity using a spatial econometric model and calculates the direct effect, spatial spillover effect, and total effect of fiscal revenue decentralization and fiscal expenditure decentralization on carbon productivity through effect decomposition. The empirical results show that 1) the spatial agglomeration effect of China's provincial carbon productivity is obvious, which shows an upward trend. The heterogeneity of carbon productivity among different provinces is obvious. The overall performance is as follows: Eastern provinces > Central provinces > Western provinces. 2) Fiscal revenue decentralization and fiscal expenditure decentralization can significantly promote the improvement of carbon productivity. Fiscal expenditure decentralization plays a greater role in promoting carbon productivity than fiscal revenue decentralization. 3) Fiscal revenue decentralization and fiscal expenditure decentralization have significant positive direct effects and negative spatial spillover effects on the improvement of carbon productivity. Increasing fiscal decentralization is conducive to improving the carbon productivity of the province, but it will inhibit the carbon productivity of neighboring provinces. Finally, it puts forward policy suggestions to promote the improvement of carbon productivity from the perspective of fiscal decentralization.

Keywords: fiscal revenue decentralization, fiscal expenditure decentralization, carbon productivity, spatial effect, low-carbon development

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1 INTRODUCTION

In 2003, Britain proposed "low-carbon economy." Low-carbon development has become an inevitable choice to solve the prominent problems of resource and environmental constraints and achieve sustainable development (Bauer et al., 2013; Shen, 2017; Lin and Li, 2022). Low-carbon economy is guided by the comprehensive green transformation of economic and social development to realize the high-quality development of industrial structure, production mode, and lifestyle. Its most remarkable characteristics are low energy consumption, low pollution, and low emission (Liu and Feng, 2011; Zhang et al., 2015; Robertson, 2016; Sengupta et al., 2020; Wu et al., 2021; Rabia et al., 2022). According to the International Energy Agency (IEA), China's total carbon dioxide emissions had nearly doubled from 5.407 billion tons in 2005 to 9.894 billion tons in 2020. According to the statistics of the World Bank, China overtook the United States to become the world's largest carbon emitter in 2005. In terms of the proportion, China's carbon emission has continuously increased in the total global carbon emission, reaching 31% at present. In

September 2020, China proposed that carbon emissions should peak by 2030 and strive to achieve "carbon neutrality" by 2060. China is in the key stage of high-quality economic development. Therefore, how to coordinate the relationship between low-carbon development and high-quality economic development has become the focus from all walks of life. As a positive indicator to measure the economic benefits of CO_2 emissions, carbon productivity has built a bridge between high-quality economic development and energy conservation and emission reduction. Therefore, improving the level of carbon productivity has become the key to the development of a low-carbon economy in China (Liu and Zhang, 2021a; Chen et al., 2022).

China's carbon emission problem is caused by extensive economic development, which originates from the government behaviors under "China's decentralization." Because China's economic development has typical characteristics of "government leading," the behavior of local governments is bound to have a great impact on the economy and environment. The behavior of local governments under the fiscal decentralization system plays a vital role in carbon dioxide emissions (Kuai et al., 2019; Wang et al., 2022). In terms of revenue, it mainly promotes low-carbon development through green taxes and green government bonds; in terms of expenditure, it mainly promotes low-carbon development through government green procurement and green transfer payment. So what effect will fiscal decentralization have on carbon productivity? Does this effect have spatial spillover effect? Will there be heterogeneity in the impact of fiscal revenue decentralization and fiscal expenditure decentralization on carbon productivity? On the one hand, answering these questions can further enrich the relevant theories of fiscal decentralization system reform, innovation-driven development, and environmental governance with Chinese characteristics. On the other hand, it can provide relevant policy suggestions on how to maintain high-quality economic development and win the battle of carbon emission reduction under the new normal.

2 LITERATURE REVIEW

Carbon productivity is one of the important bridges used to measure economic growth and carbon emissions. The improvement of carbon productivity plays an important role in achieving the goal of carbon neutrality in the world. The research on carbon productivity mainly focuses on three aspects. 1) The first kind of literature focuses on the dynamic change trend of carbon productivity from the national, provincial, and industrial levels. The research shows that with the high-quality development of economy, carbon productivity shows an upward trend and heterogeneity (Zhou et al., 2010; Yu et al., 2017a; Qiu et al., 2017; Li et al., 2018; Bai et al., 2019; Yang et al., 2020a; Du et al., 2022). 2) The second kind of literature studies the influencing factors of carbon productivity. Most studies believe that technological progress, industrial scale, industrial structure, energy efficiency, and environmental regulation are important factors affecting carbon productivity (Lu et al., 2014; Wang et al., 2016; Yu et al., 2017b; Du and Li, 2019; Hu and Wang, 2020; Liu and Zhang, 2021b; Zhou and Tang, 2021; Lin and Jia, 2022). 3) The third kind of literature focuses on the convergence and divergence of carbon productivity, but there is no consensus on the convergence and divergence of carbon productivity. Shen et al. (2021) measured China's carbon productivity by combining the directional distance function and meta-constrained production function based on the extended relaxation measure (SBM) model. The results show that China's carbon productivity has spatial condition β convergence.

The literature on the impact of fiscal decentralization on environmental governance can be divided into the following three types: 1) A higher degree of fiscal decentralization is more conducive to pollution control and carbon dioxide emission reduction. Fiscal decentralization can not only help local governments improve the efficiency of resource allocation but also improve regional environmental quality by promoting local governments to improve environmental standards (Millimet, 2003; Konisky, 2007; Rui, 2018; Yang et al., 2020b; Yacouba, 2022). 2) Many scholars believe that fiscal decentralization urges local governments to create more development space for economic development by weakening local environmental regulations, which leads to the increase of carbon dioxide emissions and is not conducive to the improvement of environmental quality (Konisky and Woods, 2015; Zhang et al., 2016; Zhang et al., 2017a; Zhang et al., 2018; Shan et al., 2021). 3) The impact of fiscal decentralization is different in different stages. Lopez et al. (2011) believed that increasing the proportion of social welfare and public goods expenditure in government expenditure will reduce pollutant emissions. However, without changing the expenditure structure, increasing the total amount of government expenditure will not reduce pollutant emissions.

By summarizing the literature on carbon productivity and fiscal decentralization, it is found that many scholars have carried out various studies on fiscal decentralization and carbon productivity from different angles, but few studies pay attention to the impact of fiscal decentralization on carbon productivity. The innovation of this study is to use the data of fiscal decentralization and carbon productivity of 30 provinces in China from 2010 to 2019 to make an empirical analysis on the impact of fiscal decentralization on carbon productivity by considering the horizontal dimension of space and the vertical dimension of time through spatial measurement methods, which broadens the perspective of fiscal decentralization and carbon productivity research. The marginal contributions of this study are as follows: first, most of the literature focuses on the impact of fiscal decentralization on carbon emissions or the environment, ignoring the impact of fiscal decentralization on carbon productivity, while this study explores the impact of fiscal decentralization on carbon productivity, which is helpful in clarifying the role path and internal mechanism of fiscal decentralization in reducing carbon emissions and promoting green economic growth. Second, corresponding to fiscal revenue and expenditure, revenue decentralization and expenditure decentralization are formed, respectively. Most literatures often choose one of them as the research object, and the analysis of the impact of the two decentralization methods on the environment is not comprehensive. Therefore, based on the dual perspective of revenue and expenditure, the two decentralization methods are introduced into the spatial econometric model at the same time, so as to better analyze the heterogeneity of the spatial effect of fiscal revenue decentralization and fiscal expenditure decentralization on carbon productivity, which has theoretical value and practical significance for realizing green development. Therefore, this study can provide more specific and targeted policy suggestions for reducing carbon emissions and realizing carbon neutralization.

The structure of the article is as follows: the second part is literature review. The third part is the model and data, which measures the impact of fiscal decentralization on carbon productivity through spatial econometric methods. The fourth part is the discussion of empirical results. The last part is policy suggestions, which puts forward policy suggestions for fiscal decentralization to improve carbon productivity.

3 MODELS AND DATA

3.1 Spatial Spillover Effect Test

This study uses the spatial correlation index of ESDA (Exploratory Spatial Data Analysis) to test the spatial spillover effect of carbon productivity among provinces, which is usually measured by Moran's I and Geary's C index:

$$\mathrm{I} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\,(x_i - \bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\sum_{i=1}^{n}(x_i - \bar{x})^2}, \tag{1}$$

$$C = \frac{(n-1)\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\,(x_i - \bar{x})^2}{2\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right)\left(\sum_{i=1}^{n}(x_i - \bar{x})^2\right)}, \tag{2}$$

where n is the 30 provinces, w_{ij} is the spatial weight matrix, x and $\bar{x}$ are the carbon productivity of provinces and the average carbon productivity of all provinces, respectively. After normalization of variance, Moran's I index will be between [-1-1]. If I > 0 indicates positive spatial correlation, the larger the value is, the more obvious the spatial correlation is. If I < 0, the smaller the value is, the greater the spatial difference is. If I = 0, the space is random. The value of Geary's C index is generally between 0 and 2. When C > 1, it means negative correlation, and when C < 1, it means positive correlation.

This study constructs the following three kinds of spatial weight matrix.

The first is based on the Queen adjacency rule, and the geographical neighbor weight matrix is constructed by using map boundary vector data:

$$w_{ij} = \begin{cases} 1, \text{when provinces i and j share a common boundary} \\ 0, \text{when provinces i and j have no common boundary or i = j} \end{cases}. \tag{3}$$

The second weight matrix constructed in this study is the economic distance weight matrix based on the reciprocal of the absolute value of economic gap. w_{ij} is the reciprocal of the absolute difference between the per capita GDP of i province and the per capita GDP of j province in the sample years.

$$w_{ij} = \begin{cases} 1\Big/\left|\overline{X_i} - \overline{X_j}\right|, \text{when } \mathrm{i} \neq \mathrm{j} \\ 0, \text{when i = j} \end{cases}. \tag{4}$$

Considering the limitations of the abovementioned single-geographical or economic weight matrix, the third kind of comprehensive weight matrix of geographical economy is constructed based on the ratio of GDP of each neighboring province in the total GDP of all neighboring provinces:

$$w_{ij} = \begin{cases} X_i\Big/\sum_{k\in J_i} X_k, \text{when provinces i and j share a common boundary} \\ 0, \text{when provinces i and j have no common boundary or I = j} \end{cases}. \tag{5}$$

Based on the abovementioned three spatial weight matrices, the results of the global spatial correlation test of China's province carbon productivity are shown in **Table 1**. It can be seen that the Moran's I index of provincial carbon productivity is greater than 0 and the Geary's C index is less than 1 under the geographical neighbor weight matrix and the comprehensive weight matrix of geographical economy, both of which are significant at the level of 1%, indicating that the distribution of provincial carbon productivity in China's cities presents the spatial positive correlation distribution characteristics of "high–high" and "low–low" agglomeration. But at the same time, it can be found that under the weight matrix of pure economic distance, the Moran's I and Geary's C indices of provincial carbon productivity are not significant, indicating that the spatial correlation of provincial carbon productivity is mainly reflected in the geographical spatial correlation and the comprehensive spatial correlation characteristics of geography and economy but not in the economic development difference. Therefore, the subsequent spatial econometric analysis is only based on the geographical neighbor weight matrix and the comprehensive weight matrix of geographical economy for consideration.

3.2 Measurement Model

Because the ordinary panel model cannot describe the spatial interaction relationship of economic variables among different regions, combined with the abovementioned analysis, the spatial econometric model is introduced when discussing the effect of fiscal decentralization on carbon productivity. Taking carbon productivity as the explained variable and fiscal revenue decentralization and fiscal expenditure decentralization as the explanatory variables, this study discusses the impact of fiscal decentralization on carbon productivity. Because different spatial models express different practical economic meanings, OLS (Ordinary Least Squares), SAR (Spatial Autoregressive Model), SEM (Spatial Error Model), and SAC (Spatial Autocorrelation Model) are used as specific model applications to estimate the specific effects of fiscal revenue decentralization and fiscal expenditure decentralization on carbon productivity. The specific models are as follows:

$$\text{OLS:} \quad \begin{cases} cp = \alpha + \beta fde_{it} + \sum_{k=1}^{5} X_{kit} + \varepsilon_{it} \\ cp = \alpha + \beta fdr_{it} + \sum_{k=1}^{5} X_{kit} + \varepsilon_{it} \end{cases}. \tag{6}$$

TABLE 1 | Moran's I and Geary's C statistical indicators of China's provincial carbon productivity under three weight matrices.

variable	Year	Geographical neighbor weight matrix		Economic distance weight matrix		Comprehensive weight matrix of geographical economy	
		Moran's I	Geary's C	Moran's I	Geary's C	Moran's I	Geary's C
CP	2010	0.368***	0.568***	0.050	0.865*	0.377***	0.586***
	2011	0.362***	0.590***	0.052	0.849*	0.335***	0.626**
	2012	0.365***	0.584***	0.047	0.875*	0.330***	0.623**
	2013	0.368***	0.589***	0.015	0.898	0.344***	0.609***
	2014	0.344***	0.596***	0.035	0.864*	0.316***	0.617**
	2015	0.308***	0.616***	0.040	0.846*	0.281***	0.635**
	2016	0.295***	0.618***	0.046	0.833*	0.261***	0.641**
	2017	0.290***	0.631**	0.043	0.840*	0.251***	0.665**
	2018	0.219**	0.696**	0.043	0.833*	0.197**	0.719**
	2019	0.214**	0.702**	0.028	0.857	0.188**	0.731*

*Note: ***, **, and * are significant at the level of 1, 5, and 10%, respectively.*

$$\text{SAR:}\ \begin{cases} cp = \alpha + \rho W fde_{it} + \beta fde_{it} + \sum_{k=1}^{5} X_{kit} + \varepsilon_{it} \\ cp = \alpha + \rho W fdr_{it} + \beta fdr_{it} + \sum_{k=1}^{5} X_{kit} + \varepsilon_{it} \end{cases}. \quad (7)$$

$$\text{SEM:}\ \begin{cases} cp = \alpha + \beta fde_{it} + \sum_{k=1}^{5} X_{kit} + \mu_{it} \\ cp = \alpha + \beta fdr_{it} + \sum_{k=1}^{5} X_{kit} + \mu_{it} \\ \mu_{it} = \lambda W \mu_{it} + \varepsilon_{it} \end{cases}. \quad (8)$$

$$\text{SAC:}\ \begin{cases} cp = \alpha + \rho W fde_{it} + \beta fde_{it} + \sum_{k=1}^{5} X_{kit} + \mu_{it} \\ cp = \alpha + \rho W fdr_{it} + \beta fdr_{it} + \sum_{k=1}^{5} X_{kit} + \mu_{it} \\ \mu_{it} = \lambda W \mu_{it} + \varepsilon_{it} \end{cases}. \quad (9)$$

Equation 9 is the spatial autocorrelation model SAC, and **Eqs 6–8** can be regarded as the OLS model, SAR model, and SEM model obtained after setting some constraints on the SAC model, respectively. When the SAC model does not consider the influence of the lag term of the explained variable on itself, that is, the coefficient of the spatial lag term of the model $\rho = 0$, the SEM model of spatial error can be obtained, as shown in **formula (8)**. When the SAC model excludes the influence of the disturbance term, that is, the coefficient of spatial error term $\lambda = 0$, the SAR model is obtained, as shown in **Eq. 7**. As the OLS model is a nonspatial econometric model and does not consider the spatial correlation among different provinces, it can be regarded as the result of excluding the influence of spatial lag term and spatial error term in the SAC model, as shown in **formula (6)**. In **Eqs 6–9**, *cp* is the explained variable, *cp* is carbon productivity, *W* is the geographic distance weight matrix or geographic economic comprehensive weight matrix, X is the control variable, μ and ε are the perturbation terms subject to independent identical distribution.

3.3 Index Selection and Statistical Description

From the perspective of data availability, this study selects 30 provinces in China (except Tibet, Hong Kong, Macao, Taiwan, etc.) from 2010 to 2019 as the research object. After combining a large number of previous literatures, it is found that scholars in various fields have conducted extensive and in-depth discussions on the influencing factors of carbon productivity. Referring to previous studies, this study selects carbon productivity as the explained variable, fiscal decentralization as the explanatory variable, and digital economy, urbanization rate, industrial structure, foreign direct investment level, and technological innovation as the control variables to study the spatial heterogeneity of the impact of provincial fiscal decentralization on carbon productivity. The statistical description of variables is shown in **Tables 2–4**.

Carbon Productivity

Carbon productivity refers to the level of GDP output per unit of carbon dioxide. First, carbon emissions are calculated, and the formula is as follows:

$$CE_t = E_i \times T_i \times LCV_i \times CEF_i \times O_i \times \frac{44}{12}, \quad (10)$$

$$CP = \frac{GDP}{CE}, \quad (11)$$

where CE_t is the total carbon emission of a province in a year *t*; *cp* is carbon productivity; *GDP* is gross domestic product. E_i, T_i, LCV_i, CEF_i *and* O_i represent the consumption of fuel *i*, the standard coal coefficient, the low heat value coefficient, the carbon emission coefficient, and the oxidation rate of fuel *i*, respectively; 44/12 is the molecular weight ratio of carbon dioxide to carbon. The data of the physical quantity of energy consumption are derived from the energy balance table in *China Energy Statistical Yearbook*. The types of energy involved include coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, and natural gas. The low calorific value coefficient and standard coal coefficient are derived from the general rules for the calculation of comprehensive energy consumption (GB/T 2589–2008), the data of the carbon emission coefficient and carbon oxidation rate are derived from the guidelines for compilation of provincial greenhouse gas inventories, and the carbon dioxide emission coefficient is derived from the guidelines for national greenhouse gas inventories.

TABLE 2 | Variable description and data source.

Variable name	Measurement method	Data sources
Carbon productivity (*cp*)	Average carbon GDP	Calculate manually according to relevant data
Fiscal expenditure decentralization (*fde*)	Proportion of local fiscal expenditure in national fiscal expenditure	Calculate manually according to relevant data
Fiscal revenue decentralization (*fdr*)	Proportion of local fiscal revenue in national fiscal revenue	Calculate manually according to relevant data
Digital economy (*de*)	Development level of digital economy	Calculate manually according to relevant data
Urbanization rate (*urban*)	Urbanization rate	China Statistical Yearbook
Industrial structure (*str*)	Ratio of the output value of secondary industry to the total output value	Calculate manually according to relevant data
Foreign direct investment level (*fdi*)	The actual use of foreign direct investment in all provinces is measured by the proportion of total foreign direct investment in GDP	China Statistical Yearbook
Technological innovation (*lninno*)	Number of patented inventions	China Statistical Yearbook

Development Level of Digital Economy

Defining the connotation of digital economy and combined with the availability of data, this study decomposes the digital economy index from three dimensions of information development, internet development, and digital transaction development and selects the following 13 measurement indicators to design the digital economy index measurement body as shown in **Table 3**. The basic data of the measurement indicators are all derived from *China Statistical Yearbook* from 2010 to 2020.

In this article, the linear weighed method is used to calculate the development level of digital economy:

$$de = \sum_{j=1}^{13} M_{it} \times N_j, \tag{12}$$

where j is the measurement index after standardization and N_j is the median weight of the jth measurement index relative to the level of digital economy. In weight processing, because there is an obvious progressive relationship in the index classification, this study refers to the *NBI* index weight determination method for weighing.

Referring to the information level index (ILI) established by Zhang et al. (2017b) and the network preparation index (NBI) constructed by Harvard University and The World Economic Forum, in order to make the digital economic index comparable across the years, this study sets the measurement index based on 2015 and standardizes the measurement indicators. At the same time, in order to make the index of each province comparable between different statistical years, the formula in the article is as follows:

$$M_{it} = \frac{V_{it} - V_{min0}}{V_{max0} - V_{min0}} \times 6 + 1\,, \tag{13}$$

where t represents the year of the measurement index, V_i represents the original data of measurement index, and V_{max0} and V_{min0} represent the maximum and minimum of the original data of the base year, respectively.

In order to test the value of the degree of multicollinearity between the observed values of independent variables, this study tests the collinearity of variables. The test results are shown in **Table 5**. The maximum variance expansion factors are 6.48, 7.42, and less than 10, and the average variance expansion factors are 3.79, 3.64, and less than 5. It shows that there is no multicollinearity between the selected variables, and the selection of variables is reasonable.

4 THE DISCUSSION OF EMPIRICAL RESULTS

4.1 Empirical Results

Through the Hausman test of panel data, the Hausman statistic is significantly positive, so this study selects the fixed-effect model. The spatial econometric model includes spatial fixed, temporal fixed, and spatiotemporal double-fixed effects. Therefore, the fixed-effect forms of the SAR, SEM, and SAC models are tested according to the likelihood ratio (LR) test and natural logarithm (Log-L) test, and the model is set in combination with the data structure. The regression results are shown in **Tables 6** and **7**. It can be seen from the results that under the SAR, SEM, and SAC models, the spatial term coefficients ρ and λ show a high significance, indicating that there is, indeed, a high spatial correlation among carbon productivity in various regions of China. Considering the spatial effect, the regression coefficients of fiscal revenue decentralization and fiscal expenditure decentralization in the model are significantly positive, and their impact on carbon productivity is significantly positive at the level of 5%, which indicates that fiscal decentralization has a positive correlation with carbon productivity, and appropriately improving fiscal decentralization is conducive to improving carbon productivity. In the spatial econometric model, the coefficient of fiscal revenue decentralization of 13.9627 is less than that of fiscal expenditure decentralization of 16.8367. The estimation results of the ordinary OLS model also have similar characteristics. This means that fiscal revenue decentralization and fiscal expenditure decentralization can not only improve carbon productivity but also have heterogeneity in their respective marginal effects. Fiscal expenditure decentralization plays a greater role in improving carbon productivity than fiscal revenue decentralization. From the estimation results of the model, compared with the SAR, SEM, and ordinary panel data OLS models, the SAC model has the most significant characteristics of spatial

TABLE 3 | Evaluation index system of the digital economy level.

Main indicators	First-level indicators	Secondary indicators	Measurement index
Development level of digital economy	Information development index	Information foundation	Optical cable density
			Density of mobile phone base station
			Proportion of informatization employees
		Impact of informatization	Total telecom services
			Software business revenue
	Internet development indicators	Mobile Internet foundation	Mobile phone penetration
		Fixed-end Internet foundation	Broadband Internet users
		Impact of mobile Internet	Proportion of mobile Internet users
	Development indicators of digital transaction	Fundamentals of digital trading	Proportion of enterprise websites
			Proportion of computers used by enterprises
			Proportion of e-commerce
		Impact of digital transactions	E-commerce sales
			Online retail sales

TABLE 4 | Variable description statistics.

Variable	Observed value	Mean value	Standard deviation	Minimum	Maximum
cp	300	0.7826	0.4854	0.1810	3.5814
de	300	2.4902	1.2659	0.7701	7.4301
fde	300	0.0281	0.0131	0.0060	0.0741
fdr	300	0.0176	0.0133	0.0013	0.0664
lninno	300	8.0024	1.4434	3.7135	10.9977
urban	300	0.5706	0.1244	0.3380	0.8961
fdi	300	0.0212	0.0162	0.0002	0.7951
str	300	0.4611	0.1122	0.2641	0.8821

effect, and the SAC model includes two spatial transmission mechanism assumptions of autocorrelation and random disturbance, which cannot be ignored for analyzing the spatial effect of fiscal revenue decentralization and fiscal expenditure decentralization on carbon productivity. In order to further verify the rationality of the SAC model, the LR test is carried out on the SAC model, and the results show that the statistic of χ^2 of *p* value is 0, that is, the original assumption that the spatial SAR and SEM models replace the SAC model is rejected. Therefore, this study selects the SAC model for empirical research. From the analysis of other variables, the improvement of the development level of digital economy and technological innovation level is conducive to the improvement of carbon productivity. This is because digital economy can promote technological progress, optimize resource allocation, and improve energy efficiency through technological effect. The industrial structure inhibits the improvement of carbon productivity because the secondary industry is mostly high-carbon industries. With the increasing proportion of the secondary industry, carbon emissions will keep rising, resulting in the decline of carbon productivity. The impact of foreign direct investment and urbanization rate on carbon productivity is not significant, which may be because they do not provide sufficient driving force for low-carbon development and do not produce significant pollution reduction or increase effects.

4.2 Sub Effect Test

In order to further reveal the extent of the spatial spillover effect of explanatory variables on the explained variables, the direct effect, indirect effect, and the total effect of fiscal revenue decentralization and fiscal expenditure decentralization on carbon productivity are calculated through effect decomposition. The direct effect is used to describe the average impact of fiscal decentralization on the carbon productivity of the region. The indirect effect, that is, spatial spillover effect reveals the average impact of fiscal decentralization on the carbon productivity of other provinces. The total effect reflects the average impact of the explanatory variable fiscal decentralization on all regions. As the empirical results shown in **Table 8**, the results show that the two decentralization models have a significant direct effect on carbon productivity, but they have a significant inhibitory effect on carbon productivity indirectly through spatial spillover effect. Judging by *p* value, the direct effect, indirect effect, and total effect are highly significant. From the perspective of fiscal revenue decentralization: the direct effect of fiscal revenue decentralization on its own carbon productivity is

TABLE 5 | Variance expansion factor test.

Variable	*VIF*	*VIF*
de	6.48	7.42
fde	3.47	
fdr		3.63
lninno	4.32	3.20
urban	3.93	3.27
fdi	1.65	1.66
str	2.88	2.88
Mean VIF	3.79	3.64

TABLE 6 | Regression results of fiscal revenue decentralization spatial panel data under geographical neighbor weight matrix.

Variable	Common panel regression	Geographical neighbor weight matrix		
		(1) SAR	(2) SEM	(3)SAC
fdr	12.4555**	11.3096**	11.1612**	13.9627**
	(2.25)	(2.18)	(2.00)	(2.53)
de	0.2421***	0.2457***	0.2393***	0.2507***
	(9.70)	(10.56)	(10.24)	(10.23)
urban	−0.3535	−0.1469	−0.4251**	0.1542
	(−0.67)	(−0.29)	(−0.84)	(0.28)
str	−1.3779***	1.1947***	−1.3196***	−1.1622***
	(−5.26)	(−4.59)	(−5.02)	(−4.34)
lninno	0.1626***	0.1702***	0.1661***	0.1610***
	(4.74)	(5.30)	(5.25)	(4.57)
fdi	−1.1878	−1.3405	−1.2818	−1.1723
	(−5.26)	(−1.16)	(−1.10)	(−1.02)
ρ		−0.1612**		−0.2683***
		(−1.98)		(−2.31)
λ			0.1988*	0.2779**
			(1.71)	(2.01)
Fixed time		No	Yes	No
Fixed space		Yes	Yes	Yes
R^2	0.6255	0.6293	0.6252	0.6308
Log*(L)*		152.46	150.70	153.26

*Note: ***, **, and * are significant at the level of 1, 5, and 10%, respectively.*

TABLE 7 | Regression results of fiscal expenditure decentralization spatial panel data under geographical neighbor weight matrix.

Variable	Common panel regression	Geographical neighbor weight matrix		
		(1) SAR	(2) SEM	(3) SAC
fde	13.1594***	11.9141**	12.8743**	16.8367***
	(2.59)	(2.50)	(2.36)	(3.30)
de	0.2408***	0.2445***	0.2404***	0.2502***
	(9.73)	(10.58)	(10.23)	(10.17)
urban	−0.4503	−0.2456	−0.4622	0.1845
	(−0.86)	(−0.49)	(−0.91)	(0.35)
str	−1.3199***	−1.1528***	−1.3111***	−1.059***
	(−4.98)	(−4.40)	(−5.01)	(−3.78)
lninno	0.1698***	0.1764***	0.1705***	0.1597***
	(5.94)	(5.59)	(5.33)	(4.37)
fdi	−1.1667	−1.3062	−1.180	−1.1018
	(-0.96)	(−1.16)	(−1.03)	(−1.00)
ρ		−0.1529*		−0.3183***
		(-1.87)		(-2.72)
θ			0.2134*	0.2816**
			(1.76)	(2.14)
Fixed time		No	Yes	No
Fixed space		Yes	Yes	Yes
R^2	0.6278	0.6326	0.6252	0.6357
Log*(L)*		153.20	150.70	155.06

*Note: ***, **, and * are significant at the level of 1, 5, and 10%, respectively.*

significantly positive, and the direct effect coefficient is 14.4292, indicating that improving the degree of fiscal revenue decentralization of local governments is conducive to the improvement of carbon productivity in all provinces and plays a positive role in the reduction of carbon emissions and the improvement of carbon intensity. The possible reason is that under China's decentralization system, on the one hand, with the increasing proportion of fiscal revenue, the government pays more and more attention to the development of local low-carbon economy and promotes the formation of environment-friendly behaviors and industries through good tax design and inductive tax burden tilt mechanism, thus inhibiting the emergence of high-carbon industries. On the other hand, the improvement of fiscal revenue decentralization expands the autonomy of local fiscal revenue. Local governments can formulate industrial policies with comparative advantages and focus on realizing green

TABLE 8 | Direct, indirect, and total effects of fiscal decentralization on carbon productivity.

Effect category	Variable	Coefficient	T Statistic	*p* value
Direct effect	*fdr*	14.4292	2.49	0.013
	fde	17.4471	3.22	0.001
Indirect effect	*fdr*	−3.1500	−1.97	0.095
	fde	−4.3798	−2.05	0.041
Total effect	*fdr*	11.2792	2.49	0.013
	fde	13.0673	3.26	0.001

*Note: ***, **, and * are significant at the level of 1, 5, and 10%, respectively.*

economic development so as to increase the intensity of environmental governance, improve regional environmental standards, and reduce pollution emissions. Fiscal revenue decentralization has a significant negative indirect spatial spillover effect on carbon productivity, with an impact degree of −3.1500, indicating that the improvement of fiscal revenue decentralization of the local government has an inhibitory effect on the improvement of carbon productivity in other provinces. The possible reason is that various regions have produced the phenomenon of "free riding" under the incentives and constraints of new development concepts and ecological protection policies.

From the perspective of fiscal expenditure decentralization: fiscal expenditure decentralization in this region has a significant positive direct effect on local carbon productivity, with an impact degree of 17.4471, indicating that the improvement of fiscal expenditure decentralization in each province has promoted carbon productivity in this province. The main reason may be that the central government continuously improves the weight of indicators such as ecological and environmental protection in the assessment mechanism, which makes local governments continuously increase the expenditure level of environmental protection and governance. Therefore, the government continuously improves environmental standards and increases governance investment and directly adjusts the distribution relationship of economic benefits to promote the development of green industry and green science and technology. The spatial spillover effect of fiscal expenditure decentralization is significantly negative, and the impact degree is −4.3798, indicating that the decentralization of fiscal expenditure in this province reduces the carbon productivity of neighboring provinces. The possible reason is that the improvement of fiscal expenditure decentralization has raised local environmental standards and increased the cost of polluting enterprises in the province, which makes local polluting enterprises migrate to neighboring provinces or other regions. However, from the perspective of the overall effect, fiscal expenditure decentralization has a positive correlation with carbon productivity, indicating that the improvement of fiscal expenditure decentralization is generally conducive to solving the prominent problems of ecological environment caused by carbon emissions and realizing green development.

4.3 Robustness Test

Robustness test under different matrix selection: based on the spatial and geographical distance, the spatial weight matrix is constructed in the research, and mainly, maximum likelihood estimation is carried out. In order to further verify the robustness of the estimation results of the model, a comprehensive weight matrix of geographical economy is constructed in each urban geographical neighboring province based on the ratio of the GDP of each neighboring province to the total GDP of all neighboring provinces, and the SAC model is estimated again to check whether the results are stable. The test results are reported in **Table 9**. It can be seen that after selecting the new spatial weight

TABLE 9 | Regression results of fiscal decentralization spatial panel data under comprehensive weight matrix of geographical economy.

Variable	Fiscal expenditure fiscal decentralization			Fiscal revenue fiscal decentralization		
	(1) SAR	(2) SEM	(3) SAC	(4) SAR	(5) SEM	(6) SAC
fdr/fde	12.5906***	13.7223***	16.8367***	11.8051**	12.0644**	13.7427
	(2.66)	(2.59)	(3.30)	(2.28)	(2.18)	(2.52)
de	0.2419***	0.2422***	0.2503***	0.2433***	0.2408***	0.2479***
	(10.50)	(10.03)	(10.17)	(10.47)	(10.02)	(10.18)
urban	−0.2457	−0.4166	0.1845	−0.1522	−0.3819	0.0671
	(−0.49)	(−0.81)	(0.35)	(−0.30)	(−0.74)	(0.12)
str	−1.1419***	−1.3431***	−1.0594***	−1.1977***	−1.3563***	−1.2110***
	(−4.32)	(−5.05)	(−3.87)	(−4.57)	(−5.06)	(−4.56)
lninno	0.1762***	0.1683***	0.1597***	0.1964***	0.1638***	0.1632***
	(5.59)	(5.14)	(4.37)	(5.27)	(5.07)	(4.73)
fdi	−1.3931***	−1.1201	−1.1017	−1.4063***	−1.2285	−1.2453
	(−1.23)	(−0.97)	(−1.00)	(−1.22)	(−1.04)	(−1.08)
ρ	−0.1612*		−0.3183***	−0.1612*		−0.2243**
	(−1.85)		−2.72)	(−1.85)		(−2.18)
λ		0.2056*	0.2231*		0.2108*	0.2246*
		(1.71)	(1.81)		(1.78)	(1.82)
Fixed time	No	Yes	No	No	Yes	Yes
Fixed space	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.6335	0.6278	0.6368	0.6299	0.6255	0.6315
Log*(L)*	153.16	151.47	154.54	152.24	150.53	152.82

*Note: ***, **, and * are significant at the level of 1, 5, and 10%, respectively.*

matrix for model estimation, the regression results show that the regression coefficient of the SAC model is still significant. The spatial term coefficients ρ and λ show a high significance, which show that it is appropriate to use the SAC model to empirically test the spatial effect of fiscal revenue decentralization and fiscal expenditure decentralization on carbon productivity. Furthermore, through the results of spatial effect decomposition, it can be seen that the estimation results of direct effect, indirect effect, and total effect of fiscal revenue decentralization and fiscal expenditure decentralization on carbon productivity are significant, and the directions of the three effects are still consistent with those of the previous conclusions. Therefore, the research results are robust and reliable.

5 CONCLUSIONS AND RECOMMENDATIONS

Using the data of fiscal decentralization and carbon productivity of 30 provinces in China from 2010 to 2019, this study empirically tests the impact of fiscal decentralization and carbon productivity. The empirical results show that 1) the spatial agglomeration effect of China's provincial carbon productivity is obvious, which shows an upward trend. The heterogeneity of carbon productivity among different provinces is obvious. The overall performance is as follows: Eastern provinces > Central provinces > Western provinces. 2) Whether based on the geographical proximity weight matrix or the geographical comprehensive weight matrix, the development of fiscal decentralization has significantly improved China's carbon productivity, and its impact on carbon productivity is significantly positive below 10%. The promotion effect of fiscal expenditure decentralization on carbon productivity is greater than that of fiscal revenue decentralization. 3) Fiscal revenue decentralization and fiscal expenditure decentralization have significant positive direct effects and negative spatial spillover effects on the improvement of carbon productivity. Improving fiscal decentralization is conducive to the improvement of carbon productivity in this province, but it will inhibit the carbon productivity of adjacent provinces. 4) For other control variables, technological innovation and digital economy can significantly promote the improvement of carbon productivity, and the industrial structure significantly inhibits the improvement of carbon productivity.

Fiscal decentralization plays an irreplaceable role in improving carbon productivity and realizing low-carbon development. Based on the abovementioned conclusions, this study puts forward the following policy suggestions: first, expanding the autonomy of fiscal decentralization appropriately. Based on the current performance appraisal system, the central government should expand the financial autonomy of local governments and provide local governments more "financial power." When the financial autonomy increases, local governments will actively increase green R&D investment while pursuing GDP growth under the pressure of the "dual carbon" goal so as to curb the generation of environmental adverse behaviors or industries and then drive the development of green technology and industry so as to promote the improvement of carbon productivity. Second: establishing the function mechanism of green fiscal revenue and expenditure. The main body of green fiscal revenue is green tax. Strengthening the scientific and feasible tax collection, promoting the formation of environment-friendly behavior and industry through good tax design and inductive tax burden tilt mechanism, and strengthening the cultivation of green environmental protection industry; the government's purchasing expenditure has an important impact on green consumption and green production. The scale of government purchasing expenditure will promote the production of green products and the progress of green technology. Third: strengthening regional cooperation and mobilizing the enthusiasm for developing low-carbon economy. In order to control the negative impact of the spatial spillover effect of fiscal decentralization on carbon productivity in other regions, formulating the development strategy of low-carbon economy, each region should not only fully consider its own resource advantage endowment but also combine the endowment of adjacent provinces. Formulating targeted policies suitable for the region and promoting the development of low-carbon economy in adjacent regions, reasonably guiding the flow of resources among regions, and realizing the stability of low-carbon economic development in the region is a part of the process.

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.

AUTHOR CONTRIBUTIONS

GF calculated the main data of carbon productivity and built the model and was a major contributor in writing the manuscript. XS contributed to the conception of the study and revised the article. SR checked the data and was responsible for the suggestions of the article. All authors read and approved the final manuscript.

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Towards Sustainable Environment in G7 Nations: The Role of Renewable Energy Consumption, Eco-innovation and Trade Openness

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Some of the globe's most economically advanced nations make up the G7 (Canada, Japan, France, Germany, Italy, United States and United Kingdom). Nevertheless, in tandem with such strong economic growth, the environmental conditions in these nations have deteriorated, raising serious issues among stakeholders. Therefore, we examine the effect of eco-innovation and trade openness on CO_2 emissions in G7 nations. We also take into account the role of renewable energy, economic growth and nonrenewable energy use using a dataset covering the period from 1990–2019. We employed recent econometric techniques such as slope heterogeneity (SH) and cross-sectional dependence (CSD), Westerlund cointegration, fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS), panel quantile regression and panel causality tests to assess these associations. The outcomes of the CSD and SH tests disclosed that using a first-generation unit root test will produce biase outcomes. Furthermore, the outcomes of the Westerlund cointegration disclosed support long-run association between CO_2 and its drivers. In addition, the results of the long-run estimators (FMOLS and DOLS) unveiled that nonrenewable energy and trade openness contribute to the damage to the environment while economic expansion, renewable energy and eco-innovation enhance the quality of the environment. Furthermore, the outcomes of GDP, REC and ECO curb CO_2 while NREC energy and TO surge CO_2. Finally, the outcomes of the panel causality test unveiled that CO_2 emissions can be predicted by all the exogenous variables.

Keywords: CO2 emissions, trade openness, eco-innovation, renewable energy consumption, panel quantile regression

INTRODUCTION

Despite the fact that the Middle East has more than two-thirds of the world's oil reserves, energy-importing nations are attempting to secure adequate energy supply in order to maintain their distinct economic development rates. Nevertheless, providing energy security should typically be achieved by increasing the availability of greener energy resources, as the combustion of filthy fossil fuels has negative environmental consequences (Adebayo, 2022a; Agyekum et al., 2022; Akram et al., 2021; Rehman et al., 2021). As a result, current international ecological development treaties, including the Paris Agreement, attempt to minimize emissions resulting from the use of filthy fossil fuels (Fareed et al., 2021a; Shahzad et al., 2021). Furthermore, the 7th goal of the United Nations' SDGs declaration intends to increase access to reliable, inexpensive and green sources of energy in order to curb CO_2 emissions and guarantee global growth (Adebayo, 2022b; He et al., 2021). As a result, global economies are attempting to identify routes that will lead to clean energy transitions within worldwide energy systems (Xu et al., 2022; Altuntaş et al., 2022).

Likewise, the G7 nations (Canada, United Kingdom, Germany, France, Italy, the United States and Japan) are dedicated to lowering CO_2 emissions through diversification of their portfolios of energy, particularly by including green energy sources into their conventional energy packages (Murshed, 2020). These countries are responsible for around 30 and 25% of global energy use and CO_2, correspondingly (Ahmad et al., 2021). Furthermore, the G7 countries rely heavily on foreign and indigenous nonrenewable energy supplies. Interestingly, the majority of G7 nations rely on non-renewable energy imports to meet their energy needs. Japan, Italy, and Germany import around 96 percent, 84 percent, and 64 percent of their total primary energy supply, correspondingly (EIA, 2022). As a consequence, these figures highlight the G7 nations' dilemma of dirty fuel reliance. These figures explain why, regardless of their economic prosperity, these countries have mainly failed to limit the degradation of their environmental protection.

Growth in the economy results in amplified energy consumption and, as a result, greater CO2 emissions. The EKC is a hypothetical curve that may be visually depicted as an inverted U-curve and is often used to propose and quantify the interrelationship between CO2 and GDP per capita. The EKC is also utilized to look at how factors like alternative energies, fossil fuel use, exports, and eco-innovation impact CO_2. Regardless of the fact that the findings of such research can only give scant details, the results obtained are nevertheless useful in presenting policy-relevant conclusions.

Trade openness is critical for boosting the movement of products and services and raising economic production, however, the significance of possible CO_2 emission sources is still debated (Ali et al., 2020; Destek and Sinha, 2020). In the G7 economies, trade is a major source of CO_2 emissions from production, and CO_2 is embedded in the final domestic demand for imported goods. Despite the fact that nations are switching their resources to focus on project efficiency and utilize numerous environmental technologies to balance trade and CO_2, ensuring greener and more efficient production remains an essential problem in this world, with international trade and growth being the principal drivers.

Through their attempts to optimize their use of renewable resources, technological breakthroughs have assisted the expansion of renewable energy and benefited nations in reducing pollution levels and altering the quality of their ecosystems. There is a strong link between renewable energy sources and innovation, as well as their final commitment to environmental and economic developments, according to a large body of literature(Cheng et al., 2021; Anwar Khan et al., 2021). The use of REC can help to minimize CO2. This is accomplished by switching from a nonrenewable source of energy that puts a massive strain on the environment to a more source of renewable energy. Economic structures are transitioning to renewable energy derivatives such as renewable energies, according to (Lin and Zhu, 2019). These countries choose ecological protection skills and environmentally relevant technological advancements that help to improve ecological protection initiatives to a certain extent. In addition, technological improvements have been identified to assist in the decrease of contaminants and the enhancement of environmental protection initiatives (Jahanger et al., 2022; Vural, 2021).

Based on the above information, the present research assesses the effect of trade openness, on CO2 emissions for the period 1990 to 2019. In a departure from previous research, our work adds to the current literature in several ways. First and foremost, we want to offer a more thorough answer to the issue of whether renewable energy can help the G7 nations reduce ecological damage. For the G7 economies, various previous research has cast light on the implications of renewable energy utilization on CO_2. Nevertheless, in the case of these nations, nothing is documented about the ecological consequences of eco-innovation. Second, over the period 1990–2019, this is the first effort to assess the impact of trade openness, economic growth, nonrenewable energy eco-innovation, and REC on CO_2 in G7 nations. Existing research has mostly focused on assessing the ecological consequences of economic growth in the G7 nations. Evaluating the consequences of eco-innovation and trade openness, on the other hand, is crucial since it contributes a holistic component to the economic expansion-environmental quality research. Finally, in order to meet the study's goals, we used robust panel econometric methodologies that account for CSD as well as slope heterogeneity issues in the data. Several current research have mainly avoided the issue of diverse slope coefficients while adjusting for cross-sectional dependency; as a result, the results published in those investigations are liable to be contradictory and biased. **Table 1** presents the summary of the literature.

The next section presents data and methods which are followed by findings and discussion in *Findings and Discussion Section*. *Conclusion and Policy Directions Section* concludes the empirical analysis.

MATERIALS AND METHOD

Data and Model

In this study, we explore the effect of trade openness, economic growth, and eco-innovation on CO2 emissions in G7 nations. We

TABLE 1 | Synopsis of Related Studies.

Authors	Nation(s)	Period	Techniques	Outcomes
Xu et al. (2022)	BRICS	1990–2018	Panel Quantile Regression	GDP and NREC increase CO_2 while REC curb CO_2
Adebayo and Kirikkaleli, (2021)	Japan	1990Q-2015Q4	Wavelet Coherence	GDP, ECO, and NREC increase CO_2 while REC curbs CO_2
Gyamfi et al. (2022a)	Mediterranean Nations	1990–2016	MMQR	GDP and URB increase CO_2 while REC curb CO_2
Tony Odu et al. (2022)	India	1990–2018	Quantile Approach	GDP, and TO, TOR increase CO_2
Adebayo, (2022a)	Spain	1990–2018	Wavelet Tools	GDP, ECI and NREC increase CO_2 while FDI and mitigate CO_2
Oladipupo et al. (2021)	Portugal	1980–2018	NARDL	GDP and TO increase CO_2 while ECO mitigates CO_2
Murshed, (2020)	South Asia	2000–2015	ARDL	ECO and REC mitigate CO_2
Ahmad et al. (2021)	G7 countries	1980–2016	CS-ARDL	EKC is valid while ECO curb CO_2
Ahmed and Le, (2021)	ASEAN	1995–2015	CUP-FM	GDP and TO increase CO_2 while ECO mitigates CO_2
Ahmed et al. (2019)	Indonesia	1971 to 2014	ARDL	GDP, URB, and TO increase CO_2 while ECO mitigates CO_2
Fan and Hossain, (2018)	India	1974–2016	ARDL	ECO and TO increase GDP
Sohag et al. (2015)	Malaysia	1985–2012	ARDL	GDP and TO increase CO_2 while ECO and REC mitigate CO_2
Anwar et al. (2021)	India	1985–2017	VECM	GDP, and FDI increase CO_2 while ECO and REC mitigate CO_2
Dauda et al. (2021)	Africa	1990–2016	Panel Techniques	GDP, HC and URB increase CO_2 while ECO and REC mitigate CO_2
Rafique et al. (2021)	BRICS countries	1990 to 2017	AMG	GDP, and TO increase CO_2 while ECO and REC mitigate CO_2

TABLE 2 | Data source and Description.

Sign	Variable	Measurement	Source
CO_2	Carbon Emissions	Metric Tonnes Per Capita	BP
GDP	Economic Growth	GDP per Capita Constant US$2010	WDI
ECO	Eco-innovation	% of total technological innovation	OECD
REC	Renewable Energy Consumption	million tonnes of oil equivalent	BP
NREC	Nonrenewable Energy Consumption	million tonnes of oil equivalent	BP
TO	Trade Openness	Trade % of GDP	WDI

also incorporate energy (nonrenewable and renewable) as a driver of CO2 emissions using a dataset from the period from 1990–2019. **Table 2** lists the measurement of the variables gathered and the unit of measurement used, as well as the sources of all the data used to generate the econometric outcomes shown in the sub-sections below. All series correspond to yearly observations from 1990 to 2019, which were selected based on available data.

We put up an econometric model, as indicated in **Eq. 1**, predicated on the topic under investigation and the data obtained, which are evaluated using robust panel econometric approaches.

$$CO_2 = f\,(GDP, ECO, REC, NREC, TO) \tag{1}$$

Where; CO_2 denotes CO_2 emissions, ECO stands for eco-innovation, REC represents renewable energy consumption, NREC denotes nonrenewable energy and TO represents trade openness.

Estimation Strategy

We commenced by utilizing the FMOLS and DOLS to catch the effect of GDP, TO, NREC, REC and ECO) on the endogenous variable (CO_2). Furthermore, we utilized the quantile regression to identify the effect of GDP, TO, NREC, REC and ECO on varied quantiles of CO2 emissions. As previously stated, fixed-effect panel quantile regression was used to analyze the influence of the regressors (NREC, ECO, GDP, TO, and NREC) on CO_2 emissions in this study. Unlike previous estimators, quantile regression provides a clearer picture of the relationship between the parameters by enabling for substantially more flexibility in empirical evaluation at different quantiles of the response parameter distribution. Additionally, outliers in the result variables have little effect on the estimated regressors. As a consequence, the panel quantile regression approach is utilized to evaluate the influence of NREC, ECO, GDP, TO, and NREC on different quantiles of CO emissions. The application of the generalized version of the median regression analysis is shown below:

$$Q_{yi}\,(\tau_k / x_i) = x_i^{\tau} \beta_{\tau} \tag{2}$$

Furthermore, unlike traditional panel quantile regression, fixed effects quantile regression is utilized to capture possible cross-sectional variability, as evidenced by cross-sectional dependency tests.

$$Q_{yi}\,(\tau_k / \alpha_i x_{it}) = \alpha_i + x_{it}^{/}(\tau_k) \tag{3}$$

Where: Υ represent CO_2 emissions and X represents the exogenous variables (REC, NREC, TO, ECO and GDP). In panel quantile regression analysis, the presence of a large

TABLE 3 | CSD and CIPS Tests Outcomes.

Tests	CSD Test Outcomes					
	GDP	REC	ECO	TO	NREC	CO_2
Breusch-Pagan LM	485.65*	306.00*	598.25*	365.36*	220.64	358.17*
Pesaran scaled LM	71.698*	43.977*	89.072*	53.137*	30.805	52.027*
Bias-corrected scaled LM	71.577*	43.857*	88.951*	53.016*	30.684	51.906*
Pesaran CD	21.664*	8.6660*	24.457*	17.076*	7.7289	18.076*

Note: *p < 0.01.

number of fixed factors poses a considerable barrier. There will be unpredictability when individuals reach infinite, but each cross-section will have fixed measurements. The goal of using fixed effects is to get rid of any unintended fixed effects. Estimates are linear in this approach, which is why provisional quantiles are utilized. To deal with these problems, (Koenker, 2004) proposed a process which deals with unobservable fixed effects, given as parameters to assess, as well as covariate influences for several quantiles. The computing concerns with this approach have been addressed by using a penalty term for assessing variables, which allows the variable estimate to be obtained as follows;

$$Min_q \sum_{k=1}^{K}\sum_{t=1}^{T}\sum_{i=1}^{N} w_k P_{\tau k}\left(y_{it} - \alpha_i - x_{it}^{\tau}\beta(\tau_k)\right) + \lambda \sum_{l}^{N} \mathrm{I}\alpha_i \mathrm{I} \qquad (4)$$

Moreover, the function of the quantile for τ for the present research variables is illustrated below:

$$Q_{yi}\left(\tau_k \mathrm{I}\alpha_i, \xi_t, x_{it}\right) = \alpha_i + \xi_t + \vartheta_0 + \vartheta_{1\tau} GDP_{it} + \vartheta_{2\tau} NREC_{it} + \vartheta_{3\tau} REC_{it} + \vartheta_4 \tau ECO_{it} + \vartheta_{5\tau} TO_{it} \qquad (5)$$

TABLE 4 | Slope Heterogeneity Test.

$\hat{\Delta}$	*p*-value	$\hat{\Delta}_{Adj}$	*p*-value
9.708*	0.000	10.901*	0.000

*Note:**p < 0.01.

TABLE 5 | CIPS Test Outcomes.

	GDP	REC	ECO	TO	NREC	CO_2
Level	−1.211	−1.048	−1.570	−1.730	−0.863	−2.1305
First difference	−3.613*	−5.20*	−4.852*	−3.944*	−5.798*	−5.352*

Note: *p < 0.01.

TABLE 6 | Cointegration Outcomes.

Statistics	Gt	Ga	Pt	Pa
Value	−3.43	−7.021	−7.923	−8.885
p-value	0.009**	0.833	0.002*	0.339

*Note:**p < 0.01 and **p < 0.05.

FINDINGS AND DISCUSSIONS

The econometric study begins by examining the data for crosssectional dependency (CSD) and slope heterogeneity (SH). **Table 3** shows the findings of the CSD analysis, which demonstrate the occurrence of CSD in the data. The test statistics have statistical significance at the 1% level, rejecting the null hypothesis of CSD and confirming the CSD concerns. This discovery is significant in light of the fact that the G7 nations are all industrialized nations that are intertwined, specifically in terms of financial and trade flows. As a result, a single macroeconomic disruption is likely to have similar effects on these nations. The SH test comes after the CSD analysis. The results of the SH test are presented in **Table 4**. The test results for the model are significant statistically, according to the estimations. To validate the existence of slope heterogeneity concerns in the data, the null hypothesis of slope homogeneity is discarded at a 1% level of significance. Even though the G7 nations are highly comparable in many ways, there are some economic contrasts between them. As a result, slope heterogeneity is warranted in this context.

The cointegration and unit root analyses are performed after the CSD and SH problems in the data have been confirmed. The 1st-generation tests are no longer appropriate because the CSD problems have been discovered. As a result, the stationarity qualities are determined using the second-generation CIPS test. **Table 5** summarizes the findings of the unit root analyses. At level, the series are non-stationary, but stationary at first difference, according to the estimations. At 1% and 5% levels of significance, the statistical significance of the anticipated test statistics rejects the null hypothesis of non-stationarity, confirming these assertions. As a result, the variables examined in this research have a common order of integration. The analysis of cointegration comes after the unit root analysis is ascertained.

Table 6 summarizes the Westerlund (2007) cointegration outcomes. The existence of cointegration in the model is confirmed by the statistically significant of the test statistics. As a result, in the framework of the G7 nations, CO_2 has long-run interrelationship with GDP, TO, NREC, ECO, and REC. The presence of long-run associations makes estimating long-run elasticity estimates straightforward.

After confirming the cointegration between CO_2 and the regressors, we proceed by examining the effect of GDP, ECO, TO, REC and NREC on CO_2 using long-run estimators (FMOLS

TABLE 7 | FMOLS and DOLS.

	FMOLS		DOLS	
	Coefficients	T-statistics	Coefficients	T-statistics
GDP	−0.4154	−6.3069*	−0.4504	−6.5966*
ECO	−0.0851	−5.2526*	−0.0683	−4.0206*
REC	−0.0378	−2.1080**	−0.0395	−2.1414**
NREC	1.0606	21.181*	1.0308	20.973*
TO	0.1663	5.5655*	0.1317	4.2226*
R^2	0.99		0.97	
Adj R^2	0.98		0.96	
S.E. of reg	0.0317		0.031338	

and DOLS). **Table 7** presents the DOLS and FMOLS outcomes. The effect of GDP on CO_2 is negative which demonstrates that a 1% upsurge in GDP caused CO_2 emissions to fall by 0.4154% (FMOLS) and 0.4505% (DOLS) respectively. Furthermore, ECO mitigates emissions of CO_2 as revealed by both FMOLS and DOLS. This implies that a 0.08% (FMOLS) and 0.068% (DOLS) decrease in CO_2 is a result of a 1% upsurge in ECO keeping other factors constant. Moreover, the effect of REC on CO_2 is negative which demonstrates that a 1% upsurge in REC caused CO_2 emissions to decline by 0.0374% (FMOLS) and 0.03955% (DOLS) respectively. Furthermore, NREC contributes to emissions of CO_2 as revealed by both FMOLS and DOLS. This implies that a 1.060% (FMOLS) and 1.0308% (DOLS) increase in CO_2 is a result of a 1% upsurge in NREC keeping other factors constant. Lastly, we observed a positive TO and CO_2 emissions association which implies that holding other factors constant, 0.1663% (FMOLS) and 0.1317% (DOLS) growth in CO2 is caused by 1% growth in TO.

The long-run estimators (FMOLS and DOLS) cannot capture the relationship between CO2 and the regressors in each quantile. As a consequence, the current paper employed panel quantile regression (PQR). The PQR outcomes are depicted in **Table 8**. In the lower and middle tails (0.1–0.60), the presence of a negative interrelationship between CO_2 and GDP is evident; however, in the higher tails (0.70–0.90), there is no significant association between CO_2 and GDP. In summary, a surge in GDP boosts the quality of the environment in the lower and middle tails (0.1–0.60). Furthermore, in each quantile (0.1–0.90), we established a negative and significant association between CO_2 and ECO. This implies that ECO curb CO_2 emissions in each tail (0.1–0.90). Moreover, REC mitigates CO_2 in the lower and middle tails (0.1–0.60); however, an insignificant association between CO_2 and ECO is evident in the upper tail (0.70–0.90). Furthermore, a surge in CO_2 is caused by a surge in NREC in each tail (0.1–0.90); though the positive effect is more pronounced in the middle and upper tails (0.35–0.90). Lastly, trade contributes to a surge in CO_2 across all quantiles (0.1–0.90) which implies that trade openness is a major driver of emissions of CO_2 in the G7 nations. These outcomes are consistent with the long-run estimators' outcomes. **Figure 1** presents the graphical outcomes of the PQR.

The results of the (Dumitrescu and Hurlin, 2012) causality test are presented in **Table 9**. There is evidence of feedback causal association between ECO and CO_2 suggesting that both ECO and CO_2 can forecast each other. Furthermore, NREC and CO_2 can forecast each other which supports the proof of bidirectional causal linkage. In addition, REC and CO_2 can significantly predict each other as reported in **Table 8**. This demonstrates that any policy towards REC will impact CO_2 and vice-versa. Furthermore, feedback causality exists between TO and CO_2 suggesting that they can forecast each other Lastly, GDP can predict CO_2; however, no evidence of causality from CO_2 to GDP affirms unidirectional causality from GDP to CO_2. **Figure 2** presents the empirical findings from FMOLS, DOLS and Panel Quantile Regression.

Discussion of Findings

We established that surge in economic expansion mitigates CO2 emissions. This outcome is as anticipated given the fact that the G7 nations are all developed nations. This implies that they are at the technique and composition phases of growth where countries becomes more aware of their environment. At this stage, they consider environmental sustainability when formulating growth agenda. This outcome complies with the research of (Irfan Khan et al., 2021), (Dingru et al., 2021), and (Usman et al., 2020) who reported that GDP growth augments the quality of the ecosystem. Nevertheless, the studies of (Adebayo, 2022a) for Spain, (Awosus et al., 2022a), and (Güngör et al., 2021) refuted this outcome.

Furthermore, we established that renewable energy use curbs damage of the ecosystem. This demonstrates that the utilization of renewable energy perform a significant role in abating the environmental deterioration in the G7 nations. The study outcome agrees with the study of (Miao et al., 2022) for BRICS nations using a dataset from the period 1990–2018 which reported that a surge in green energy abate CO_2.

TABLE 8 | Panel quantile Regression Outcomes.

	Lower Quantile				Middle Quantile		Higher Quantile		
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
GDP	−0.5218*	−0.7316*	−0.5959**	−0.4795**	−0.4149***	−0.2308***	0.1728	0.0961	0.2570
ECO	−0.0307*	−0.0349*	−0.0303*	−0.0420*	−0.0461*	−0.1645*	−0.1595*	0.1368*	−0.1434*
REC	−0.0263*	−0.0287*	−0.0249**	−0.0238**	−0.0259**	−0.0920**	0.2272	0.2309	0.1656
NREC	0.5099*	0.5924*	0.5590*	0.5703*	0.5606*	0.3135*	0.2838*	0.2721*	0.3174*
TO	0.0443*	0.3070*	0.2834*	0.3013*	0.2802*	0.2199*	0.2271*	0.3008*	0.3397*
C	3.7490	4.3965	3.3132	2.0171	1.5521	−3.5436	−2.8798	−2.3829	−4.0666
Pseudo R^2	0.5844	0.5760	0.5709	0.5497	0.5208	0.5361	0.5942	0.5869	0.5882

Note: *p < 0.01, **p < 0.05 and ***p < 0.10.

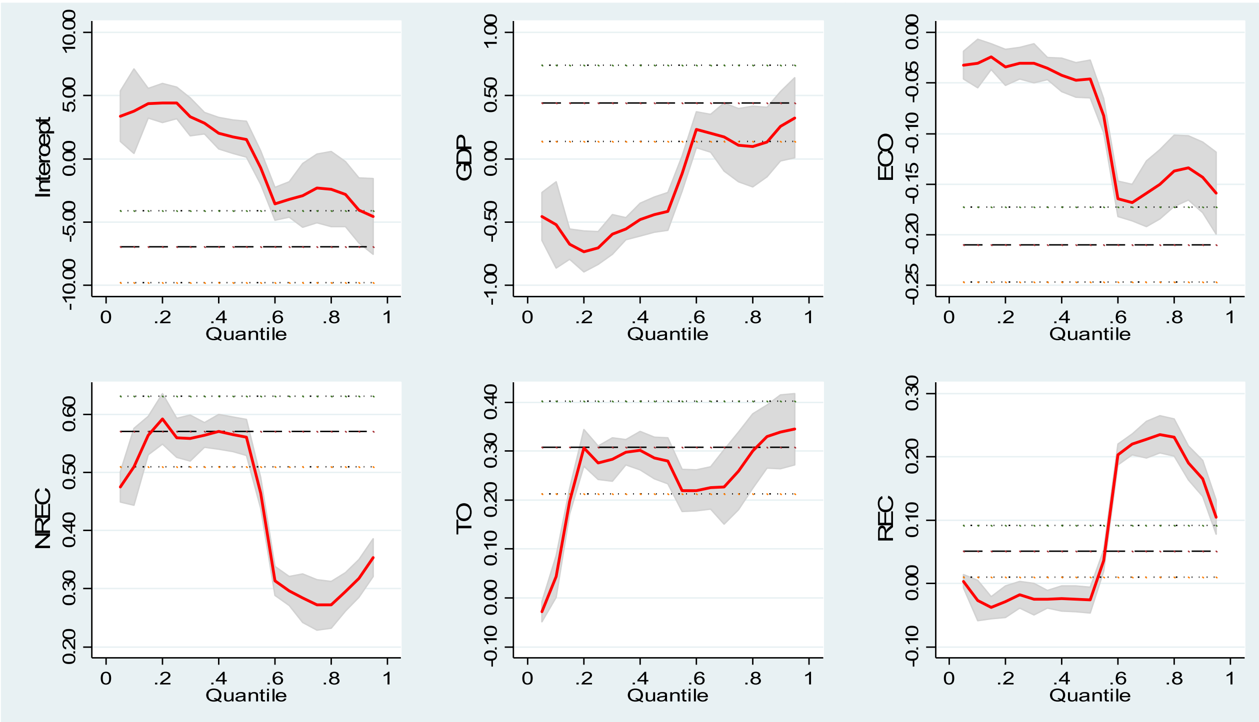

FIGURE 1 | Graphical outcomes of Panel Regression.

TABLE 9 | Panel causality Outcomes.

Path of Causality	W-stat.	Zbar-stat.	Probability	Decision
ECO →CO_2	3.72654	4.28197	0.0000	Feedback Causality
CO2 →ECO	4.14483	4.95960	0.0000	
NREC →CO_2	3.60727	4.08876	0.0000	Feedback Causality
CO_2→NREC	3.48886	3.89694	0.0001	
REC →LCO_2	3.59553	4.06974	0.0000	Feedback Causality
CO_2 →REC	3.73596	4.29725	0.0000	
TO →CO_2	4.32106	5.24510	0.0000	Feedback Causality
CO_2 →TO	2.16141	1.74649	0.0807	
GDP →CO_2	5.30687	6.84210	0.0000	Unidirectional Causality
CO_2 →GDP	0.58998	−.79922	0.4242	

Likewise, the studies of (Adebayo et al., 2022) and (Kirikkaleli and Adebayo, 2020) reported that green energy promotes ecological sustainability.

Moreover, we uncovered that eco-innovation stimulates sustainability of the environment. This means that investments in environmental-related technological innovation, particularly the replacement of older equipment with newer technologies, cut emissions of CO_2 in G7 countries. Low-carbon technical innovation, for instance, can be used on both the supply and demand sides in buildings, transportation and industry. Furthermore, encouraging eco-innovation in these nations decreases energy intensity, lowering dependency on fossil fuels and, as a result, lowering CO_2. This result is in line with the studies of (Kihombo et al., 2021), (Su et al., 2021), (Agyekum et al., 2022), (Awosusi et al., 2022b), (Akadiri et al., 2021) and (Fareed et al., 2021b).

Furthermore, there is proof of positive interconnection between TO and CO_2 in G7 nations. This demonstrates that a surge in trade openness contributes to the deterioration of the G7's ecosystem. Based on this finding, the G7 nations need to re-strategize their trade policies to be more eco-friendly. The study of (Oladipupo et al., 2021) for Portugal and (Soylu et al., 2021) for China complies with this outcome.

Moreover, the research discovered that nonrenewable energy stimulates the deterioration of the environment. This result is to be anticipated, given that energy is understood as a crucial part of the

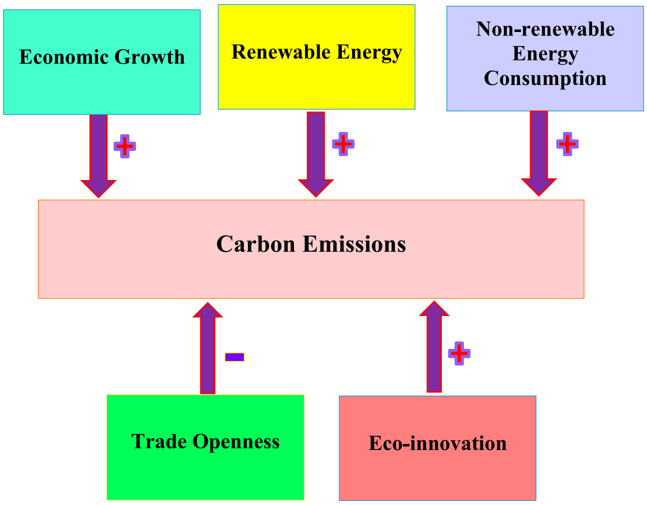

FIGURE 2 | Empirical findings from FMOLS, DOLS and panel quantile regression.

production, and an increase in energy use is assumed to raise economic productivity (Adebayo et al., 2022). Higher energy consumption, on the other hand, can have an effect on the quality of the environment since the burning of energy resources, particularly fossil fuels, results in the release of GHG; hence, energy utilization can be said to be harmful to the environment. This outcome complies with the research of (Yuping et al., 2021) for Argentina, (Shahbaz et al., 2021), and (Gyamfi et al., 2022b).

Finally, the results of the panel causality test unveiled that CO_2 emissions can be predicted by all its drivers ECO, GDP, NREC, TO and REC in the G7 economies. Therefore, policy initiatives directed at any of the CO_2 emissions drivers in the G7 nations will have a substantial influence on CO_2 emissions.

CONCLUSION AND POLICY DIRECTIONS

Conclusion

In this empirical investigation, we examine the effect of eco-innovation and trade openness on CO_2 emissions in G7 nations. We consider the role of renewable energy, economic growth and nonrenewable energy use using a dataset covering the period from 1990–2019. We employed recent econometric techniques such as SH and CSD, Westerlund cointegration, FMOLS, DOLS, panel quantile regression and panel causality tests to assess these associations. The outcomes of the CSD and SH tests disclosed that using a first-generation unit root test will produce bias outcomes. Furthermore, the outcome of the Westerlund cointegration was disclosed to support the long-run association between CO_2 and its drivers. In addition, the results of the long-run estimators (FMOLS and DOLS) unveiled that NREC and TO contribute to the damage to the environment while ECO, REC and GDP enhance the quality of the environment. Furthermore, the outcomes of the panel quantile regression unveiled that in the majority of the quartiles, economic expansion, renewable energy, and eco-innovation enhance the quality of the environment while nonrenewable energy and trade openness contribute to the damage to the environment. Finally, the outcomes of the panel causality test unveiled that CO_2 emissions can be predicted by all its drivers (eco-innovation, economic growth, renewable energy, trade openness and nonrenewable energy use) in the G7 economies. Therefore, policy initiatives directed at any of the CO_2 emissions drivers in the G7 nations will have a substantial influence on CO_2 emissions.

Policy Suggestions

The results of the selected techniques specifically point to ECO, REC, and GDP as potential best practices for reducing G7 emissions. As a result, it is critical for the governments of the G7 economies to focus more on energy transition (from fossil fuels to more sustainable energy sources). As per empirical evidence, economic growth promotes environmental sustainability in G7 countries. This suggests that the growth trajectory of the G7 economies remains stable. The study backs up this need by claiming that renewable energy decreases CO_2 emissions and hence improves the quality of the environment. This demonstrates that the G7 economies are on the right track in terms of reducing environmental deterioration. Nevertheless, in order to attain environmental sustainability, she needs to make further efforts to include other alternative and greener sources of energy into her energy mix.

Furthermore, G7 nations' policymakers should develop liberalization and privatization policies that would encourage both public and private parties to participate in renewable energy. In addition, as previously stated, policymakers or governments should undertake strategies to support ecological integrity by enforcing more carbon taxes on production and assisting sectors in transitioning from conventional high CO_2 emitter technologies to cleaner technologies in order to preserve ecological integrity. Furthermore, because trade openness promotes the destruction of the environment, officials in these nations should reduce trade openness to prevent environmental damage from dirty products 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

VO, MI, and MA contributed to conception and design of the study. EA organized the database. SK and ME performed the statistical analysis. MA wrote the first draft of the manuscript. VO, MI, EA, and MF wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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The Relationship Between Fiscal Decentralization and China's Low Carbon Environmental Governance Performance: The Malmquist Index, an SBM-DEA and Systematic GMM Approaches

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Despite the People's Republic of China government being the most aggressive in pursuing the carbon neutrality goal, it remains the world's largest carbon emitter and polluting country. This study used 31 provinces' panel data from 2010 to 2019 to compare fiscal decentralization's impact on regional carbon emissions. It applied SBM-DEA undesirable models to calculate the Malmquist index and study environmental governance performance. It then used the systematic GMM model to explore fiscal decentralization's influence on environmental governance performance. It is found that fiscal decentralization in eastern China exhibited a strong positive relationship with environmental governance performance. With high tax autonomy, local governments implemented the best tax policies for clean production, raising enthusiasm for enterprises' green production. Nevertheless, there was no relationship between fiscal decentralization and environmental governance in poorer central and western regions with less tax collected. Benefits that arose from fiscal decentralization were limited. Moreover, more elite officials working in affluent cities and wealthier citizens have a higher expectation of environmental governance. These lead to better environmental and carbon emission policies. This paper also brings policy implications: 1) the central government should raise local government flexibility to use financial resources for environmental management. 2) Local government performance appraisal should include environmental protection (including carbon emission control). 3) The production taxes retained by local governments should be minimized to reduce governments' incentives to obtain taxes from polluting/high energy consumption industries. 4) Raise government officials' income in poorer regions to attract talented officials to work.

Keywords: fiscal decentralization, environmental governance performance, carbon emissions, SBM-DEA undesirable models, malmquist index

1 INTRODUCTION

China's economy has grown over the last few decades, accumulating vast wealth. Nevertheless, rapid economic expansion has been associated with massive energy and resource consumption, resulting in serious environmental problems (Lin and Liu, 2016; Song et al., 2020). Even though the Chinese government has promoted environmental protection, environmental pollution remains a severe concern (Liu L. et al., 2019; Wu et al., 2021). Indeed, many local government officials focus on economic development, which allows "pollution first" and then controls pollution problems later. Nevertheless, high-quality development needs to minimize carbon emissions to reduce related climate change adversities (Li Z.-Z. et al., 2021) and increase the effectiveness of environmental control. According to National Aeronautics and Space Administration (NASA) statistics released in 2010, the mean PM2.5 concentration from 2001 to 2006 was 50–80 ug/m3, while the mean PM2.5 concentration in developed countries was below 15 ug/m3. China has been the world's first in carbon dioxide (CO2) and sulfur dioxide (SO2) emissions for many years. A cost-effective method for reducing emissions and saving energy is to improve environmental performance (Zhang et al., 2020; Zhang et al., 2021). However, resource conservation and carbon emission reduction are hard to achieve without institutional incentives and fiscal support (Lin and Zhu, 2019; Cheng et al., 2021). Many countries, including China, have delegated environmental responsibility to local governments in recent years (Khan et al., 2021). Local governments benefit from power devolution by being encouraged to take on more environmental and public service responsibilities (Bhattacharyya et al., 2017; Song et al., 2018).

China's 1994 tax-sharing reform established a fiscal decentralization framework by separating the central and local governments' expenditure responsibilities and fiscal authorities. (Zhang, 2020). For example, the central government received a 75 percent value-added tax, tariffs, and other significant levies. However, local governments received 25 percent only. Furthermore, the sources and rates of taxation were severely restricted. Because of this, local governments' autonomy in receiving tax is limited. The Chinese form of fiscal decentralization allows local governments to exercise their freedom to spend rationally to promote economic growth, support public services, and environmental protection. Under China's GDP-based appraisal system, local governments invest and spend more on infrastructure to meet the goals of economic expansion (Li and Du, 2021). Local governments bore an excessive expenditure obligation under this system with few options on funding sources.

Moreover, unequal changes in revenue and spending worsened regional fiscal imbalance (Jia et al., 2020). Fiscal decentralization does not directly affect environmental pollution, but it affects environmental pollution by influencing government choices. The role of fiscal decentralization reform in strengthening environmental governance has gained importance under China's national "13th Five-Year Plan" strategy. So, what will be the impact of the reform of the fiscal decentralization system within these 10 years on urban environmental pollution in China? Does fiscal decentralization encourage local governments to govern the environment or encourage them to sacrifice the environment for a better economy? These issues will be discussed in this paper.

Environmental preservation and sustainable development promotion are inextricably linked to local government funding. Regional fiscal imbalance drives local governments to adopt measures that raise GDP and tax revenue in the short run at the expense of long-run environmental benefits (Boqiang and Yicheng, 2021). While it is foreseeable that fiscal decentralization affects environmental performance, research that throws light on China, a planned economy country, is scarce. This research aims to fill this gap.

Specifically, this study aims to: 1) study how fiscal decentralization affects China's environmental governance performance while limiting carbon emissions using panel data from 31 Chinese provinces from 2010 to 2019. 2) Quantify environmental governance performance in all regions by calculating the Malmquist index to build SBM-DEA undesirable models. 3) Study the impact of interregional fiscal decentralization differences on environmental governance performance by using a systematic GMM model. As the environmental governance performance is affected by the governance performance level of the previous period and many other factors, this paper followed Zhang et al. (2014). It used the GMM approach to study the governance lags between this year and the previous years.

This paper's contribution is threefold. First, while there is much scholarly research about the relationship between fiscal decentralization and environmental governance performance, most have not included carbon emission governance into environmental governance performance. However, the PRC government envisaged lowering carbon emissions by 40–45 percent from 2005 to 2020. This paper studied the influence of fiscal decentralization on China's environmental governance performance, including CO2 emission control. Second, this research compared the impact of regional fiscal decentralization disparities on environmental governance performance, including carbon emission. Finally, the results have policy implications and provide insights to government officials regarding the factors that reduce CO2. This research's results indicated that a higher level of fiscal decentralization in eastern China could inform financial officials in China when they design and implement related fiscal policies in the future.

This paper's structure is as follows: the literature review and theoretical analysis are introduced in **Section 2**. The methods and data are presented in **Section 3**. The empirical findings and discussion are presented in **Section 4**. Conclusions and policy implications are covered in **Section 5**.

2 LITERATURE REVIEW

2.1 Impact of Fiscal Decentralization on Environmental Governance Performance

Previous studies have examined the impact of fiscal decentralization on environmental governance performance but have not reached a consensus. Some studies proposed that the decentralization of government increases energy consumption and pollution. While fiscal decentralization aids economic progress, it impedes regional carbon emission reduction. Local governments choose short-term economic gains over environmental preservation in fiscal decentralization (Zhang K. et al., 2017; You et al., 2019). This phenomenon is often described as a "race to the bottom" (Liu and Ding, 2019; Li X. et al., 2021). Guo et al. (2020) used China's province data from 2007 to 2015 to build a fixed-effect model and discovered that fiscal decentralization considerably worsens environmental pollution. Liu et al. (2016) studied the Beijing-Tianjin-Hebei region's environmental policies and historical processes and found fiscal decentralization worsened government fragmentation.

On the other hand, another school of thought's justification for fiscal decentralization is decreasing energy use and pollution emissions. Fiscal decentralization benefits local governments by raising environmental awareness and expenditures on environmental management (Kuai et al., 2019). Cheng et al. (2021) and Khan et al. (2021) shared similar conclusions. Elheddad et al. (2020) conducted quantile regression on provincial panel data from 2006 to 2015. They discovered a non-linear relation between fiscal decentralization and energy use.

Some found that fiscal decentralization reduced carbon emissions. Cheng et al. (2019) conducted a time-series econometric study based on China's data from 2005 to 2018 and discovered that a higher degree of fiscal decentralization reduced carbon emissions. Song et al. (2018) came up with similar conclusions. Zhou et al. (2018) found that fiscal decentralization might increase ecological energy conservation from 2000 to 2016. Utilizing the co-integration test and CS-ARDL technique, Su et al. (2021) discovered that fiscal decentralization raised renewable energy utilization and decreased fossil fuel consumption in OECD countries from 1990 to 2018. Ahmad et al. (2021) discovered that fiscal decentralization improved ecological efficiency sometimes but worsened between 2003 and 2016. Others discovered that fiscal decentralization had no impact on pollution and even stimulated environmental investment (He, 2015).

2.2 Data Envelopment Analysis Based Environmental Governance Research

Selecting indicators, collecting data, and analyzing and evaluating outcomes are methods for assessing environmental status and performance (Godínez-Cira et al., 2010). The Environmental Performance Index (EPI), Global Reporting Initiative (GRI), and the ISO 14001 norm usage, among other approaches, have been established to measure the environmental performance (Oregi and Galera, 2013). These approaches assessed environmental legislation compliance, pollution reduction, effective use of natural resources, waste and emissions generation, and ecosystem and biodiversity protection (Quiroga, 2001).

Several aspects are involved in an evaluation, and a single and unilateral indicator is typically insufficient to demonstrate the actual environmental situation. Thus, DEA assesses a group of decision-making units' relative efficiencies by measuring each unit's efficiency score using various resources (inputs) and multiple results (outputs). DEA also allows for comparison between Decision-Making Units (DMUs) and can be used in various situations (Charnes et al., 1978; Jahanshahloo et al., 2005; Halkos and Petrou, 2019).

DEA is a sophisticated tool for examining decision alternatives and evaluating performances (Zhu, 2009). Using mathematical programming techniques, DEA reviews the effectiveness of each DMU in a collection of decision-making units about all other Decision-Making Units in the set and generates an adequate border where the most efficient units are located. Inefficient units are not on the efficient Frontier; DEA determines how decision-making units should become efficient by radial projection to the border (Avil'es-Sacoto et al., 2016). Because it allows businesses under assessment to be measured best practices that are not visible in other management methods, DEA has lately been dubbed "balanced benchmarking" (Cook and Zhu, 2013).

DEA is a linear programming method that uses a single integrated model to handle many metrics. Multiple measures are made up of inputs that should be minimized and outputs that should be optimized (Charnes et al., 1978). It has been utilized extensively in numerous contexts, including environmental applications. For example, Shabani et al. (2015) used DEA to evaluate the environmental efficiency of 163 countries. Zeng et al. (2019) designed a DEA model with two stages for evaluating renewable energy technical ideas. Wen et al. (2019) conducted another study that investigated regional differences in the energy efficiency of the construction sector, considering China's incredible regional diversity. Jiang et al. (2019) employed a DEA model to assess the efficacy of wastewater treatment plants in terms of sustainability. Finally, Finally, Mohebali et al. (2020) employed DEA considering both outputs- and input-oriented approaches to assess environmental groups considering the industrial project's positive benefits.

2.3 Literature Gap

Although academics have researched the relationship between fiscal decentralization and environmental governance or carbon emissions, research gaps remain. First, even though academics have focused on CO2 emissions and the impact of fiscal decentralization, there is still a lack of knowledge about carbon emission governance. Scholars have either studied environmental governance or carbon emissions only. Second, the study of environmental governance performance should include carbon governance because reducing carbon emissions is China's environmental governance goal. The impact of fiscal decentralization on China's environmental governance performance, including carbon control, was investigated in this research.

3 METHODOLOGY AND DATA

3.1 SBM-DEA Undesirable Model

3.1.1 Model Analysis

DEA was created by Charnes et al. (1978) as a nonparametric method for coping with multiple inputs and outputs scenarios. It is usually used to assess and quantify the effectiveness of DMUs' many impacting elements (Boussofiane et al., 1991). In general, these variables can be classified into input and output variables. Labor, money, machinery, equipment production, and materials are input factors, whereas the value of the outputs like value-added and production are output variables (Halkos and Petrou, 2019). Once the optimal operating distance has been determined in DEA, an inefficient DMU's performance and efficiency can be improved by decreasing inputs or increasing outputs (Seiford and Zhu, 2002).

The DEA is founded on the idea that inputs should be minimized while maximizing outputs. However, the assessment process might produce undesirable results and inputs in some cases. It was recommended to raise desirable output factors to improve decision-making units' efficiency while minimizing undesired outputs (Jahanshahloo et al., 2005; Rashidi and Saen, 2015).

An undesirable model can be utilized to deal with negative variables, often known as unwanted or undesirable outputs. The undesirable model is concerned with negative variables and undesired or harmful outcomes. There are a few options for dealing with negative variables.

First, consider the negative output variable to be an input variable. This technique cannot use the existing positive output variable. However, because the weight is applied in proportion to the input variables, an improper weight may be imposed during the weighting process.

Second, they can be dealt with using an analysis that includes negative output variables only. A lower efficiency score indicates that the decision-making unit is operating at a higher efficiency level.

Third, a variable can be multiplied by "−1" to deal with the undesired variables. Multiplying by a value chosen at random, the weight must be considered together with the positive output variables like the first method. However, there is a risk of applying the wrong weight.

Fourth, utilizing the SBM model, multiply the negative value of the output variable by a multiplier by using predetermined weights. This method compares efficiency fluctuations caused by an undesirable output variable. It is simple to determine the surplus in the number of variables and suggest ideas for boosting efficiency because the benchmark is surplus efficiency (You and Yan, 2011; Rashidi and Saen, 2015). The formulae are as shown as follows:

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

$$\text{s. t. } x_0 = x\lambda + s^-,$$
$$y_0^g = y\lambda - s^g$$
$$y_0^b = y\lambda - s^b$$
$$L \le e\lambda \le u$$
$$\lambda, s^-, s^g, s^b \geqq 0,$$
$$\lambda \ge 0.$$

In these equations, the product is denoted by y. The decision-making units are the topic of the evaluation and is denoted by 0. Input excess, general output shortage, and negative output excess are represented by the letters s, s^g, and s^b. The optimal values of ρ, s, s^g, s^b And λ were calculated using this equation.

3.1.2 Variable Selection

To measure the environmental governance performance indicators, scholars have used different research methods, such as the questionnaire (Zhou and Tang, 2017), principal component method composition method (Qi et al., 2015), comprehensive index method (Zhang et al., 2014) and DEA-Malmquist index method (Yang, 2016). This paper intends to use the DEA-Malmquist index method to measure environmental governance's performance level in various regions of China.

The SBM-DEA undesirable model referred to Lin Chun (2017) to select the input and output variables and added the carbon emission in undesirable output to analyze China's Low carbon environmental governance performance. We selected the investment of people, equipment, and capital in environmental governance and included 6 input variables: the number of environmental protection employees, industrial wastewater treatment facilities, industrial waste gas treatment facilities, sewage treatment plants, harmless waste treatment plants, and investment regarding the contamination of the environment treatment. Considering environmental treatment, sewage, air, solid waste, and other treatment effect indicators are selected as the output indicators. This paper chooses the output variables of solid waste, industrial wastewater reuse rate, urban sewage treatment rate, and household garbage disposal rate (**Table 1**). Total particulate, nitrogen oxide, sulfur, and carbon dioxide emissions do not have a governance effect index and are undesirable outputs.

The rate at which solid waste is fully utilized was calculated by using typical industrial solid waste in its entirety and general industrial solid waste; discharge referred to the carbon emission of each province. It represented the energy consumption j in the region I during t and the emission coefficient of j energy consumption. The formula for emission coefficient of energy consumption would be:

Discount carbon dioxide coefficient = average low calorific value * carbon content per unit calorific value * carbon oxidation rate * [10(-6)] * 44/12"

The average low heat generation data was obtained from China Energy Statistical Yearbook, and the amount of carbon and how fast carbon burns per unit of calorific value was derived from Table 1.5 and Table 1.7 of the Guide for the Compilation of Provincial Greenhouse Gas List (Trial), respectively. Thus, the coefficients of coal, coke, gasoline, kerosene, diesel, fuel oil, and natural gas were 1.9003,

TABLE 1 | Input and output variables.

Input and output variables in the undesirable model	
Input variables	**Output variables**
Number of environmental protection employees	Comprehensive utilization of solid waste
Number of industrial wastewater treatment facilities	The industrial wastewater reuse rate
Number of industrial waste gas treatment facilities	Urban sewage treatment rate
Number of sewage treatment plants	The household garbage disposal rate
Number of harmless waste treatment plants	Total particulate emissions (undesirable output)
Investment in environmental pollution treatment	Total nitrogen oxide emissions (undesirable output)
	Sulfur dioxide emissions (undesirable output)
	Carbon dioxide emissions (undesirable output)

2.8604, 2.9251, 3.0179, 3.0959, 3.1705, and 2.1605, respectively, so carbon dioxide emissions from fossil energy and natural gas consumption in 31 provinces and cities were estimated.

3.2 GMM Model

3.2.1 Model Setting

The econometric model based on the dynamic panel data below shows the influence of fiscal decentralization on China's environmental governance performance. The system GMM estimator was used to estimate our model. It was applied to study the dynamic relationship between factors that affected the accidents' compensation (Li et al., 2017). The system GMM estimator overcomes issues such as the presence of fixed control variables' effects and endogeneity; the correlation of independent variables and the past and errors; the presence of fixed effects and endogeneity of control variables; heteroskedasticity and autocorrelation in individual variables; and omitted factors persisted across time (Roodman, 2009). The model would then be:

$$\text{Environment}_{i,t} = \beta_0 + \beta_1\text{Environment}_{i,t-1} + \beta_2\text{FD}_{i,t} + \beta_3\text{Control}_{i,t-1} + \varepsilon_{i,t} \quad 2$$

Where environment referred to the environmental governance performance, FD represented fiscal decentralization, control indicated the control variable affecting environmental governance performance, and ε was a random disturbance term.

3.2.2 Variable Description

3.2.2.1 Independent Variables—Environmental Governance Performance.

Environmental governance performance: the DEA-Malmquist index approach has the advantage of being no need to construct the production function and could explore the reasons for the change in environmental governance performance. Therefore, this paper used it to measure the environmental governance performance.

3.2.2.2 Dependent Variable- Fiscal Decentralization.

Fiscal decentralization: regarding the measurement of fiscal decentralization indicators, scholars mainly discussed revenue decentralization (He and Miao, 2016) and expenditure decentralization (Chun and Shao, 2017). If the fiscal decentralization index is measured from a single perspective, it cannot reflect its decentralization characteristics well. The fiscal decentralization reflected local governments' fiscal revenue power and the scope of expenditure responsibility. To raise accuracy, this paper measured the fiscal decentralization index from two perspectives: fiscal decentralization (FD1) from the perspective of revenue (FD1) and fiscal decentralization from the perspective of expenditure (FD2) (Chun, 2017).

The effect of fiscal decentralization on greenhouse gas emissions is reflected in fiscal decentralization, revenues from local and national government items are detailed differences, and local governments can decide their fiscal expenditure budgets according to their revenue. In theory, local governments can attract targeted investment according to the characteristics of local economic structure and rapidly increase regional fiscal revenue to strengthen environmental governance, such as an increase in low-carbon equipment, research and development, and technical personnel training high-carbon emission enterprises to reduce regional carbon emission level.

3.2.2.3 Control Variables and Moderator Variables.

Degree of economic development (income): the per capita GDP of each province reflects the degree of economic development. To obtain the real per capita GDP, the per capita GDP of all provinces from 2010 to 2019, GDP of each year and the total population at the end of each province were obtained from the China Statistical Yearbook.

Industrial structure (ind): the proportion of the secondary industry's added value in the provincial GDP was included. Regional carbon emission was closely related to its industrial structure. To promote the rapid development of the local economy, local governments encouraged secondary industry development to fasten the pace of local economic development. However, in accelerating industrialization, the immaturity of technology that utilized energy and the inefficiency with which fossil energy directly led to increased carbon emissions.

Fixed Assets Investment (inv): the purchase and construction of fixed assets for social production reflected new production activities, increasing carbon emissions. In addition, the process promotes the development and production of advanced technology and equipment and indirectly adjusts the industrial structure. This paper used the fixed asset investment in each province from 2010 to 2019, and the deflated fixed asset

TABLE 2 | The descriptive statistics of variables.

Variables	Variable symbol	Description
Environmental governance Performance	TFP	DEA-Malmquist index
Fiscal decentralization1	FD1	The provincial financial general budget revenue/revenue from the central government's general budget
Fiscal decentralization2	FD2	The provincial financial general expenditure/expenditure in the central government's general budget
Degree in economic development	Income	Real GDP per capita in each province
Industrial structure	Ind	The value-added of the secondary industry accounts for the GDP of each province
Fixed assets investment	Inv	The real value of the local fixed-asset investment
Foreign direct investment	Fdi	The real value of the foreign direct investment in various regions
The effect of opening degree of foreign trade	Tra	The real value of the import and export volume
Total retail sales of social consumer goods	Cus	The real value of the total retail sales of local social consumer goods
Population density	Pop	The ratio of population and area at the end of the year

investment price index refers to the actual fixed asset investment. Government investment in science and technology (tech) reflects the region's production technology level. In general, the higher the production technology level, the more advanced its industrial structure and the higher the energy utilization level, conducive to regional carbon emission reduction (Boqiang and Yicheng, 2021). The data on government investment in science and technology included the potential exploration transformation of enterprises and the local financial science and technology expenditure index. The data is deducted through the regional GDP index to obtain its real value.

Foreign direct investment (fdi): The impact of foreign investment on regional environmental conditions can be divided into two categories. One is based on the "pollution paradise" hypothesis, which states that developed countries transfer heavy polluting and high-carbon industries by investing in developing countries. In addition, some scholars believed that there was a complex mechanism regarding foreign direct investment's impact on the environmental situation, and the technology spillover effect brought by foreign investment might reduce carbon emission (Zhang H. et al., 2017).

The effect of the degree of open foreign trade (tra): the import and export trade of the high-carbon industry has the most noticeable impact on carbon emissions. Developed countries may transfer carbon emissions to developing countries with greater needs for economic growth through trade than carbon emissions reduction. In this paper, each province's total import and the export amount provided insight into the degree of opening to the outside world (Zhang et al., 2011). This value is multiplied by an annual average price of the RMB exchange rate over the years and converted to RMB, and then the production price index is deduced.

Total retail sales of social consumer goods (cus): this paper measured the indirect energy consumption of consumers through total retail sales of socially beneficial products, thus reflecting the indirect generation of carbon emissions. The data was obtained from the National Bureau of Statistics website, and the deflated index is the actual provincial index of retail commodity prices.

Regarding population density (pop), some scholars believe that energy efficiency exhibits a scale effect. The more dispersed the population, the higher the cost of using energy, and vice versa. A higher population density emits more carbon. Carbon emission data of provinces and regions were obtained from the official website of the people's government. The end-of-year total population data was obtained from the National Bureau of Statistics website. Meaning of each variable are shown in **Table 2**.

3.3 Data and Analysis Methods

The panel data of 31 Chinese provinces (municipalities and autonomous regions) used in this paper are available from 2010 to 2019. The data was obtained from the China Statistical Yearbook, China Financial Yearbook, China Environmental Statistical Yearbook, China Energy Statistical Yearbook, and government statistical bulletins and yearbooks.

4 EMPIRICAL RESULTS AND DISCUSSION

4.1 Environmental Governance Performance Analysis

This study used 31 Chinese provinces' panel data from 2010 to 2019 and applied the MaxDEA software program to analyze the SBM-DEA undesirable model. The variables and their sums are given in **Table 3** after including 6 input variables and 8 output variables. Following software operation and analysis, the Malmquist index results displayed in **Table 4** measured the performance of environmental governance in all regions. It shows that the performance of environmental governance improved annually, the best performance was in 2018, and the national average environmental governance performance over the years was 1.02.

According to the classification standards of provinces and cities in eastern, central, and western China in the China Statistical Yearbook, the average Malmquist index of eastern, central, and western regions were 1.03, 1.06, and 0.99 (**Table 4**). As higher values indicate better environmental governance, the performance of environmental governance in the eastern and central areas was better than the national average (1.02). At the same time, it is inferior in the western regions.

4.2 GMM Model Regression Analysis

4.2.1 Benchmark Regression Analysis

GMM model and panel data from 31 Chinese provinces from 2010 to 2019 indicated no clear relationship between fiscal decentralization and environmental governance performance. Differences in fiscal decentralization across provinces are not

TABLE 3 | 31 Chinese provinces' input and output variables.

Variable name and category			Mean	Max	Min	Median	Standard deviation	Number
Input variables		Number of environmental protection employees	8.19	20.44	0.16	8.16	4.20	310
		Number of industrial wastewater treatment facilities	2563.71	10608.00	16.00	1943.50	2328.36	310
		Number of industrial waste gas treatment facilities	9362.69	57278.00	46.00	6404.00	8539.47	310
		Number of sewage treatment plants	62.03	301.00	0.00	48.00	52.08	310
		Number of harmless waste treatment plants	28.08	111.00	0.00	25.00	18.82	310
		Investment in environmental pollution treatment	241.42	1,416.20	0.30	197.10	193.82	310
Output variables	Desirable variables	Comprehensive utilization of solid waste	0.64	1.00	0.01	0.62	0.22	310
		Industrial wastewater reuse rate	76.55	96.70	4.14	85.10	21.17	310
		urban sewage treatment rate	87.25	100.30	0.00	91.30	14.34	310
		household garbage disposal rate	90.02	100.00	38.00	95.00	13.29	310
	Undesirable variables	total particulate emissions (Bad Output)	371759.75	1575417.00	1,000.00	330102.00	280329.08	310
		total nitrogen oxide emissions (Bad Output)	449706.43	1843045.18	2491.00	348610.50	402664.65	310
		sulfur dioxide emissions (Bad Output)	437113.77	1827397.00	880.00	334294.00	377006.57	310
		carbon dioxide emissions (Bad Output)	41320.85	147817.65	3,696.51	31374.09	28987.54	310

TABLE 4 | 2011–2019 Malmquist index test results in various provinces.

	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean
AH	0.89	0.90	0.96	0.89	0.97	0.95	0.95	0.97	0.83	0.92
BJ	0.55	1.04	3.43	1.01	1.08	1.18	1.22	1.01	0.99	1.28
HJ	0.69	1.05	0.98	0.96	0.88	1.07	0.93	1.02	0.84	0.93
GS	0.96	0.85	1.00	0.95	1.00	1.15	1.09	0.91	0.94	0.98
GX	0.84	1.03	1.01	0.99	0.95	1.09	1.03	0.99	0.89	0.98
GD	1.04	1.05	0.89	0.99	1.02	0.88	1.20	0.84	0.84	0.97
GZ	0.28	0.97	0.90	0.87	0.98	1.05	0.90	1.00	0.94	0.88
AHN	0.88	0.98	1.02	0.96	0.99	1.12	1.01	1.04	0.98	1.00
AHB	0.82	1.00	1.02	0.96	1.03	0.95	1.02	1.04	1.04	0.99
BHN	0.90	0.92	0.97	0.96	0.97	0.87	0.90	1.03	0.92	0.94
HLJ	0.95	0.97	1.03	1.04	1.03	1.19	0.91	1.11	0.89	1.01
BHB	0.68	1.13	1.05	0.92	0.96	1.07	1.00	1.01	0.87	0.97
CHN	0.90	0.88	1.06	0.96	0.88	1.26	1.15	1.01	0.89	1.00
JL	0.93	0.99	1.09	0.96	0.93	1.22	1.07	0.94	0.96	1.01
JS	0.85	0.95	0.98	0.93	0.94	0.97	1.10	1.00	0.96	0.96
JX	0.80	1.05	0.90	0.97	0.90	0.90	0.98	0.96	0.96	0.93
LN	0.88	0.94	1.13	0.95	0.98	1.34	1.04	1.14	1.12	1.06
NMG	0.74	1.07	0.98	0.94	0.98	0.96	0.90	9.61	0.14	1.81
NX	0.76	1.58	0.97	0.99	0.82	0.99	0.74	0.95	1.92	1.08
QH	0.97	0.96	0.95	1.00	0.96	1.07	1.12	1.07	0.97	1.01
SD	0.87	0.95	0.95	0.93	0.92	0.95	0.95	0.93	0.96	0.94
ASX	0.91	0.96	0.97	0.97	0.87	0.83	1.13	0.94	0.95	0.95
BSX	1.01	1.06	0.99	0.92	0.97	0.96	0.73	0.84	0.92	0.93
SH	1.04	0.52	0.45	0.93	2.08	0.99	2.59	1.01	1.06	1.18
SC	0.83	1.01	0.86	0.94	1.09	0.91	1.00	1.10	0.86	0.95
TJ	0.95	0.99	1.00	1.00	0.99	1.08	1.02	1.02	0.96	1.00
XZ	0.82	1.09	1.02	1.01	1.01	0.97	1.00	0.89	1.02	0.98
XJ	0.86	0.86	1.36	0.91	0.85	1.01	0.95	1.26	1.10	1.02
YN	0.82	0.79	1.05	1.03	1.02	0.98	0.85	1.06	0.92	0.94
ZJ	0.91	0.90	1.03	0.93	1.00	0.91	1.22	1.03	0.94	0.99
CQ	2.18	0.95	1.04	0.89	0.97	0.91	0.96	0.97	1.08	1.11
Mean	0.89	0.98	1.07	0.96	1.00	1.02	1.05	1.28	0.96	1.02

the cause of differences in environmental governance performance between provinces. Although the role of fiscal decentralization reform heightened environmental governance under the national "13th Five-Year Plan" strategy, and the Chinese government proposed in 2009 that carbon emissions in 2020 should be reduced by 40%–45% from 2005, indicating

TABLE 5 | Results of weight heterogeneity regression.

	Revenue perspective			Expenditure perspective		
	East	Middle	West	East	Middle	West
TFP(-1)	−0.083	−0.210[a]	−0.080	−0.084	−0.216[a]	−0.073
FD1	4.359[b]	−6.206	4.356			
FD2				4.359[c]	1.884	0.158
Income	1.264e–06	0.000	4.931e–06	1.264e–06	0.000	4.030e–06
Ind	−0.006	−0.009	0.000	−0.006	−0.0175	0.001
Inv	−6.534e to 06[a]	|−9.519e to 07	−0.000	−6.534e to 06[a]	−8.590e to 06	−0.000
Fdi	−0.000	0.000	−0.000	−0.000	−0.000	−0.000[c]
Tra	−5.494e to 10	−1.482e to 09	−1.834ev09	−5.494e to 10	−4.023e to 10	−6.892e to 10
Cus	3.066e–06	−0.000	0.000	3.066e–06	−0.000	0.000[b]
Pop	−0.040	7.638	−0.896	−0.040	7.118	−0.173
Hansen Test	0.3187	0.000	0.028	0.3205	0.000	0.032

[a]p < 0.1.
[b]p < 0.05.
[c]p < 0.01.

that the Chinese government is increasingly emphasizing the role of fiscal decentralization on environmental governance, it remained in infancy.

4.2.2 Analysis of Regional Heterogeneity

To determine the relationship between different levels of fiscal decentralization and environmental governance performance, this article classified and compared three regions: eastern, central, and western. Regarding fiscal decentralization revenue and spending, the eastern region has more fiscal decentralization than the central and western regions. The fiscal decentralization is higher than in the eastern regions. The central and western areas were below the national average; however, the central region has a modest advantage over the western sections. The regression results of fiscal decentralization on environmental governance performance in the eastern, central, and western areas are shown in **Table 5**.

The findings showed that fiscal decentralization in the eastern region had a strong and beneficial relationship with environmental governance performance. With a high tax autonomy, the government could decide preferential tax policies, provide preferential tax policies for clean production enterprises, boost enterprises' green production enthusiasm and promote environmental governance performance. There appears to be no clear relationship between fiscal decentralization and environmental governance effectiveness in the central and western regions, which are on average poorer than the eastern part of China. It is speculated that poorer regions have a lot less tax being collected, and the benefits that arise from fiscal decentralization are also limited. Moreover, there may be more elite officials working in more affluent cities, and wealthier citizens might have a higher expectation of environmental governance as poorer ones mainly focus on how to make ends meet. All these lead to more careful planning and implementation of environmental policies in more prosperous eastern China when the officials have the right to exercise their decisions on carbon emissions policies.

4.3 Robustness Check

We conducted a robustness check to confirm that the regression results are reliable for fiscal decentralization and environmental governance performance. The robustness test examined the strength of the variables' explanatory power, that is, when certain indicators changed, whether the results remained relatively consistent and stable. This study removed the control variable of industrial

TABLE 6 | Robustness testing and endogenous problem handling.

	Revenue perspective			Expenditure perspective		
	East	Middle	West	East	Middle	West
TFP(-1)	−0.063	−0.205[b]	−0.080	−0.062	−0.206[b]	−0.073
FD1	4.109[b]	−9.287	4.627			
FD2				1.126[c]	−0.842	0.164
Income	1.584e–06	0.000	5.022e–06	2.219e–06	0.000	4.077e–06
Inv	−9.358e to 06***	−5.474e to 08	−0.000	−8.875e to 06[c]	−6.908e to 06	−0.000
Fdi	−9.192e to 06	−0.000	−0.000[b]	−8.974e to 06	−0.000	−0.000[c]
Tra	−5.347e to 10	−1.731e to 09	−1.936e to 09	−3.433e to 10	1.425e–10	−7.502e to 10
Cus	3.964e–06	−0.000	0.000[b]	1.392e–06	−0.000	0.000[b]
Pop	0.034	5.716	−0.868	0.152	2.196	0.0164
Hansen test	0.1745	0.000	0.023	0.3205	0.000	0.030
R-squared	0.081	0.105	0.102	0.109	0.104	0.095

[a]p <0.1.
[b]p <0.05.
[c]p <0.01.

structure to test whether the results remained valid. **Table 6** shows that the regression coefficients of fiscal decentralization and environmental governance performance in the eastern region of **Eq. 1** and **Eq. 2** were 4.109 and 1.126, respectively, and significant at 5% and 1% levels, indicating that fiscal decentralization promoted the performance of environmental governance in eastern China, which was consistent with the regression results of the national benchmark model.

Empirical studies demonstrated that varying levels of fiscal decentralization have different regional impacts on environmental governance performance: a high level of fiscal decentralization in eastern China has a considerable favourable influence on environmental governance performance. The eastern area has a high level of fiscal decentralization and has enough finance for environmental governance to control and eliminate pollution efficiently. Furthermore, pollution emissions lowered when most polluting companies in the east relocated to the central and western regions. Compared to national averages, central China had a higher-level environmental governance performance. But the region had low-level fiscal decentralization. The western region's environmental governance performance was lower than the national average level; nonetheless, environmental governance did not directly correlate with fiscal decentralization in both regions. Central and western regions with low fiscal decentralization fell short of funds, making it challenging to undertake industrial transfer, especially in backward areas of the west. Although the central region's environmental governance performance is comparatively high, this is not due to its high fiscal decentralization. Nevertheless, fiscal decentralization significantly promoted the performance of environmental governance in eastern China.

5 CONCLUSION AND POLICY IMPLICATIONS

5.1 Conclusion

After the Paris Climate Conference, most developing countries face challenges in reaching the goal of carbon neutrality and sustainable economic development (Shao et al., 2021). The importance of fiscal decentralization reform in improving environmental governance has been listed top of the national "13th Five-Year Plan" agenda. The impact of fiscal decentralization on the performance of environmental governance of China while regulating carbon emissions is investigated using panel data of 31 Chinese provinces from 2010 to 2019. As shown in **Table 4**, the Malmquist index quantified environmental governance performance in all regions. It was calculated using SBM-DEA undesirable models. The systematic GMM model was then utilized to investigate how fiscal decentralization affected China's environmental governance performance.

According to Guo and Yang (2014), Lin Chun (2019), fiscal decentralization has a highly detrimental impact on environmental governance performance. However, their study did not include carbon emissions in the environmental governance performance. This research fills the research gap.

The results showed that varying levels of fiscal decentralization have different regional effects on environmental governance performance: the high level of fiscal decentralization in eastern China has a considerable favourable influence on environmental governance performance, whereas environmental governance performance in low-level fiscal decentralization, compared to national averages, central and western China has a higher level. The western region's environmental governance performance was poorer than national average; nonetheless, environmental governance does not have a direct correlation with fiscal decentralization in both regions. Besides, fiscal decentralization significantly promoted the performance of environmental governance in eastern China.

To summarize, fiscal revenue strengthened environmental policies in the eastern region, with environmental and environmental governance being a prominent area of fiscal expenditure. The eastern area has a high level of fiscal decentralization and has enough finance for environmental governance to control and eliminate pollution efficiently. Furthermore, pollution emissions lowered when most polluting companies in the east relocate to the central and western regions. However, due to their low level of fiscal revenue and insufficient growth momentum, central and western regions with low fiscal decentralization fall short of financial funds, making it challenging to undertake industrial transfer, especially in backward areas of the west. Although the central region's environmental governance performance is comparatively high, this is not due to its high fiscal decentralization. We find out that there appears to be no clear relationship between fiscal decentralization and environmental governance effectiveness in the central regions the regional government prioritizes environmental degradation. They are boosting the degree of decentralization of fiscal revenue to increase it so that more funds may be invested in environmental pollution control. According to the study, the previous phase of pollution emissions and the current phase of pollution emissions, namely environmental pollution, are a continuous, cumulative process, and reasonable fiscal decentralization can prompt local governments to manage current pollution promptly, avoiding the "ratchet effect" of environmental pollution, achieving sustainable economic and social development. Capital investment positively impacts the environment, demonstrating that increasing capital investment in local governments benefits environmental governance. However, to avoid investment speed lag caused by productivity lag and excessive production and resource waste, investment speed must be maintained steadily and reasonably.

5.2 Policy Implications

Considering the above conclusion, a country should strengthen the fiscal decentralization reform, especially under the current new normal economic conditions; the central government should give local government more flexibility to use financial resources as they have the most updated local knowledge. It can improve the most effective allocation of local resources, promoting the quality of environmental protection.

Second, fiscal reform must reduce carbon emissions and increase environmental governance efficiency. The central government should continue to promote fiscal and tax system reform, incorporate the incentive mechanism that effectively improves carbon emissions and environmental protection into the local government performance appraisal index, build a multi-dimensional local government evaluation system, and realize the long-term development mechanism of local economic development.

Third, the central government should alter the current tax rate structure to provide local officials with financial incentives, link the VAT rate to commodity pollution, and raise the cost of polluting enterprises from a tax standpoint, so that local governments can strike a balance between tax base expansion, pollution prevention and control.

Finally, the federal government should overhaul the relationship between finance and the federal, state, and local governments and distribute financial and administrative power among all levels of government. The production taxes retained by local governments should be as little as possible. This can counteract local governments' incentives to obtain excessive productive taxes, minimize the "race to the bottom" phenomenon, and lower pollution levels. We should accelerate the shift in economic development, achieve effective transformation and upgrade industries with high energy consumption and pollution, improve energy recycling efficiency, reduce pollutant emissions, and lower environmental governance investment costs to fully exploit the key role of local governments in environmental governance.

5.3 Limitations and Further Research

A limitation should be pointed out: First, this paper uses the panel data model to analyze the correlation between fiscal decentralization and China's environmental governance performance, but it does not clarify the internal mechanism and transmission mechanism of the interaction between tax structure environmental quality. Second, when studying the environmental effect of fiscal decentralization, the article further analyzes the environmental effect of different fiscal policies, providing a specific basis for optimizing fiscal and tax policies. However, there is room for improvement as per the analysis depth.

In addition, the existing research conclusion realizes that the environmental effect of both tax and fiscal expenditure are closely related to the financial system. Therefore, it needs to further study the problems from the level of the financial system on the environmental effect of financial policy research; and further analysis of the tax linkage reform.

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

JX: Writing—original draft, Formal analysis, Data curation. XZ: Supervision. RL: Writing—review and editing. LS: literature review.

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SUPPLEMENTARY MATERIAL

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A Gravity Model Analysis of China's Trade in Renewable Energy Goods With ASEAN Countries as Well as Japan and South Korea

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Focusing on the components of both solar photovoltaic technology and wind energy technology and using the gravity model approach with panel data, this study empirically investigated the determinants of bilateral trade in renewable energy goods among ASEAN countries as well as with China, Japan, and South Korea for the period 2012–2019, and also identified China's export efficiency and export potential. The results showed that the economic sizes of both the exporting and importing countries, the economic freedom of the exporter, and trade agreements and membership of common trade areas significantly encouraged bilateral trade, while geographical distance exerted a significantly negative influence. In general, it was found that China had great potential to export renewable energy goods. We propose that the ASEAN Plus Three region needs to formulate and implement a comprehensive and carefully coordinated renewable energy policy package. We also suggest that China should promote joint efforts with ASEAN, Japan and South Korea to further deepen cooperation on the low-carbon economy and tap the great potential for trade in renewable energy goods.

Keywords: renewable energy goods, solar photovoltaic technology, wind energy technology, trade efficiency, trade potential, gravity model

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1 INTRODUCTION

Optimizing the energy structure of countries' economies is an important component of the 17 Sustainable Development Goals (SDGs) proposed by the United Nations in 2015. The region encompassed by the Association of Southeast Asian Nations (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Singapore, Thailand, the Philippines, and Vietnam) plus China, Japan, and South Korea—more commonly known as ASEAN Plus Three (APT), which, in 2019, comprised 29.2% of the global population and 27.7% of global gross domestic product (GDP), is one of the most dynamic and rapidly growing regions in the world. However, along with its rapid economic development in recent decades, the APT region has become a dominant energy consumer (Cabalu et al., 2010). Its energy consumption has increased massively, especially the consumption of primary energy sources such as oil, gas, coal, and electricity, leading to a sharp rise in greenhouse gas (GHG) emissions. International Energy Agency (IEA) data show that, from 1990 to 2019, regional emissions of carbon dioxide—the primary GHG emitted through human activities—almost quadrupled, from 3.91 gigatons in 1990 to 13.13 gigatons in 2019, growing at more than twice the global average rate of 1.72% and accounting for 39% of global emissions in 2019. Expanding economic activity and continuously growing energy consumption have exacerbated the region's energy stresses, making the region as a whole heavily dependent on external energy supplies—mostly fossil fuel energy.

The APT economies face severe challenges with regard to the adverse impacts of fossil fuel use, including the growth of carbon emissions, environment pollution, and energy price volatility (Zhao et al., 2020), as well as energy security, an issue of great importance, given the region's strong dependence on external energy supply. Addressing these issues is therefore vital for economies in the region if they wish to strive for sustainable "green" development. Some progress has been made in recent years in respect of coordinated climate and energy policies. A regional renewable energy goods (REG) trade perspective offers a way forward for reducing environment degradation and climate change, improving regional energy security, and strengthening sustainable economic development.

Renewable energy sources—such as solar, wind, tidal, hydro, and geothermal heat—can offer energy independence, reduce carbon dioxide emissions, and mitigate climate change (Algieri et al., 2011). Although characterized by abundant endowments of solar, wind, hydro, and geothermal resources, many APT countries are often hindered by multidimensional constraints that prevent access to these new energy resources, among which the lack of the necessary technological and engineering solutions, as well as the power generation facilities for developing energy generation, transmission, and distribution capacities, are acknowledged to be the major barriers. The promotion of green trading of cost-effective and efficient REG is crucial for the development of a low-carbon economy (Sawhney and Kahn, 2012; Kalirajan and Liu, 2016) because it can relieve the aforementioned technical barriers by accelerating the deployment of REG and the dissemination of low-carbon technologies, stimulate additional investment, and develop local industries producing renewable energy systems and components to meet demand (Lewis and Wiser, 2007; Matsumura, 2021). This will lead overall decarbonization and help to attain goal 7 of the SDGs (affordable and clean energy) by substituting conventional fossil fuels with renewable energy (Yu, 2003; Algieri et al., 2011; Zaman and Kalirajan, 2019; Qadir and Dosmagambet, 2020). For these reasons, it is crucially important to explore the dynamics of REG trade. Using gravity models of international trade, Costantini and Crespi (2008) and Costantini and Mazzanti (2012) concluded that the stringency of environmental regulation, supplemented by the strength of the national innovation system, had a significant positive effect on the export of a broad category of environmental goods. Algieri et al. (2011) analyzed the determinants of exports of photovoltaic (PV) panels by the United States (US), finding a positive impact of foreign income and a negative impact of relative prices. Sawhney and Kahn (2012) examined the determinants of US imports of a total of 13 wind and solar power generation equipment products classified according to six-digit harmonized system (HS) codes, demonstrating that US sector-specific foreign direct investment (FDI) and the exporting country's domestic renewable power generation were significant drivers. Jomit (2014) showed that the GDP of the importing countries, the common colonizer, and membership of bilateral trade agreements were all positive determinants of India's exports of environmental goods. Groba (2014) provided evidence that regulatory policies and import tariffs determined the exports of solar thermal and solar PV energy systems and their components (solar PV). Cantore and Cheng (2018) concluded that a substitution effect exists between environmental regulation stringency and trading of environmental goods; increased capacity to innovate, cultural ties, geographical proximity, and financial uncertainty also play a role. Kuik et al. (2019) clarified the positive effects of renewable energy support policies on exports of wind energy technology systems and their components (WETC) and solar PV goods. Matsumura (2021) concluded that regional integration accelerates trade in regional environmental goods, while bilateral tariff rates discourage regional trade.

The APT countries share a common environment, and the promotion of intraregional "clean trade" has aroused great interest among both policymakers and academics. Not only can it improve this region's energy security in terms of energy availability, accessibility, acceptability, and affordability, it can also foster a well-interconnected and integrated market and closer economic ties, as well as more harmonious bilateral relations (Sattich et al., 2021). The Renewable Energy Policy Network for the 21st Century (REN21) Renewables 2012 Global Status Report showed that considerable progress has been made in global investment in renewables in 2011: it rose 17% to a new record USD 257 billion, more than six times the figure for 2004 and almost twice the total investment in 2007, the year before the global financial crisis. Since then, most APT countries have stepped up their ambitions for and actions aimed at decarbonization and sustainability, and the intraregional trading of REG and related technologies has assumed a growing share in the overall trade of the APT region. The United Nations Conference on Trade and Development (UNCTAD) Comtrade (https://comtrade.un.org) statistics show that the value of intraregional trade in solar PV and WETC goods in APT countries increased between 2012 and 2019, rising from USD 36.46 billion in 2012 to USD 47.85 billion in 2019, an average growth rate of 3.93%. Among the APT countries, China has a major role to play in intraregional REG trade. Although rated as the largest energy consumer in the world, China is also the largest producer and consumer of renewable energy, laying a solid foundation for China's participation in renewable energy cooperation with ASEAN plus Japan and South Korea (Zhao et al., 2020; Shuai et al., 2022; Zhao et al., 2022). Since 2007, the total international trade volume of REG in China has grown rapidly, from USD 139.447 billion in 2007 to USD 202. 908 billion in 2017 (Shuai et al., 2020). More specifically, China ranks among the world's leading producers and exporters of solar PV and WETC products, which have shown significant growth and considerable trading opportunities (Algieri et al., 2011; Sawhney and Kahn, 2012). In the early 2000s, China accounted for only 10% of the global market share of WETC trade and 15% of global trade in solar PV, but it had doubled its share by 2011 (Kuik et al., 2019). The REN21 Renewables Global Status Reports indicate that China has dominated the world market for these products, as well as for their manufacture. In particular, China plays an important role in promoting REG trade among emerging and developing countries (Steenblik, 2005).

With China's continually increasing economic ties with ASEAN members, Japan, and South Korea, these countries have become important markets for China's exports of REG. The different resource endowments and development stages of the renewable energy industry of the APT countries have made them highly complementary and deeply integrated into the REG industrial and value chains and increased the potential of their cooperation in producing renewable energy. In September 2020, at the 75th session of the UN General Assembly, China announced its commitment to realizing a carbon emissions peak by 2030 and achieving carbon neutrality by 2060, which is important for energy transformation, low-carbon development, and REG trade in the APT region because the setting of renewable energy targets and climate commitments in one country may spur similar efforts in others (Sattich et al., 2021).

Given the enormous potential for the development and utilization of renewable energy and intraregional trade in REG, as well as China's status as an important REG exporter, the traditional focus on the REG trade of European Union (EU) and Organisation for Economic Co-operation and Development (OECD) countries is no longer warranted (Kuik et al., 2019). However, the dynamics of REG trade in the APT region remains under-investigated, and, in general, earlier studies did not account for the potential for trade between China and ASEAN plus Japan and South Korea, which is important for promoting regional energy cooperation. Several earlier studies examined other country groupings, including some of the APT countries, but they reached mixed conclusions regarding the factors affecting the potentials for trade. Zaman and Kalirajan (2019) used a gravity model extended with the determinants of efficiency models in order to analyze the trade in 16 low-carbon REG with six-digit HS codes in South and East Asia. Their results demonstrated that, for most countries, intraregional exports of REG are positively influenced by the GDP of the trading pairs and the regional trade agreements (RTAs) between them, and negatively related to tariffs and geographic distance. They further defined export efficiency as the ratio of exports under the impacts of country-specific infrastructural and institutional factors to those without those impacts, and they found that China and Japan are the most efficient in respect of renewable energy exports, while Bangladesh remains the least efficient. Focusing on three solar PV products and seven WETC products with six-digit HS codes, Groba and Cao (2015) empirically identified the determining factors of China's REG exports to 43 developed and developing economies between 1996 and 2008 by conducting maximum likelihood estimation using a gravity model. They found that bilateral income, renewable energy market size, and demand-side policy support schemes, as well as trade costs (i.e., tariffs applied to imports from China) are all important. Leng et al. (2020) selected 19 wind energy-related products for the period 2007–2017 and measured China's potential exports to 65 "Belt and Road" countries by adopting a gravity model. Their results revealed that the GDP and energy consumption of the importing country, as well as China's wind power generation capacity, both have positive impacts on China's exports, while the distance between the country capitals has a negative effect. Moreover, the traditional ASEAN and Central and Eastern European markets for China's exports have become increasingly saturated, i.e., China's wind energy products have been overtraded in these regions, while countries in the Commonwealth of Independent States (CIS), West Asia, and East Asia (Mongolia) have untapped or growing potential. Shuai et al. (2020) adopted a gravity model and the data for 81 REG from 2007 to 2017 in order to examine China's REG trade potential in the 65 "Belt and Road" countries. Their findings indicated that the GDP and renewable power generation capacity of the "Belt and Road" countries and the total energy consumption of the two trading parties are the main factors promoting China's REG exports, while distance has significant negative influence. China has great exporting potential in Central and Eastern Europe and the CIS, and a certain (growing) potential in East Asia (Mongolia), West Asia, South Asia, and ASEAN; its trade potentials for REG increased year on year for 2007–2017 in the 16 countries in Central and Eastern Europe and fluctuated in other regions.

The motivation to undertake this study arose from the unsatisfactory nature of the abovementioned mixed findings. We focused on the bilateral trade in solar PV and WETC products—which are the most frequently discussed REG in the framework of clean energy adoption (Groba and Cao, 2015)—and employed a gravity model using cross-country panel data for the period 2012–2019 to investigate the drivers of bilateral REG trade flows among APT countries, identify China's export efficiency and export potential, and explored how this trend may evolve with time.

The aims of this study were threefold. First, we wanted to quantify the drivers of bilateral trade in solar PV and WETC goods among APT countries and estimate China's export efficiency and export potential, both of which have been underemphasized in the literature. Second, our equipment studied in the analysis, corresponding to 16 solar PV-related products and 29 WETC-related products with six-digit HS codes, represented a good approximation of trade in the solar PV and WETC sectors (Kuik et al., 2019). Third, in addition to the traditional components of the generalized gravity model, such as economic size, distance, population, exchange rate, trade agreements, and common trade unions, we incorporated the renewable energy generation capacity of the importing country, the energy consumption of the exporting country, and, particularly, the economic freedom indices of the trading pairs that reflected their policy and institutional settings—which has seldom been investigated in such an analysis—into our gravity equation as factors that had a direct bearing on trade in REG.

The remainder of this paper is organized as follows: **Section 2** develops the specification of the gravity model, describes the data, and discusses the estimation methods; **Section 3** presents the main estimated results, applies the estimated parameters to derive China's potential exports to ASEAN plus Japan and South Korea and assess China's export efficiency and export potential; and **Section 4** presents our conclusions, policy implications, study limitations, and future research directions.

2 METHODOLOGY AND DATA

2.1 Model Specification

The gravity model has been widely applied to formulating bilateral trade flows among countries. Using the metaphor of the law of universal gravitation, the gravity model simply predicts that the bilateral trade between two economies is directly proportional to the product of their respective market sizes (e.g., GDP) and inversely related to their trade costs (e.g., geographical distance) (Tinbergen, 1962).

Owing to its considerable robustness and explanatory power, the gravity model has been used by a large number of studies to examine the trade flow effects of a wide variety of real or dummy explanatory variables, including country-specific characteristics (e.g., GDP, population, and income) and bilateral characteristics (e.g., the geographical distance between exporter and importer), and variables incorporating the drivers of and barriers to trade (e.g., geographical contiguity, ethnic ties, linguistic identity, colonial links, island or landlocked status, exchange rates, tariff and non-tariff barriers, currency unions, trade agreements, and common trade unions) (Anderson and Wincoop, 2003; Martinez-Zarzoso, 2003; Baier and Bergstrand, 2007; Novy, 2013; Narayan and Nguyen, 2016; Yotov et al., 2016; Matsumura, 2021). In addition, the gravity model is used to measure trade efficiency or trade potential by calculating the differences between predicted and observed trade flows (Egger, 2001; Papazoglou, 2007; Zaman and Kalirajan, 2019; Leng et al., 2020; Shuai et al., 2020).

The basic form of the gravity model has the following structure:

$$Ex_{ij} = C\frac{Y_i Y_j}{TC_{ij}^2} \tag{1}$$

where Ex_{ij} is the value of the specific export from country i to country j and C is a constant term; Y_i and Y_j refer to the scale of economy of both trading parties, proxying for potential supply and demand, respectively; and TC_{ij} is the trade cost or trade barrier between countries i and j.

To accurately measure the trade flows of solar PV and WETC goods among the APT countries, we built a gravity equation based on recent developments in the literature. In addition to the fundamental determinants that explain the size of bilateral trade flows, such as GDP, geographical distance, population, common language(s) shared by the trading pair, real exchange rates, and membership of RTAs and common trade areas, we incorporated into our model other factors that may affect bilateral trade flows: the solar and wind power generation capacity of the importer, the energy consumption of the exporter, and, specifically, the economic freedom indices of the exporting and importing countries, making a total of 13 independent variables.

The specification that transforms the general form of the gravity model with a greater number of variables into a linear relationship for the empirical computation is given by:

$$\begin{aligned}\ln Ex_{ijt} &= \alpha + \beta_1 * \ln GDP_{it} + \beta_2 * \ln GDP_{jt} + \beta_3 * \ln DISCap_{ij} \\ &+ \beta_4 * COMlang_{ij} + \beta_5 * \ln Pop_{it} + \beta_6 * \ln Pop_{jt} + \beta_7 * \ln EC_{it} \\ &+ \beta_8 * \ln REOut_{jt} + \beta_9 * \ln Exc_{ijt} + \beta_{10} * \ln EFW_{it} \\ &+ \beta_{11} * \ln EFW_{jt} + \beta_{12} * RTA_{ijt} + \beta_{13} * APEC_{ijt} + \varepsilon\end{aligned} \tag{2}$$

where the i, j, and t subscripts correspond to the exporting country, importing country, and year, respectively; Ex_{ijt} stands for the sum of the exports of solar PV and WETC goods in millions of US dollars from country i to its trading partner j in year t; and $REOut_{jt}$ is the output of solar and wind energy of the importing country.

In order to reduce aggregation biases, and following Anderson and Yotov (2012), we subdivided **Eq. 2** into **Eqs 3**, **4**, in which the export volumes of solar PV ($\ln ExSol$) and WETC ($\ln ExWind$), as well as the outputs of solar energy ($\ln SolOut$) and wind energy ($\ln WindOut$), of the importing country, appear separately (the remaining factors are as before):

$$\begin{aligned}\ln ExSol_{ijt} &= \alpha + \beta_1 * \ln GDP_{it} + \beta_2 * \ln GDP_{jt} + \beta_3 * \ln DISCap_{ij} \\ &+ \beta_4 * COMlang_{ij} + \beta_5 * \ln Pop_{it} + \beta_6 * \ln Pop_{jt} + \beta_7 * \ln EC_{it} \\ &+ \beta_8 * \ln SolOut_{jt} + \beta_9 * \ln Exc_{ijt} + \beta_{10} * \ln EFW_{it} \\ &+ \beta_{11} * \ln EFW_{jt} + \beta_{12} * RTA_{ijt} + \beta_{13} * APEC_{ijt} + \varepsilon\end{aligned} \tag{3}$$

$$\begin{aligned}\ln ExWind_{ijt} &= \alpha + \beta_1 * \ln GDP_{it} + \beta_2 * \ln GDP_{jt} \\ &+ \beta_3 * \ln DISCap_{ij} + \beta_4 * COMlang_{ij} + \beta_5 * \ln Pop_{it} + \beta_6 * \ln Pop_{jt} \\ &+ \beta_7 * \ln EC_{it} + \beta_8 * \ln WindOut_{jt} + \beta_9 * \ln Exc_{ijt} \\ &+ \beta_{10} * \ln EFW_{it} + \beta_{11} * \ln EFW_{jt} + \beta_{12} * RTA_{ijt} + \beta_{13} * APEC_{ijt} \\ &+ \varepsilon\end{aligned} \tag{4}$$

where GDP in nominal terms (Baldwin and Taglioni, 2006; Shepherd, 2013) is used as a proxy for economic size; $DISCap$ corresponds to the geographical distance between the capitals of the paired countries; $COMlang$ is a dummy variable that equals 1 if both countries share the same official language, and 0 otherwise; Pop represents the country's population; EC_{it} denotes the energy consumption of the exporting country; and Exc_{ij} represents the real bilateral exchange rate at which currency i is exchanged for currency j. The real exchange rate that affects the relative prices of imported goods is determined by dividing the nominal exchange rate by the consumer price index (CPI). EFW_{it} and EFW_{jt} are the trading pairs' indices of the Economic Freedom of the World (EFW) at year t, which are provided by the Frazer Institute, a research organization based in Vancouver, Canada. The EFW index measures the degree to which the policies and institutions of a country are supportive of economic freedom, and its cornerstones include voluntary exchange, freedom to enter markets, and competition. The dummy variable RTA is used as a proxy for entry into and participation in bilateral or multilateral trade agreements. The dummy variable $APEC$ is used as a proxy for membership of the common trade area of the Asia-Pacific

Economic Cooperation (APEC). $RTA_{ij} = 1$ if an RTA is in force between the home and partner countries, and 0 otherwise; $APEC_{ij} = 1$ if both paired countries are members of APEC, and 0 otherwise. We do not consider the dummy variable WTO because all APT countries are World Trade Organization (WTO) members.

According to the theoretical framework of the gravity model, increasing GDP for each country is expected to encourage bilateral trade. On the supply side, an increase in the GDP of the exporting country indicates more resources available as inputs and greater domestic production available for exports. By contrast, on the demand side, an increase in the GDP of the importing country indicates a sufficiently large market, which would stimulate more imports (Edmonds et al., 2008). $DISCap$ is expected to have a negative correlation with trade volume, as distance represents the transportation and transaction costs between trading partners. The linguistic ties between countries, $COMlang$, are expected to have a trade-enhancing effect because countries sharing the same language tend to have more established ties and lower transaction costs (Bussière and Schnatz, 2009). The effects of the population variables may be ambiguous. The population of the exporting country, Pop_i, can be export-inhibiting, given specific resource endowments: a country with a larger population will export less in order to meet higher domestic demand. By contrast, a large population indicates high market demand, which may expand local investment and the production capacity for more goods to be produced and exported. The coefficient of the population of the importing country, Pop_j, can bear a positive sign, as a large population may have a sizable market, which can increase demand for imports. However, a larger population may indicate more resource endowment, higher self-sufficiency, and less reliance on imports (Papazoglou, 2007); therefore, the importing country's population may be trade-inhibiting. The effect of the energy consumption of the exporting country, EC_{it}, is indeterminate. On the one hand, EC_{it} can be expected to have a trade-creating effect because high energy consumption can stimulate domestic investment, and thus produce more goods available for export. On the other hand, an increase in energy consumption indicates a rise in domestic demand, which decreases exports. The expected effect of the renewable energy output of the importing country, $REOut_j$, as well as $SolOut$ or $WindOut$, may be ambiguous. The coefficient can have a positive sign when the expansion of the production of renewable energy increases demand for solar PV and WETC imports, while a negative sign can appear when a country's market and local demand for energy are limited. The coefficient of the bilateral exchange rate, Exc_{ij}, is expected to be negative. For example, the appreciation of the CPI-deflated Chinese yuan against its trading partner's currency—an increase in the bilateral exchange rate—would reduce China's exports. The sign of the coefficient of the EFW index of the exporting country is expected to be positive since economies that are more free market-based tend to experience greater levels of investment and growth, which expands production capacity and boosts exports. However, the benefits of economic freedom in the importing country are not yet clear. A higher degree of economic freedom may lead to increased openness to imports, whereas it may discourage imports because countries that are more economically free tend to have more domestic production capacities. Finally, mutual memberships of RTAs or APEC could raise trade among member countries because trade agreements and common trade areas represent closer ties; furthermore, they reduce trade costs primarily through the layering of trade barriers and the provision of more favorable tariff treatments (Papazoglou, 2007; Narayan and Nguyen, 2016; Matsumura, 2021).

Using the results obtained by the gravity model, we can identify China's potential exports and compare them with its actual exports in order to examine the efficiency or potential of China's exports to ASEAN plus Japan and South Korea. We use the ratio of actual export flows to estimated export flows in order to measure export efficiency:

$$E_{ijt} = Ex_{ijt} \Big/ Ex^{*}_{ijt} \quad (5)$$

where Ex_{ijt} and Ex^{*}_{ijt} denote the actual export value and the theoretically estimated value, respectively. Once export efficiency is calculated, the level of inefficiency, i.e., $1 - E_{ijt}$, is referred to as untapped export potential (Zaman and Kalirajan, 2019). Thus, the lower the export efficiency E_{ij}, the higher the potential for exports from country i to country j, and vice versa. A ratio of $E > 1.2$ indicates the presence of "limited potential" or "excessive exports," suggesting that the paired countries have close trade ties and trade potential is limited; if $0.8 < E \leq 1.2$, there is "growing potential," suggesting that the trade ties of the two trading countries are close and trading potential is rising; if $E \leq 0.8$, there is "huge potential" or "insufficient exports," suggesting great potential between the trading pairs (Leng et al., 2020; Shuai et al., 2020).

The analysis period ran from 2012 to 2019. The global financial crisis of 2008–09 and the post-crisis period, as well as the COVID-19 period, were excluded, and thus we analyzed trade in a "normal" economic environment. In the empirical analysis, we first used a balanced dataset representing annual bilateral solar PV and WETC trade among APT countries in order to capture the trade patterns of APT countries. The estimated parameters were then used to generate China's potential exports to ASEAN plus Japan and South Korea. Export efficiency and export potential were estimated by comparing the estimated export volume with the existing volume. We first conducted the analysis using solar PV and WETC together, and then repeated the tests for solar PV and WETC separately.

2.2 Data

We used cross-country panel data for the bilateral trade of solar PV and WETC goods for the period 2012–2019 in order to investigate results for the gravity model. Solar PV and WETC are defined as the investment goods and associated products required in solar PV energy systems and their components and in wind energy technology systems and their components, respectively. The six-digit HS classification is a commonly used and globally harmonized classification system for distinguishing between

TABLE 1 | HS codes used for the solar PV and WETC goods (Sourced from Kuik et al., 2019).

Type of goods	HS code	Product
Solar PV goods	700991	Unframed glass mirrors
	700992	Framed glass mirrors
	711590	Other articles of precious metal or of metal clad with precious metal
	732290	Solar collector, air heater, hot air distributor, and parts thereof
	830630	Photograph, picture or similar frames; mirrors, and parts thereof, of base metal
	841280	Other engines and motors
	841919	Other instantaneous or storage water heaters, non-electric
	841950	Heat exchange units
	841989	Other apparatus for treatment of materials by temperature
	841990	Parts of apparatus for treatment of materials by temperature
	850230	Other generating sets
	850440	Static converters
	854140	Photosensitive semiconductor devices; light-emitting diodes
	900190	Other: prisms, mirrors, and other optical elements, of any material
	900290	Other optical elements, of any material, mounted
	900580	Other instruments: monoculars, other optical telescopes; other astronomical instruments
WETC goods	730820	Towers and lattice masts, of iron or steel
	841290	Parts of other engines and motors
	848210	Ball bearings
	848220	Tapered roller bearings, including cone and tapered roller assemblies
	848230	Spherical roller bearings
	848240	Needle roller bearings
	848250	Other cylindrical roller bearings
	848290	Other bearings, including combined ball or roller bearings
	848340	Gears and gearing; ball screws; gear boxes and other speed changers
	850161	AC generators of an output not exceeding 75 kVA
	850162	AC generators of an output exceeding 75 kVA but not exceeding 375 kVA
	850163	AC generators of an output exceeding 375 kVA but not exceeding 750 kVA
	850164	AC generators of an output exceeding 750 kVA
	850230	Other generating sets
	850300	Parts, of motors, of generators, of generating sets, of rotary converters
	850421	Liquid dielectric transformers, not exceeding 650 kVA
	850422	Liquid dielectric transformers, power handling capacity 650–10,000 kVA
	850423	Liquid dielectric transformers, exceeding 10,000 kVA
	850431	Other transformers, power handling capacity not exceeding 1 kVA
	850432	Other transformers, exceeding 1 kVA but not exceeding 16 kVA
	850433	Other transformers, exceeding 16 kVA but not exceeding 500 kVA
	850434	Other transformers, power handling capacity exceeding 500 kVA
	854459	Other electric conductors, exceeding 80 V but not exceeding 1,000 V
	854460	Other electric conductors, for a voltage exceeding 1,000 V
	890790	Other floating structures
	902830	Electricity meters
	903020	Cathode-ray oscilloscopes and cathode-ray oscillographs
	903031	Multimeters
	903081	With a recording device (voltmeters, ammeters, circuit testers)

internationally traded goods (Kuik et al., 2019). The solar PV and WETC product groups based on the six-digit HS product category codes identified by the International Centre for Trade and Sustainable Development (ICTSD) were constructed as suggested by Kuik et al. (2019). **Table 1** lists the HS codes.

The bilateral trade data for the solar PV and WETC goods were extracted from the UNCTAD Comtrade database (https://comtrade.un.org). The annual nominal GDP and population data, as well as the official exchange rate (local currency unit (LCU) per USD, period average) data and CPI data, which were used to convert the nominal exchange rates into real exchange rates, were obtained from the World Bank (https://databank.worldbank.org). The data for geographical distances and common language(s) were retrieved from the Centre d'étude prospectives et d'informations internationales (CEPPII; http://www.cepii.fr) in Paris. The annual data for solar and wind power generation, as well as energy consumption, were obtained from the IEA (https://www.iea.org). RTAs were as according to the WTO (https://www.wto.org). APEC membership statuses were obtained from the APEC website (https://www.apec.org). The data for the EFW index (2012–2019) were extracted from the annual Economic Freedom of the World report (2014–2021) issued by the Frazer Institute (https://www.fraserinstitute.org).

All the time-variant series were transformed into natural logarithms to render them close to the normal distribution for the statistical tests. Some zeros appeared in the bilateral trade flows. However, as the logarithm of zero does not exist, and

TABLE 2 | Descriptive statistics.

Natural logarithm of variables and dummy variables	Obs	Mean	Std. Dev	Min	Max
ln *Ex*	1,248	13.554	7.141	−2.996	22.7
ln *ExSol*	1,248	12.689	7.633	−3.689	22.601
ln *ExWind*	1,248	10.997	8.324	−3.689	21.23
ln *GDP*	1,248	26.356	2.036	23.045	30.29
ln *DISCap*	1,248	7.662	0.645	5.754	8.664
COMlang	1,248	0.154	0.361	0	1
ln *Pop*	1,248	17.496	1.927	12.897	21.058
ln *EC*	1,248	14.363	1.921	10.735	18.289
ln *REOut*	1,248	5.402	3.769	−0.856	13.354
ln *SolOut*	1,248	4.789	3.658	−0.916	12.319
ln *WindOut*	1,248	2.225	5.548	−4.605	12.914
ln *Exc*	1,248	0	4.914	−9.559	9.559
ln *EFW*	1,248	1.948	0.111	1.68	2.18
RTA	1,248	0.974	0.158	0	1
APEC	1,248	0.577	0.494	0	1

dropping zero observations from the sample might have led to biased estimates (Kuik et al., 2019), we therefore replaced the zeros with an arbitrarily small number, 0.025, when taking the logs, as suggested by McCallum (1995) and Raballand (2003). In addition, we replaced the missing values for Laos in 2012 and 2013 with their average EFW index values for the previous 6 years.

3 RESULTS AND DISCUSSION

3.1 Gravity Model Results for the Sum of Solar PV and WETC Goods

Table 2 lists the summary statistics for the variables used in this study. First, the Fisher-ADF test, a frequently used panel unit root test, was employed. The results indicated that all the variables were stationary at the level and integrated of order zero. This suggested that the panel data could be used for the regressions, with no need to test the co-integration relationship among the time series variables.

To examine the determinants of the bilateral trade flows within our gravity model framework, three estimation approaches were employed: pooled ordinary least squares (OLS), fixed effects, and random effects (RE) models. Because fixed effects estimation does not allow for time-invariant variables in a gravity model (Prehn et al., 2016), we conducted a Lagrange multiplier (LM) test to select the preferred regression model. The results were significant, and the reported p-value was 0, suggesting that the RE model was to be preferred to the pooled OLS model. Hence, we selected the RE model for further empirical analysis. The pooled OLS estimation was also applied to the robustness check analysis. **Table 3** presents the results.

The first column in **Table 3** reports the RE results. The estimated coefficients of all the variables had the expected signs in the RE regression. The economic sizes of both the exporting and importing countries, measured by GDP, exerted significantly positive effects on a country's exports. These results were consistent with the predictions of the generalized gravity model. By contrast, geographical distance was found to be a natural impediment to REG trade. The effect of economic freedom, which is concentrated solely on the exporter, was positive and statistically significant. As expected, the coefficients of the RTA and $APEC$ dummies were positive and statistically significant, indicating that if the trading partners were mutual members of an RTA or APEC, exports would be encouraged. Our findings with respect to RTA and $APEC$ were in line with those reported in the literature (Narayan and Nguyen, 2016; Matsumura, 2021). The dummy variables $COMlang$, Pop_i, Pop_j, EC_i, $REOut_j$, Exc, and EFW_j also showed the expected signs but did not present statistically significant effects.

The results estimated for the robustness check using the pooled OLS model in column 2 confirmed that GDP_i, GDP_j, EFW_i, RTA, and $APEC$ had highly significant positive impacts, while $DISCap$ had a negative effect. In addition, in the pooled OLS estimation, Pop_i, Pop_j, and $COMlang$ showed similar positive, but insignificant, impacts to those in the RE estimation, while the coefficients of EC_i, $REOut_j$, Exc, and

TABLE 3 | Estimated results for the sum of solar PV and WETC goods.

Natural logarithm of variables and dummy variables	RE	Pooled OLS (Robustness check)
ln GDP_i	1.904***	0.953**
	(0.502)	(0.377)
ln GDP_j	1.210***	1.242***
	(0.347)	(0.196)
ln *DISCap*	−2.962***	−3.108***
	(0.470)	(0.215)
COMlang	0.570	0.293
	(0.799)	(0.358)
ln Pop_i	−0.265	−0.174
	(0.351)	(0.171)
ln Pop_j	0.209	0.081
	(0.291)	(0.147)
ln EC_i	0.888	1.830***
	(0.602)	(0.431)
ln $REOut_j$	0.059	0.161**
	(0.078)	(0.065)
ln *Exc*	−0.044	−0.074**
	(0.066)	(0.030)
ln EFW_i	5.268**	12.840***
	(2.552)	(1.620)
ln EFW_j	1.990	3.354**
	(2.455)	(1.394)
RTA	5.520***	6.083***
	(1.755)	(0.794)
APEC	2.388***	2.025***
	(0.708)	(0.328)
_cons.	−78.890***	−84.670***
	(10.80)	(5.798)
R-squared	0.714	0.721
Wald/F-test	0.0000 (Wald-test)	0.0000 (F-test)
Obs	1,248	1,248

*Note: *p < 0.1; **p < 0.05; ***p < 0.01; numbers in parentheses are standard errors.*

TABLE 4 | Export efficiency and export potential estimates for the sum of solar PV and WETC goods.

Natural logarithm of variables and dummy variables	RE	Pooled OLS (Robustness check)
ln GDP_i	2.560***	2.605***
	(0.148)	(0.069)
ln GDP_j	1.511***	1.623***
	(0.146)	(0.069)
ln *DISCap*	–3.160***	–3.316***
	(0.434)	(0.196)
ln EFW_i	5.793***	8.805***
	(1.948)	(1.037)
RTA	5.962***	6.473***
	(1.691)	(0.759)
APEC	2.366***	1.989***
	(0.617)	(0.284)
_cons.	–87.960***	–97.050***
	(7.086)	(3.594)
R-squared	0.711	0.713
Wald/F-test	0.0000 (Wald-test)	0.0000 (F-test)
Obs	1,248	1,248

*Note: ***p < 0.01; numbers in parentheses are standard errors.*

EFW_j were significant. These results indicated the overall robustness of our findings.

3.2 Export Efficiency and Export Potential Estimates for the Sum of Solar PV and WETC Goods

To accurately measure China's export efficiency and export potential, we removed the insignificant variables in **Table 3** stepwise, keeping only the explanatory variables that were significant at the level above 10%, namely, GDP_i, GDP_j, $DISCap$, EFW_i, RTA, and $APEC$. All six variables were significant at the 1% level (**Table 4**). The pooled OLS estimation (the robustness check) results were consistent with those of the RE regression.

The economic freedom of the exporting country and mutual memberships of RTAs had relatively large impacts on REG exports. A 1% increase in economic freedom of the exporter increased energy trade by 5.79% on average, and countries tended to increase trade by 5.96% when they entered a bilateral or multilateral trade agreement with each other. By contrast, the GDP of paired countries had relatively small impacts. Economic growth of 1% in either the exporting or importing country increased REG trade between partners by 2.56 and 1.51%, respectively. Furthermore, a 1% increase in the physical distance between the two trading countries reduced REG trade by 3.16% on average. Additionally, mutual memberships of RTAs were revealed to be more important than those of APEC. The estimates revealed that trading partners within an RTA traded 152% more than country pairs within APEC.

Using the parameters estimated by the RE approach and calculating export efficiency, we tested China's potential exports to ASEAN plus Japan and South Korea for the period 2012–2019 and compared them with its actual exports in order to obtain its export efficiency, and thus export potential.

Table 5 demonstrates the evolution of trade efficiency (trade potential) over time and across countries, from which we made the following observations.

First, in 2019, other than Cambodia and Laos, to which China's actual exports substantially exceeded its potential exports, ASEAN plus Japan and South Korea were found to have huge trade potentials with China (i.e., China's actual exports to these countries fell substantially below the estimated levels). China's export efficiency (export potential) with respect to ASEAN plus Japan and South Korea was, in descending (ascending) order: Cambodia, Laos, Myanmar, Japan, Brunei, Singapore, Malaysia, Vietnam, Indonesia, Thailand, the Philippines, and South Korea. The UNCTAD Comtrade statistics show that, over the period 2012–2019, China was the largest intraregional exporter of solar PV and WETC goods, with an average annual export value of USD 12.70 billion. It was also the leading importer, followed by Japan, South Korea, Thailand, and Vietnam, with annual average imports of USD 8.63, 6.65, 3.64, 2.87, and 2.80 billion, respectively. The imports of Singapore, Malaysia, and Myanmar were approximately USD 2 billion. Brunei, Laos, and Cambodia were the smallest intraregional importers, with annual average imports of USD

TABLE 5 | Time trend of the export efficiency values of China's exports to ASEAN plus Japan and South Korea.

Country	Year							
	2012	2013	2014	2015	2016	2017	2018	2019
South Korea	0.002229	0.001598	0.001288	0.001074	0.000777	0.000478	0.000282	0.000330
Philippines	0.080527	0.08301	0.107559	0.125614	0.058052	0.031529	0.021031	0.022589
Thailand	0.261281	0.16635	0.139798	0.189239	0.121191	0.061793	0.055376	0.032706
Indonesia	0.230065	0.189367	0.148245	0.127146	0.082044	0.049902	0.045161	0.040297
Vietnam	0.30209	0.253095	0.364029	0.160336	0.106136	0.073284	0.066371	0.116865
Malaysia	0.791353	0.661748	0.433896	0.511482	0.33746	0.224473	0.155794	0.145365
Singapore	0.953712	0.68385	0.587575	0.714435	0.368853	0.241744	0.171406	0.180297
Brunei	0.433162	0.865804	0.912284	0.455634	0.284545	0.161117	2.26709	0.319368
Japan	1.676432	2.379771	2.659037	2.290963	1.381972	0.813748	0.54022	0.486587
Myanmar	6.802387	6.216313	4.589849	5.059432	3.070313	2.060911	1.246185	0.764831
Laos	13.03438	20.80261	8.018321	9.719278	7.379016	5.325684	3.535989	2.753722
Cambodia	20.82271	18.87008	6.552691	7.226096	5.613714	4.079709	1.890406	4.135964

42.91, 83.44, and 89.67 million, respectively. Moreover, IEA data show that over the period 2000–2019, Brunei and Laos were net energy exporters. Due to their small market size, the potential export market opportunities for China's REG to these three countries were relatively small. Both the regression results and trade statistics indicated that ASEAN plus Japan and South Korea other than Brunei, Laos, and Cambodia are potentially important markets for China's future exports of REG.

Second, between 2012 and 2019, China's export efficiency (export potential) with respect to ASEAN plus Japan and South Korea showed a downward (upward) trend. This finding indicated that the tendency for China to export at levels lower than the theoretically estimated ones has generally increased over time. This may be due to the rapid economic development of the APT region, China's widening and deepening economic reform and open door policy, and its signing of key trade agreements at the bilateral, sub-regional, regional, and multilateral levels, which can all raise the theoretically estimated values of China's exports. By contrast, the high dependence on fossil fuels might limit the imports of ASEAN plus Japan and South Korea, thus increasing the difference between China's actual and potential exports.

Third, China's export efficiency and export potential differed markedly by partner countries. The export efficiency values of China's exports to South Korea, the Philippines, Thailand, and Indonesia were relatively stable and low between 2012 and 2019, indicating untapped trade potential between China and these countries. By contrast, the potential to trade with Cambodia and Laos remained limited over this period. Moreover, China's export efficiency values to Cambodia, Laos, Myanmar, and Singapore fluctuated greatly, dropping from 20.82271, 13.03438, 6.802387, and 0.953712 in 2012 to 4.135964, 2.753722, 0.764831, and 0.180297 in 2019, respectively. Hence, Myanmar changed from having limited potential to huge potential, while Japan and Singapore evolved from having growing potential to huge potential. China's REG have many competitors in the global market, including developed countries such as the United States, Germany, the United Kingdom (UK), and Japan, newly industrialized countries such as South Korea, and emerging countries such as India. It is worth noting that, between 2012 and 2019, following China, both Japan and South Korea were the leading intraregional exporters of solar PV and WETC goods, with average annual export values of USD 8.18 and 5.03 billion, respectively. China should readjust and optimize the product structure of its renewable REG trade in a targeted manner and enhance the quality of its REG in order to appeal more to the market demand of importing countries (Shuai et al., 2022).

It should be noted that the finding that China has a huge REG trade potential differs from that obtained by Shuai et al. (2020), who concluded that China has a certain (growing) potential in ASEAN. There are two possible reasons. First, Shuai et al. (2020) used data of 81 products of solar energy, wind energy, hydro energy, bio-energy, geo-thermal energy and marine energy from 2007 to 2017 to examine China's REG trade potential in the 65 "Belt and Road" countries and finally, five explanatory variables entered their equation for obtaining trade potential: foreign GDP, foreign renewable power generation, China's energy consumption, foreign energy consumption, and the distances between capitals of China and the importing countries. This leads to the differences in the predictions of theoretical trade flows, and therefore trade potentials in their model from ours. Second, the examination of aggregate data in Shuai et al. (2020) may include bias and hide useful information about the behavior of a sub-region and individual industries (Choi, 2021).

3.3 Separate Regression Results for Solar PV and WETC Goods

Table 6 summarizes the results for the estimation of solar PV and WETC goods separately.

The key results for the RE regressions were consistent with those for the full sample, except that the insignificant effects of Pop_i and EC_i on WETC goods became significant. These qualitatively similar results provided further support for the results obtained for the full sample. The results of the pooled OLS estimation indicated that most of the main results remained effective.

3.4 Separate Export Efficiency and Export Potential Estimates for Solar PV and WETC Goods

We eliminated the insignificant variables in **Table 6** stepwise and retained the explanatory variables significant at the 1% or 5% level. The pooled OLS estimation results were found to be consistent with the findings of the RE regression. We then estimated China's potential exports of solar PV and WETC goods separately using the RE regression (**Table 7**). **Tables 8**, **9** list the time series of the export efficiency values of China's exports of solar PV and WETC goods, respectively, to its 12 trading partners.

In 2019, the efficiency (potential) values of China's exports of solar PV goods to ASEAN plus Japan and South Korea were, in descending (ascending) order: Cambodia, Laos, Myanmar, Japan, Brunei, Singapore, Malaysia, Vietnam, Indonesia, Thailand, the Philippines, and South Korea—the same as in the full sample analysis. Cambodia had limited potential, Laos had growing potential, and the other 10 countries had huge potential. The efficiency (potential) values of China's exports of WETC goods in 2019 were, in descending (ascending) order: Laos, Cambodia, Myanmar, Japan, Malaysia, Singapore, Brunei, Indonesia, Vietnam, Thailand, the Philippines, and South Korea, among which Laos, Cambodia, and Myanmar had limited potential and the rest had huge potential.

In general, the separate trends of China's potential exports of solar PV and WETC goods to ASEAN plus Japan and South Korea were similar to those of the full sample, indicating that China and ASEAN plus Japan and South Korea had tremendous potential for REG trade in the period 2012–19. ASEAN plus Japan and South Korea may be important markets in the future, with huge growth opportunities for China's solar

TABLE 6 | Separately estimated results for solar PV and WETC goods.

Natural logarithm of variables and dummy variables	Solar PV		WETC	
	RE	Pooled OLS (Robustness check)	RE	Pooled OLS (Robustness check)
$\ln GDP_i$	1.857***	1.280***	1.515***	−0.653
	(0.547)	(0.413)	(0.569)	(0.437)
$\ln GDP_j$	1.193***	1.242***	1.208***	1.137***
	(0.373)	(0.215)	(0.376)	(0.195)
$\ln DISCap$	−3.244***	−3.379***	−3.186***	−3.161***
	(0.516)	(0.235)	(0.543)	(0.247)
$COMlang$	0.442	0.223	0.687	0.348
	(0.874)	(0.390)	(0.941)	(0.414)
$\ln Pop_i$	−0.195	−0.039	−1.019**	−1.048***
	(0.386)	(0.187)	(0.411)	(0.198)
$\ln Pop_j$	0.258	0.142	0.329	0.432**
	(0.322)	(0.163)	(0.342)	(0.171)
$\ln EC_i$	1.076	1.555***	2.299***	4.541***
	(0.657)	(0.471)	(0.688)	(0.498)
$\ln SEOut_j$	0.065	0.156**		
	(0.066)	(0.064)		
$\ln WEOut_j$			−0.084	−0.093**
			(0.076)	(0.043)
$\ln Exc$	−0.027	−0.057*	−0.063	−0.076**
	(0.073)	(0.033)	(0.078)	(0.035)
$\ln EFW_i$	6.781**	12.210***	6.581**	19.160***
	(2.781)	(1.770)	(2.844)	(1.873)
$\ln EFW_j$	2.080	2.715*	3.066	5.772***
	(2.685)	(1.519)	(2.784)	(1.619)
RTA	5.845***	6.353***	5.302***	5.229***
	(1.931)	(0.868)	(2.054)	(0.921)
$APEC$	2.707***	2.475***	3.575***	3.529***
	(0.788)	(0.365)	(0.824)	(0.386)
_cons.	−84.300***	−89.490***	−83.250***	−87.520***
	(11.41)	(6.372)	(11.21)	(6.171)
R-squared	0.704	0.708	0.715	0.725
Wald/F-test	0.0000 (Wald-test)	0.0000 (F-test)	0.0000 (Wald-test)	0.0000 (F-test)
Obs	1,248	1,248	1,248	1,248

*Note: *p < 0.1; **p < 0.05; ***p < 0.01; numbers in parentheses are standard errors.*

PV and WETC exports, given their urgent need to mitigate climate change, promote transition to renewable energy systems, and improve energy security.

In summary, there were untapped potentials in China's solar PV exports to South Korea, the Philippines, Thailand, Indonesia, Vietnam, Malaysia, and Singapore, particularly the first four countries. The potential for China's WETC exports to South Korea, the Philippines, Thailand, Vietnam, Indonesia, Brunei, Singapore, and Malaysia were also extremely large, particularly to South Korea, the Philippines, and Thailand. The finding on WETC exports differed from that obtained by Leng et al. (2020), as they showed that the traditional ASEAN markets for China's exports of WETC goods had become increasingly saturated, and China's wind energy products had been overtraded in those countries. This can be attributed multiple factors such as number of countries involved, categories of WETC adopted and the impacting factors in the models of Leng et al. (2020) and this study are different, which leads to different theoretical and actual trade values, and therefore different trade potentials.

4 CONCLUSION, POLICY IMPLICATIONS, LIMITATIONS, AND FUTURE RESEARCH DIRECTIONS

Most APT countries rely heavily on imports of fossil fuels to meet their energy demands. Intraregional REG trade plays a crucial role in strengthening energy security and low-carbon growth in this region (Zaman and Kalirajan, 2019). Focusing on solar PV and WETC goods, this study estimated the determinants of bilateral trade flows in REG among the APT countries for the period 2012–2019 using a gravity model and cross-country panel data. We found that the GDP of both exporting and importing countries, the economic freedom of the exporter, trade agreements, and membership of trade associations all significantly stimulated bilateral trade, while geographical distance between trading partners had a significantly negative effect. A comparison of China's potential exports to ASEAN plus Japan and South Korea with its actual exports revealed that there is great potential for increasing China's future exports of REG.

We believe that the findings of this study will be useful from a policy perspective. In this respect, the APT countries could

TABLE 7 | Separate regression results for estimating export efficiency and export potential of solar PV and WETC goods.

Natural logarithm of variables and dummy variables	Solar PV		WETC	
	RE	Pooled OLS (Robustness check)	RE	Pooled OLS (Robustness check)
ln GDP_i	2.765***	2.800***	1.705***	−0.287
	(0.161)	(0.075)	(0.551)	(0.425)
ln GDP_j	1.569***	1.659***	1.329***	1.364***
	(0.159)	(0.075)	(0.175)	(0.082)
ln $DISCap$	−3.471***	−3.585***	−3.384***	−3.343***
	(0.473)	(0.213)	(0.515)	(0.230)
ln Pop_i			−1.231***	−1.286***
			(0.376)	(0.185)
ln EC_i			2.335***	4.443***
			(0.687)	(0.501)
ln EFW_i	6.542***	8.121***	6.390**	18.230***
	(2.119)	(1.128)	(2.799)	(1.865)
RTA	6.402***	6.777***	5.951***	5.916***
	(1.842)	(0.826)	(2.008)	(0.885)
APEC	2.479***	2.224***	3.432***	3.257***
	(0.672)	(0.310)	(0.759)	(0.343)
_cons.	−95.350***	−101.100***	−75.260***	−76.220***
	(7.711)	(3.911)	(9.600)	(5.246)
R-squared	0.702	0.703	0.710	0.719
Wald/F-test	0.0000 (Wald-test)	0.0000 (F-test)	0.0000 (Wald-test)	0.0000 (F-test)
Obs	1,248	1,248	1,248	1,248

*Note: **p < 0.05; ***p < 0.01; numbers in parentheses are standard errors.*

TABLE 8 | Time trend of the export efficiency values of China's solar PV exports to ASEAN plus Japan and South Korea.

Country	Year							
	2012	2013	2014	2015	2016	2017	2018	2019
South Korea	0.001661	0.001143	0.000914	0.000761	0.000527	0.000306	0.000167	0.000204
Philippines	0.082821	0.09278	0.105296	0.144851	0.063231	0.02937	0.020622	0.020809
Thailand	0.259271	0.173344	0.136546	0.195519	0.098969	0.040366	0.030782	0.029214
Indonesia	0.207018	0.165239	0.121469	0.117304	0.070776	0.038232	0.029056	0.031867
Vietnam	0.197501	0.168866	0.339706	0.116421	0.078792	0.053926	0.05609	0.108623
Malaysia	0.865769	0.752172	0.472494	0.577304	0.361102	0.244301	0.167425	0.148588
Singapore	1.102393	0.808187	0.708759	0.925339	0.441293	0.260864	0.190742	0.198377
Brunei	0.733241	1.419783	1.455016	0.728302	0.343554	0.112225	3.305963	0.434577
Japan	2.228287	3.375797	3.758604	3.215232	1.861452	1.017233	0.636431	0.558118
Myanmar	5.909532	6.391413	4.335918	4.352041	2.563343	2.117159	0.713582	0.650287
Laos	9.620937	13.69605	9.462474	1.951614	1.32149	1.853202	0.928458	1.073056
Cambodia	14.07764	17.9461	6.423686	8.280929	5.780738	3.305702	1.998319	4.669313

facilitate intraregional REG trade by exerting policy efforts focusing on the key factors determining bilateral REG trade, for example, promoting economic development, creating and maintaining a market-based economy, and reducing transportation costs by improving cross-border transportation systems and distribution networks. Developing close economic relationships and strengthening regional integration are also likely to contribute to regional REG trade because the promotion of effective cross-border trade requires regional cooperation among countries (Ratnayake et al., 2011). In this sense, there are grounds for optimism about the growth prospects for REG trade among APT countries ever since the 15 Asia-Pacific nations (APT countries, Australia, and New Zealand), which account for nearly one-third of global GDP, signed the Regional Comprehensive Economic Partnership (RECP) agreement in 2020. The resulting strengthening of economic ties, enhancement of trade and investment-related activities, and RECP-induced reductions or elimination of tariffs, may all contribute to a strong boost in the REG trade of the APT countries.

Along with the urgent need to meet GHG emission reduction targets, the increasing awareness of environmental protection, and the need to improve regional energy security, the APT countries are showing a keen interest in making renewable energy more affordable, accessible, and locally sourced. To this end, the APT region needs to formulate and implement a comprehensive and carefully coordinated renewable energy policy package, consisting of general policies that improve the infrastructural and institutional frameworks for facilitating the investment, production, and trading

TABLE 9 | Time trend of the export efficiency values of China's WETC exports to ASEAN plus Japan and South Korea.

Country	Year							
	2012	2013	2014	2015	2016	2017	2018	2019
South Korea	0.000807	0.000609	0.000443	0.000361	0.000308	0.000214	0.000156	0.000147
Philippines	0.041855	0.028175	0.055247	0.027266	0.017666	0.016671	0.008172	0.011086
Thailand	0.175788	0.091041	0.085672	0.096313	0.106945	0.073456	0.078576	0.021444
Vietnam	0.271339	0.220615	0.170346	0.124841	0.079701	0.054813	0.035143	0.041029
Indonesia	0.281116	0.233479	0.191284	0.138379	0.099135	0.070533	0.077684	0.053546
Brunei	0.02805	0.060199	0.068533	0.034887	0.10379	0.122965	0.205358	0.054449
Singapore	0.58828	0.363177	0.261619	0.208666	0.159326	0.138524	0.078538	0.083802
Malaysia	0.545164	0.383859	0.264443	0.276016	0.209008	0.120255	0.079899	0.086824
Japan	1.019887	0.854773	0.799902	0.704887	0.534044	0.409696	0.325675	0.318813
Myanmar	15.59664	11.42928	9.187348	11.46719	7.168449	3.536397	4.089602	1.747975
Cambodia	48.22426	33.7702	11.13312	9.921546	9.139457	8.815745	2.87534	5.34709
Laos	25.30791	43.96595	8.685978	30.39067	23.92321	15.95589	11.80446	8.177485

of REG; trade policies that are conducive to the establishment of a well-interconnected and integrated regional market and promote trade in REG and discourage trade in relatively carbon-intensive goods; investment policies that promote domestic and foreign investment in the development and production of REG; financial policies that put a cost on carbon and support trade, investment, and the utilization of REG; industrial policies that provide support for research and development of renewable energy technologies and encourage enterprises to adopt "green" technologies, and hence gain competitive advantages in international trade; and, finally, policies to strengthen regional cooperation in support of REG trade and investment, technology transfer, adoption and diffusion, harmonization of the many different sets of national-level policies, and the formulation of common principles, rules, and standards (Ratnayake et al., 2011).

China, while known for its very large energy consumption and GHG emissions associated with its rapid economic growth, has taken a global lead in the development, investment, utilization, and export of solar PV and WETC goods, mainly as a result of its awareness of the environmental costs of development and the urgent need to address these costs (Ratnayake et al., 2011). The results of our study show that there is much scope for China to expand REG trade with ASEAN plus Japan and South Korea. China should promote joint efforts with these countries in order to further deepen cooperation on the low-carbon economy, tap the great potential for trade in REG, and strive for a win-win outcome.

Our study had some limitations, however. The bilateral trade flows of solar PV and WETC goods may have been affected by factors not captured in this study. Thus, further research needs to consider technological and infrastructural development, supportive policies on renewable energy, global energy market conditions, geopolitical concerns, trade barriers arising from regulatory and policy regimes, and other macro- and micro-level factors in order to fully comprehend the determinants of REG trade flows. In addition, the classification of REG in cross-border trade is a technical issue. Using the common six-digit HS codes cannot sufficiently differentiate whether a product is used for renewable energy systems. Thus, the categories of solar PV and WETC goods used in this study were relatively broad and the HS classification only partially reflected the true trade in these goods. Future studies need to subdivide the product categories that are most likely to contain renewable energy supply technologies to better match the six-digit HS codes for renewable energy technologies.

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

WZ undertook the formal analysis and was a major contributor to writing the article. KY contributed to data curation and methodology. YF revised the article. All authors read and approved the final manuscript.

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CONCEPTUAL ANALYSIS
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Linking Financial Development and Environment in Developed Nation Using Frequency Domain Causality Techniques: The Role of Globalization and Renewable Energy Consumption

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The topic of whether globalization, energy consumption and financial development can substantially reduce emissions during the globalization era remains unanswered. In this context, this research highlights empirical indications supporting this theoretical discord; assessing the effect of globalization, energy consumption and financial development on the CO_2 emissions in Japan (utilizing a dataset that spans between 1990 and 2019). The study employed the Autoregressive Distributed Lag (ARDL) technique and frequency domain causality to probe these relationships. Unlike other conventional causality tests, the frequency domain causality test can capture causality at different frequencies. The findings from the ARDL analysis disclosed that globalization and renewable energy contribute to the mitigation of CO_2 emissions while fossil fuel, economic growth and financial development caused an upsurge in CO_2 in Japan. Furthermore, the frequency domain demonstrated that all the exogenous variables can forecast CO_2 mostly in the long-term which implies that any policy initiated based on the exogenous variables will impact emissions of CO_2. Based on the results obtained, Japan has to improve its financial systems and increase its use of renewable energy. Furthermore, Japan needs to restructure its policy regarding globalization owing to the fact that it contributes to the degradation of the environment. Since globalization is a major driver of economic growth, the government should concentrate on luring and licensing investors that use environmentally beneficial (net-zero) technology.

Keywords: financial development, globalization, renewable energy consumption, CO_2 emissions, Japan

1 INTRODUCTION

Climate alteration and global warming are key sources of the issue in many narratives as a fundamental threat, notably in this globalized age of reduced geographical heterogeneity and the eradication of national borders (Awosusi, Adebayo, et al., 2022; Adebayo, 2022b). The Kyoto Protocol was implemented to mitigate the level of greenhouse gases (GHGs) that have a major contribution to atmospheric change in response to global warming, which was recognized as a calamity (crisis). CO_2 emissions contribute roughly 58.8% to climatic variability and global warming (Kyoto Protocol, 1997). Furthermore, the Paris Agreement, which aims at limiting GHG emissions, was signed in 2016, and it follows in the footsteps of the Kyoto Protocol in combating global warming and climate change. To attain these goals, all partner states (member nations) decided to sign this pact, demonstrating their understanding and commitment to curbing the threat of climate change and global warming. Nonetheless, all of these accords point to a minor bright light, with 2016 being recorded as the world's warmest year (NASA, 2020). Chlorofluorocarbons (CFCs), methane (CH_4), water vapor (H_2O), CO_2 and nitrous oxide (N_2O) are among the scientifically (empirically) recognized gases that contribute to climate change and global warming (NASA, 2020). CO_2 makes up around 81% of all these GHGs. Globalization, Financial development, and fossil fuel energy have also been identified as key contributors to rising CO_2 emissions (Shahzad, 2020; Ikram et al., 2021; AbdulKareem et al., 2022; Gyamfi, Adebayo, et al., 2022).

The financial sector's competency is boosted by an economy's thriving ability and serves as a function in supporting economic development. Lowering investment hurdles and putting less pressure on financial resources, helps to boost investors' and consumers' confidence in a company's development. However, obtaining such wealth through an established financial business is not without cost (Baloch et al., 2019). Energy consumption can be utilized more effectively with improved technical services, and ecological security requirements may be supported with minimal cost and maximum returns, thanks to a strengthened financial sector (Acheampong et al., 2020; Ahmad et al., 2021; Sadiq-Bamgbopa et al., 2022; Tony Odu et al., 2022). There is a large body of recent work that has identified and studied the significant relationship between a robust financial sector and ecological deficit (Abbasi & Riaz, 2016; Anwar et al., 2021).

Nonetheless, empirical study findings have yielded a wide range of outcomes for both poor and advanced nations. Against the backdrop of an uncertain (insignificant) link between financial development (FD) and environmental deterioration, a few research have produced perplexing results (Demetriades & Hussein, 1996; Bekhet et al., 2017; Baloch et al., 2019; Fakher et al., 2021). For example, a thriving finance sector is capable of supporting businesses overcome planning constraints and achieve economies of scale in the manufacturing sector; ensuing in reduced contamination generation (Taiwo Onifade et al., 2021; Erdoğan et al., 2022; Onifade, 2022). Another viewpoint contends that the financial sector may facilitate the establishment of new conventional, polluting, traditional, and unproductive sectors that pose a menace to ecological quality. As a consequence, the available literature results are extremely diverse, necessitating further empirical investigation in order to provide a more accurate image of reality (Awosusi et al., 2022; Gyamfi, Bekun, et al., 2022).

Another focus of our work is to re-assess the contaminant degradation function and evaluate the ecological quality of Japan by using the globalization index, renewable and fossil fuel. Moreover, (Koengkan et al., 2020) on the other hand, defined globalization as the connectivity, growth, and interdependence of many areas of society. Globalization, on the other hand, is defined by Leal & Marques (2021a) and Rahman (2020) as a broad and multifaceted phenomenon that encompasses cross-national social, economic, technical, environmental, and cultural, linkages. It brings nations together to trade which eventually results in foreign direct investment (FDI) to speed up economic activity, financial development, and energy consumption, as well as their degree of openness (Leal & Marques, 2021b; Wani & Mir, 2021). Apart from these possible reasons, economic deprivation and worldwide economic integration raise the level of environmental repercussions owing to elevated human stress on the environmental ecosystem (Shittu et al., 2020; Lyulyov et al., 2021; Ngoc et al., 2021; Wani & Mir, 2021; Yameogo et al., 2021). Clearly, it contributes to the well-being of our planet, but there are significant variable approaches as to how these changes can be implemented.

Energy sources have an important influence in determining ecological integrity. Currently, empirical analysis is performed by separating energy usage into two categories: non-renewable and renewable energy usage, in order to truly comprehend the impact of these separating types of energy usage on CO_2 and, as a result, to make more effective specific proposals. It is critical to evaluate the significant influence of renewable and fossil fuel on ecological responsibility in order to accomplish additional advantages to the existing structure of economic growth and accomplish the Sustainable Development Goals (SDGs) targets. Another vacuum in the empirical studies remains unresolved without taking into account the differential impacts of these two types of energy sources. As a result, the current work contributes to the empirical studies of finance, environmental and energy economics by offering models and establishing policies.

In our study, three important research issues will be examined based on the three qualities described above. To begin, how do Japan's established financial sectors contribute to improved environmental protection? Secondly, can Japan's economic expansion withstand the country's ecological pressures? Thirdly, in the globalization era, which type of energy has a greater capacity to reduce environmental damage, renewable or non-renewable?

This current study differs from previous research in five ways: Most importantly, the current study examines the connections between FD and CO_2, including fossil fuel renewable energy, throughout the globalization mode. According to the best of the researchers' knowledge, this is the first study to highlight a link between the abovementioned factors in the context of Japan. (ii) The financial development index provided by the International Monetary Fund (IMF) was considered in this research to integrate many aspects of financial development, including relative nation rankings based on access, efficiency and depth. (iii) This research introduces a novel technique for investigating the causal influence of FD, globalization, renewable energy, and fossil fuels on CO_2. Investigating the vague interrelationships between globalization, financial development and renewable energy usage provide Japan's pivotal bodies and decision-makers with a central database for formulating policies related to financial development and renewable energy usage during the globalization mode. The investigators utilized the frequency domain causality test which is capable of detecting short, medium and long-term causality between time series variables. This will help policymakers understand new aspects of ecological sustainability. (v) Lastly, Japan is a leader in the implementation of SDG-related goals. To maintain environmental brilliance throughout this pursuit, it is critical to understand how Japan uses its financial and energy mix resources. In light of these goals, the essential results of this research emphasize the importance of efficient and eco-friendly initiatives for new comprehensive economic and financial advancement, as well as sustainable energy-efficient investment that does not pose a threat to Japan's atmosphere.

The remainder of the study is as follows: **Section 2** presents the current state of the art, **Section 3** presents the data and methods, **Section 4** presents findings and **Section 5** presents the conclusion and policy directions.

2 LITERATURE REVIEW

Over the years, studies have been undertaken regarding the factors driving environmental degradation. As a result, several scholars have used different proxy of environmental degradation such as CO_2 emissions, ecological footprint and load factor etc to assess these interrelationship. For instance, Ali & Kirikkaleli (2021) investigated the connection between economic growth, financial development and trade openness in Turkey. The findings from the study using the FMOLS and DOLS reported that economic growth and trade openness stimulate environmental degradation. Similarly, He et al. (2021) using the BRICS nations as a case study examined the drivers of CO_2 emissions using the panel regression. The study outcomes reveal that economic growth and energy use contribute to the degradation of the environment while renewable energy and globalization curb environmental degradation. Similarly, Usman & Makhdum (2021) in their study on the determinants of environmental degradation in United States using the ARDL approach and the study findings disclosed that economic growth and financial development lessens environmental degradation while energy consumption increase environmental degradation.

Moreover, Saidi & Hammami (2015) examined the relationship regarding energy consumption, renewable energy and ecological pollution in 58 nations employing a 1990–2012 dataset. The authors employed the panel methodology and discovered that energy consumption increase CO2 while renewable energy renewable energy consumption. This means that increasing energy consumption degrades the ecological efficiency. Furthermore, Leal & Marques (2021a) examined the relationship between CO_2 pollution and energy (renewable energy and nonrenewable), economic progress in the MINT countries utilizing a dataset spanning 1980–2018 and recently established econometric panel methods The empirical evidence indicates that energy usage and economic growth has effect on CO_2 pollution while renewable energy decreases emissions. With respect Mexico, Acheampong and Boateng (2019) investigated the effect of trade openness, energy consumption and trade openness on CO_2 pollution employing wavelet coherence and ARDL techniques. The empirical findings indicate that energy consumption and trade openness impact CO_2 pollution positively, implying that energy consumption degrades the atmosphere while renewable energy use enhances the quality of the environment. Additionally, Shan et al. (2021) examined the connection between CO_2 pollution, globalization, financial development, and energy usage utilizing data from 1990 to 2012. The authors established this connection using ARDL, output signal, and Granger causality tests. The ARDL long-run analysis showed that energy consumption and globalization impact CO_2 emissions while renewable energy decrease emissions. However, (Dogan & Inglesi-Lotz, 2020) examined the relationship between trade openness, financial development, energy consumption and ecological degradation in 17 African nations using non-parametric quantile causal link. Their results reveal a causal correlation regarding financial development, energy use and environmental degradation in both directions.

Furthermore, Farhani et al. (2014) observed that by including urbanization in their framework and focusing on eleven (11) Middle East and North Africa (MENA) nations, their results enhanced and reduction in CO_2 levels. Gao & Zhang (2021), in an analysis of 8 Asia-Pacific countries established a long-run connection between trade openness; while Awosusi et al. (2022) explored this on the level of energy usage, economic development, as well as CO_2. Begum et al. (2015) on the other hand used Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) to investigate the complex impact of energy usage population expansion and GDP advancement on CO2 pollution over the duration 1970–2009. The study observed that there is a long-run cointegration relationship among GDP expansion, CO2 emissions, population increase, and energy utilization in Malaysia The environmental Kuznets curve (EKC) is not accurate, as shown by empirical evidence. Additionally, energy consumption and GDP have a long-term beneficial impact on CO2, whereas population increase has no noticeable impact on CO2 emissions. Moreover, Ayobamiji and Kalmaz (2020), on the other hand, used the wavelet approach to obtain the frequency domain dependence of CO_2 as well as potential income, which affirms the findings of (Samour et al., 2022).

3 DATA AND METHODS

3.1 Data

Using Japan as a case study the current paper, out study probes into the drivers of CO_2 emissions (namely globalization,

TABLE 1 | Variable description.

Indicators	Symbol	Measurement	Sources
CO_2 emissions	CO_2	Per capita emission	BP
Globalization	GLO	Globalization Index	KOF
Economic growth	GDP	GDP per constant 2010	WDI
Fossil fuel	FF	Addition of gas, coal and oil energy consumption	BP
Renewable energy	REC	Addition of nuclear, geothermal, wind, and solar energy consumption	BP
Financial development	FD	Financial development index	IMF

economic growth, fossil fuel, and financial development). The dependent variable is CO_2 while the regressors are globalization, economic growth, fossil fuel, and financial development. The dataset used in this study spans between 1990 and 2019 (30 observations). The data sources and measurements are presented in **Table 1**.

The current investigation function presented by **Eq. 1** as follows:

$$CO_{2t} = f\,(GDP_t, GLO_t, REC_t,\ FF_t, FD_t) \tag{1}$$

Where; FF depicts fossil fuel, GLO represents globalization, REC denotes renewable energy, FD means financial development, CO_2 represents carbon emissions, and GDP denotes economic growth.

3.2 Models Construction

Given that the Japanese economy is one of the world's leading emitters of CO_2 emissions, the world's third-largest economy, and operates as an open market, this investigation is essential. Based on the economic function above, we construct economic model which is depicted by **Eq. 2** as follows:

$$CO_{2t} = \vartheta_0 + \vartheta_1 GDP_t + \vartheta_2 GLO_t + \vartheta_3 REC_t + \vartheta_4 FF_t + \vartheta_5 FD_t +\ \varepsilon_t \tag{2}$$

Where; FF is representative of fossil fuel, GLO represents globalization, REC denotes renewable energy, FD means financial development, CO_2 represents carbon emissions, and GDP denotes economic growth. $\vartheta_{1\ldots\ldots\ldots}\vartheta_5$ represents the coefficient of the exogenous variables and ε_t denotes the error term.

3.3 Econometric Methods

The stationarity feature of time series data determines the trustworthiness of empirical outcomes. As a result, we employed both Phillips–Perron (PP) and Augmented Dickey-Fuller Test (ADF) test stationarity to catch the variable's stationarity properties.

The current empirical analysis utilized the ARDL to investigate the interrelationship between CO_2 and the exogenous variables. It addresses the endogeneity and serial correlation issue among the variables through a suitable selection of lag and robust estimates, allowing for the use of relatively small sample sizes to signal both short and long-run interrelationships. In contrast to Johansen's cointegration approach, the ARDL model permits all variables to be integrated in a different order. The equations for the three models are illustrated as follows:

$$\begin{aligned}\Delta CO_{2t} &= \beta_0 + \sum_{k=1}^{p}\theta_{1k}\Delta CO2_{t-k} + \sum_{k=0}^{p}\theta_{2k}\Delta GDP_{t-k} + \sum_{k=0}^{p}\theta_{3k}\Delta GLO_{t-k}\\ &+ \sum_{k=0}^{p}\theta_{4k}\Delta REC_{t-k} + \sum_{k=0}^{p}\theta_{5k}\Delta FF_{t-k} + \sum_{k=0}^{p}\theta_{6k}\Delta FD_{t-k}\\ &+ \varphi_1 GDP_{t-1} +\ \varphi_2 GLO_{t-1} + \varphi_3 REC_{t-1} + \varphi_4 FF_{t-1}\\ &+ \varphi_5 FD_{t-1} + \xi ECM_{t-1} + \varepsilon_t\end{aligned} \tag{3}$$

Subsequently, to gather the causal relationship between ecological footprint and the exogenous variables we utilized the (Breitung & Candelon, 2006) causality test to identify (a) whether REC, GLO, FD, FF and GDP granger cause CO_2, and (b) at which frequency does this causality occur. The test has advantages over typical time-domain techniques because it provides more degrees of variation than standard time-domain tests, which only provide variation over a set timeframe. As a result, the frequency domain method is more resistant to seasonality variations. Moreover, the approach is consistent in nonlinear topography, and causality cycles occur at higher or lower frequencies.

4 FINDINGS AND DISCUSSION

Table 2 presents brief information regarding the variables used. The GDP(43519.16) is the highest and it ranges from 38074.46 to 49187.83. This is followed by FF(4840.137) which ranges from 4355.192 to 5198.311, REC(866.5147) which ranges from 333.0990 to 1198.267, GLO(69.13010) which ranges between 55.91589 and 79.53600, CO_2(9.661274) which ranges from 8.723510 to 10.24598 and FD(0.748023) which ranges from 0.568429 to 0.876659. With the exemption of GDP, all the variables (GLO, FF, REC, FD, and CO_2) are negatively skewed. Furthermore, the values of all variables are less than 3 which implies that the series are platykurtic. The value of the JB also disclosed evidence of normality of variables of investigation.

Next, we probe the stationarity attribute of the variables using the conventional PP and ADF tests which are presented in **Table 3**. At level, all the variables are nonstationarity with GLO exemption; however, at the first difference, REC, GLO, CO_2, FD, FF and GDP are stationary. This implies that our series are I(1) and I(0) variables. Therefore using the ARDL approach is permitted based on these outcomes.

TABLE 2 | Descriptive statistics.

	GDP	GLO	FF	FD	CO_2	REC
Mean	43519.16	69.13010	4840.137	0.748023	9.661274	866.5147
Median	43207.85	68.84033	4881.384	0.788227	9.771878	954.8144
Maximum	49187.83	79.53600	5198.311	0.876659	10.24598	1198.267
Minimum	38074.46	55.91589	4355.192	0.568429	8.723510	333.0990
Std. Dev.	3094.765	6.937207	234.3127	0.106257	0.377413	290.7360
Skewness	0.114993	−0.254488	−0.448348	−0.364164	−0.622106	−0.733119
Kurtosis	2.052145	2.008619	2.260401	1.608524	2.793841	2.105325
Jarque-Bera	1.189153	1.552364	1.688837	3.083334	1.988209	3.687872
Probability	0.551796	0.460159	0.429807	0.214024	0.370055	0.158194

TABLE 3 | Stationarity test outcomes.

	ADF		PP		ZA			
Variables	Level	Δ	Level	Δ	Level	BD	Δ	BD
GDP	−3.1841	−5.6342*	−3.0870	−7.7549*	−4.3620	2009	−6.9401*	2009
FF	−1.9335	−6.3504*	−1.3501	−14.908*	−3.2085	2009	−5.1032***	2010
REC	−2.2638	−5.6900*	−2.0003	−3.6893*	−4.4897	2012	−5.9305*	2012
GLO	−3.5439**	−4.2649*	−3.2743***	−10.786*	−4.9147***	1997	−6.2700*	1999
CO_2	−1.9827	−4.4882*	−1.1525	−5.1370*	−3.6439	2012	−4.9217***	2007
FD	−2.2138	−4.6796*	−2.5941	−4.8097*	−3.7833	2008	−5.2295**	2008

**p < 0.01, **p < 0.05, and ***p < 0.10*

TABLE 4 | ARDL bounds test.

F-bounds test		Ho: No levels of association		
T-Statistic	Value	Signif.	I(0)	I(1)
			Asymptotic: n = 1000	
F-statistic	5.6393*	10%	2.26	3.35
k	5	5%	2.x62	3.79
		2.5%	2.96	4.18
		1%	3.41	4.68

Table 4 presents the bounds test outcomes which are utilized to check the cointegration attributes of the variables of investigation. The Ho hypothesis of "no cointegration" is dismissed since the F-statistic is higher than the Lower and upper critical values. Therefore, we conclude that there is strong proof of an association between CO_2 and the exogenous variables in the long-run. This gives room for the ARDL utilization to catch the long-run interrelation between CO_2 and the regressors.

The association between CO_2 emissions and the exogenous variables is unveiled by the ARDL long and short-run outcomes in **Table 5**. The effect of GDP on CO_2 is found negative and significant at 5% which suggests that a 1% shift in the GDP will cause CO_2 to increase by 0.5301% by keeping other elements constant. The growth in Japan's economy is not eco-friendly i.e., it is not sustainable. Though in the short term, no significant association was found between GDP and CO_2.

TABLE 5 | ARDL outcomes.

	Long-run			Short-run		
Variable	Coefficient	t-statistic	Prob	Coefficient	t-statistic	Prob
GDP	0.5301**	2.3210	0.0310	0.7453*	5.1570	0.0001
GLO	−0.7024*	−5.0605	0.0000	−0.5298	−1.4639	0.1169
FD	0.1629**	2.5853	0.0258	0.2336*	2.9230	0.0100
REC	−0.0348*	−3.2651	0.0039	−0.1618***	−1.9273	0.0719
FF	0.7668*	6.4674	0.0000	0.7917*	11.740	0.0000
DUM	0.2911	−0.1503	0.8820	—	—	—
ECT(-1)	—	—	—	−0.3967*	−6.5390	0.0000
R^2	0.9383					
Adjusted R^2	0.9237					
F-statistic	38.060					
Prob (F-statistic)	0.0000					

*Note: 1%, 5%, and 10% level of significance are denoted by *, **, and ***.*

TABLE 6 | Diagnostic tests.

	X^2 (*p*-values)
Normality test	0.9183 (0.8901)
RESET test	0.2110 (0.8301)
Heteroskedascity test	1.7941 (0.1803)
Serial correlation LM	4.0836 (0.1101)

This shows that similar to most Asia economies, Japan's policy is pro-growth. Therefore, policymakers in Japan need to re-strategize their policy regarding growth due to its damaging effect on the ecosystem. This outcome is preached by several scholars. For instance, the study of (Miao et al., 2022) for BRICS reported that the growth-emissions association is positive using the MMQR. Similarly, the studies of (Adebayo, 2022a) and (Adebayo, 2022b) for India and Spain respectively reported that GDP is the major cause of deterioration of the ecosystem. Moreover, the studies by Ali & Kirikkaleli (2021), Qayyum et al. (2021), Xu et al. (2022), Qayyum et al. (2022), Shabir et al. (2022) and Akadiri et al. (2022) disclosed similar findings.

Furthermore, we established that emissions increase in Japan is caused by financial development increases. Thus, a 0.16% surge in emissions in Japan is caused by a 1% increase in FD when other elements are constantly held. This shows that the financial system of Japan is at its early stage. In this stage, financial development is anticipated to worsen the ecosystem. The study of He et al. (2021) preached a similar result by establishing positive FD-emissions nexus. Similarly, the paper by Ahmad et al. (2021), Fakher et al. (2021), and Haseeb et al. (2018) reported that FD does not lessen emissions but rather amplifies it. Nonetheless, the research of Agyekum et al. (2022) established that decrease in emissions within the global context is caused by the amplification of FD. Contrarily, the study of Zhang et al. (2021) refuted the study of Kirikkaleli & Adebayo (2020), Güngör et al. (2021), and Kirikkaleli & Adebayo (2021) by establishing an insignificant FD-emissions connection.

Moreover, the effect of globalization on CO_2 is negative in both the short and long-run at 1% and 10% respectively. This implies that globalization favors the environment in Japan. Therefore 0.70% and 0.51% decrease in CO_2 in Japan in the short and long-term is caused by a 1% surge in globalization keeping other factors constant. This also corroborates the PHH-pollution hallow hypothesis for the case of Japan. A similar outcome is reported by the research of (Dingru et al., 2021) for BRICS using MMQR and dataset from 1990–2018. Likewise, the study (Adebayo, 2022a) using the load capacity facto which is a new proxy of ecological quality reported that globalization boosts the integrity of the environment. However, the research (Acheampong & Adebayo, 2021) for Australia reported positive globalization-emissions interconnection. This is also backed by the research of (D. Xu et al., 2022) who preached a positive emissions-globalization association.

As anticipated, negative emission-renewable energy surfaced. Therefore, the growth in REC in Japan is curbing CO_2. In terms of climate change, the use of renewable energy sources has been thought to have a substantial impact on ecological integrity by dropping GHG emission levels in the atmosphere. Besides, as noted by the OECD (2013), renewables investment is typically regarded to be less carbon-intensive than traditional energy. Nations may promote ecological responsibility and build a globally sustainable and resilient ecosystem by supporting the adoption of renewable energy. This result conforms with the research of Fareed et al. (2021, 2022) who reported that REC is vital for curbing the constant surge in emissions. Similarly, the studies of Anwar et al. (2021) and Alola et al. (2021) reported that the decrease in emissions is caused by REC intensification.

Fossil fuel use effect on CO_2 is positive, which is as expected. Therefore, a 0.766% upsurge in emissions is triggered by a 1% intensification in fossil fuels. Several studies revealed similar findings (Adebayo et al., 2022; Gyamfi, Adebayo, et al., 2022). Furthermore, the dummy variables does not have significant effect on CO_2 emissions. As expected, the coefficient of ECT is −0.39, which is significant and negative at significance level of 1%. The result proves that corrections made in previous periods can be corrected in subsequent periods. The diagnostic tests also revealed that there is no issue of serial correlation, normality and heteroscedasticity (see **Table 6**). In addition, **Figures 1A,B** affirm stability in the model. **Figure 2** presents the empirical results.

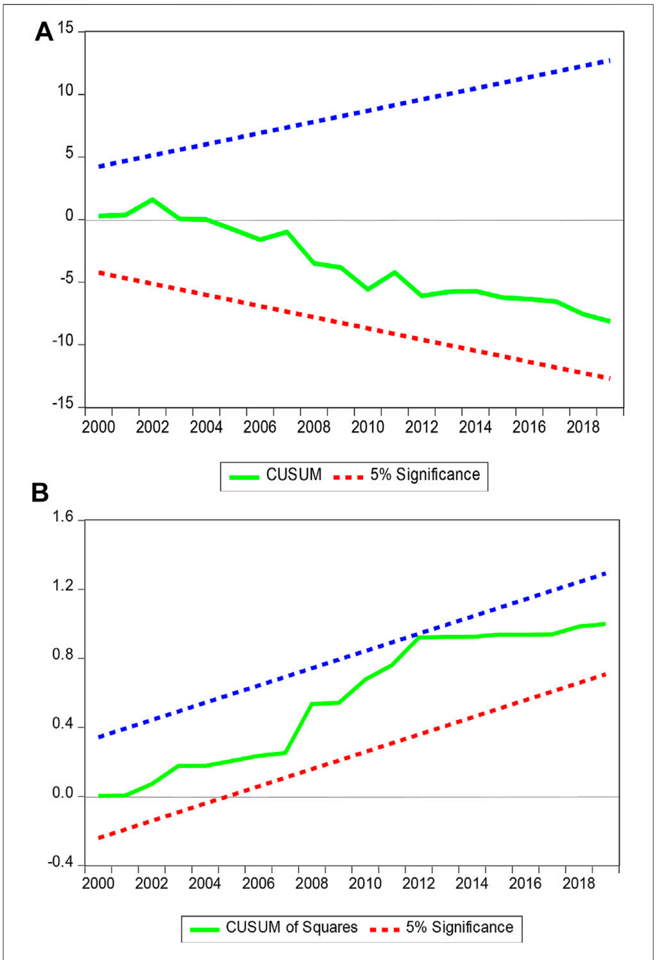

FIGURE 1 | **(A,B)** CUSUM.

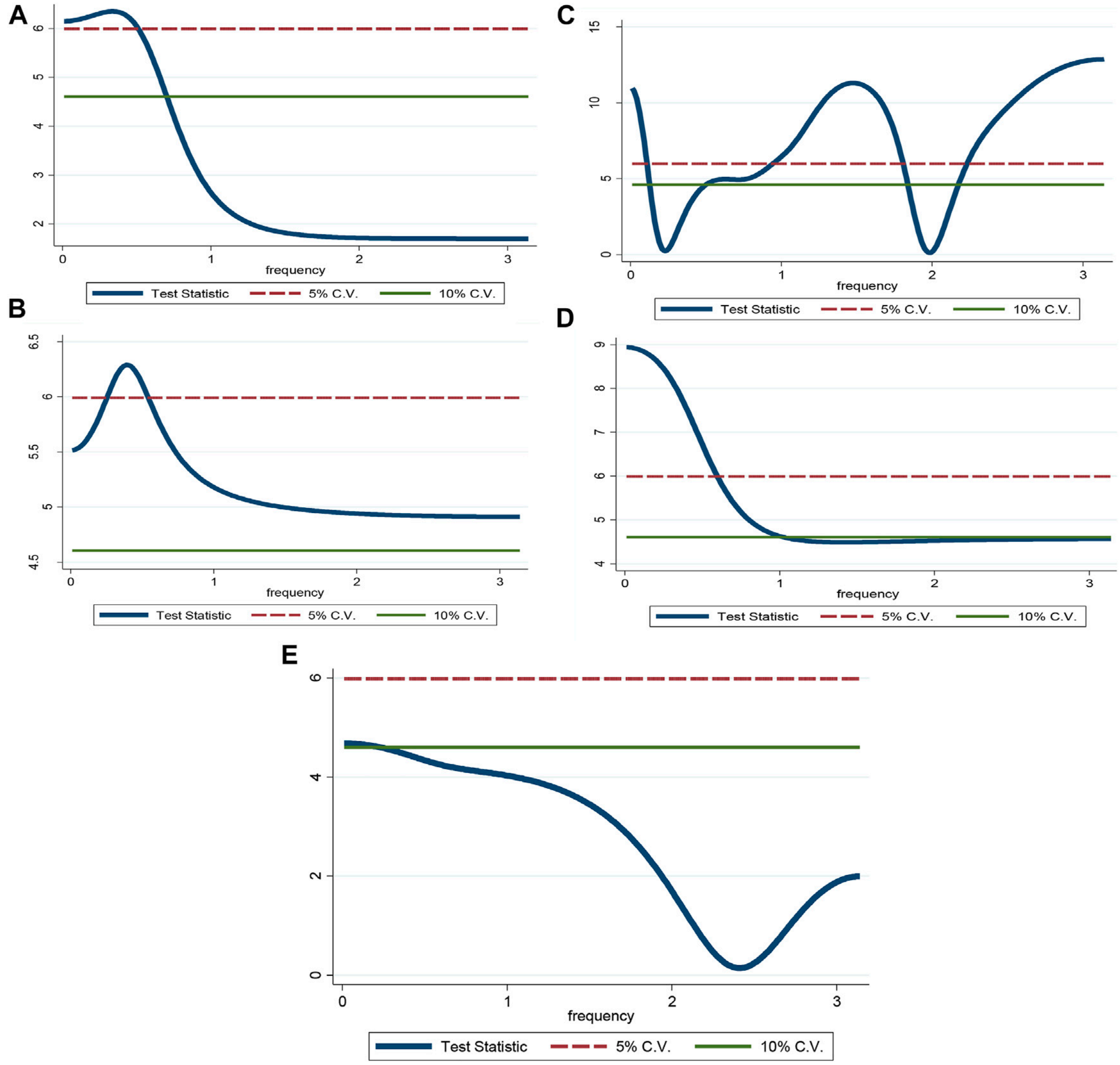

FIGURE 2 | (A) Spectral Causality from REC to CO_2. **(B)** Spectral Causality from GLO to CO_2. **(C)** Spectral Causality from FD to CO_2. **(D)** Spectral Causality from GDP to CO_2. **(E)** Spectral Causality from FF to CO_2.

Next, we examine the causal interrelationship between CO_2 and FD, GDP, REC, FF and GLO using the BC-breighton abd Calderon (2006) test which is presented in Figures. **Figure 2A** presents the causal link from REC to CO_2. At a level of significance of 5% and 10%, there is causality from REC to CO_2. Furthermore, evidence of causality from GLO to CO_2 is surfaced 5% level of significance which shows that in the long-run CO_2 can be predicted by GLO (See **Figure 2B**). Moreover, in all frequencies, causality from FD to CO_2 is evident which illustrates that in the short, middle and long-run FD can forecast CO_2 (**Figure 2C**). Furthermore, we established causality from both GDP to CO_2 in both the middle and long-term as shown in **Figure 2D** which suggests that CO_2 can be forecasted by GDP. Lastly, **Figure 2E** supports causality from FF to CO_2 suggesting that CO_2 can be forecasted in the long-term. These outcomes suggest that all the exogenous variables can forecast CO_2 mostly in the long-term which implies that any policy initiated for the exogenous variables will impact emissions of CO_2.

5 CONCLUSION AND POLICY SUGGESTIONS

5.1 Conclusion

Ecological dilapidation is one of the most immediate issues affecting modern society. Environmental degradation has gotten a lot of devotion from scholars and policymakers because of its huge influence on billions of people's lives. As a result, this empirical research probes the effect of renewable energy and globalization on CO_2 emissions in Japan using a dataset from 1990 to 2019. We also consider other determinants such as financial development and economic growth in the framework. The study employed the ARDL and frequency domain causality to probe these relationships. The findings from the ARDL disclosed that GLO and REC contribute to the mitigation of CO_2 emissions while fossil fuel, FD and GLO caused an upsurge in CO_2 emissions in Japan as shown in **Figure 3**. Furthermore, the frequency domain demonstrated that all the

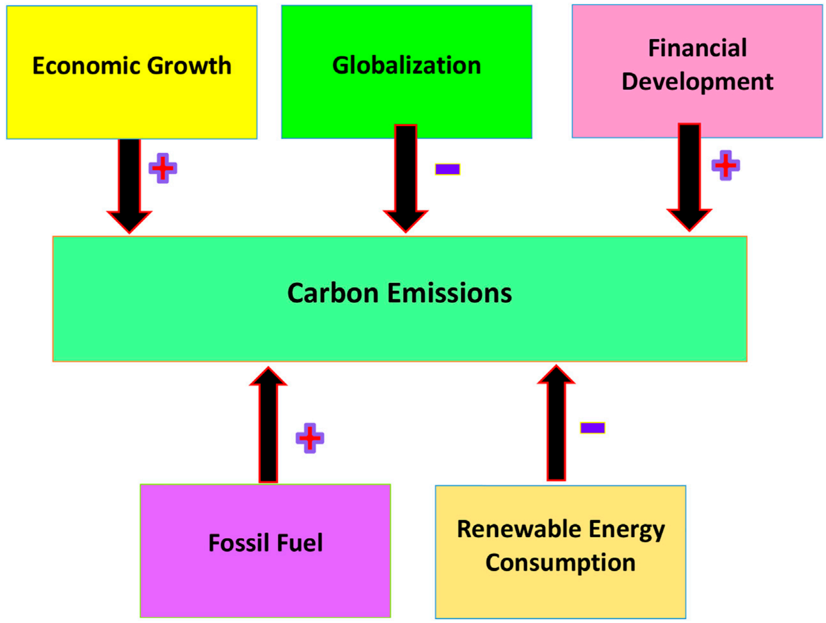

FIGURE 3 | Empirical findings.

exogenous variables can forecast CO_2 mostly in the long-term which implies that any policy initiated for the exogenous variables will impact emissions of CO_2. The problems of autocorrelation and heteroscedasticity was also investigated using diagnostic approaches. The results show that the accepted model has no contradictory concerns with heteroscedasticity and autocorrelation, as evidenced by a Chi-square value of higher than 0.10%.

5.2 Policy Recommendations

The aforementioned variables are significant aspects in Japan's environmental deterioration. To achieve more ecological profits, the government should concentrate on shifting away from non-renewable energy sources that add to growing CO2 levels and toward more reliable and cost-effective sources of renewable that maintain a better ecosystem and long-term growth. Furthermore, additional government funding should be allocated to research and development of more innovative approaches to the nation's environmental problems. Additional government energy research and development spending will raise the production of energy resource efficiency and attract FDI into the nation. Moreover, Japan's ecologically sustainable development goals may be met by swapping renewable energies for fossil fuels in order to lessen GHGs emissions.

Moreover, the growing impact of globalization on Japan's CO_2 emissions shows that the country is transitioning from ecological responsibility. Because globalization is a major driver of economic growth, the government should concentrate on luring and licensing investors that use environmentally beneficial technology. Likewise, technology brought into the nation for commerce should be ecologically benign in order to avoid harmful environmental consequences. Moreover, using ecologically sustainable techniques including polluter payments, carbon taxes, and pollution credits, the government should set guidelines for emissions, and corporations that violate these criteria and contaminate should be penalized. A program of this nature has the ability to both slow and ameliorate environmental degradation while boosting economic expansion.

5.3 Limitation of Study and Future Directions

This research has its limitations, which can be addressed in the future. Though the research assesses the effect of economic growth and energy (renewable and nonrenewable) on CO_2 emissions, the study did not verify the EKC hypothesis. Therefore, future studies can incorporate this into their model. Furthermore, future studies can also include interaction terms of financial development with other variables, such as economic growth, and energy use to comprehend its indirect effect on CO_2 emissions. Since the data was only available for a brief time, this study only investigated a few variables in the model. Future efforts in this area may include technology, environmental taxation, green innovation, and other variables to provide intriguing outcomes.

AUTHOR CONTRIBUTIONS

SM, SA-G, and OL contributed to conception and design of the study. MA and EA organized the database. EBA performed the statistical analysis. EA wrote the first draft of the manuscript. SM, SA-G, OL, EA, SK and ME-N wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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The Nexus Between CO_2 Emission, Economic Growth, Trade Openness: Evidences From Middle-Income Trap Countries

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In recent years, the carbon dioxide emissions generated by the massive consumption of fossil energy have been increasing year by year, resulting in more and more obvious greenhouse effect, and the occurrence of climate disasters around the world has become more and more frequent. This study analyses the long-term effects of economic growth, trade, foreign direct investment (FDI) and gross domestic product (GDP) on carbon dioxide (CO_2) emissions in Latin American countries that are in the middle-income trap (MIT). Using annual time-series data for the period 2000–2020, the results of middle-income countries of Latin America are compared with higher-income countries (Singapore, the United States, and South Korea) and an upper-middle-income country, China. Specifically, we examine the role of sector value addition to GDP on the CO_2 emission nexus for middle-income economies, controlling for the effects on GDP, FDI, and trade. Using regression and path analysis (multiple regression) we find that for higher-income countries FDI, GDP and trade are the important variables that have a strong positive impact on CO_2 emission, but that positive impact is weak in MIT countries, which makes this study significant as it highlights important variables needed for MIT countries to remain focused. Autoregressive distributed lag (ARDL) model results also explore that FDI, GDP growth and trade variables can significantly accelerate the environmental quality by CO_2 emission, while tourism/travel services and education do not much impact the environment. Hence, our paper provides solid ground for developing a sustainable and pro-growth policy for MIT countries because they are plagued by the decline or stagnation of economic growth.

Keywords: middle-income trap, Latin America, ARDL model, economic growth, CO_2 emission

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1 INTRODUCTION

With the development of world trade, the economies of various countries, especially developing countries, have achieved unprecedented growth, but at the same time, it has also brought about the problem of increased carbon dioxide emissions, which in turn leads to climate warming (Chunling et al., 2021; Qayyum et al., 2022; Yang et al., 2022). However, there are still many differences among countries on the definition of emission responsibilities and actions taken (Ali and Kirikkaleli, 2022). Developed countries believe that developing countries are currently the main source of carbon emissions, and require less developed countries, including China and Latin American countries, to take greater measures to reduce emissions (Qayyum et al., 2021; Yang et al., 2021; Shabir et al., 2022). The less developed countries pointed out that the accumulated carbon dioxide emissions of developed countries in history far exceeded the current carbon emissions of developing countries, and the commitment of developed countries to provide financial and technical assistance to less developed countries to reduce emissions has not been fully implemented (Yang et al., 2020a; Yang et al., 2020b; Fan et al., 2020). Therefore, developed countries require less developed countries. It is unreasonable for developed countries to shoulder the same level of responsibility for reducing emissions. Such differences in emission reduction actions will have an impact on global carbon emissions (Kirikkaleli et al., 2022).

The rapid development of world trade after World War II has directly promoted the economic growth of various countries, but on the other hand, it has led to the problem of carbon dioxide emissions. Especially in the context of global warming, it is particularly important to divide the emission responsibilities of each country, and the carbon embodied in trade has thus become a subject of research (Bhatti et al., 2021a; Bhatti et al., 2022; Yuan et al., 2022). Debone et al. explored the relationship between Brazil's economic structure changes and carbon emissions and found that there was a significant correlation between those factors (Debone et al., 2022). In particular, the increase in Brazil's carbon emissions in the 1990s was largely attributable to the transition to energy-intensive production in its production, in which 6.6% of energy use and 7.1% of carbon emissions were caused by the export sector. In addition, carbon accounting from a production perspective can lead to carbon leakage issues, which raises concerns about shifting carbon emissions. Liu et al. estimated that carbon emissions embodied in global trade reached 5.3 billion tons, and some countries were net importers of carbon embodied in trade, which was related to the country's size, geographical features, and other national characteristics (Liu et al., 2017).

Many economies can easily grow from a low-income country to a middle-income country, but it is difficult to cross the middle-income stage and become a high-income country (Smit and Pilifosova, 2003; Green and Stern, 2017; Zhang et al., 2017). CO_2 emission is one that is playing a vital role in extracting the relationship between MIT and trade. Latin American countries such as Brazil, Argentina, and Mexico jumped from low-income countries to middle-income countries in a very short period of time, creating a miracle of growth in the national economy and per capita income, but they experienced economic regressions one after another between 1970 and 1980 (Parrique et al., 2019). Among Asian economies, only Japan has successfully overcome the "middle-income trap" and achieved a leap in economic development (Taylor, 2005). After being hit by the Asian financial turmoil, Indonesia, the Philippines, India, and other countries have remained in the middle-income ranks because they could not resume their previous prosperous economic development (Kang et al., 2016). The "middle-income trap" (MIT) is a common economic phenomenon that occurs in countries with different historical, cultural, and economic backgrounds, accompanied by declining economic growth and fragile financial systems. In order to help countries, avoid falling into or escape from the "middle-income trap", many research institutions and scholars have studied its development theories, causes, and avoidance mechanisms (Ozturk and Al-Mulali, 2015). Even if not all countries or regions fall into the "middle-income trap", they will always be affected by the "middle-income trap" to varying degrees in the process of their economic development (Wang and Zhao, 2015). Few countries or regions can be avoided. In addition to the "middle-income trap" occurring in developing countries, similar phenomena have also occurred in some developed countries in the early stages of development, such as the United States and the United Kingdom (Zhang et al., 2018).

The fundamental reason for the occurrence of the "middle-income trap" is that the engine that supported economic growth in the past was unsustainable (Dinda, 2004; Ran et al., 2020). If a country wants to make a breakthrough in economic development and enter the ranks of high-income countries, it needs to change this stagnant or even retrogressive economic state, adjust the backward growth mechanism, and inject new impetus into economic development (Su, 2017). From the perspective of international trade, the root cause of the "middle-income trap" is that with the rapid social and economic development, middle-income countries have ushered in opportunities for development. When the economy grows to a certain level, the advantages of labor no longer exist, and labor remuneration continues to increase, but the economic structure has not been upgraded, and the international competitiveness has been further weakened (Edwards, 2017). Therefore, the international trade situation has not only not improved year-on-year but has deteriorated, and the industrial structure has not been improved. To optimize and adjust, economic development has fallen into difficulties, which has caused social turmoil and intensified social contradictions, and the economic development of middle-income countries has fallen into difficulties (Susilo, 2021); (Gonçalves and Salles, 2008).

The arrival of the industrialization era not only made the world economy develop rapidly but also released a large number of greenhouse gases, thus causing global warming. In this process, CO_2, as the main component of greenhouse gases, plays a major role (Kaygusuz, 2009). The damage by global warming hinders the sustainable development of the economy and affects human health at the same time. At present, the issue of global warming has received widespread attention, and CO_2 emission reduction has become an important issue for all countries. Therefore, in the process of economic development, the question of when the kuznets inflection point of CO_2 emissions comes and whether relevant measures can be taken to make the inflection point come earlier, is particularly important. Therefore, many scholars have commenced studies on the impact of economic development on CO_2 (Khan et al., 2020).

Saud et al. (2019) used cross-sectional data from developed and developing countries to conduct an empirical analysis of the correlation between economic development and environmental pollution, thus formally launching the EKC hypothesis. In fact, before this, scholars had studied the correlation between the above two variables and obtained similar results. Lowering barriers to trade often expands the scale of economic activity, changes the composition of economic activity, and changes production techniques, thereby affecting the environment. The inauguration of the North American Free Trade Agreement comes as U.S. environmental groups voice concerns about the agreement, fearing that free trade could worsen the environment in Mexico while affecting the environment in the United States. Therefore (Grossman and Krueger, 1991), used cross-sectional data from 42 countries to explore the correlation between economic development and air quality, and the results showed an inverted, roughly U-shaped correlation. Galeottia et al. found through empirical analysis that the nonlinear impact of economic development on CO_2 emissions presents an inverted U-shape and proved the robustness of this relationship by replacing the relevant data of CO_2 emissions in the empirical analysis (Galeotti et al., 2006). Loganathan et al. explored the impact of CO_2 tax and economic development on environmental quality in Malaysia with the cointegration test and Granger causality test, using time-series data from 1974 to 2010, and found that economic development and CO_2 are directly related with positive relation (Loganathan et al., 2014). There is an inverted U-shaped nonlinear relationship between emissions, and the CO_2 tax policy fails to play its role in controlling CO_2 emissions (Cederborg and Snöbohm, 2016). and (Yang et al., 2015) also conducted empirical research on the relationship between economic development and CO_2 emissions, and the results showed that there was an inverted U-shaped correlation between them (Liu et al., 2016). investigated the joint effects of economic development and urbanization on CO_2 emissions based on a partial linear additive model. The impact on CO_2 emissions presents a “roller coaster” mode with three turning points. Using the data from 1975 to 1998 of 22 countries that made CO_2 emission reduction commitments in the Kyoto Protocol (Mensah et al., 2019), determined to verify by pooled mean group (PMG) whether the environmental Kuznets curve is suitable for CO_2. The results show that the nonlinear effect of economic development on CO_2 emissions exhibits an N-shape rather than an inverted U-shape (Xiumei et al., 2011). used the VAR model to empirically analyze the dynamic correlation between CO_2 emissions and economic development in Zibo City, Shandong Province. The results show that there is no inverse U-shaped correlation in the dynamic sense between the above two variables, but the per capita GDP has a very large contribution to the interpretation of the variance decomposition of CO_2 emissions, so the realization of CO_2 emission reduction goals is certain (Shuai et al., 2017). combined the STIRPAT model with panel data and time-series data to study the impact of population, level of technology, and economic growth on CO_2 emissions in 125 countries with different incomes levels, from 1990 to 2011. It shows that from a global perspective, the key factor affecting CO_2 emissions is the degree of economic development, but for high-income countries, the level of technology has the greatest impact on CO_2 emissions.

TABLE 1 | List of selected countries with income level and region.

Country Name	Income Level	Region
Argentina	Upper-middle-income	Latin America
Belize	Lower-middle-income	
Bolivia	Lower-middle-income	
Brazil	Upper-middle-income	
Colombia	Upper-middle-income	
Costa Rica	Upper-middle-income	
Dominica	Upper-middle-income	
Dominican Republic	Upper-middle-income	
Ecuador	Upper-middle-income	
Grenada	Upper-middle-income	
Guatemala	Upper-middle-income	
Guyana	Upper-middle-income	
Honduras	Lower-middle-income	
Jamaica	Upper-middle-income	
St. Lucia	Upper-middle-income	
Mexico	Upper-middle-income	
Nicaragua	Lower-middle-income	
Panama	Upper-middle-income	
Peru	Upper-middle-income	
Paraguay	Upper-middle-income	
El Salvador	Lower-middle-income	
Suriname	Upper-middle-income	
Venezuela, RB	Lower-middle-income	
South Korea, Rep	High-income	East Asia
China	Upper-middle-income	South Asia
Singapore	High-income	Southeast Asia
United States	High-income	—

There are two aspects of innovation:

- First, an ARDL is employed in a way that has never been done before to extract the relationship between trade, FDI, economic growth, and CO_2 in Latin American nations that are a part of the MIT.
- Second, the impact of CO_2 emissions in higher-income countries and MIT countries is explored. MIT Latin American countries are supplied with policy advice regarding the factors that need to be focused on.

The remainder of the study is structured as follows. The section Literature review describes the impact of MIT on economic growth. Section methodology describes the data source, and techniques used for analysis using ARDL. shows the estimation outputs of the panel data estimators. Discussion on findings and implications with conclusion is provided in Section discussions and conclusion. The conclusion describe the policy recommendation and future prospects of this study.

2 METHODOLOGY

2.1 Study Area and Data Description

Latin America refers to central America, the Caribbean, and South America, all south of the United States. It is named thus because most countries use Spanish and Portuguese, both of which belong to the Latin family, as their national languages. Located in the central and southern parts of the western hemisphere, it is bordered by the Atlantic Ocean in the east, the Pacific Ocean in the west, bordering North America (United States) in the northwest, and facing Antarctica across the Drake Passage in the south. There are 33 countries in Latin America, out of which we selected a total of 19 countries and categorized them according to their income level i.e., upper-middle- and lower lower-middle-income. We selected three higher-income countries, the United States, Singapore, and Korea, as models for comparison as they had escaped the MIT. China is also selected although it is an upper-middle-income country but will probably leave this level due to its silk road and other programs (Sener and Karakas, 2019). **Table 1** shows the list of the selected countries.

2.2 Data Selection

Data for different factors have been selected from the World Bank website for the period from 2000 to 2020 for the selected countries (Glawe and Wagner, 2020). The focus factors that impact the MIT are health, GDP, travel services/tourism, trade (high-technology exports, information etc.), and FDI. Descriptive analysis of the data is shown in supplementary material A. Statistical analysis of the data was performed using SPSS software (version 25; IBM). Results of statistical analysis are shared in supplementary material A.

2.3 Regression Model

This paper uses regression analysis to obtain the relationship of variables that impact CO_2 emission. Regression analysis is a method of making predictions on continuous data. The purpose is to analyze whether two or more variables are related, and the direction and strength of the relationship. Regression analysis can observe specific variables by building mathematical models or predict variables of interest to researchers.

The simplest regression model can be represented as the data object to be fitted is $X = \{x_1, x_2, \ldots, x_m\}$, the corresponding real value is $Y = (y_1, y_2, \ldots, y_m)$, the linear model can be written as:

$$\hat{y} = Xw \tag{1}$$

Where w is the regression coefficient, we use a square error to measure the fitting error:

$$L(X) = \sum_{i=1}^{m} \left(y_i - x_i^T w\right)^2 = \left(y - Xw\right)^2 \tag{2}$$

The above formula is equal to 0 to the w.

$$\frac{\partial L(X)}{\partial w} = \frac{\partial\left(y^T y - w^T X^T y - y^T Xw - w^T X^T Xw\right)}{\partial w} = 2X^T\left(y - Xw\right) = 0 \tag{3}$$

It can determine:

$$\hat{w} = \left(X^T X\right)^{-1} X^T y \tag{4}$$

The above is easy to interact with training data; a good solution is partial weighted linear regression, increasing a weight w_i for each error (here w is not the above $\hat{w}$), at this time, the error function can be written:

$$L(X) = \sum_{i=1}^{m} w_i \left(y_i - x_i^T w\right)^2 = \left[W\left(y - Xw\right)\right]^2 \tag{5}$$

Among them, W is a diagonal matrix, also called the core; the type of core can choose freely, and the most common is the Gaussian nucleus. The weight corresponding to the Gaussian nucleus is as follows:

$$W(j, j) = \exp\left(\frac{\left\|x^i - x^j\right\|^2}{-2k^2}\right) \tag{6}$$

Similarly, the new error function *L (X)* is governed to obtain the regression coefficient at this time:

$$\hat{w} = \left(X^T W X\right)^{-1} X^T W y \tag{7}$$

The W here is actually $W^T W$, but using W replaces the same meaning and is simple.

2.4 Path Analysis

After linear regression, we applied path analysis for multiple regression. Path analysis multiple linear regression reflects the direct effect between independent variables and dependent variables, but the relationship between variables is often intricate; some are unidirectional influence relationships, and some are mutual influence relationships, so it is often difficult for analysts to use only one regression model (World Bank, 2022).

In path analysis, to distinguish variables with different characteristics, statisticians give them names that reflect their characteristics: exogenous variables, endogenous variables, and final outcome variables. Exogenous variables refer to those variables in the model that only affect other variables and are not affected by other variables. Endogenous variables are the exact opposite of exogenous variables, referring to variables that can both affect and be affected by other variables in the model. If the endogenous variable is only affected by other variables, but not affected by other variables at all, such an endogenous variable is called the final outcome variable.

Path analysis includes the following four ways:

- A may have an effect on B, but B will not affect A. (A→B)
- B may have an effect on A, but A will not affect B. (A←B)
- There is a two-way influence relationship between A and B. (A←→B)
- The exact mode of influence between AB is unknown, but there is a correlation.

If the coefficients in the path analysis model are statistically significant, the problem will be much simpler, which may be the result, but when there are coefficients that are not statistically significant in the model, the model needs to be simplified, raising the question of how to evaluate the effect of the simplified model. In path analysis, an endogenous variable corresponds to a regression equation, and each regression equation has a coefficient of determination R_2, representing the proportion of the variance of the corresponding endogenous variable that can be explained by the equation, $(1–R_2)$, that indicates the remaining unexplained part of the equation.

2.5 ARDL Model

The ARDL model has been in use for decades to model the relationship between economic variables in a single-equation time-series setup. Its popularity also stems from the fact that the cointegration of nonstationary variables is equivalent to an error correction (EC) process, and the ARDL model has a reparameterization in EC form (Aamir et al., 2021). The existence of a long-run/cointegrated relationship can be tested, based on the EC representation. A bounds testing procedure is available to draw conclusive inference without knowing whether the variables are integrated of order zero or one, I (0) or I (1), respectively (Kripfganz and Schneider, 2016).

The regression model studies the analysis of univariate series, while the ARDL model models multivariate time series. In the ARDL model, not only the lag part of the original data, but also other influencing factors are added to adjust the autoregressive results.

The specific definition of the autoregressive (AR) model is shown below.

If $\psi_0, \psi_1, \psi_2, \ldots, \psi_p\,(\psi_p \neq 0)$ are real numbers, $\{e_t\}$ is a white noise sequence, and the random variables X_1, X_2, ..., X_t, ... satisfy the following difference equation of order p.

$X_t = \psi_0 + \psi_1 X_{t-1} + \psi_2 X_{t-2} + \cdots + \psi_p X_{t-p} + e_t, t = 1, 2, \cdots,$ this equation is called an autoregressive model of order p, or it can be simply written as AR (p) model, call $\{X_t\}$ an autoregressive sequence of order p, abbreviated as AR(p) sequence, and call it $\boldsymbol{\psi}: = (\psi_0, \psi_1, \psi_2, \ldots, \psi_p)^{\mathrm{T}}$ is the autoregressive coefficient of the above model. If the first coefficient ψ_0 in the above model is equal to 0, then $\{X_t\}$ is called a p-order autoregressive sequence with mean 0, satisfying.

$$X_t = \psi_1 X_{t-1} + \psi_2 X_{t-2} + \cdots + \psi_p X_{t-p} + e_t, t = 1, 2, \cdots \quad (8)$$

Special attention should be paid to the fact that when ψ_0 is not equal to 0, the p-order autoregressive sequence can be transformed into a p-order autoregressive sequence with a mean of 0, which can also be called a centralized p-order autoregressive sequence. Without loss of generality, the p-order autoregressive sequences involved in this paper are all centralized p-order autoregressive sequences.

As we all know, time series can be divided into stationary and nonstationary. Similarly, autoregressive series are also stationary and nonstationary. The definition of a stationary autoregressive series of order p is as follows.

Definition 2.3.1 For the p-order autoregressive model (2.3.1), if its coefficients $\psi_1, \psi_2, \ldots, \psi_p$ make , the solution is called (2.3.1) is a p-order stationary autoregressive model, and the p-order autoregressive sequence in this model is a p-order stationary autoregressive sequence. The above condition is called the stability condition of the p-order autoregressive model.

The p-order autoregressive models involved in this paper are all p-order stationary autoregressive models, and the p-order autoregressive sequences involved are all p-order stationary autoregressive sequences.

3 RESULTS AND DISCUSSION

A generally accepted view as to the cause of the MIT is that with economic growth, labor costs increase, and the comparative advantage of cheap labor costs is lost; a new economic growth model guided by knowledge and innovation has not yet been formed, thus making economic growth momentum insufficient. Therefore, the causes of the MIT can be roughly divided into the following three levels: first, the direct impact variables of sustained economic growth, such as education, industrial structure and its changes; second, the internal and external environmental variables affecting economic growth, such as trade, macroeconomic policies, demographic factors, and FDI; and the third is the fundamental reason that affects long-term economic performance, such as social and economic systems, for example, tourism and services (Egawa, 2013; Satrovic, 2017). Given this, travel services, high-technology exports, service exports, and FDI are selected as independent variables affecting a country's per capita GDP, GDP as an independent factor and carbon emission CO_2 (y) as a dependent variable. **Table 2** shows the studies which use similar factors in their literature review and experiments.

According to the above analysis, with *ln(free)*, *ln(open)*, *ln(con)*, *ln(ind)*, *ln(hon)*, *ln(tec)*, *inf*, *ln(lab)*, *ln(inv)* and *ln(ci)* as the independent variables and *ln(y)* as the dependent variable, establish the following panel data econometric model:

$$\begin{aligned} In(y_{it}) = c_0 + \alpha_i + c_1 ln(tec_{it}) + c_2 ln(free_{it}) + c_3 inf_{it} \\ + c_4 ln(open_{it}) + c_5 ln(hea_{it}) + c_6 ln(edu_{it}) \\ + c_7 ln(inv_{it}) + c_8 ln(ind_{it}) + c_9 ln(hon_{it}) \end{aligned} \quad (9)$$

where i represents the countries' element, i = 1, 2,., 14 (here Singapore and Korea are also considered for evaluation); i = 1, 2,...., 26, t represents time, c_0 is the intercept term, and α_i is the difference intercept term. $In(y_{it})$ is the logarithm of a country's per capita GDP, $ln(tec_{it})$ is the logarithm of a country's technological level, $ln(free_{it})$ is the logarithm of economic freedom, and inf_{it} is the logarithm of the inflation rate. $ln(open_{it})$ represents the logarithm of the proportion of trade volume in GDP, $ln(hea_{it})$ represents the logarithm of health, $ln(inv_{it})$ represents the logarithm of the proportion of FDI in GDP, $ln(ind_{it})$ represents the logarithm of the proportion of secondary industry output in GDP, $ln(ci_{it})$ is the logarithm of the urbanization rate, and ε_{it} is the random error term.

The results of the Hausman test found that the fixed effects model was the most suitable for the data in this paper. However, the static panel ignores the dynamic influence of the lag term of the independent variable on itself, which may lead to large deviations in the estimation results. Since the economic growth of the previous period has an impact on the economic growth of the current period, it is necessary to introduce the lag term of economic growth to reflect the dynamic lag effect. On the basis of the static panel model, the first-order lag term of the dependent variable is incorporated into the model to obtain the dynamic panel model as follows:

TABLE 2 | Variable selection and studies.

Variables	Studies
GDP	Qayyum et al. (2021), Yang et al. (2021), Satrovic, (2017), Egawa, (2013)
Tourism	Qayyum et al. (2022), Chunling et al. (2021), Ali and Kirikkaleli, (2022), Qayyum et al. (2021), Satrovic, (2017), Egawa, (2013)
FDI	Qayyum et al. (2022), Yang et al. (2020b), Satrovic, (2017), Egawa, (2013)
CO_2	Ali and Kirikkaleli, (2022), Shabir et al. (2022), Satrovic, (2017), Egawa, (2013)
Trade	Qayyum et al. (2021); Fan et al. (2020), Kirikkaleli et al. (2022), Satrovic, (2017), Egawa, (2013)

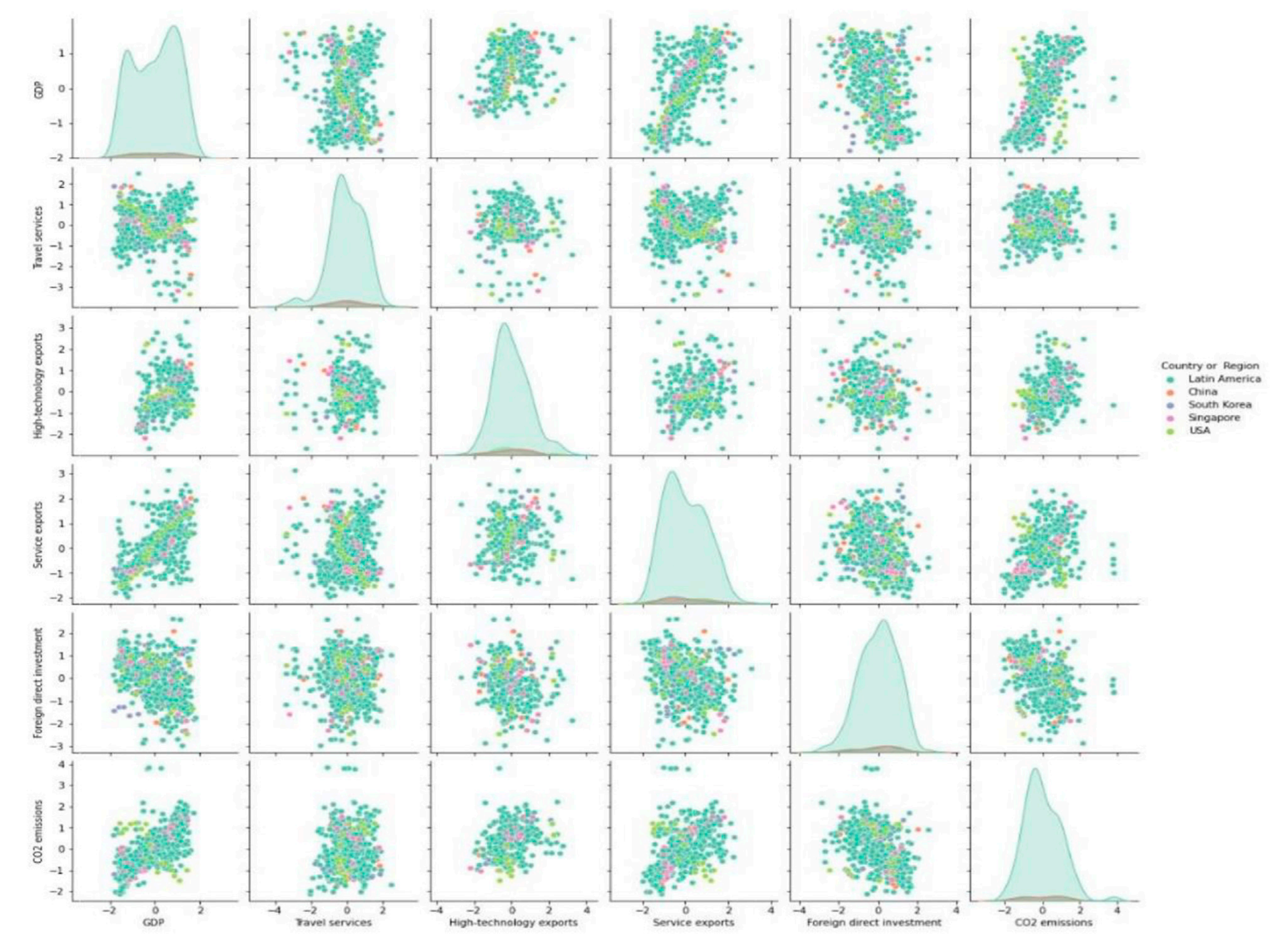

FIGURE 1 | Correlation analysis of different factors in different countries.

$$In(y_{it}) = c_0 + \alpha_i + c_1 ln(tec_{it}) + c_2 ln(free_{it}) + c_3 inf_{it} + c_4 ln(open_{it}) + c_5 ln(lab_{it}) + c_6 ln(con_{it}) + c_7 ln(inv_{it}) + c_8 ln(ind_{it}) + c_9 ln(hon_{it}) + c_{10} ln(ci_{it}) + c_{11} ln(y_{i,t-1}) + \varepsilon_{it} \quad (10)$$

Using the lagged term of the dependent variable as an independent variable will cause endogeneity problems in the regression model. To better deal with the correlation and endogeneity between cross-sections, regression analysis was performed on the data. First, using correlation analysis between different factors highlights that for high-income countries, such as Singapore, CO_2 emission has a strong correlation with GDP (0.825**), high-technology exports (0.871**) and services exports (0.867**), while there is a negative correlation with travel services (−0.149). South Korea showed a strong correlation of CO_2 with GDP (0.922**), high-technology exports (0.849**), services export (0.828**) and FDI (0.920**). The United States demonstrates a strong correlation of CO_2 with high-technology exports (0.803**) and travel services (0.300), while there is a negative relationship with GDP (−0.874**). For Latin American countries, a strong correlation of CO_2 is observed with GDP (0.907**), high-technology exports

TABLE 3 | Regression model for Latin America and other countries.

Country Name	GDP	Travel Services	High-Technology Exports	Service Exports	Foreign Direct Investment	R^2
Argentina	0.818*	0.198	−0.018	−0.280	0.009	0.866**
Belize	0.547	−0.738	0.0309	−0.016	−0.095	0.719
Bolivia	1.127**	0.089	−0.014	−0.218	0.034	0.992***
Brazil	0.737	−0.325	−0.334	0.592	0.162	0.689
Colombia	0.443	0.568	0.480**	−0.010	0.028	0.945**
Costa Rica	−0.312	0.467	0.133	1.138*	0.015	0.927**
Dominica	1.662**	1.268*	NA	−2.170*	0.111	0.464
Dominican Republic	2.020	−0.578	0.017	0.100	0.163	0.896***
Ecuador	1.905*	−0.964	0.118	−0.089	−0.074	0.929**
Grenada	1.664	0.880	−0.297	−1.022	0.710	0.688
Guatemala	1.554	1.313	0.374	0.672	0.178	0.952***
Guyana	2.318***	−0.229	0.428*	−0.089	0.105	0.980***
Honduras	−0.188	0.087	−0.030	0.827	0.005	0.792
Jamaica	−0.776	1.963	0.691*	−0.728	−0.439*	0.862*
Saint Lucia	−0.822	1.414	−0.086	0.906	0.902	0.316
Mexico	−0.145	−0.022	0.244	−0.206	−0.024	0.063
Nicaragua	1.474	0.352	0.276	−0.688	−0.083	0.900**
Panama	0.061	1.104	−0.200	1.231	0.239	0.896*
Portugal	−1.212	−0.072	0.126	2.216**	−0.072	0.916**
El Salvador	−2.530	−0.627	−0.140	2.152	−0.306	0.575
Suriname	0.615	−0.038	−0.069	0.141	−0.865	0.820
Vietnam	0.943	0.157	NA	−0.001	−0.037	0.889***
China	0.557	0.379	0.345	−0.095	NA	0.968***
S. Korea	1.035**	0.233*	0.222	−0.883***	0.449*	0.906***
Singapore	1.272	0.313	−0.079	0.315	0.068	0.949***
United States	−0.188	0.088	−0.030	0.827	0.006	0.792

(0.774**) and services exports (0.625**), while there is a negative correlation with FDI (−0.760**). China shows a strong correlation of CO_2 emission with GDP (0.8935**), high-technology exports (0.974**), and services exports (0.905**), while there is a negative correlation with travel services (−0.422) and FDI (−0.333). These are areas where Latin American countries need to focus by increasing industrialization. **Figure 1** shows further detailed comparisons of correlation between regions or countries. Results of correlation analysis are shared in supplementary material B.

The next step is to apply regression analysis to further check regression results. **Table 3** shows the regression between different variables with the significance between their relationship with the CO_2 of each country. However, **Figure 2** shows the relationship of variables with countries and the Latin American region. From **Table 3**, it can be seen that GDP has significant positive impact on CO_2 emission in Argentina (β = 2.182*), Bolivia (β = 1.127**), Dominica (β = 1.661**) and Guyana (β = 2.318***) while other countries specially China (β = 0.557) and other developed countries like South Korea (β = 0.650), United States (β = 2.563) and Singapore (β = 0.578) also have significant positive relationship. FDI shows a positive relationship with CO_2 emission in Argentina (β = 0.205), Bolivia (β = 0.034), Brazil (β = 0.196), Dominican Republic (β = 0.316), Grenada (β = 0.710) and Panama (β = 0.239), while it shows a negative relationship with other Latin countries like Ecuador (β = −0.152), Jamaica (β = −0.720), Nicaragua (β = −0.083) and Suriname (β = −0.865). Similar positive and negative relationships are also observed in developed countries like the United States (β = -0.046), Singapore (β = 0.358) and South Korea (β = 0.179). The high-technology exports relationship with CO_2 is positive in Argentina (β = 0.125), Belize (β = 0.030), Colombia (β = 0.432), Costa Rica (β = 0.135), Dominican republic (β = 0.057), Ecuador (β = 0.093), Guatemala (β = 0.625),Jamaica (β = 0.896) and Portugal (β = 0.126) while this relationship is negative in other Latin American countries like Suriname (β = −0.069), El Salvador (β = −0.140), Panama (0.200), Saint Lucia (β = −0.086) and Honduras (β = −0.030). For developed countries the relationship is positive in South Korea (β = 0.407), Singapore (β = 0.049) and the United States (β = 0.322).

Figure 2. Taking Latin American countries as a region, the relationship between CO_2 and GDP is weak, R^2 = 0.43 shows that it is lower, while strong in China (R^2 = 0.87) and other developed countries like Singapore (R^2 = 0.68), United States (R^2 = 0.76) and South Korea (0.85). Similarly, for the trade of high-technology exports and CO_2, Latin America has a weak relationship with R^2 = 0.05 while other countries have a strong relationship, like China (R^2 = 0.95), South Korea (R^2 = 0.72), United States (R^2 = 0.64) and Singapore (R^2 = 0.76). FDI shows a weak relationship with CO_2 in Latin America (R^2 = 0.22) and China (R^2 = 0.11), while for developed countries the relationship is strong, such as South Korea (R^2 = 0.85) and Singapore (R^2 = 0.49). Trade of services exports is a strong predictor for CO_2 emission in China (R^2 = 0.82), South Korea (R^2 = 0.69), Singapore (R^2 = 0.75) and the United States (R^2 = 0.93), while it is a weak predictor in Latin American countries (R^2 = 0.22). Results of regression are similar to the study by (Wang et al., 2019) where a direct positive relationship

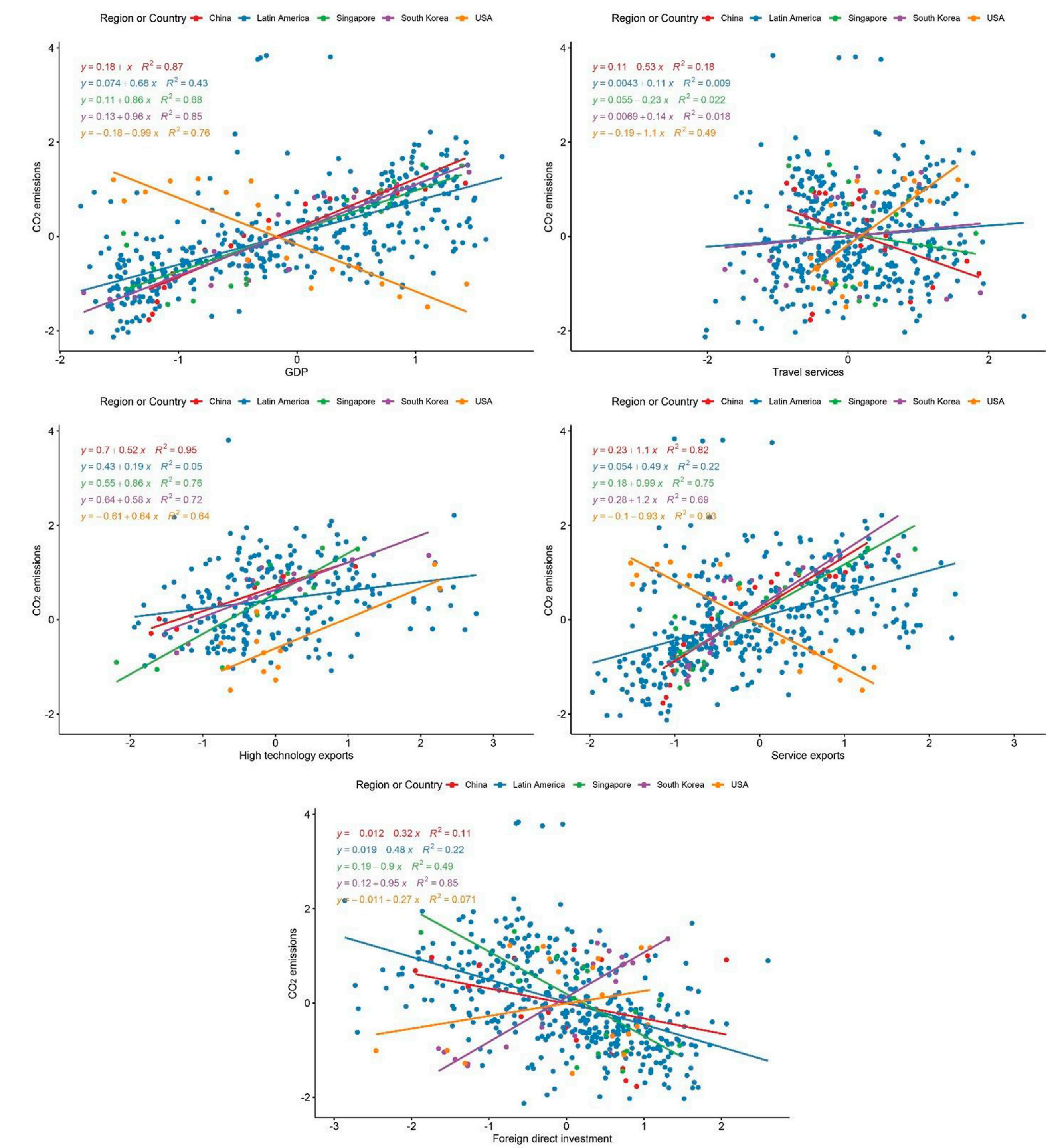

FIGURE 2 | Regression analysis of different factors in different countries.

between CO_2 emission and trade exists in China and Australia. A study by (Khaskheli et al., 2021) indicated a similar results pattern in low-income countries by using the panel smooth transition regression model. This study result confirmed that the nexus between the variables is nonlinear. Moreover, it also shows that high trade and FDI increase the CO_2 emissions, but as the economy of MIT states progresses to a higher regime, the association between the two variables becomes significant. (Koengkan et al., 2020), in research on CO_2 emission in 18 Latin American and Caribbean countries, also found

TABLE 4 | ARDL model for Latin America and other countries.

	β Coefficient	Std. Error	t value	Pr (>|t|)	Multiple R^2
Latin America					
(Intercept)	0.045	0.044	1.034	0.303	0.842 ***
L (CO2 emissions, 1)	0.827	0.052	15.877	0.000	
GDP	0.270	0.107	2.517	0.013	
L (GDP, 1)	0.010	0.139	0.075	0.940	
L (GDP, 2)	−0.129	0.087	−1.482	0.141	
Travel services	0.030	0.040	0.748	0.456	
High technology exports	0.014	0.054	0.266	0.791	
L (High technology exports, 1)	0.016	0.064	0.247	0.806	
L (High.technology.exports, 2)	−0.041	0.065	−0.640	0.523	
L (High technology exports, 3)	−0.012	0.066	−0.184	0.854	
L (High technology exports, 4)	−0.024	0.050	−0.484	0.629	
L (High technology exports, 5)	0.049	0.044	1.102	0.272	
L (High technology exports, 6)	−0.073	0.037	−1.974	0.050	
Service exports	0.046	0.068	0.677	0.499	
L (Service exports, 1)	−0.144	0.070	−2.069	0.041	
FDI	0.042	0.041	1.005	0.317	
L (FDI, 1)	−0.018	0.044	−0.396	0.692	
L (FDI, 2)	−0.021	0.043	−0.481	0.631	
L (FDI, 3)	−0.120	0.042	−2.874	0.005	
China					
(Intercept)	0.328	0.137	2.395	0.062	0.998***
L (CO_2 emissions, 1)	0.523	0.353	1.481	0.198	
GDP	−0.744	0.651	−1.143	0.305	
L (GDP, 1)	0.772	0.714	1.081	0.329	
Travel services	0.110	0.047	2.349	0.065	
L (Travel services, 1)	0.052	0.091	0.576	0.589	
High-technology exports	−0.070	0.050	−1.400	0.220	
L (High-technology exports, 1)	−0.072	0.072	−1.004	0.361	
Service exports	0.356	0.321	1.110	0.317	
L (Service.exports, 1)	0.324	0.371	0.873	0.422	
Foreign direct investment	−0.195	0.069	−2.835	0.036	
L (FDI, 1)	0.011	0.058	0.190	0.856	
South Korea					
(Intercept)	0.268	0.262	1.021	0.341	0.967***
L (CO_2 emissions, 1)	0.201	0.439	0.458	0.661	
GDP	0.662	0.622	1.064	0.323	
L (GDP, 1)	0.231	0.586	0.395	0.705	
Travel services	0.219	0.196	1.114	0.302	
L (Travel services, 1)	−0.095	0.214	−0.444	0.671	
High-technology exports	0.589	0.331	1.778	0.119	
L (High-technology exports, 1)	−0.325	0.141	−2.311	0.0541	
Service exports	−2.058	1.378	−1.493	0.179	
L (Service.exports, 1)	1.424	1.433	0.994	0.353	
FDI	0.323	0.243	1.327	0.226	
L (FDI, 1)	0.057	0.300	0.191	0.854	
Singapore					
(Intercept)	−0.293	0.240	−1.219	0.290	0.961*
L (CO_2 emissions, 1)	0.316	0.688	0.460	0.669	
GDP	1.632	1.732	0.942	0.399	
L (GDP, 1)	−1.242	1.565	−0.793	0.472	
Travel services	0.246	0.582	0.424	0.693	
L (Travel services, 1)	0.063	0.512	0.124	0.908	
High-technology exports	0.170	0.300	0.569	0.600	
L (High-technology exports, 1)	0.175	0.373	0.469	0.664	
Service exports	0.896	1.926	0.465	0.666	
L (Service.exports, 1)	0.115	1.662	0.069	0.948	
FDI	0.543	0.346	1.570	0.191	
L (FDI, 1)	0.544	0.662	0.823	0.457	
United States					
(Intercept)	3.3177	0.4545	7.299	0.0867	0.997*
L (CO_2 emissions, 1)	0.3231	0.1675	1.929	0.3045	
GDP	−16.9782	3.9464	−4.302	0.1454	
L (GDP, 1)	23.5397	5.6189	4.189	0.1492	

(Continued on following page)

TABLE 4 | (*Continued*) ARDL model for Latin America and other countries.

	β Coefficient	Std. Error	t value	Pr (>|t|)	Multiple R^2
Travel services	2.8327	0.3822	7.412	0.0854	
L (Travel services, 1)	−0.7995	2.8034	−0.285	0.8231	
High-technology exports	0.9272	0.159	5.83	0.1081	
L (High-technology exports, 1)	−1.7482	0.2074	−8.428	0.0752	
Service exports	−0.3117	1.239	−0.252	0.8431	
L (Service.exports, 1)	−3.8073	4.1696	−0.913	0.5289	
Foreign direct investment	0.623	0.1134	5.494	0.1146	
L (FDI, 1)	1.182	0.2078	5.687	0.1108	

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05.*

asymmetric effects on globalization and identified that economic globalization, social globalization and political globalization exert an adverse impact on CO_2 emissions.

After collecting significant factors from correlation and regression models, the next step is to validate the results by checking with the ARDL econometric model (**Table 4**). The result of the ARDL model in **Table 3** shows that in the Latin American model the R^2 value is 0.597. The lag coefficient β has shown that a weak GDP has a weak impact on CO_2 i.e., β = 0.251 for the best lag model. Similarly, high-technology export (β = 0.065) and FDI (-0.065) have a weak impact on CO_2 for Latin American countries. For China, the R^2 value is 0.998, showing a significant impact of variables on CO_2 emission. Lag coefficient β is 0.772 for GDP showing that CO_2 emissions are impacted by the economic growth of the country. Similarly, β is weak for services exports (0.356) and FDI (0.011) while negative for high-technology exports (0.070). In South Korea, the GDP has a strong impact on CO_2 emissions, where β is 0.497. For travel services β is 0.233 and services export β is 2.328, for FDI it is 0.375 and for high-technology exports it is 0.481, which shows a positive impact on CO_2 emission. For Singapore, the R^2 is 0.951, showing a strong relationship of variables with CO_2. GDP is strongly related to CO_2 emission with β = 1.632 and travel services β is 0.063. Similarly, in the United States the CO_2 emission shows a strong relationship with GDP with β = 4.603, high-technology exports with β = 0.213 and travel services with β = 0.406. These results were similar to the study by (Hotak et al., 2020) using the long-term ARDL approach and finds a positive relationship between trade balances and CO_2 emissions for high-income countries, which is the same as in our study (Sun et al., 2019). results contradicted our study on China because his study finds a negative impact of services trade and a positive impact of FDI, using long-term ARDL. As shown in **Figure 3**, at the significant level of 5%, both CUSUM and CUSUMSQ curves are within the bounds (the red dotted line is the boundary), suggesting that the stability of the model is proved.

To ensure the stability of the proposed model, an ARDL series is tested by adding the recursive residuals, cumulative sum (CUSUM), and cumulative sum of square (CUSUMSQ) analyses. **Figure 3** shows plots of the CUSUM and CUSUMSQ graphs. If the curves of CUSUM and CUSUMSQ remain within the critical range of 5%, it represents the parameter stability and the stability of the model.

Path analyses were used to find the relationship between CO_2 (dependent variable) and other factors (independent variable). The path analysis model was used to predict the direct and indirect relationships between the CO_2 and the other factors such as FDI, economic growth and trade (**Figure 4** and **Table 5**). β is the correlation coefficient that shows the degree of the relationship. The higher the value of beta, the stronger the association between the variables. It can be observed that for China, the CO_2 β coefficient with the GDP is 0.787, whereas it is low but positive for travel services i.e., 0.378, and for high-technology exports it is 0.495. In China, it has a negative relationship with FDI, with the β coefficient being -0.078. For South Korea the results are similar i.e., CO_2 emission has a strong relationship with GDP at β = 1.095, a weak relationship with FDI at β = 0.475, travel services at = 0.246 and high-technology exports at β = 0.194. Korea has a negative relationship of CO_2 with services exports i.e., β = -0.934. In the United States, CO_2 emission has a strong relationship with GDP at β = 1.217, while the weak relationship with high-technology exports is β = 0.421, and travel services it is β = 0.268. FDI and services exports have a negative relationship with CO_2 emission with β that is −0.159 and −1.297 respectively. In Singapore, the CO_2 emission has a positive relationship with GDP (β = 0.392), travel services (β = 0.533), high tech exports (β = 0.050), services exports (β = 1.386) and FDI (β = 0.366). In the case of Latin America, the CO_2 emission has a weak relationship with GDP (β = 0.363) and high-technology exports (β = 0.076), while it has a negative relationship with travel services (β = −0.104), services exports (β = −0.015) and FDI (−0.129).

By using the Granger test, the calculated t-statistics of the lagged value of the ECT indicates that there is a long-run causality from the travel services, FDI, services exports, and economic growth on carbon emissions. The tabulated (F) statistics values (**Table 6**) indicate that there is a unidirectional causal relationship from travel services, FDI, services exports, and economic growth on carbon emissions. This study is significant for middle-income countries as it focuses on various factors that can help to avoid MIT. Overall, changes in industrial scale, trade structure, marketization and export dependence can explain changes in CO_2 emissions to a

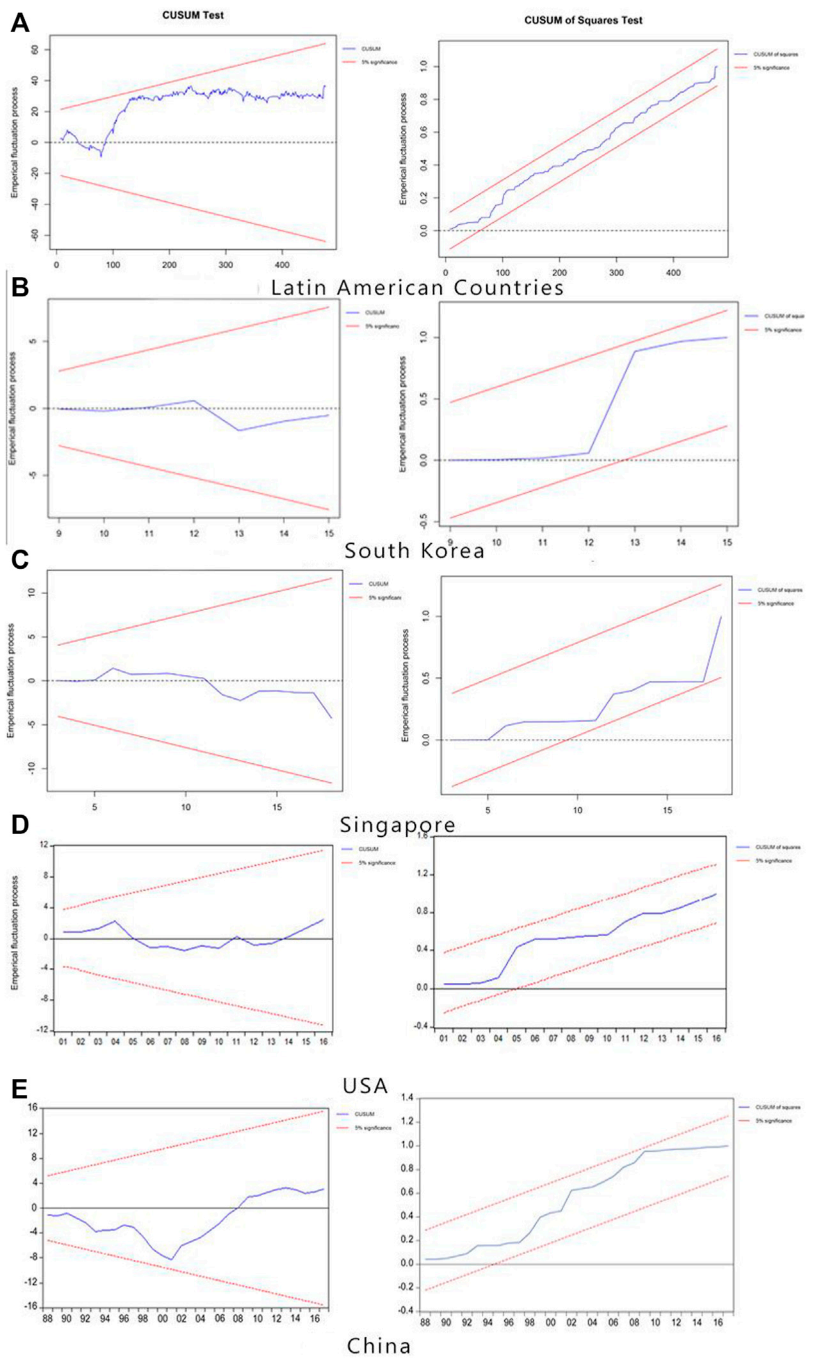

FIGURE 3 | The plot of the cumulative sum and cumulative sum of squares of recursive residuals.

certain extent. The effects of CO_2 emissions from export trade in other industries are very significant, except that there is no scale or structural effect in the mining industry, no structural effect in the leather, fur, down and related products industry, and no market effect in the pharmaceutical manufacturing industry, and no policy effect in the metal products industry (Adebayo and Rjoub, 2021). The combined force of industry scale, trade structure, marketization, and export dependence lead to both negative and positive effects of export trade on CO_2 emissions. Purely from an industry perspective, there are obvious differences in the intensity and direction of the impact of the scale, trade structure, marketization degree, and export dependence of various industries on CO_2 emissions. Most industries have a negative impact on CO_2 emissions, while trade structure has a positive effect on CO_2 emissions. That is to say, the expansion of the industrial scale leads to the

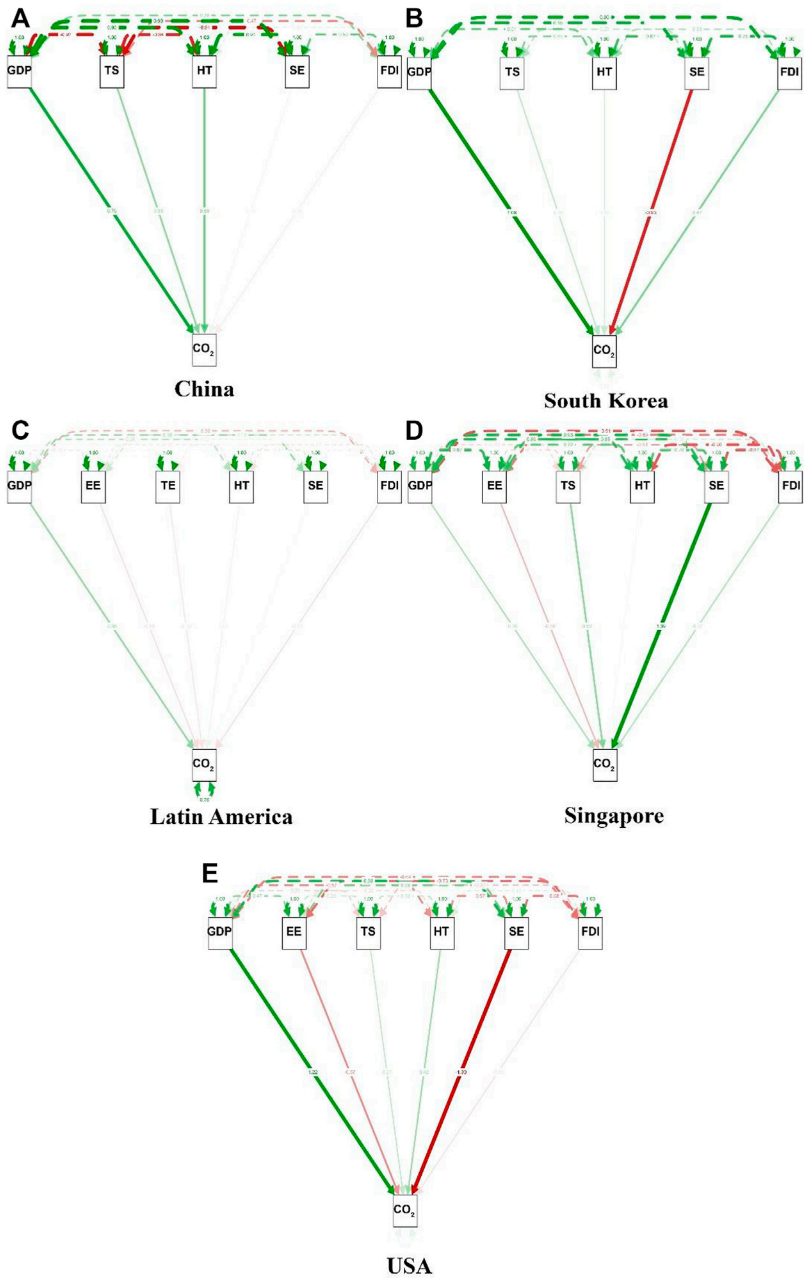

FIGURE 4 | Path analysis of different factors in different countries.

deterioration of CO_2 emissions, while the trade structure has a positive effect. Advances have led to improvements in CO_2 emissions; however, there is a big difference between market effects and policy effects. Changes in the degree of marketization and dependence on export trade in some industries are conducive to reducing CO_2 emissions (Wenlong et al., 2022). In the long run, the expansion of the industrial scale will still exacerbate CO_2 emissions, and the upgrade of the trade structure will promote the reduction of CO_2 emissions. Although export trade growth is an important factor affecting CO_2 emissions, export trade may not necessarily lead to an absolute increase in CO_2 emissions. Therefore, we believe that the fundamental way to reduce CO_2 emissions lies in optimizing trade structure and scientifically managing export trade. Future work is directed towards using the latest machine learning methods like recommendation system (Bhatti et al., 2018; Bhatti et al., 2019) or hybrid models (Bhatti et al., 2021b).

TABLE 5 | Path analysis model results for all countries.

Countries/Factors	Estimate	Std.Err	z-value	P (>|z|)	Std. lv	Std.all	R^2
China							
GDP	0.563	0.443	1.27	0.204	0.563	0.787	0.969
Travel services	0.398	0.157	2.533	0.011	0.398	0.378	—
High-technology exports	0.262	0.2	1.311	0.19	0.262	0.495	—
Service exports	0.044	0.442	0.1	0.92	0.044	0.06	—
FDI	−0.034	0.065	−0.516	0.606	−0.034	−0.078	—
South Korea							
GDP	1.035	0.223	4.643	0	1.035	1.095	0.907
Travel services	0.233	0.084	2.778	0.005	0.233	0.246	—
High technology exports	0.222	0.128	1.74	0.082	0.222	0.194	—
Service exports	−0.883	0.152	−5.829	0	−0.883	−0.934	—
FDI	0.449	0.172	2.618	0.009	0.449	0.475	—
Latin America							
GDP	0.552	0.085	6.469	0	0.552	0.43	0.281
Travel services	−0.047	0.062	−0.76	0.447	−0.047	−0.044	—
High technology exports	0.064	0.049	1.305	0.192	0.064	0.077	—
Service exports	−0.05	0.06	−0.833	0.405	−0.05	−0.052	—
FDI	−0.169	0.052	−3.243	0.001	−0.169	−0.194	—
Singapore							
GDP	1.272	0.521	2.44	0.015	1.272	0.862	0.950
Travel services	0.313	0.204	1.532	0.126	0.313	0.171	—
High technology exports	−0.079	0.189	−0.416	0.678	−0.079	−0.08	—
Service exports	0.315	0.387	0.814	0.415	0.315	0.285	—
FDI	0.068	0.179	0.379	0.705	0.068	0.062	—
United States							
GDP	1.53	0.451	3.392	0.001	1.53	1.495	0.778
Travel services	0.279	0.195	1.432	0.152	0.279	0.321	—
High technology exports	0.326	0.132	2.465	0.014	0.326	0.426	—
Service exports	−1.981	0.49	−4.041	0	−1.981	−1.614	—
FDI	0.155	0.145	1.07	0.284	0.155	0.232	—

TABLE 6 | Granger Test with ECT.

				Short Run			Long Run
(Y/X)	ΔlnCO_2	ΔlnGDP	ΔlnTravelServices	ΔlnHighTech exports	ΔlnFDI	ΔlnServicesexports	ECTt-1
ΔlnCO_2	—	7.93**	4.91	7.14**	7.51**	7.78**	−0.051 (−2.615) **
ΔlnGDP	2.44	—	—	6.21	3.45	3.77	−0.024 (−1.29)
ΔlnTravelServices	1.34	2.87	2.78	1.97	1.91	3.27	−0.19 (−0.13)
ΔlnHighTech exports	3.25	3.54	2.74	—	2.79	3.51	−0.017 (−0.88)
ΔlnFDI	201	5.78*	3.04	8.76**	—	1.91	−0.0.791 (−0.89)
ΔlnServicesexports	1.03	6.22	2.91	6.58**	3.36	—	−0.003 (−0.13)

*Note: *, ** denotes significance at the 1 and 5% level, respectively.*

4 CONCLUSIONS AND POLICY IMPLICATIONS

4.1 Conclusions

This study compares and analyzes different criteria for determining the MIT in Latin American countries and provides possible reasons for the MIT. Our research finds that the social and economic development of Latin American MIT countries contains some common characteristics, and the findings help us understand the mechanism of the MIT. In South Korea, the United States and Singapore, with an analysis of the proportion of trade exports of various types of export commodities, a reasonable explanation for the difference in the export commodity structure between MIT and non-MIT countries is obtained. For non-MIT countries, the industrial upgrading process seems to be consistent with the flying geese pattern of development, but it is also increasing the environmental issues related to CO_2 emissions. Government should either follow green environment policies to reduce the burden of CO_2 emissions or develop a sustainable environment policy by creating a trade balance. It follows that industrial upgrading through backward linkages between consumer goods and capital goods is more successful in high-income countries that are not in MITs. For countries that are MITs, there is a tendency to rely on exports of primary products, while industrialization is driven by forward linkages of finished products. Limitations of this study are to its focus on few variables, which can impact on quality on results. In future we will be focused on more high quality variables.

4.2 Policy Implications

From the empirical results of this study, the transfer of environmental load through international trade could be forecasted regularly using the relationship extraction between factors with regression, and long-term impact can be monitored with the ARDL model. The environmental loads of international trade, such as water, land use, and energy use, are considered under the current international division of labor between countries. According to the producer-based responsibility principle, a country has responsibility only for the emissions or pollutants that are generated directly within its borders; a typical case is the international climate change regime. To achieve CO_2 reduction targets, countries have the incentive to outsource CO_2 emissions to other countries, and both the national and global efforts toward CO_2 reduction could be undermined by this "CO_2 leakage" phenomenon. Therefore, it would be difficult to devise effective environmental policies if the real distribution and balance of the environmental impacts of trade are not considered. For countries that are facing MIT, it is important to focus on trade factors as the results reveal that in China, trade components are directly impacting the economic growth and CO_2 emissions, and other high-income countries show the same results as China. The policy implications of the findings of this study are very direct. It is necessary to develop the consumer goods industry and maintain competitiveness in promoting the upgrading of industries to capital goods through backward linkages. Although there are many problems in the economic development of Latin America, these difficulties can be addressed by economic and social policies. Based on the reasons analyzed above, Latin American governments can implement the following policies:

- Raise the national education level and train workers in advanced technology
- Increase scientific research funding and encourage R&D innovation
- Promote industrial upgrading
- Create a favorable environment for foreign investment and encourage overseas investment to stimulate the economy
- Improve the role of taxation; allow taxation to reduce the gap between the rich and the poor, and increase social welfare

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

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A study on the impact of fiscal decentralization on carbon emissions with U-shape and regulatory effect

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The Chinese government set a goal in 2009 to cut carbon emissions by 40–45 percent of 2005 GDP per unit by 2020. The role of fiscal decentralization reform in strengthening environmental governance has gained importance. This paper explored the impact of fiscal decentralization reform from 2010 to 2019 on carbon dioxide emissions in China. We utilized the first-order differential dynamic panel econometrics model to examine the correlation between fiscal decentralization and carbon dioxide emission under fiscal imbalance and transfer indirect effects. The findings revealed that 1) fiscal imbalance reduced CO_2 emissions due to the decentralization of revenue, and expenditure asymmetry undermined CO2 emissions control. 2) The central government's transfer payments offset the negative consequences of a fiscal imbalance. The fiscal decentralization of the government caused a difference between regional income and expenditures in the budget. However, it could affect local government expenditure on carbon emission control through central transfer payments, which could restrain carbon emissions and control environmental pollution. 3) The impact of fiscal decentralization on carbon dioxide emissions was influenced by the industrial structure with the U-Shape effect. This was because the adjustment of the industrial structure was cross-term. In the early stage of the industrial structure adjustment, there was a significant decline in coal consumption demand and carbon emissions reduced. However, as the proportion of the secondary industry increased, there was a significant positive correlation between the secondary sector and carbon dioxide emissions in China. Our findings have important policy implications. First, while the promotion of Chinese officials is based on local GDP performance, locals may introduce green GDP as the criterion for rating governments' performance. Second, local governments should improve environmental governance by increasing technical, environmental protection, and innovation investment. All in all, the findings provide a theoretical basis for relevant research and policy suggestions for China.

KEYWORDS

fiscal decentralization, carbon emissions, fiscal imbalance, transfer payments, industrial structure, environmental economics, empirical analysis, econometrics

1 Introduction

Climate change and global warming recently emerged as two main concerns worldwide, and there is a growing consensus that countries must find solutions (Boutabba, 2014; Ma et al., 2019; Dong et al., 2020a, 2020b). According to World Bank figures, carbon dioxide (CO_2) emissions have drastically expanded during the past 3 decades, rising 64.29% from 1990 to 2018 (World Bank 2020).

China has enjoyed fast economic growth since implementing the Open Door Policy. Nevertheless, it resulted in a significant increase in carbon dioxide emissions. The Chinese government set a goal in 2009 to cut per-GDP carbon emissions from 2005 by 40–45 percent by 2020. China is under enormous pressure to reduce emissions and reduce pollution. According to Cai et al. (2008), China's environmental difficulties are caused by the "Chinese-style decentralization." Local governments play a critical role in CO_2 emissions under the fiscal decentralization framework. Fiscal decentralization affects carbon dioxide emissions in both direct and indirect means. The direction of the indirect effect is determined by fiscal revenue, governmental fiscal receipts, and expenditure. Fiscal decentralization is impacted by political and economic centralization. Environmental taxes raise local government revenue and reduce pollution, which may harm the economy.

The role of fiscal decentralization reform in strengthening environmental governance has gained importance under China's national "13th Five-Year Plan" strategy. So, how will the fiscal decentralization reform impact CO_2 emissions in China in these 10 years? Does the fiscal decentralization system support or hinder local governments' efforts in carbon emissions reduction? On the other hand, GDP-based incentives may drive local governments to put more effort into economic growth at the expense of the environment. So, what is the impact of China's fiscal imbalance and transfer on CO_2 emissions?

China's taxation reform in 1994 allowed fiscal decentralization where the central and local governments' shared expenditure duties (Zhang, 2020). The federal government receives the most fiscal revenue, and tax collection and administration are the federal government's responsibility. The central government must achieve two goals during this process: increase fiscal revenue and improve macro-control. Local governments benefit from fiscal decentralization to the best use of limited financial resources, fiscal decentralization and autonomy in expenditure. They may spend more financial resources to reach the central government's target developments by supporting polluted and/or energy-intensive enterprises, such as petroleum, chemical, steel, and electricity. In addition, the regional market segmentation and repeated construction of local economic growth and revenue immediately affected the short-run (Liu, 2005). Local governments began to compete for resources to meet the goal in the short run. In China's GDP-oriented appraisal system, local governments often spend money on infrastructure and investment to achieve economic growth requirements (Li and Du, 2021).

Nevertheless, they have few fiscal revenue sources. As a result, uneven revenue devolution and expenditure decentralization exacerbate fiscal imbalance (Jia. et al., 2020). As environmental goals cannot be achieved in a short time, it is often sacrificed (Lin and Du, 2021).

Although existing studies have recognized the existence of fiscal imbalance (Bouton et al., 2008; Meloni, 2016), the research on the impact of fiscal imbalance is rare. As for the relationship between fiscal imbalance and CO_2 emissions, previous studies discussed it from the perspective of fiscal decentralization, but there is no consensus on this relationship. Several governments and academics consider fiscal decentralization a viable option to reduce carbon dioxide emissions; they argue that it leads to a "race to the top" among local governments by requiring stricter environmental standards to create environmentally friendly surroundings. As a result, they were reducing contamination in the affected areas (Mu, 2018; Chen and Chang, 2020). Indeed, governments have delegated their environmental policy responsibilities to local governments recently.

Nevertheless, in recent years, a divergent perspective on fiscal decentralization's impact on carbon dioxide emissions has heightened worries (Zhang K. et al., 2016). The proponents of this point of view think fiscal decentralization might "race to the bottom": municipal governments neglect environmental standards to entice international firms, increasing CO_2 emissions. Due to contradicting findings, scholars have become interested in fiscal decentralization's impact on carbon dioxide emissions. Despite the long history of fiscal decentralization, the US treasury remains centralized, and few research has studied the effects of fiscal decentralization on CO_2 emissions. Furthermore, past research has largely ignored the possibility of panel data cross-sectional dependency and slope variability. Based on Ahmed et al. (2020), the abovementioned contradicting results could be accounted for by human capital and institutions. As a result, it is worth investigating whether fiscal decentralization can indirectly impact carbon dioxide emissions via human capital and institutions, despite the functions of human capital and institutions that have yet to be examined thoroughly.

Furthermore, given the dynamic game and adverse selection between the central and local governments, fiscal decentralization has both positive and negative externalities, and its impact may be nonlinear. Elheddad et al. (2020) studied the provincial panel data from 2006 to 2015 using quantile regression. They discovered a nonlinear relationship between fiscal decentralization and energy consumption. Greater fiscal decentralization could lower carbon emissions, according to Cheng et al. time-series econometric analysis of Chinese data from 2005Q1 to 2018Q (Cheng et al., 2020). Song et al. (2018) came to similar conclusions. Additionally, some researchers

TABLE 1 The descriptive statistics of variables.

Variables	Variable symbol	Description
Carbon emission	CO_2	Emission formula
Fiscal Decentralization	FD	Revenue within the provincial financial general budget /revenue from the central government's general budget
Fiscal Imbalance	FI	Budget revenue/budgetary expenditure at the provincial level
Fiscal transfer	FT	Local fiscal revenue of each region/(The region's fiscal revenue + central transfer payments)
Industrial structure	IND	The added value of the secondary industry accounts for the proportion of the GDP of each province
Degree in Economic Development	Income	Real GDP per capita in each province
Foreign direct investment	Invest	The real value of the amount of foreign direct investment completed in various regions
The effect of the opening degree of foreign trade	Trade	The actual value of the total import and export volume
Population density	Pop	The ratio of population and area at the end of the year
Environmental regulation	Pol	the completed amount of environmental pollution control investment
Technology investment	Tech	number of industrial waste gas treatment facilities
Greenland area	GA	Per capita green area

found that fiscal decentralization increased investment in environmental protection and had no discernible effect on pollution, which may be explained by Chinese culture and emotion (He, 2015).

This paper examines the impact of fiscal decentralization on CO_2 emissions from the perspective of indirect effect. It aims to: 1) Review how fiscal decentralization influences carbon emissions through fiscal imbalance, fiscal transfer, and industrial structure and offer some insights and recommendations for China's budgetary reform. 2) Conduct a theoretical and empirical investigation of the regulatory effect of fiscal imbalance and transfer on carbon dioxide emissions and make policy recommendations. 3) Research the effect of fiscal decentralization and industrial structure on carbon dioxide emissions.

This paper's contribution is threefold; first, despite many studies examining the relationship between fiscal decentralization and CO_2 emissions. There is no consensus on their relationship because fiscal decentralization frequently involves either expenditure or revenue decentralization. This study reviews the impact of carbon emissions based on environmental regulation factors and more comprehensively analyses fiscal decentralization's impact on carbon emissions to improve the effectiveness of model regression parameter estimation. We discover that fiscal decentralization can directly reduce carbon dioxide emissions. Second, in the context of fiscal imbalance, this study discusses the role of fiscal imbalance. The lack of literature on the fiscal imbalance in carbon dioxide emissions and fiscal decentralization makes this study particularly noteworthy. Third, while some academics focused on the impact of fiscal decentralization on carbon dioxide emissions, there is a lack of knowledge on fiscal decentralization's nonlinear impact on environmental quality. This paper examines the nonlinear effect of industrial structure on CO_2 emissions. Finally, this research has policy implications. The findings demonstrate a negative connection between fiscal decentralization and carbon emissions. Fiscal imbalances are the main factor in this indirect effect. As a result, refining the tax system can reduce carbon emissions.

The following is the structure of this paper: Section 2 introduces the literature review and theoretical analysis. The three section is the research hypothesis. Section 4 records the data and methodology. Section 5 presents the empirical findings and discussion. Section 6 discusses the findings and policy implications.

2 Literature review and theoretical analysis

2.1 Research into the effect of fiscal decentralization on CO_2 emissions

Although academics have begun investigating the carbon dioxide emissions and the impact of fiscal decentralization ((Matheus et al., 2019; Yang et al., 2020), there is no consensus regarding the impact of fiscal decentralization on carbon dioxide emissions.

The first school contends that greater fiscal decentralization better serves pollution control and CO_2 emission reduction. Those who believe in this viewpoint argue that in addition to aiding local governments, fiscal decentralization can be beneficial to improving resource-efficient use of resources and comprehension of pollution in the area and residents' preferences for demand (Millimet, 2003; Mu, 2018). Nevertheless, it can also result in local governments'

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TABLE 2 31 Chinese provinces' panel data descriptive statistics.

Variable	Mean	Max	Min	Median	Standard deviation	Number
CO_2	41,320.85	147,817.65	3,696.51	31,374.09	28,987.54	310
FD	0.04	0.14	0.00	0.03	0.03	310
FI	0.49	0.93	0.07	0.45	0.20	310
FT	0.99	1.00	0.90	1.00	0.01	310
IND	46.14	59.21	16.16	48.53	8.81	310
Income	48,285.91	154,199.91	11,437.66	41,466.83	24,959.52	310
Invest	1,465.55	18,392.20	4.45	523.70	2,469.94	310
Trade	8,183.25	69,424.58	34.65	2,501.81	1,360.85	310
Pop	0.04	0.23	0.00	0.03	0.04	310
Pol	241.10	1,416.20	0.30	195.25	193.59	310
Tech	9,362.69	57,278.00	46.00	6,404.00	8,539.47	310
GA	0.339	10.57	0.003	0.079	1.103	310

competition for resources due to nimbyism which encourages environmental regulations implemented by local governments (Levinson, 2003). On the other hand, local authorities can bring about economic development while improving environmental quality under fiscal decentralization (Yang et al., 2020). For instance, Hao et al. (2020a) found that the impact of fiscal decentralization on CO_2 emissions was negative.

Others suggested fiscal decentralization raised carbon dioxide emissions, pinpointing the 'race to the bottom' phenomena (Liu et al., 2019). Many academics have backed this claim, claiming that local governments are more likely to "race to the bottom", reducing local environmental restrictions to allow for more economic development, favoring an increase in CO_2 emissions. The impact of fiscal decentralization on the operational processes of environmental policy in China while allowing for spatial correlations in CO_2 emissions, resulting in the green paradox. Zhang D. et al. (2016) also came to the same conclusion.

Several governments and academics considered fiscal decentralization a viable option to reduce carbon dioxide emissions (Matheus et al., 2019). They argued that fiscal decentralization could lead to a "race to the top" among local governments. By requiring stricter environmental standards environmentally friendly could reduce contamination in the affected areas (Mu, 2018; Chen and Chang, 2020). Indeed, in recent decades, several global central governments have outsourced their environmental policy responsibilities to local governments. The governments at issue oversee most nations in the Economic Cooperation and Development Organization (OECD).

Nevertheless, a divergent perspective on fiscal decentralization's impact on carbon dioxide emissions has heightened worries (Zhang D. et al., 2016bib_Zhang_et_al_2016abib_Zhang_et_al_2016abib_Zhang_et_al_2016a). The proponents of this point of view think fiscal decentralization might "race to the bottom" in which municipal governments neglect environmental standards to attract international firms, increasing CO_2 emissions. Due to contradictory findings, scholars have become interested in relating fiscal decentralization to carbon dioxide emissions. Despite a long history of fiscal decentralization, the US treasury remains centralized. Research on the effects of fiscal decentralization on CO_2 emissions is scarce.

Furthermore, previous research has largely ignored the possibility of panel data cross-sectional dependency and slope variability. Based on Ahmed et al. (2020), the abovementioned contradicting results could be accounted for by human capital and institutions. As a result, it is worth investigating whether fiscal decentralization can indirectly impact carbon dioxide emissions via human capital and institutions, despite the functions of human capital and institutions that have yet been thoroughly examined.

This study collected a well-balanced panel dataset of China's 31 provinces from 2010 to 2019 to examine the effect of fiscal decentralization on CO_2 emissions based on scholarly gaps in prior studies. It also investigated the role of fiscal imbalance in how fiscal decentralization affects greenhouse gas emissions to understand the influencing factors better.

2.2 Studies on fiscal imbalance affecting CO_2 emissions

Many emerging and developed countries have gone through fiscal decentralization, and local governments' fiscal revenue and expenditure are often out of balance (Bhattacharyya. et al., 2017; Bellofatto and Besfamille et al., 2018; Jia et al., 2020). Bellofatto et al. showed that vertical fiscal imbalance was inherent to multi-level governments. Eyraud and Lusinyan (2013) presented stylized facts on vertical fiscal imbalances in OECD countries,

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TABLE 3 Results of regression.

	Model (1)	Model (2)	Model (3)	Model (4)
CO_2(-1)	1.050***	1.048***	1.050***	1.054***
FD	−5.162*	−11.256***	−2.468**	−5.259*
FI		0.187*		
FD*FI		10.721**		
FT			2.319*	
FD*FT			2.138**	
IND	36.250**	35.124**	36.803***	−290.610***
IND^2				4.202***
Income	0.001	−0.009	0.001	0.002
Invest	0.204*	0.288**	0.235**	0.192*
Trade	6.209e-06	−1.962e-06	5.701e-06	6.792e-06
Pop	−4.097	−1.129*	−5.931	−0.414
Pol	0.727	−0.311	−0.377	−0.340
Tech	−0.069**	−0.047**	−0.067**	−0.057*
GA	−0.163*	-0.170**	−0.074	−0.145**
R^2	0.9927	0.9929	0.9928	0.9929
AR (2)	0.933	0.854	0.909	0.947
Sargan test	0.917	0.985	0.923	0.917

Legend: $^*p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$.

which showed a negative empirical relationship between fiscal imbalance and fiscal performance. Jia et al. (2020) found that higher fiscal imbalance induced a form of fiscal indiscipline. According to traditional fiscal federalism, decentralization of fiscal authority would create a competitive advantage in information, encouraging local governments to adjust to their preferences (Tiebout, 1956; Oates and Schwab, 1988). However, decentralization of revenue and expenditures are often not aligned during implementation. As a result of the expanding fiscal deficit, local governments might choose to invest in productive projects and infrastructure, which will generate a significant short-term increase in tax receipts and economic performance. Meanwhile, the promotion of Chinese officials is based on GDP performance to boost economic performance and win political capital (Tang et al., 2012; Yao and Zhang, 2015). Local governments are likely to continue to scale back environmental regulations to entice investment and redirect scarce budgetary resources toward economic development while neglecting the importance of environmental protection and carbon reduction.

The structure of an advanced industrial sector can reduce CO_2 emissions. Since different industries have different energy demands, which may directly affect pollution emissions, the change in industrial structure will first result in a change in CO_2 emissions. Because steel, cement, and chemicals are energy-intensive and highly polluting, secondary industries tend to reduce CO_2 emissions (Zhang D. et al., 2016; Feng. et al., 2020a). On the other hand, the tertiary sector might lower energy use and environmental pollution (Luan et al., 2021). Regression analysis of Chinese provincial data from 1999 to 2016 by Zhu et al. (2019) revealed that the advancement of the industrial structure had a more significant impact than the adjustment of the industrial structure on the green economy efficiency. Local governments may prioritize introducing and developing industries that can generate economic benefits and tax revenue in the short run to relieve fiscal pressure and boost the local economy as the fiscal imbalance grows. As a result, one of the potential pathways for fiscal imbalance will be the industrial structure.

2.3 Literature gap

Although more study was conducted on fiscal decentralization's environmental impacts, there are still some research gaps. First, even though some academics have begun to examine the effects of fiscal decentralization on CO_2 emissions, there is still a lack of knowledge in incorporating nonlinear terms with fiscal decentralization in conjunction with their impact on environmental quality. Second, we believe that apart from the immediate influence. We anticipate the indirect effect of fiscal decentralization on CO_2 emissions via various channels, such as fiscal imbalance, fiscal transfer, and industrial structure. To the best of our knowledge, however, relatively little research has carefully examined the functions of these variables which could restrict CO_2 emissions. Few research studies have examined indirect roles while nonlinearly investigating fiscal decentralization's influence on CO_2 emissions. Lastly, although prior studies have acknowledged the presence of fiscal imbalance (Bouton L et al., 2008), research on the impact of fiscal imbalance on carbon dioxide emission is scarce.

3 Research hypothesis

China attaches great importance to environmental and ecological protection. It strengthens pollution control, prevention, and ecological improvement and promotes green development. Fiscal departmentsat all levels follow the guidance of ecological progress, optimize the structure of expenditures in the face of apparent conflicts between government revenue and expenditure, and prioritize investment in environmental protection while reducing general expenditures to provide strong support for the tough battle against pollution. From 2016 to 2018, 2.451 billion yuan was allocated, with an annual growth rate of 14.8%, 6.4 percentage points higher than government expenditure in the same period. The proportion of government expenditure increased from 3.7 to 4.2%. Of this total, 1,076.4 billion yuan was allocated by the central government to ecological and environmental protection. In 2019, amid the apparent inconsistency between government

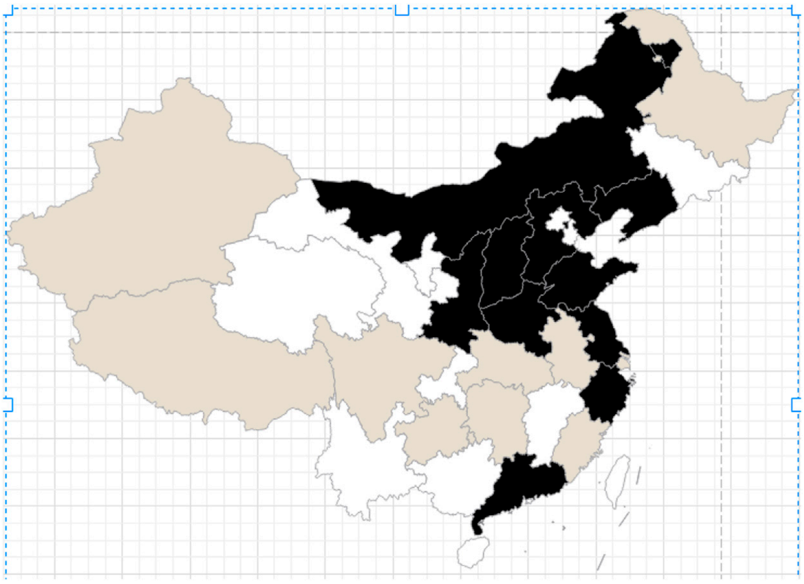

FIGURE 1
Regional differences in carbon emissions in 2010–2019.

revenue and expenditure, governments continued to enhance support for environmental and ecological preservation (China Environmental Statistical Yearbook, China Financial Yearbook).

From 2016 to 2018, the central government allocated 47.4 billion yuan to reduce and regulate air pollution and 57.9 billion yuan for restructuring industrial enterprises to promote structural adjustment in key industries, support steel, reduce coal overcapacity and reduce resource consumption and pollution emissions. With the support of financial funds, the urban air quality has been improving. The fraction of days with favorable air quality in 338 cities in 2018 was 79.3%, up 1.3 percentage points; PM2.5 concentration was 9.3, 22, 22.2, 6.5, 11.8%; and 1899 days, 412 days, pollution intensity, duration, and influence range of heavy pollution weather. Thus, we suggest hypothesis 1.

Hypothesis 1. The higher the fiscal decentralization, the lower the carbon dioxide emissions.

China's market-oriented reform brings fiscal decentralization, which gives local governments significant autonomy in fiscal expenditure. Still, at the same time, local governments should also be responsible for the central government's assessment mechanism predominately concerned with GDP. Since public spending on education, medical care, and environmental protection is slow and cannot be used as political performance assessed by the central government, the most direct and effective way to promote local economic growth is to increase productive expenditures such as economic construction. Through the construction of infrastructure and investment, capital and labor-intensive industries development are encouraged, thus increasing the local tax revenue. Through empirical research, Lopez et al. (2011) concluded that only boosting the government expenditure without changing the expenditure structure could not improve the environmental quality. When the fiscal expenditure structure is devoted to social public goods, it will effectively reduce environmental pollution. Moreover, these capital and labor-intensive industries are easy to cause environmental pollution. From a carbon dioxide emissions perspective, these "competing for growth" local governments may trade-off environmental benefits for economic gains, resulting in increased carbon emissions. Therefore, the regional fiscal revenue growth is faster than expenditure. The gap widens and hinders carbon emissions reduction. Coupled with the abovementioned mechanism, this proposes two hypotheses to be tested:

Hypothesis 2. the wider the gap between fiscal revenue and expenditure, the higher the carbon dioxide emissions.

Hypothesis 3. the fiscal revenue and expenditure gap of local governments impose a negative role on carbon dioxide control under fiscal decentralization

In evaluating the implementation effect of transfer payments, previous research mainly focused on countries' implementation efficiency and ecological benefits (Fiscal Transfers Scheme). Santos et al. (2012) studied the transfer payment system in Portugal and found that the transfer payment funds mainly flew to areas with sizeable ecological protection and relied heavily on fiscal transfer payments. The incentive of transfer payments was enhanced by establishing a suitable information transfer mechanism. Sauquet et al. (2014) and others analyzed the implementation efficiency of ecological VAT with the help of the Bayesian space Tobit model. The study found that there was no cutthroat competition between local governments, but the environmental decisions of various governments had strategic alternatives. Droste et al. (2018a) also evaluated the transfer payment system of Portugal, using the Bayesian time series analysis and simulation of counterfactual time series comparison empirical means found that the system significantly promoted the increase in the number of municipal and national ecological reserves, the implementation of the system and the causal relationship between the rise of the number of reserves. Zhang and Li (2015a) and Zhang and Li (2015b) constructed the mathematical model for analyzing the relationship between the county government and the central government as an example, that is, the dynamic "principal-agent" of the ecological benefit output of the previous phase, and the signal transmission model to consider the heterogeneity of the ecological protection ability of the county-level government. Liu. (2015) built a local government response function and spatial measurement model and identified the eastern six provinces and 46 cities' transfer payment incentive effect of urban environmental governance. "Punishment" was more helpful in strengthening the environmental regulation, the current system limited the incentive role, target compatibility, and system design was the key conclusion. Kong et al. (2017) constructed a general "principal-agent" model between the central government and county-level government. The mathematical analysis results proved that the introduction of variables such as county-level governments and the relative performance incentive mechanism improved the incentive effect of transfer payments. The research hypothesis is thus proposed:

Hypothesis 4. The higher the proportion of fiscal transfer payments, the lower the carbon dioxide emissions

Hypothesis 5. The more significant the proportion of fiscal transfer payments, the stronger the role of fiscal decentralization' effect on controlling carbon emissions increases.

Carbon concentration is directly determined by the level of economic growth and carbon emissions. Industrial structure changes impact carbon intensity because different industries have distinct energy demands. If the energy demand industry occupies a more significant proportion of the national economy and rises faster, energy consumption and carbon emissions will increase. Guo (2012) believed that changes in industrial structure drive the growth of carbon emissions, but in the grand scheme, changes in carbon dioxide emissions are reduced by industrial structures. Li and Zhou (2012) pointed out that the primary factor is the secondary industry affecting the regional carbon emission intensity. Structural changes exhibited a significant impact on China's usage of energy: a decline in the percentage of the primary sector significantly reduced the coal consumption demand, the rise of the industrial proportion drove oil consumption demand, and electricity became the immediate energy consumption in China due to the change of structure and the improvement of the overall economic level (Shi, 2009). On the other hand, economic development has always been the central government target. Local officials in the "promotion championship" and "GDP championship" strongly drives regional economic development. To collect more taxes, highly polluted and/or energy consumption enterprises like petroleum, chemical, steel, and electricity become the primary targets. For their immature development and extended profit cycle, high-tech and service industries are unlikely to soon become local governments' primary taxation source. Local governments lack the motivation to upgrade industries. However, rapid economic growth that relies on highly polluted and high energy consumption industries causes significant environmental damage. Fiscal revenue and official promotion incentives often drove local governments to focus more on capital increment (Fu and Zhang, 2007). To increase fiscal revenue, local governments relax environmental control, lower environmental access threshold, and attract heavy industrial enterprises with good economic benefits and can pay more taxes, resulting in the rapid air quality deterioration. Therefore, when the secondary industry's added value exceeds a certain threshold, it increases carbon emissions. The research hypothesis is based on the initial analysis:

Hypothesis 6. Industrial structure exhibits a "U-type" role in carbon emissions. Specifically, when the secondary industry's added value is small, the carbon emission is suppressed; when the secondary industry's added value increases to a certain extent, the carbon emission will gradually increase.

4 Empirical model and data

4.1 modeling setting

Carbon dioxide emissions are a dynamic process. The carbon emissions of a period could be affected by the current political and economic factors and emissions in the previous period. Because China's industrial capital adjustment and residents' energy consumption habits have inertia, the change in carbon emissions has a certain degree of lag. Therefore, this study uses panel data from 31 provinces and cities from 2010 to 2019 to set up a dynamic panel model for empirical tests. The models are listed as follows:

$$CO_{2i,t} = a_i + \beta_1 CO_{2i,t-1} + \beta_2 FD + \beta_3 FI + \beta_4 FD*FI + \beta_5 Control_{i,t-1} + u_{i,t} \quad (1)$$

$$CO_{2i,t} = a_i + \beta_1 CO_{2i,t-1} + \beta_2 FD + \beta_3 FT + \beta_4 FD*FT + \beta_5 Control_{i,t-1} + u_{i,t} \quad (2)$$

$$CO_{2i,t} = a_i + \beta_1 CO_{2i,t-1} + \beta_2 FD + \beta_3 IND + \beta_4 IND^2 + \beta_5 Control_{i,t-1} + u_{i,t} \quad (3)$$

FD, FI, FT, and IND indicate fiscal decentralization, fiscal imbalance, fiscal transfer, and industrial structure. Among them represents 31 provinces and municipalities directly covering China's central government and autonomous areas, t represents CO_2 carbon dioxide emissions from 2010 to 2019, and CO_2i,t-1 are emissions of the first phase lag. This paper also introduced the indirect variables of fiscal imbalance, fiscal transfer, and industrial structure to verify whether fiscal decentralization affects carbon emissions through indirect variables. The x represents the control variables, including the degree of economic development (income), Foreign direct investment (Invest), The effect of the opening degree of foreign trade (trade), Regarding population density (pop), Environmental regulation (pol), Government investment in science and technology (tech), Greenland area (GA).

4.2 Variable description

4.2.1 Independent variables

Carbon emission (CO_2): the rate at which solid waste is fully utilized was calculated by using typical industrial solid waste in its entirety and general industrial solid waste; the formula of discharge was the total emission of each province. It represented the energy consumption j in the region I during t and the emission coefficient of j energy consumption. The formula for emission coefficient of energy consumption would be: discount carbon dioxide coefficient = average low calorific value * carbon content per unit calorific value * carbon oxidation rate * [10̂(-6)] * 44/12. The average low heat generation data was obtained from China's Statistical Yearbook on Energy, the amount of carbon and how fast carbon burns per unit of calorific value were derived from Table 1.5 and Table 1.7 of the Guide for the Compilation of Provincial Greenhouse Gas List (Trial), respectively. Thus, the coefficients of coal, gasoline, coke, diesel, kerosene, fuel oil, and natural gas were 1.9003, 2.8604, 2.9251, 3.0179, 3.0959, 3.1705, and 2.1605, respectively, so carbon dioxide emissions from fossil natural gas and energy consumption in 31 provinces and cities were estimated.

4.2.2 Dependent variable

Fiscal decentralization (FD): regarding the measurement of fiscal decentralization indicators, scholars mainly discuss it from the perspective of revenue decentralization (He D. and Miao W., 2016) and expenditure decentralization (Lin C. and Yingjie, 2017). If the fiscal decentralization index is measured from a single perspective, it could not reflect its decentralization characteristics well. The fiscal decentralization is reflected in local governments' fiscal revenue power and expenditure responsibility scope.

Fiscal Imbalance (FI): The essence of FI aims to quantify the disparity under the fiscal decentralization system, the relationship between local fiscal revenue and spending, representing the federal and state governments' fiscal ties. Referring to Li and Du (2021), the procedure for calculating FI is fiscal revenue decentralization/fiscal expenditure decentralization. As a result, this paper estimated FI from the standpoint of a decentralization system.

Fiscal transfer (FT): To measure the fiscal decentralization of local income by using the self-sufficiency rate of local income, local income self-sufficiency rate = regional own fiscal revenue/(The region's fiscal revenue + central transfer payments).

The effect of fiscal decentralization on greenhouse gas emissions is mainly reflected in fiscal decentralization revenues from local and national government items are apparent differences, and local governments decide their fiscal expenditure according to their revenue. In theory, local governments can attract targeted investment according to the characteristics of local economic structure and rapidly increase regional fiscal revenue to strengthen environmental governance, such as increasing low-carbon equipment, research and development, and technical personnel training for high-carbon emission enterprises to reduce the regional carbon emission level.

Industrial structure (IND): the percentage of the secondary industry's added value in the provincial GDP is included. Regional carbon emission is closely related to its industrial structure. To encourage the rapid growth of the local economy, local governments tend to encourage secondary industry development to fasten the pace of regional economic development. However, during the process of industrialization acceleration, the immaturity of technology for utilizing energy and the inefficiency of fossil energy directly lead to increased carbon emissions.

4.2.3 Control variables and moderator variables

Degree of economic development (income): the per capita of each the GDP of a province shows its level of economic growth. To obtain the real per capita GDP, the per capita GDP of all regions from 2010 to 2019, the GDP of each year, and the total population at the end of each region were obtained from the China Statistical Yearbook.

Foreign direct investment (invest): The influence of international investment on regional environmental conditions could generally be classified into two groups. One is based on the hypothesis of a "pollution paradise", which states that developed countries transfer heavy polluting and high-carbon industries by investing in developing countries. In addition, some scholars believe that there is a more complex mechanism regarding foreign direct investment's impact on the environmental situation, and the technology spillover effect brought by foreign investment may promote the reduction of the release of carbon (Zhang. et al., 2017b). The level of foreign direct investment in each province was utilized to complete the status of foreign direct investment in this article. It converted the average price of the RMB exchange rate, and finally, the regional GDP index offset the price changes.

The effect of the opening foreign trade (trade): the import and export trade of the high-carbon industry has the most noticeable impact on carbon emissions. Developed countries may transfer carbon emissions to developing countries with a more urgent demand for economic growth through trade. In this paper, the total amount of imports and export of each province provides insight into the degree of opening to the outside world (Zhang et al., 2011). This value is multiplied by the annual average price of the RMB exchange rate throughout the years and converted into RMB, and then the production price index was deduced.

Regarding population density (pop), some scholars believed that energy efficiency exhibited a scale effect. The more dispersed the population, the higher the cost of using energy, and vice versa. It can be inferred that a higher population density in a region may lead to more carbon emissions. The area data of provinces and regions are obtained from the official website of the people's government. This paper obtained the end-of-year total population data from National Bureau of Statistics website.

Environmental regulation (pol): formulation of national environmental regulation policies directly led to an increase in production costs of enterprises, but it could promote the reduction of carbon emissions. In this study, the completed amount of environmental pollution control investment in each region is used to express the region's environmental regulation level. The data is selected from the China Environmental Statistical Yearbook over the years, and the regional GDP index processes the value, and the real value is obtained.

Investment by the government in science and technology (tech): Government science and technology investment reflected the level of production technology in the region to some extent. The higher the production technology level in the region, the more advanced the industrial structure, and the higher the energy utilization level, further conducive to reducing regional carbon emissions (Lin and Liu, 2010). This paper used the number index characterization of industrial waste gas treatment facilities invested by the government in science and technology.

Greenland area (GA): On a global scale of ecological civilization, a crucial tool is the carbon trading mechanism for realizing the creation of ecological civilization. Carbon trading lowers carbon emissions from the perspective of carbon sources. On the other hand, green land ecological construction is a carbon sink for carbon absorption. The ecological civilization is measured by per capita green area (Wang. et al., 2022).

The meanings of each variable are shown in Table 1.

4.3 Data and analysis methods

This study utilized the panel data of 31 Chinese provinces (municipalities and autonomous regions) from 2010 to 2019 from the China Statistical Yearbook, China Environmental Statistical Yearbook, China Financial Yearbook, China Energy Statistical Yearbook, and government statistical bulletins and yearbooks.

5 Empirical results and discussion

5.1 Descriptive statistics

It used 31 Chinese provinces' panel data from 2010 to 2019, mainly from the Statistical Yearbook of China over the years and the government unification of various provinces and regions Planning Bulletin and Yearbook. The total number of samples was 310, descriptive statistics were scored for the data analysis, and the detailed results are shown in Table 2. Statistical characteristics of the dependent and independent variables are listed in the table.

5.2 Empirical results

This paper used a robust first-order difference dynamic panel measurement analysis to estimate the impact of fiscal decentralization, fiscal imbalance, fiscal transfer, and industrial structure on carbon dioxide emissions on a national scale. Through the second-order sequence correlation AR test of the three models in Table 3, the results showed that the correlation of second-order sequences did not exist for the error terms receiving the estimated equation. At the same time, the results of the Sargan overidentification test also showed that the null hypothesis of the validity of the instrumental variables could not be rejected (the *p*-values are all significantly greater than 0.1). This demonstrated the author's model setting's logic and the validity of the instrumental variables.

The regression results of Table 3 model 1) showed that the estimated coefficient of carbon emissions in the lagging phase was significant and positive at the 1% level. Carbon dioxide emissions in the previous stage increased by 1% or 1.050% in the current period. The symbol remained significantly positive after other control variables are added later. This showed a positive correlation between the carbon emissions of the last period and the current time frame. China's carbon dioxide emissions are a continuous and dynamic cumulative adjustment process.

Because China's industrial capital investment, energy consumption habits, and related macro-control have a time lag, the more carbon emissions in the last phase, the increased emissions in this period. The estimated coefficient of fiscal decentralization indicators was negative and significant at the statistical 10% level. Fiscal decentralization increased by 1%, and per capita carbon dioxide emissions decreased by 5.162%, testing the hypothesis of 1. The higher the fiscal decentralization, the smaller the per capita carbon dioxide emissions. The fiscal decentralization's role reform in strengthening environmental governance gained importance under the national "13th Five-Year Plan" strategy. Financial departments at all levels follow the guidance of ecological progress. Yet, there was an apparent conflict between government revenues and expenditures, means to optimize the spending structure, attach great importance to the environmental protection investment, reduce the general expenditures, and provide strong support for the hard fight against pollution. Fiscal decentralization is critical for reducing carbon dioxide emissions.

Table 3 model 2) showed that fiscal imbalance exhibited a positive and significant calculated coefficient. Increases fiscal imbalance by 10% and carbon dioxide emissions by 0.187%. This verifies the authors' hypothesis 2 that the higher the government fiscal imbalance, the greater the CO_2 emissions. Because local government officials generally have short terms, policymakers invest fiscal spending in economic areas where they can achieve political results as soon as possible. However, environmental protection is often not favored because of its characteristics of significant investment, long effective period, and insignificant short-term political performance. Therefore, many local governments will take economic development as the focus of fiscal expenditure and attract enterprises to invest in local factories by building infrastructure, reducing taxes, and environmental supervision. Local governments' enthusiastic pursuit of attracting investment weakens local environmental quality standards and indirectly connives at enterprises' carbon dioxide emissions.

To some extent, fiscal decentralization reflects the government's ability to control fiscal expenditure. So, the interesting question is, was the impact of fiscal decentralization on CO_2 emissions varied at different levels of fiscal expenditure or not? Therefore, the author added the interaction phrase of government fiscal decentralization and fiscal imbalance in the model to explain this problem. The partial impact of fiscal decentralization on carbon emission included the direct effect of fiscal decentralization; the indirect influence was dependent on government fiscal revenue and expenditure. The interaction term coefficient in the model 2) was significantly positive, demonstrating that the effect of fiscal decentralization on CO_2 emissions could be realized through government fiscal revenue and expenditure. In areas with considerable government fiscal revenue and expenditure gap, the fiscal decentralization's role in controlling carbon emissions was gradually weakened and supported hypothesis 3. The interaction term coefficient had a critical value of government fiscal imbalance. When the fiscal imbalance exceeded the threshold, government fiscal decentralization boosted carbon dioxide emissions if the latter would reduce carbon dioxide emissions. In other words, for regions like Guangdong, Shanghai, and Jiangsu with significant fiscal revenue gaps, the increase in fiscal decentralization would not be conducive to improving local carbon emissions. For some areas where fiscal revenue is less than the critical value, the increase in fiscal decentralization will reduce local carbon emissions. This conclusion explains the "double-sided" function of fiscal decentralization in promoting and limiting carbon dioxide emissions. The author compensates for the lack of existing literature. The existing literature rarely examines the "suppression" mechanisms of the effect of fiscal decentralization on carbon dioxide emissions. The author solved this problem by adding the interaction term.

Table 3 model 3) shows that the estimated coefficient of the fiscal transfer degree (central government subsidy provided to close the gap of fiscal imbalance) is positive and significant. That is, the fiscal transfer degree increased by 10%, and the carbon dioxide emissions increased by 2.319%. This also verifies the authors' hypothesis 4 that the higher the government fiscal transfer degree, the lower the transfer payments, and the greater the CO_2 emissions. The restraining influence of the central transfer payments on carbon emissions is verified. The interaction term coefficient in model 3) was significantly positive, implying that the function of fiscal decentralization on CO_2 emissions would be realized through government transfer payments. In areas where the central government makes large government transfer payments, the role of fiscal decentralization in controlling carbon emissions gradually increased. Thus, the results supported hypothesis 5. The fiscal decentralization of the government caused the difference between regional fiscal revenue and expenditure. Still, it implied that local government expenditure for carbon emission control through central transfer payments to restrain carbon emissions and control contamination of the environment. This conclusion was in line with the research results of Xu H. and Zhang W (2017), showing that transfer payments significantly enhanced the quality of the ecological environment. It was more efficient to allocate transfer payments to areas with high financial decentralization. At the same time, Miao X. and Zhao Y (2019) found that transfer payment affected fund compensation, improved environmental governance efficiency, increased capital scale, and strengthened institutional constraints helped realize the institutional incentive effect, which is supported.

Table 3 illustrated model 4) results. The coefficient of the square term showed that industrial structure was statistically significant at the level of 1%, indicating a significant "U-shaped" curve in the connection between industrial structure and carbon emissions. This was because the adjustment of the industrial structure was cross-term. In the early stage of industrial structure adjustment, there was a more significant decline in coal consumption demand and reduced carbon emissions.

Nevertheless, as the proportion of the secondary industry increases, there was a strong positive association between the secondary industry and carbon dioxide emissions in China, and confirmed hypothesis 6. Currently, the secondary industry is still dominant in the national economy with high energy consumption. As a result, the increase in the share of the secondary industry in GDP increased carbon dioxide emissions. To obtain more fiscal revenue, local governments pay more attention to productive investment in infrastructure construction and economic development, vigorously develop the local economy and introduce industrial enterprises. Influenced by the GDP-oriented promotion championship, the rational government was concerned more with local economic development, environmental protection, and livelihood, resulting in deteriorating air quality.

The long-term development of the Chinese nation requires the construction of an ecological civilization. Control variables were introduced in the model and the estimation results were robust. The estimated Foreign direct investment coefficient was positive. There is a more complex mechanism regarding foreign direct investment's impact on the environmental situation, and the technology spillover effect brought by foreign investment may promote the reduction of the release of carbon (Zhang. et al., 2017a). The government investment in science and technology was estimated as a negative correlation: Investment in research and technology by the government can represent the level of manufacturing technology in the region to a certain extent, which is further conducive to the reduction of regional carbon emissions (Lin and Liu, 2010). The Greenland area was significantly negative, indicating that the increasing the amount of green space available, thus reducing net carbon emissions, and increasing carbon absorption.

5.3 Analysis of regional differences

The carbon dioxide emissions of different regions in China vary considerably. As per Figure 1, China's carbon emissions showed an uneven distribution trend. The provinces with relatively large carbon emissions are mainly concentrated in the areas rich in coal resources, with large populations, and developed economies. However, the provinces included in the high-emission zone have a specific regional agglomeration, mainly situated in the middle and north of China and the Bohai Rim region. This is due to the spatial correlation of environmental pollution and the unbalanced distribution in neighboring areas. However, the provinces, including the high-emission areas, have similarities in the local resource endowment and energy consumption structure. Because provinces with medium and high emission areas are mainly rich in coal resources and high levels of industrialization, economically developed areas, such as Shanxi, have many coal resources and are the largest thermal power generation province. Hebei, Shandong, Jiangsu, and other provinces were big steel-producing provinces that would consume much coal. Under the original resource endowment and economic structure conditions, these local governments will naturally vigorously develop the local pillar industries, resulting in increased carbon emissions.

6 Conclusions and policy implications

6.1 Conclusion

There is debate over the connection between fiscal decentralization and carbon dioxide emissions. This research examines the influence of Chinese-style fiscal decentralization on carbon dioxide emissions and control from the standpoint of indirect variables, providing some fresh empirical evidence. We make the following findings utilizing statistics from Chinese provinces from 2010 to 2019. 1) Fiscal imbalance reduces CO_2 emissions because the devolution of revenue and expenditure undermines CO_2 emissions control. Fiscal decentralization and imbalance in the Chinese model could result in significant incentive distortion. 2) The central government's transfer payments offset the negative consequences of fiscal imbalance. The fiscal decentralization of the government causes a difference between regional income and expenditures in the budget. Still, title local government expenditure towards carbon emission control through central transfer payments to restrain carbon emissions and control environmental pollution. 3) The effect of fiscal decentralization on CO_2 emissions was influenced by the industrial structure with the U-Shape effect. This is because the adjustment of industrial structure is cross-term. In the early stage of industrial structure adjustment, it manifested more in the significant decline in coal consumption demand and reduced carbon emissions. Nevertheless, as the proportion of the secondary industry increases, there was a strong link between the secondary industry and carbon dioxide emissions in China.

6.2 Policy implication

Our findings have significant policy consequences. China experienced increasing resource scarcity and environmental pressure, and building an ecological civilization is vital to achieving high-quality economic development (Du et al., 2021). Environmental governance in China was primarily the responsibility of local governments (Feng T. et al., 2020). In this framework, fostering the development of the green economy requires establishing a fiscal link between the national and local governments that is balanced and coordinated.

For starters, controlling FI is critical for CO_2 control. The Chinese government is currently undertaking a fresh wave of fiscal reforms. The fiscal link between the federal and state governments should be improved by a scientific separation of Taxing authority and spending responsibilities for local governments, which may inspire increased spending on the environment and public services by local governments. During this procedure, the central government should increase the control and local government oversight and decentralize revenue authority even more. That local government must balance its revenue and expenditure responsibilities. To summarize, local governments' fiscal deficits and pressures should be minimized to prevent them from engaging in some economically shortsighted actions.

Second, policymakers should consider the role of various forms of financial compensation. The central government should construct the system of transfer payments properly and increase the efficiency with which fiscal revenues are used. Local governments should also keep an eye on the GDP over environmental issues and prioritize investment. The administration should strengthen its tactics of political promotion, focusing on GDP, and organize local governments' enthusiasm for energy saving and pollution control.

Third, the Chinese economy is in an advanced stage of development, with essential contents such as modernization of the industrial structure and technology innovation. Our empirical findings demonstrated that changing the traditional fiscal decentralization structure benefited energy conservation and pollution reduction, as well as the modernization of industrial structures and technological innovation. As a result, municipalities should optimize their fiscal expenditure structure, increase spending on technology and sustainable protection, and continuously better environmental management. Local governments should limit their involvement in resource management and environmental governance allocation and encourage development based on the market. Furthermore, FI's unnecessary administrative interference will degrade the quality of the environment.

Finally, this analysis included policy recommendations for other emerging countries in transition. As part of the global carbon-neutral movement gains traction, countries should restructure and improve their taxation procedures to reflect the economic and political climates in which they live, ensuring institutional support for the growth of the green economy. Most underdeveloped countries also face fiscal decentralization issues, which impede green economic development. On the other hand, complementary efforts based on restoring grass and replanting trees aligned with the realities of establishing a market for carbon trading, which enhanced CO_2 sinks and reduced CO_2 sources. The constant was significant carbon sequestration, which assured that the net CO_2 emissions were controllable under this virtuous loop mechanism.

6.3 Limitations and further research

This study has some limitations, for example, the data could be expanded to other countries. The research strategies presented in this paper could be applied to other nations, regions, pollutants and industries to study the varied effects of fiscal decentralization. For example, how does fiscal decentralization impact environmental laws and regulations compliance (Lai et al., 2007).

Data availability statement

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

Author contributions

JX: Writing—original draft. RL: Writing—original draft, review and editing. XZ: Supervision. LS: Literature review. WB: Formal analysis, Data curation.

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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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Publisher's note

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Time Series Analysis and Forecasting of Air Pollutants Based on Prophet Forecasting Model in Jiangsu Province, China

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Due to recent developments in the global economy, transportation, and industrialization, air pollution is one of main environmental issues in the 21st century. The current study aimed to predict both short-term and long-term air pollution in Jiangsu Province, China, based on the Prophet forecasting model (PFM). We collected data from 72 air quality monitoring stations to forecast six air pollutants: PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3. To determine the accuracy of the model and to compare its results with predicted and actual values, we used the correlation coefficient (R), mean squared error (MSE), root mean squared error (RMSE), and mean absolute error (MAE). The results show that PFM predicted PM_{10} and $PM_{2.5}$ with R values of 0.40 and 0.52, RMSE values of 16.37 and 12.07 μg/m^3, and MAE values of 11.74 and 8.22 μg/m^3, respectively. Among other pollutants, PFM also predicted SO_2, NO_2, CO, and O_3 with R values are between 5 μg/m^3 to 12 μg/m^3; and MAE values between 2 μg/m^3 to 11 μg/m^3. PFM has extensive power to accurately predict the concentrations of air pollutants and can be used to forecast air pollution in other regions. The results of this research will be helpful for local authorities and policymakers to control air pollution and plan accordingly in upcoming years.

Keywords: prophet forecasting model, time series model, air pollution, machine learning, jiangsu province, China

INTRODUCTION

Due to developments in the global economy, transportation, and industrialization, air pollution is one of the main widespread environmental issues. The World Air Quality Report noted that many Asian countries have experienced high levels of air pollution, particularly in cities in China, Pakistan, India, and Bangladesh (AirVisual, 2018; AirVisual, 2019). China, with its substantial population, transportation, and industries, is the largest developing country in the world, and in the last 3 decades, many cities and regions of the country have faced serious air pollution (Zhao et al., 2020). In the last few years, due to strict restrictions on industrial emissions, transportation, and heating activities, China experienced a slight decline in air pollution, but efforts are still required to secure the environment at a significant level (Wu et al., 2020). Associated with adverse effects and an impact on climate change, air pollution has attracted widespread interest from scholars and administrations (Lee et al., 2020; Wang et al., 2022).

Pollutants that threaten human health include particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3), as studied by Li and Shi (2016). Particulate matter can be defined as a combination of strong particles and liquid droplets, which has a more significant impact on human health than other pollutants (WHO-World Health Organization, 2018; Guo et al., 2020). PM_{10} and $PM_{2.5}$ contain inducing materials such as lipopolysaccharide and polycyclic aromatic hydrocarbons and transition metals (zinc, copper, manganese) (Bilal et al., 2021; Yang et al., 2022). PM_{10} can infiltrate the lower airways in the form of thoracic particles with an aerodynamic diameter of fewer than 10 μm. PM_{10} causes various lung diseases, such as asthma, and cardiovascular diseases (Huang et al., 2016; Hasnain et al., 2021). $PM_{2.5}$, which is particulate matter with a diameter of 2.5 μm or less, has been proven to have adverse health impacts (Conibear et al., 2018; Zhang et al., 2020).

Two other important air pollutant factors are SO_2 and NO_2, which pose a hazardous risk to human health and threaten the environment (Zhang et al., 2019). SO_2 is extremely reactive with other compounds, which can cause additional environmental pollution, such as particulate matter and acid rain (Tang et al., 2016; Liu and Sun, 2019). NO_2 severely degrades the human respiratory system, leading to respiratory symptoms and asthma (Liu and Sun, 2019). NO_2 can also cause additional environmental pollution with other compounds and cause severe damage to both human health and the environment (Su et al., 2017; Shairsingh et al., 2021). CO is another major primary air pollutant in the atmosphere that affects human health and causes air pollution (Choi et al., 2017; Petetin et al., 2018). CO is an odorless and colorless gas with a long-life cycle of roughly 2–3 months. In the atmosphere, CO plays a vital role that also involves O_3 production (Liu et al., 2018; Fan et al., 2020; Qayyum et al., 2021). Although O_3 is a necessity for life on earth and plays an important role, it also has harmful effects and is linked with numerous respiratory issues such as lung scarring and loss of lungs (Fajersztajn et al., 2013; Dehghani et al., 2017; Wang et al., 2019; Aamir et al., 2021; Zhao et al., 2020). Due to its adverse effects and high phytotoxicity, O_3 is also responsible for the reduced production of agricultural yields worldwide (Salonen et al., 2019; Duan et al., 2021; Yang et al., 2021).

In early 2013, due to an unprecedented pollution event that caused inordinate risk to people's lives and property, there was need to implement preventive measures to improve the air quality of the country. In this scenario, the Chinese State Council issued the Action Plan on Prevention and Control of Atmospheric Pollution on 10 September 2013 (The State Council of China, 2013; Dai et al., 2018). After the plan was implemented, the air pollution status across the country was reduced compared with the previous year. No doubt due to control policies and strict restrictions, China experienced a slight decline in recent years, but many cities and regions of the country still suffer from haze pollution (Duan et al., 2021). In this scenario, there is a dire need to take preventive measures and accurately forecast pollution events as early as possible. For this purpose, this paper attempts to predict main air pollutant factors (PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO and O_3) based on the Prophet forecasting model (PFM) in Jiangsu Province, China. The study provides useful information and credible outcomes for local authorities and policymakers to control air pollution and to plan accordingly in upcoming years.

The rest of the paper is organized as follows: Section 2 comprises a literature review. Section 3 presents the study area, data set, data processing, the model and statistical analysis to evaluate the model's performance. Section 4 presents the results and discussion. Section 5 discusses the conclusions, policy implications, limitations and future research directions.

LITERATURE REVIEW

The time series prediction method is widely used by scholars and researchers in many fields to predict air pollutant concentrations (Appel et al., 2017; Zhao et al., 2020; Qayyum et al., 2022). Chen and Li (2022) used the hedonic regression model, Google AutoML and Microsoft AutoML for forecasting the housing prices and found that the Google AutoML model is robust and performs better with R square (0.820) is higher. About other models, it has been noted that to make long-term air pollution predictions, current non-machine-learning models have major flaws and errors, such as the community multiscale air quality modeling system (CMAQ), which is severely disadvantaged due to its intricate and complex system and source list and its requirement for and regular updates (Xi et al., 2015; Deters et al., 2017). In air pollution prediction models, this has led to many studies concentrating on the premise of machine learning. Li et al. (2015) and Deters et al. (2017) presented models that were unable to make accurate predictions and relied deeply on meteorological parameters. As a result, these models are unable to effectively predict meteorological events amid the climate change crisis (Scher and Messori, 2019). Pasero and Mesin (2010) and Maleki et al. (2019) used artificial neural networks (ANNs) for air pollution prediction. They noted that the ANNs relied on meteorological factors as highlighted in previous studies and showed many deficiencies. Their results indicated that due to overfitting of data, the model had the poor capability to predict time series and still failed

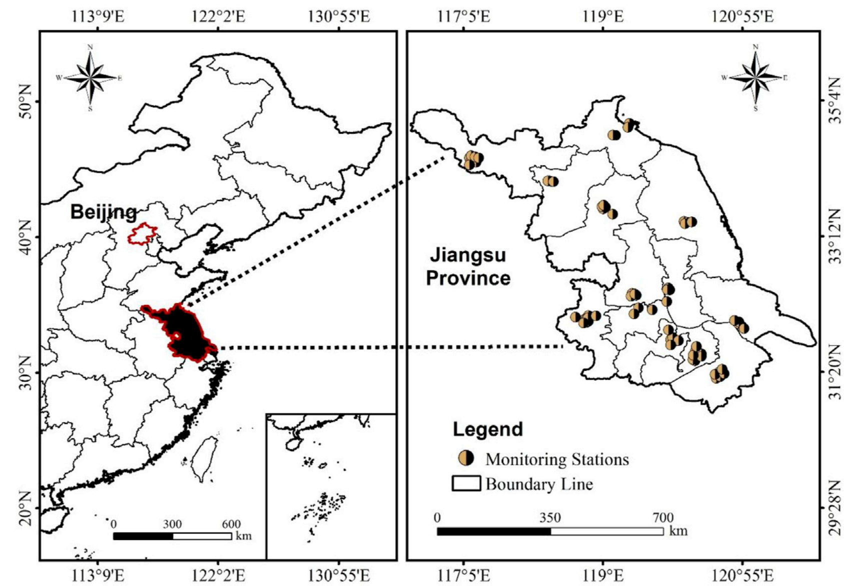

FIGURE 1 | Location of the study area and distribution of monitoring stations in Jiangsu Province.

to accurately forecast air quality. Meanwhile, for air pollution forecasting based on ANNs, Cabanerosa et al. (2019) showed that to forecast long-term air pollutant factors with optimization approaches, feed-forward and hybrid ANN models were predominantly used. Yang et al. proposed a vector regression model to predict air pollutant concentrations by considering spatial assortment (Deng et al., 2018). In recent years, such data-driven methods with low accuracy in predicting air quality have been studied. Bhatti et al. (2021) used a time-series prediction model for forecasting air pollution using SARIMA and a factor analysis approach. This method using SARIMA approached the accuracy of 67% with better results than the ARIMA time series model. Used AutoML approach for forecasting the price index approach and providing useful predictions for future prices. Bhatti et al. (2019) used K-nearest neighbor method for recommendation and prediction using pattern recognition of datasets which provided an accuracy of more than 70% for the used datasets. Kamińska (2018) presented the same machine learning method with random forest regression (RFR); due to its nonlinear pattern, it is a popular approach based on the alteration of a few parameters. However, RFR has low accuracy of prediction because its highest and lowest values are bound to the training set data (Ivanov et al., 2018). Fuller et al. (2002) developed a model to predict PM_{10} concentration and its relationship with NOx. Their results revealed that the model did not have good potential to predict other important air pollutants. Another study predicted the concentration of PM_{10} using generalized linear models (GLMs). The study focused on the relationship between meteorological variables and air pollutant concentrations (Garcia et al., 2016). The concentration of PM_{10} was considered a dependent variable in GLM, while meteorological variables and gaseous pollutants were considered independent variables. He et al. (2018)7 presented two methods to predict $PM_{2.5}$, the linear method and the non-linear method of support vector regression.

Against this background, we used the Prophet forecasting model (PFM), which was developed by Facebook, concerning time forecasts with an anticipated and desired variable. The PFM has an extensive capacity to predict accurately without an overabundance of multifaceted or complex sources, and the model is also able to activate successfully even if the data have missing values and numerous outliers (Taylor and Letham, 2017). In addition, in the prediction of air pollution, PFM has been successfully established over other acceptable models, such as autoregressive integrated moving average (ARIMA) and seasonal autoregressive integrated moving average (SARIMA), which are widely used in many fields. Compared with ARIMA, PFM takes approximately 10 times less time to train (Scher and Messori, 2019). As mentioned earlier, compared with other models, PFM has a unique ability to predict accurately and effectively without the use of other parameters, which makes it a preferred method over current approaches to predict air pollution, and only a few studies have applied it (Shen et al., 2020). Comparatively, China's air pollution is different from air pollution in other places in the world, and the current work aimed to examine and predict the air quality in the most polluted region of China. In this research, we aimed to predict main air pollutants, PM_{10}, $PM_{2.5}$, SO_2, NO_3, CO, and O_3, based on the Prophet forecasting model (PFM) for accurate short-term and long-term forecasting in Jiangsu Province, China, which will help support appropriate measures to control air pollution and plan accordingly in upcoming years.

MATERIALS AND METHODS

Study Area

Jiangsu Province, located at the Yangtze River in eastern China (**Figure 1**), is one of the most developed areas of the country. The

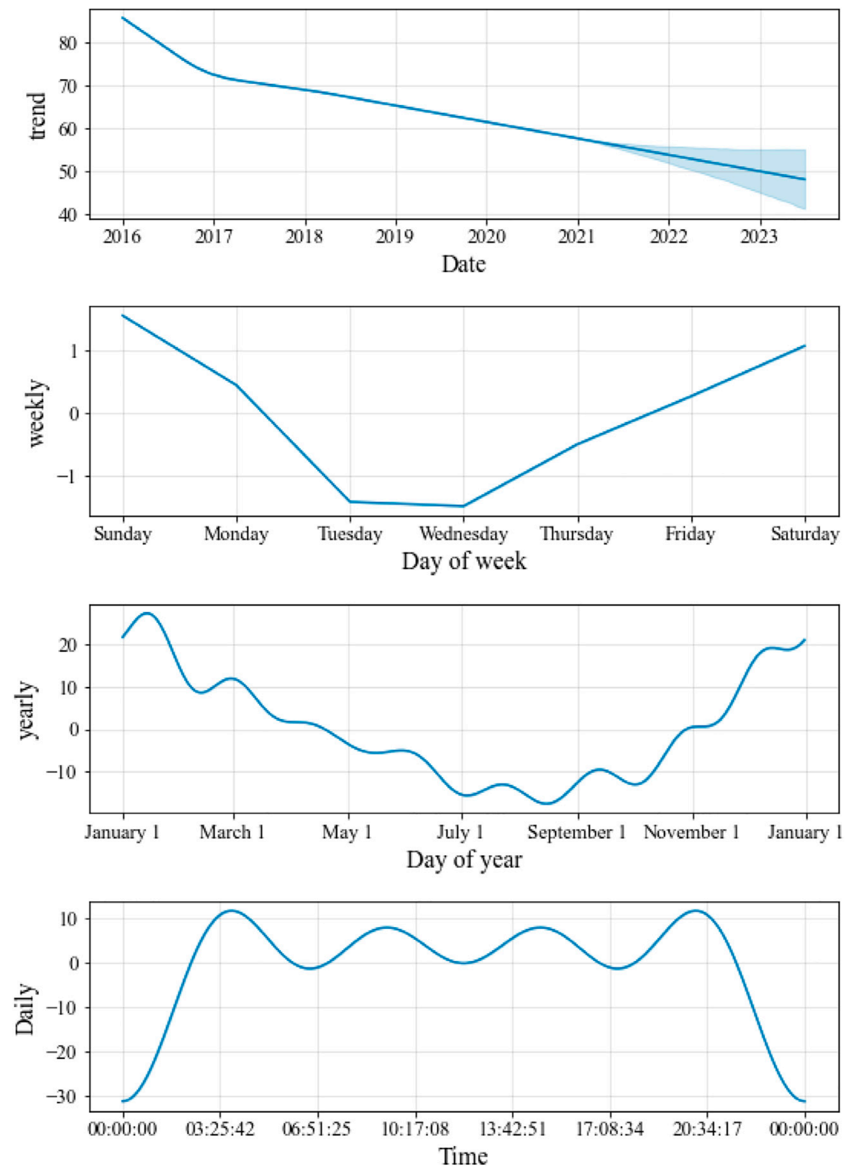

FIGURE 2 | Components of the Model ($PM_{2.5}$ trends graph, overall trend, yearly, weekly and daily).

province has a large population and well-developed industrial sectors. Occupying an area of around 107,200 km^2, it has 13 cities and, as of 2019, a population of approximately 80.5 million. In recent years, due to rapid economic development, Jiangsu Province has experienced the worst air quality (Zhang et al., 2020; Bhatti et al., 2022).

Data

Data on the daily average concentrations of air pollutant factors, including PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3, were collected between 1 January 2016 and 31 December 2020. The website of historical data of air quality in China has allowed downloading of air pollution data since 13 May 2014 (Wang 2019). The data on the selected air pollutants were from the China Environmental Monitoring Station (CNEMC, 2019). In Jiangsu Province, 72 monitoring stations that collect and record air quality data are scattered over 13 cities. The distribution of these monitoring stations is shown in **Figure 1**.

TABLE 1 | PM_{10} 2020 model performance statistics with different time period in Jiangsu Province.

Time	y	R	MSE	RMSE	MAE
15 Days	0.31x+42.58	0.31	835.63	28.91	24.25
1 Month	0.36x+38.60	0.41	570.36	23.88	19.27
3 Months	0.32x+40.09	0.36	433.39	20.82	17.46
6 Months	0.39x+32.74	0.36	287.41	16.95	13.33
1 Year	0.43x+25.69	0.40	268.03	16.37	11.74

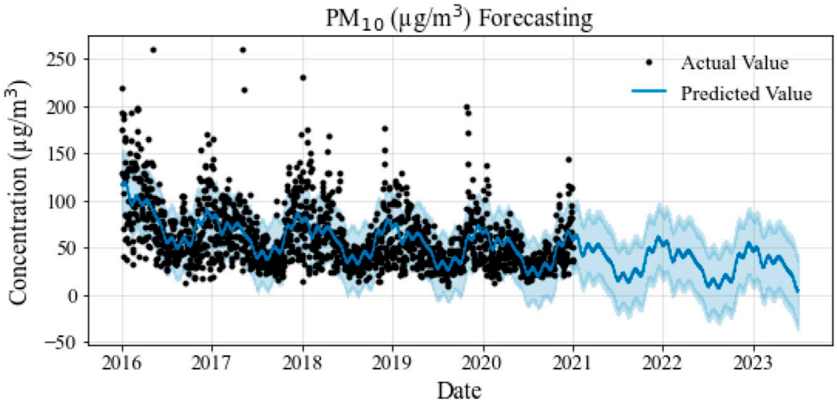

FIGURE 3 | PM_{10} (μg/m^3) forecasting in jiangsu province.

TABLE 2 | $PM_{2.5}$ 2020 model performance statistics with different time period in Jiangsu Province.

Time	y	R	MSE	RMSE	MAE
15 Days	0.27x+37.62	0.39	632.79	25.16	21.30
1 Month	0.34x+31.95	0.45	428.40	20.70	16.44
3 Months	0.40x+27.73	0.52	273.27	16.53	13.18
6 Months	0.50x+19.16	0.51	162.03	12.73	9.50
1 Year	0.52x+15.29	0.52	145.76	12.07	8.22

Data Processing

To predict the concentrations of air pollutants, to meet the input requirements of the model, the values were manually processed in Excel for appropriate fitting and to satisfy the PFM formatting requirements, with timestamps in YYYY-MM-DD format. PFM has the broad ability to replace missing values with nearby points by fitting the model for the prediction, and any error was replaced with "NA" read from the devices denoted by "-1".

Proposed Model

For analyzing time series and forecasting with trends, seasonality, and holidays, PFM is an influential and powerful tool for accurate and effective prediction, and it takes only a few seconds to fit the model. The model uses the following formula:

$$y(t) = g(t) + s(t) + h(t) + \in t. \tag{1}$$

To evaluate the performance of the PFM, **Eq 1** was employed, where y(t) is the predicted value determined by a linear or logistic equation; g(t) and s(t) represent seasonality or time series based on yearly, monthly, daily or another period; h(t) is the holiday outliers; and €t represents the unexpected error. For better understanding, the model has numerous parameters and the type of model can be assumed as linear or logistic. There is no maximum or minimum limit set in a linear model, while in a logistic model, the highest and lowest values are specified and used for saturated forecasts. Linear models were utilized to make sure the PFM reported and accounted for the typical outliers observed in air quality tendencies. To forecast and smooth time series data, the model accepts a Bayesian-based curve fitting technique, which is one of the model's most distinctive features compared to other forecasting models, such as ARIMA and the Holt-Winters method. PFM has more power to handle temporal patterns easily compared to traditional

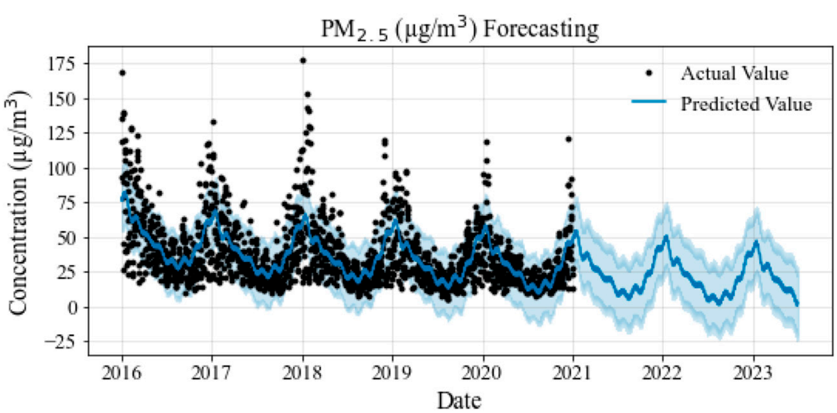

FIGURE 4 | $PM_{2.5}$ (μg/m^3) forecasting in jiangsu province.

TABLE 3 | SO_2 2020 model performance statistics with different time period in Jiangsu Province.

Time	y	R	MSE	RMSE	MAE
15 Days	0.66x+4.21	0.16	7.59	2.76	2.32
1 Month	0.43x+5.11	0.10	6.77	2.60	2.22
3 Months	0.19x+5.86	0.04	5.93	2.44	2.15
6 Months	0.32x+5.18	0.08	3.63	1.91	1.52
1 Year	0.35x+4.10	0.17	2.46	1.57	1.16

exponential smoothing models and has requirements for frequent measurements (Taylor and Letham, 2017).

In PFM, change points are significant parameters and the explicit values of change points or the fitting scale can be specified; with higher change points, the model showed better performance when fitting the data. However, in predicting future trends, the model lost efficacy and effectiveness due to the use of fewer change points and was unable to be well-fitted. Initially, PFM plots a large value to determine the number of change points, and then the model uses L1 regularization to pick out a few points to use. To avoid overfitting due to a lack of change points, L1 regularization was used for this purpose, which picks out only the significant change points.

$$L(x, y) \equiv \sum_{i=1}^{n} (y_{i-}h_\theta(x_i))^2 + \lambda \sum_{i=1}^{n} |\theta_i| \tag{2}$$

Eq 2 represents L1 regularization, where x and y are the coordinates of the change points.

$\sum_{i=1}^{n} (y_i - h_\theta(x_i))^2$ represents the change between actual and forecasted value squared. The purpose of $\lambda \sum_{i=1}^{n} |\theta_i|$, is to maintain the balance in weights to avoid overfitting, where λ shows how much the weights are penalized; a high-value results in underfitting, while a low value means high bias. PFM has a value in determining the value of λ based on the number of estimators, or the average rate of change value can be specified.

Seasonality is another important parameter in predicting new values. PFM represents seasonality over daily, weekly, yearly, or other periods (**Figure 2**). **Figure 2** shows the seasonality of $PM_{2.5}$ concentrations with daily, weekly, yearly, and overall time trends. PFM can also plot any custom seasonality or holiday component. Cross-validation was performed for the model to forecast the error given historic data. Data from the first 4 years (2016–2019) comprised the initial training data. PFM was used to forecast air quality for 2020 after training data from 2016 to 2019. To determine the model performance, these values were compared to the actual values. The model then predicted air quality for the upcoming 2.5 years.

Statistical Analysis

In this work, four metrics were employed to evaluate the model's performance: correlation coefficient (R), mean squared error (MSE), root mean squared error (RMSE), and mean absolute error (MAE). The correlation coefficient (R) was used to determine the degree of fit of the forecasted values to the overall actual values. MSE is the average change of actual and forecast values, and RMSE is the square root of MSE, while MAE is proposed as the average change between actual and predicted values. Compared with MAE, RMSE places higher importance on the variance between data outliers. These metrics are calculated with the following formulas:

$$R = \frac{n\sum_{i=1}^{n} (x_i \hat{x}_i) - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} \hat{x}_i\right)}{\sqrt{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}\sqrt{n\sum_{i=1}^{n} \hat{x}_i^2 - \left(\sum_{i=1}^{n} \hat{x}_i\right)^2}} \tag{3}$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n} (x_i - \hat{x}_i)^2 \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (x_i - \hat{x}_i)^2} \tag{5}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |x_i - \hat{x}_i| \tag{6}$$

where x_i and $\hat{x}_i$ are the actual and predicted values and n represents the number of samples.

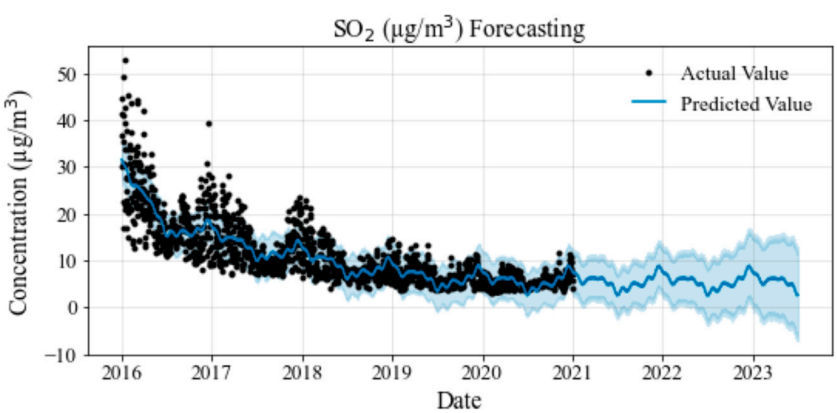

FIGURE 5 | SO_2 (μg/m^3) forecasting in jiangsu province.

TABLE 4 | NO_2 2020 model performance statistics with different time period in Jiangsu Province.

Time	y	R	MSE	RMSE	MAE
15 Days	0.50 x +16.95	0.37	29.81	5.46	4.57
1 Month	0.52 x +16.60	0.68	58.58	7.65	6.61
3 Months	0.49 x +16.60	0.57	68.97	8.30	7.15
6 Months	0.49+14.16	0.46	46.74	6.84	5.49
1 Year	0.53x+11.79	0.54	45.13	6.72	4.99

RESULTS AND DISCUSSION

PM_{10} Prediction

A linear model was inputted to specify the features of PFM, and error and change points were determined using the LI regularization technique from PFM. The model accurately predicts PM_{10} concentrations, and it is not overfitted during the entire year of 2020. We can see that all of the statistical indicators (R, MSE, RMSE, and MAE) show that the model predicts PM_{10} concentration more accurately for the long-term prediction than short-term. In a 15 days prediction, the model predicted PM_{10} with R, RMSE, and MAE values of 0.31, 28.91 μg/m^3, and 24.25 μg/m^3, respectively (**Table 1**). It can be seen that as the prediction time increased, the RMSE value decreased. The MAE value also showed a decreasing trend with the increase of time from 15 days to 1 year. In the 1 year prediction of PFM, the R, RMSE, and MAE values for PM_{10} are 0.40, 16.37 μg/m^3, and 11.74 μg/m^3, respectively (**Table 1**). The decreasing error values show that the model predicts PM_{10} with high accuracy as the time frame increases. Sayegh et al. (2014) developed five models to predict PM_{10} concentration, while Ye (2019) utilized an ARIMA-PFM model to predict PM_{10} concentrations in the time frame of 2 days. All indicators show that in the current work, PM_{10} concentrations are forecast more effectively compared with those studies. The results of predicted PM_{10} concentrations in Jiangsu Province are shown in **Figure 3** and **Table 1**.

$PM_{2.5}$ Prediction

To illustrate the performance of PFM, in a 15 days prediction the model predicted $PM_{2.5}$ with R, RMSE, and MAE values of 0.39, 25.16 μg/m^3, and 21.30 μg/m^3, respectively (**Table 2**). The results demonstrate that as the time increased from 15 days to 1 year the model predicted $PM_{2.5}$ more efficiently according to the statistical indicators shown in **Table 2**. In a 1-year prediction by PFM, the R, RMSE, and MAE values for $PM_{2.5}$ were 0.52, 12.07 μg/m^3, and 8.22 μg/m^3, respectively (**Table 2**). The results indicate that the model appropriately forecast the concentration of $PM_{2.5}$ in Jiangsu Province, as shown in **Figure 4** and **Table 2**. Many studies have proposed methods for predicting $PM_{2.5}$ concentrations (Li et al., 2015; Xi et al., 2015; Deters et al., 2017; Ye, 2019), and compared with these studies our study provides more accurate results for $PM_{2.5}$ concentrations.

SO_2 Prediction

In the prediction of SO_2 concentrations by PFM, within the time frame of 15 days, the R, RMSE and MAE values for SO_2 are 0.16, 2.76 μg/m^3, and 2.32 μg/m^3, respectively (**Table 3**). Similarly particulate prediction, the performance of the model in predicting SO_2 concentrations improved with an increase of time as indicated by RMSE and MAE values. In the 1-year time frame, the model predicts SO_2 concentrations with R, RMSE, and MAE values of 0.17, 1.57 μg/m^3, and 1.16 μg/m^3, respectively (**Table 3**). In previous studies, Shaban et al. (2016) developed M5P model trees, artificial neural network (ANN), and support vector machine to predict short-term air pollution, and Ye (2019) proposed an ARIMA-PFM model to forecast air pollution. Compared with these studies, our results of RMSE and MAE values in the prediction of SO_2 concentrations are improved. The prediction results of PFM for SO_2 in Jiangsu Province are presented in **Figure 5** and **Table 3**.

NO_2 Prediction

PFM provides better performance in predicting NO_2 concentrations in Jiangsu Province, with R, RMSE and MAE

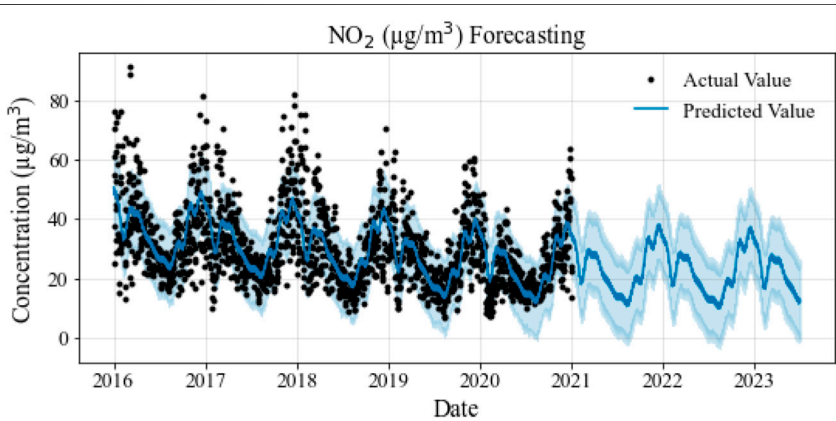

FIGURE 6 | NO_2 (μg/m^3) forecasting in jiangsu province.

TABLE 5 | CO 2020 model performance statistics with different time period in Jiangsu Province.

Time	y	R	MSE	RMSE	MAE
15 Days	0.22x+0.63	0.26	0.04	0.20	0.17
1 Month	0.32x+0.52	0.39	0.03	0.17	0.14
3 Months	0.39x+0.46	0.46	0.03	0.17	0.15
6 Months	0.43x+0.38	0.34	0.02	0.14	0.11
1 Year	0.49x+0.33	0.38	0.01	0.12	0.09

values of 0.37, 5.46 μg/m^3, and 4.57 μg/m^3, respectively, for a period of 15 days (**Table 4**). PFM predicted NO_2 with an R of 0.68, which was the best performance in predicting NO_2 concentrations within the time frame of 1 month. The results indicate that in contrast to other air pollutants, the model provides better performance in short-term prediction with RMSE and MAE values for NO_2. It can be seen that there were slight fluctuations in these values over an entire year (2020). In 1-year prediction by PFM, the R, RMSE, and MAE values for NO_2 are 0.54, 6.72 μg/m^3, and 4.99 μg/m^3, respectively (**Table 4**). Comparing short- and long-term predictions, the MAE and RMSE values for NO_2 are similar in Jiangsu Province, with small differences (**Figure 6** and **Table 4**).

CO Prediction

In predicting CO concentrations, PFM predicts with R, RMSE and MAE of 0.26, 0.20 μg/m^3, and 0.17 μg/m^3, respectively, in a period of 15 days (**Table 5**). The model predicts CO with R of 0.46 in 3-months prediction. Similar to other air pollutant parameters, the results show that the accuracy of the model improved with an increase of time for CO prediction. From 15 days to 1 year, the RMSE and MAE values gradually decreased from 0.20 to 0.12 μg/m^3 and 0.17 to 0.09 μg/m^3, respectively. With 1 year prediction, the model predicts with R = 0.38, RMSE = 0.12, and MAE = 0.09 in Jiangsu Province (**Table 5**). Overall, the results demonstrate that PFM provides significant results for CO concentrations over long-term prediction intervals in Jiangsu Province (**Figure 7** and **Table 5**).

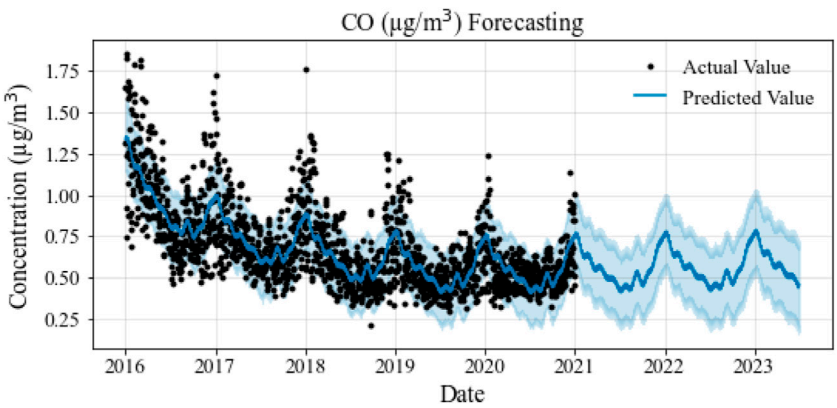

FIGURE 7 | CO (μg/m^3) forecasting in jiangsu province.

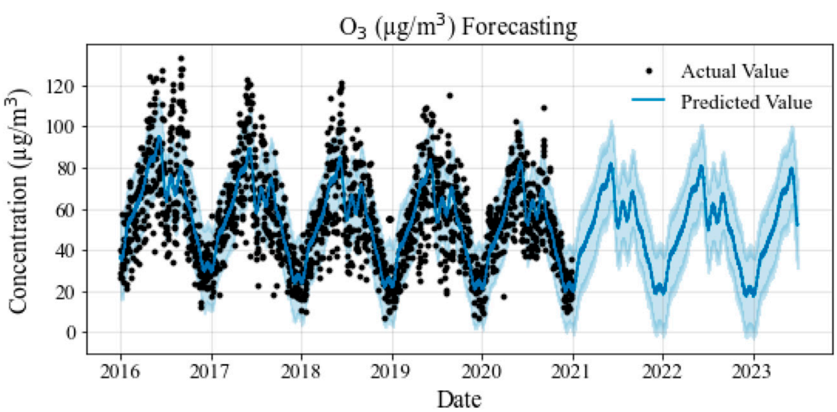

FIGURE 8 | O_3 (μg/m^3) forecasting in jiangsu province.

TABLE 6 | O_3 2020 model performance statistics with different time period in Jiangsu Province.

Time	y	R	MSE	RMSE	MAE
15 Days	0.32x+18.33	0.47	40.22	6.34	5.14
1 Month	0.44x+15.11	0.84	86.27	9.29	7.81
3 Months	0.60x+17.30	0.49	95.96	9.80	7.81
6 Months	0.74x+14.36	0.62	136.59	11.69	8.98
1 Year	0.73x+13.74	0.66	128.28	11.33	8.84

O_3 Prediction

PFM provides superior results in both short-term and long-term O_3 prediction in Jiangsu Province. In 15 days prediction, the model predicts with R = 0.47, RMSE = 6.34 μg/m^3, and MAE = 5.14 μg/m^3 for O_3 forecasting. PFM has the best R value for O_3 (0.84) in 1 month prediction. The smallest and highest RMSE and MAE values are 6.34 and 11.69 μg/m^3 and 5.14 and 8.98 μg/m^3, respectively. Compared with other air pollutant factor prediction, PFM has superior performance for O_3 prediction. In 1-year prediction by PFM, the R, RMSE, and MAE values for O_3 are 0.66, 11.33 μg/m^3, and 8.84 μg/m^3, respectively. We can see that all statistical measures demonstrate that the model has adequate performance. The forecasting values for O_3 and the actual and predicted values are significantly fitted. The prediction results of PFM for O_3 in Jiangsu Province are presented in **Figure 8** and **Table 6**.

CONCLUSION

To the best of our knowledge, this is the first provincial study that predicts six air pollutant parameters based on the prophet forecasting model (PFM). To control the threat and mitigate the hazardous effects of air pollution, a crucial step is to predict accurate air pollution over both short-term and long-term intervals. This allows policymakers and lower-level authorities to make strategies and plan accordingly to control air pollution as early as possible. In this study, the PFM is used to predict air pollution factors, including PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3, using 5 years of data in Jiangsu Province. The results demonstrate that the model has the unique ability to accurately forecast both short-term and long-term air quality, supporting its effectiveness. Few studies have reported the use of PFM to predict air pollution, and in the field of environmental modeling, applications of the model are still unexplored (Ye, 2019; Shan et al., 2020). This work illustrates that PFM has a wide ability to predict air pollution, and due to the fast-training time (approximately 10 times faster than ARIMA) and lack of a complex system, it can be applied to other regions. Compared with other models, as discussed in Section 2, the PFM has a unique ability to forecast air pollution and the model provides superior results in predicting air pollutants in Jiangsu Province. This study provides useful information and credible outcomes for the Chinese administration, scientific community and policymakers to mitigate air pollution problems and to plan accordingly in upcoming years.

Policy Implications, Limitations and Future Research Directions

It is best to stop air pollution at its source, but until that day comes, experts suggest the following. Avoid spending time on busy roads and places with pollution. When you walk or bike away from congested streets, you can reduce exposure by half by using backstreet routes. Even on busy streets, cyclists experience less pollution than drivers. Scientists recommend parents cover their buggies with covers to protect their infants. Make sure you get to work early before rush hour begins and pollution levels rise. Exercise indoors or reduce strenuous outdoor exercise when air pollution is high or if you have a lung condition such as asthma.

(1) Comprehensively implement pollution reduction. Coordinate and promote structural emission reduction, engineering emission reduction and management emission reduction: It is strictly forbidden to build new capacity projects in industries with severe overcapacity, adjust and optimize the industrial structure, and promote industrial transformation and upgrading. Eliminate outdated thermal power units and cement production capacity, strictly control the newly added emissions of sulfur dioxide and nitrogen oxides in the power industry, and simultaneously build and put into operation flue gas desulfurization and denitrification facilities for newly built coal-fired units. Focus on the reduction of emissions in the thermal power industry.
(2) Strengthen coal control and management: Speed up the elimination of small coal-fired boilers. Strengthen the replacement of clean energy, vigorously develop cogeneration and regional central heating, and adopt methods such as “coal to gas”, “coal to electricity”, and “coal to biomass” to promote the elimination of small coal-fired boilers.
(3) Strengthen the control of industrial air pollution: Promote the prevention and control of industrial pollution, and promote the replacement of old dust collectors with high-efficiency wet electrostatic and wet desulfurization dust collectors.
(4) Completely ban the burning of crop straws and improve the comprehensive utilization rate of straws. Comprehensively improve the comprehensive utilization level of straw, and promote the demonstration projects of comprehensive utilization of straw, technologies such as straw returning to the field and wood replacement, and energy utilization such as curing and molding.

In current study, we used the PFM model to predict six air pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3) in Jiangsu Province, China. The model shows good performance and provides better results in predicting air pollutant concentrations. The current research emphasizes air quality, the model should also be used in other fields as a forecasting method, such as in environmental economics to evaluate economic variations and the impact of climate change on the market. After the identification of the COVID-19 pandemic, strict restrictions and control measures have been taken to control its rapid spread by the affected countries. Many scholars reported that due to strict restrictions and control actions, the air quality of these areas and regions was improved at a significant level (Li et al., 2020; Hasnain et al., 2021; Islam et al., 2021). Future research can be conducted to predict air quality trends during the COVID-19 pandemic and the current trends. The results of both periods can be compared to find out the changes and obtain new findings for policy implications. The study can be further extended to explore the impact of the COVID-19 pandemic on economic and industrial activities. Moreover, the current study focuses to predict air pollutants; future work can be conducted to predict meteorological factors. In the future, the model should also be used to predict the impact of climate change on agriculture production. The next step of the research is to extend the PFM to other fields and regions to obtain new findings, and it will be useful in areas such as effective preparation, health alarms for liable categories, reduced monitoring expenditures, etc.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: CNEMC (2019). China national environmental monitoring centre. http://www.cnemc.cn/. Accessed 08 August 2019.

AUTHOR CONTRIBUTIONS

AH: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing, Visualization; YS: Supervision, Conceptualization, Resources, Investigation, Project administration, Funding acquisition; MZH: Supervision, Investigation, Writing - review & editing; UAB: Investigation, Data curation, Writing - review & editing; AH: Data curation, Writing - review & editing; MH: Data curation, Writing - review & editing; SM: Data curation, Writing - review & editing; SUB: Data curation, Writing - review & editing; MAH: Data curation, Writing - review & editing; MS: Data curation, Writing - review & editing; RAW: Data curation, Writing - review & editing; YZ: Supervision, Conceptualization, Resources, Investigation.

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Environmental regulation, abatement strategy, and labor income share

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Firms need to adopt abatement strategies and change their modes of production and resource allocation under the strict environmental policy, which affects the labor income share. Based on the firm-level data of China's Industrial Enterprise Database and Pollution Emission Database from 1998 to 2013, this study uses the difference-in-differences framework to test the effects and mechanisms of environmental policy on labor income share with different abatement strategies. We find that the Two Control Zone policy coupled with Environmental Performance Assessment policy (EPA-TCZ policies) in China, significantly increases the labor income share by 2.6% and reduces sulfur dioxide (SO_2) emissions. Mechanism analyses further find that firms primarily adopt abatement strategies of source control and end-of-pipe treatments to cope with environmental regulation, and labor income share is enhanced through the factor-substitute effect and the cost effect. As the result of labor income share, low-skilled firms and state-owned firms are more sensitive to environmental regulation. The results from this study provide an empirical basis for the formulation and evaluation of environmental policies in developing countries.

KEYWORDS

environmental regulation, labor income share, air pollution, abatement strategy, China

Introduction

Environmental pollution is the negative externality of economic and social activities to the environment. In order to solve this massive, spatio-temporal externality, we must internalize the externality. The implementation of a strict environmental policy is an important method for solving the internalization of externalities, but it will also lead to social problems, such as unemployment and a widening income gap. In particular, China as a developing country in the process of rapid development, the question of how to balance environmental protection and social stability is the key issue of environmental policy-making. Recently, some relevant studies have primarily examined the environmental effects, the output effects, and the trade effects of environmental policy (Chen et al., 2018). Research about the social effect of environmental policy focus on employment and income distribution (Fan, 2019; Liu et al., 2021), and the study on the labor income share effect of environmental policy is becoming an important research topic. In particular, low-income employments and low-skilled workers are more easily affected by environmental regulation, and the widening income gap will cause serious social problems.

The existing literature mainly believes that with the continuous improvement of environmental regulation, the relative changes in labor productivity and average wages are caused by cost effects and innovation compensation effect, and the effect of the labor income share is uncertain from a theoretical point of view (Hu and Yang, 2020; Li and Hu, 2021). To cope with strict environmental policies, profit-maximizing firms will choose differentiated abatement strategies, such as "changes in production processes", and "end-of-pipe" treatments, to alter the mode of production and resources allocation, leading to relative changes in labor productivity and wages, and thus affect the labor income share. Therefore, the total impact of environmental policy on the labor income share is uncertain and requires empirical analysis. This study attempts to explore the effects and mechanisms of environmental policy on labor income share through the identification of a firm's abatement strategy, which is helpful in the formulation and evaluation of environmental policies.

Theoretically, the effects of environmental regulation on income distribution are mainly reflected in three components: skill premium, firm scale, and industry characteristics (Qin and Qi, 2019). Environmental regulation changes the firm's factor structure and affects the income distribution of workers with different skill levels (Fullerton and Monti, 2013). Small firms, polluting firms, and labor-intensive firms are more susceptible to environmental regulation policies (Wang et al., 2019). Empirically, there is no consistent conclusion on the income distribution effect of environmental regulation (Chao et al., 2012; Fan, 2019), and requires sufficient empirical evidence (Pi and Shi, 2018).

In previous empirical studies, three articles were very similar to this study which all considered that environmental rules had a non-linear relationship with labor income share (Hu and Yang, 2020; Liu and Wang, 2020; Li and Hu, 2021). Using industry data, Hu and Yang (2020) found that environmental regulation was an important factor affecting labor income share. More specifically, environmental regulation had a significant U-shaped impact on labor income share through the labor skill structure. Liu and Wang (2020), using provincial panel data from 1997 to 2015, explained the inverted-U-shaped impact of environmental pollution and environmental regulation on labor income share based on the wage compensation theory. Li and Hu (2021) argued that the impact of environmental regulation on labor income share was near the inverted U-shaped inflection point using provincial panel data, with technological innovation, industrial structure adjustment, and foreign direct investment contributing to the improvement of the labor income share. The above literatures use provincial or industry data, however, the research on micro firm-level data is very scarce. How environmental policies affect firms abatement strategies and the heterogeneous impacts on labor income share remain to be explored.

Previous studies had shown that the indicators of environmental regulation were difficult to select. Investments in pollution control, pollutant emissions, and the number of administrative penalty cases were usually used to measure environmental regulation in existing studies, which may lead to estimation bias because of endogenous problems. This study chooses two landmark policies, China's Two Control Zones (TCZ) policy during the10th Five-Year Plan (FYP) and the Environmental Performance Assessment (EPA) policy of the 11th FYP as quasi-natural experiments, which may overcome the endogenous problem of environmental pollution indicators used in previous studies. According to the TCZ policy in 1998, 64 cities were classified as sulfur dioxide pollution control areas and 109 cities were designated as acid rain control areas depending on the level of regional pollution, which represents a total control policy for key areas of pollution sources. The EPA policy takes the total discharge of major pollutants as a binding indicator for governments at all levels, which is a total control policy for different pollutants. The combination of TCZ and EPA (hereafter, EPA-TCZ) policies promotes the achievement of abatement targets since 2005.

This study considers the impact of the environmental regulations on the labor income share using the EPA-TCZ policies. The effects of the TCZ policy or EPA policy on the environment, trade, employment and infant mortality were respectively analyzed (Hering and Poncet, 2014; Tanaka, 2015; Cai et al., 2016). However, there are few studies about the effects of EPA-TCZ policies. Only Chen et al. (2018) and Zhang et al. (2020) combine the TCZ policy and EPA policy to study their impacts on resource allocation and economic growth.

Unlike existing studies that have paid more attention to the cost effect, innovation compensation effect and wage compensation effect (Hu and Yang, 2020; Liu and Wang, 2020; Li and Hu, 2021), we explore the influence mechanism from the view of the factor-substitute effect. Under the strict environmental policy, firms need to adopt abatement strategies and change their modes of production and resource allocation, such as replacing polluted raw materials with clean raw materials. What's more, this paper examines the effects and mechanisms of environmental regulation on labor income share with different abatement strategies, which serves as a useful supplement to the existing research from the theoretical and empirical view.

This study enriches the empirical research on the resource allocation effect of firms' abatement strategies. Abatement strategies discussed in the literature mainly consist of "changes in production process" and "end-of-pipe" treatments (Berman and Bui, 2001; Liu et al., 2021). In practice, firms may use fuel coal with lower sulfur content or replace pollution factors with more labor, and this "source control" strategy has been ignored in existing research. This paper shows that in addition to the above two abatement strategies, firms will also adopt "source control" strategy to cope with environmental policy, and thus influence the labor income share. These results have practical values for making environmental policy.

This study also provides a sample of empirical research about the impact of environmental regulation on labor income share in developing countries. As China's economy continues to grow, more attention will be paid to environmental protection, and more stringent environmental policies will be implemented, which may create more problems in income distribution. This study matches firm-level data of China's Industrial Enterprise Database (CIED) and Pollution Emission Database (CPED) to test the effect of the total amount control policy on labor income share. This study provides support for the social effect assessment of China's environmental policy.

The remainder of this article is arranged as follows. The second section introduces the TCZ policy and EPA policy background. The third section presents a theoretical analysis about the impact of environmental regulation on labor income share under abatement treatments. The fourth section is estimation strategy. The fifth section is the empirical analysis, which estimates the impact of EPA-TCZ policies on labor income share with the robustness test, and presents the mechanism test and heterogeneity analysis. Finally, the sixth section offers the conclusion and presents policy implications.

Policy background

Since the implementation of "Environmental Protection Law" in 1998, the central government has continuously deepened its understanding and protection of the ecological environment, and successively issued a series of environmental policies. These policies are roughly divided into three stages, the exploration stage based on the introduction of laws and regulations, the policy implementation stage based on the government performance assessment and the promotion stage of diversified environmental policies based on the combination of government administrative instructions and marketization (Yu and Yin, 2022). Among them, the most iconic policies are the TZC policy and EPA policy. The former embodies total pollution control at the regional level, and the latter addresses the discharge of various pollutants, which are respectively in the first two stages of environmental policies. During this period, the attributes of emission reduction indicators have changed from anticipatory to binding.

In 1998, the State Council formulated a sulfur dioxide emission reduction plan (that is TCZ policy) to address the increase of SO_2 emissions and the severity of acid rain. The policy classifies 64 cities as sulfur dioxide pollution control areas and 109 cities as acid rain control areas, where SO_2 emissions account for more than 60% of total emissions. The emission reduction measures proposed by the central government mainly include restricting high sulfur coal's mining, production, transportation and use, and emphasizing pollution control throughout the whole production process from the selection of raw materials to the production process management and "end-of-pipe" treatments. The TCZ policy also sets short-term and long-term environmental control objectives for the TCZ cities. Specifically, by the end of 2000, the SO_2 emissions in TCZ city will be lower than the quota set by the central government. By the end of 2010, the SO_2 emission will not exceed the level of 2000, and the SO_2 density in TCZ city should meet the environmental quality standard (lower than $60ug/m^3$).

However, the emission reduction effect of the TCZ policy was not remarkable by the end of 2000, which may be related to the anticipation of emission reduction targets and the lack of specific abatement targets (Zhang et al., 2020). In 2002, the central government assigned exact SO_2 reduction targets to provincial governments at all levels, but the reduction effect was still unsuccessful. SO_2 emissions fluctuated down from 1998 to 2002, but then increased rapidly (Figure 1). By 2005, total SO_2 emissions in TCZ cities had not declined, but enhanced by 2.9% compared to that of 2000, which may be due to the lack of effective restraint mechanism for local governments (Chen et al., 2018).

In 2005, the central government allocated the 10% reduction in major pollutants to governments at all levels as a binding condition, which has been a part of the 11th FYP (2006–2010) for the first time and a close relation to the promotion of local officials. Environmental objectives were incorporated into the environmental performance assessment of local officials, which was EPA policy implemented at the end of 2005.

During the 11th FYP period, total SO_2 emissions decreased by 12.5%. As of 2010, the SO_2 emission reduction target was achieved, and the total national SO_2 emission had decreased by 14.29%. The EPA policy continued through the 12th FYP (2011–2015). Implementation of EPA policy is helpful for the emission reduction target of the TCZ policy, which is a successful practice of the total amount control policy (Zhang et al., 2020). This study analyzes the impacts of these two combination policies (EPA-TCZ policies) on labor income share, which gives more accurately evaluation of the income distribution effect of comprehensive environmental policies and provides practical significance in the formulation and assessment of environmental policies.

Theoretical analysis

The existing studies mainly discuss the impact of environmental regulation on labor income share through two mechanisms. The first is the cost effect. Pollution emission is a part of the production function in the form of input or output (Fullerton and Metcalf, 1998; Berman and Bui, 2001; Sanz and Schwartz, 2013). Strict environmental policies make pollution emissions have a "price" and increase the marginal cost, which not only crowds out productive investment, reducing labor productivity (Ferjani, 2011), but also reduces the output and profitability, falling average wages. The impact of environmental regulation on labor income share depends on the relative extent of the decline in labor productivity and wages[1]. The second is the innovation compensation effect. Firms may adjust production behavior under environmental policies, and turn to increase research to innovate green or production technology (Porter and van der Linde, 1995), which may offset the negative impact of cost effect on output. Meanwhile, the proportion of high-skilled workers is enhanced and the average wage level is increased (Hu and Yang, 2020). Thus, the effect of environmental regulation on labor income share depends on the relative extent of the improvement in wages and labor productivity under the innovation compensation effect.

In addition to the above cost effect and innovation compensation effect, this paper regards that environmental policy may also affect the labor income share by factor-substitute effect. Environmental protection activities may be more labor-intensive than traditional production (Morgenstern et al., 2002; Zhang et al., 2020). For example, cleaner operations may require less polluting fuel and materials, or more labor for inspection, installation and maintenance activities. Firms tend to use labor to replace capital and other polluting factors of production to reduce pollution, and the demand for labor is relatively increasing, which means the labor income share has risen. However, environmental regulation policies may cause firms to adopt advanced technology processes and reduce labor demand (Berman and Bui, 2001), leading to the replacement with labor by capital and a decline in labor income share. From the above, we find that the factor-substitute effect of environmental regulation on labor income share is closely related to abatement strategy.

Abatement activities are mainly divided into two categories: "changes in production processes", and "end-of-pipe" treatments (Liu et al., 2021). The former, such as the adoption of advanced production technology or green technology, and updating equipment to generate less emission, may require more capital and less labor. The latter refers to technologies used at the end of a production process to reduce emissions by removing produced pollutants, such as the installation of desulfurization devices. This paper regards that in response to stringent environmental policy, firms may reduce pollution emissions from the production source and adopt clean production factors to replace high-emission factors, such as the use of cleaner energy and more labor rather than capital. We refer to this abatement strategy as "source control" strategy.

The impact mechanism of environmental regulation policies on labor income share depends on different abatement strategies. If a "source control" strategy is adopted, on the one hand, the stringent environmental policies make firms use more labor to replace capital and other polluting factors. The demand for labor is relatively increasing with the factor-substitute effect, and the labor income share is rising. On the other hand, firms input cleaner energy, and production costs increase, which makes the impacts of environmental regulation on labor income share depend on the relative decline of labor productivity and wage growth rate through the cost effect. With the strategy of "changes in production processes", labor productivity and wage level are both improved through the innovation compensation effect, which will cause uncertain changes in the labor income share. In addition, the adoption of advanced production processes may raise the substitution of capital for labor, reducing labor demand and labor income share through the factor-substitute effect. If firms adopt "end-of-pipe" treatments, they not only need to purchase decontamination equipment, but also match the labor for maintenance and operation, which may reduce production investment and result in the decline of labor productivity and wage level with the cost effect. From the above theoretical analysis, it can be seen that the impact of environment regulation on labor income share is uncertain, and further empirical analysis is needed.

Estimation strategy

Estimation framework

To evaluate the labor income share effect of EPA-TCZ policies, we divide TCZ cities into treatment groups and non-TCZ cities into control groups, and then compare the changes in labor income share before and after the implementation of EPA policy using a difference-in-differences (DID) model. Referring to Chen et al. (2018), the regression model is as follows:

$$ls_{ijt} = \beta TCZ_i \times Post_t + \rho \ln(SO_2)_i \times f(t) + \alpha_i + \delta_t + \varepsilon_{ijt} \quad (1)$$

where ls_{it} represents labor income share in firm j at year t. According to Lu and Tian (2020), a firm's labor income share is defined as the proportion of total wages to total income including wages, profits, depreciation, and tax. TCZ_i equals one if firm i is located in TCZ city i in 1998, and otherwise TCZ_i equals 0. $Post_t$ equals one for all years after 2005 (policy period) and otherwise equals 0. We control city fixed effect and year fixed effect, and cluster the standard errors at the city level, following the suggestion of Bertrand et al. (2004). α_i is city fixed effect, catching the time-invariant city-specific characteristics. δ_t is

1 By definition, labor income share (ls) can be written as wage (w) divided by labor productivity (y), $ls = w*L/Y = w/(Y/L) = w/y$. It can be inferred that $\Delta\ln(ls) = \Delta\ln(w) - \Delta\ln(y)$, which depend on the relative changes in wages and labor productivity. If the changes in wage are greater than that of labor productivity, the labor income share will increase. Conversely, the labor income share will decrease

year fixed effect, capturing factors that impact all cities over time such as macroeconomic shocks, and ε_{it} is the error term.

The coefficient β measures the DID effect of the EPA-TCZ policies on labor income share as follows:

$$\beta = \left[E\left(ls_{ijt}|TCZ = 1, Post = 1\right) - E\left(ls_{ijt}|TCZ = 1, Post = 0\right)\right] - \left[E\left(ls_{ijt}|TCZ = 0, Post = 1\right) - E\left(ls_{ijt}|TCZ = 0, Post = 0\right)\right] \quad (2)$$

The coefficient estimation of β with the DID method requires random grouping that if there is no EPA policy in 2005, the labor income share of TCZ cities has the same time trend as that of non-TCZ cities after 2005. Otherwise, there is a systematic difference between the control group and the treatment group before the implementation of the policy in 2005, which may cause the selection bias from the correlation between $TCZ_i \times Post_t$ and ε_{it}. The classifications of TCZ cities are based on the "Air Pollution Prevention and Control Law" (APPCL) revised in 1995, which stipulates that according to natural condition, such as meteorological, topographical, and soil conditions, areas producing acid rain or other areas with serious sulfur dioxide pollution are designated as acid rain control areas or sulfur dioxide pollution control areas. Obviously, TCZ cities are not randomly grouped. In order to reduce the estimation error caused by the non-random grouping of policies, we calculate the average surface concentration of urban sulfur dioxide ($\ln(SO_2)$) from 1990 to 1997 and multiplies it with the third-order polynomial of time trend ($f(t)$), which is used to capture the changes of SO_2 emissions before 1998. In addition, we perform a common trend test and a placebo test, as well as robustness tests such as replacing variables and changing sample size.

The implementation of the TCZ policy may change the characteristics of the treatment group and the control group, making them incomparable when the EPA policy was in place at the end of 2005. Existing studies show that the TCZ policy has affected exports (Hering and Poncet, 2014), GDP growth (Chen et al., 2018), and employment (Zhang et al., 2020). In order to solve this problem, we add a set of variables known in the literature that are affected by TCZ policy, including export and size at the firm level, per-capita GDP and unemployment rate at the city-level. In addition, market structure is added to reflect industry characteristics. The specific models are as follows:

$$ls_{ijt} = \beta TCZ_i \times Post_t + \rho \ln(SO_2)_i \times f(t) + \gamma Z_{ijt} + \alpha_i + \delta_t + \varepsilon_{ijt} \quad (3)$$

Where Z_{ijt} contains city and industry characteristic variables that affect labor income share, namely, urban unemployment rate, per-capita GDP, and market structure, as well as export and size at the firm level. The labor market, one of the important variables that affect the labor income share, is competitive intense and labor income share will increase (Mangin and Sedlacek, 2017). The actual per-capita GDP measured by its logarithmic form represents the economic growth of the city and is deflated by the GDP deflator in 1998 as the base year. Previous studies have shown that market structure is also the main factor affecting labor income share, and measured by market concentration with the Herfindahl-Hirschman index in this paper. Considering the availability of data, the variable of export is measured with dummy variables, which equals one if the export delivery value of the firm is greater than 0 and otherwise equals 0. Size represented the scale of the firm, which is measured by the logarithmic form of the number of workers.

Data sources and descriptive statistics

In order to analyze the effect of the EPA-TCZ policies on labor income share, this study uses combined firm data with CIED and CPED from 1998 to 2013. We also use economic data at the city and industry levels including China's City Statistical Yearbooks from 1999 to 2014.

China's Industrial Enterprise Database (CIED) contains rich economic and financial information on industrial firms, such as output, assets and liabilities, and the number of employees, which are self-reported quarterly and annually by the firm and collected in a step-by-step process undertaken by the National Bureau of Statistics. The CIED covers all state-owned and nonstate-owned firms with an annual business income of more than five million, whose total output is accounting for roughly 90% of total industrial output in China, and thus has been widely used in economic literature. In this paper, we use information on the output value, the number of employees, wages, profits, value-added tax, ownership type, city, and industry code.

China's Pollution Emission Database (CPED) is currently the most comprehensive firm-level pollution emission data in China, covering 85% of the emissions of major pollutants in each region, including SO_2, chemical oxygen demand, and so on. This data is the original environmental data reported by industrial firms collected by the National Bureau of Statistics, and it is the specific data source for China's Environmental Statistics Yearbooks issued every year, which has only recently been made available to researchers. The CPED contains basic firm information (firm name, legal representative information, area code, industry code), including energy use, major pollutant discharges, and treatment information, etc. In this study, we extract SO_2 emissions, SO_2 production, average sulfur of fuel coal, clean energy use, statistical year, ownership type, city, and industry code from the CPED.

Referring to the research of Brandt et al. (2012), First, CIED and CPED are matched respectively across years according to the firm name, postal code, legal representative, etc. Then, the two databases are matched according to the firms' organizational code[2] in the CIED and CPED. The data from

2 Considering there is some deviations in the organizational code when entering data, we remove words that are not helpful in matching the firm name to improve the matching rate

TABLE 1 Descriptive statistics.

Variables	N	Mean	SD	Min	Median	Max
ls	313742	0.351	0.196	0.0260	0.329	0.885
Export	313742	0.498	0.500	0	0	1
Size	313742	5.732	1.094	2.197	5.697	11.990
HHI	313742	0.256	0.077	0.200	0.228	0.658
Unemployment	313742	0.017	0.012	0	0.016	0.427
ln (GDP)	313742	10.128	0.900	6.905	10.179	13.056

2008 to 2010 is dropped due to the lack of wage information. In addition, we also delete samples with missing key variables and outliers that do not meet the following accounting standards as follows. 1) the number of employees in the firm is greater than 8; 2) total asset is greater than fixed assets; 3) total asset is greater than the liquid asset; 4) the accumulated depreciation value is greater than the depreciation value in the current year; 5) the output is less than five million; 6) the labor income share is between 0 and 1. The variable of labor income share is winsorized at the 1% level. Finally, we get the unbalanced panel data of 81,735 firms and 313,742 observations.

The city-level variables are from the China Statistical Yearbook and the China City Statistical Yearbook, providing some city-level economic variables, such as unemployment rate and per capita GDP. The descriptive statistics of the variables are shown in Table 1.

TABLE 2 Baseline results.

Variables	(1)	(2)	(3)	(4)
	ls	ls	ls	ls
$TCZ \times Post$	0.041***	0.035***	0.035***	0.026***
	(0.009)	(0.008)	(0.008)	(0.007)
Export	—	—	−0.005	−0.003
	—	—	(0.004)	(0.004)
Size	—	—	0.007***	0.006***
	—	—	(0.001)	(0.001)
HHI	—	—	—	0.014
	—	—	—	(0.016)
Unemployment	—	—	—	0.119
	—	—	—	(0.128)
ln (GDP)	—	—	—	−0.083***
	—	—	—	(0.009)
$\ln(SO_2) \times f(t)$	NO	YES	YES	YES
City Fixed Effect	YES	YES	YES	YES
Year Fixed Effect	YES	YES	YES	YES
Ownership Fixed Effect	NO	YES	YES	YES
Industry Fixed Effect	NO	YES	YES	YES
N	313742	313742	313742	313742
R^2	0.089	0.165	0.166	0.170

Note: Standard errors in parentheses are clustered at the city level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. If the firm is in the TCZ cities, *TCZ* equals one; otherwise, *TCZ* equals 0. *Post* = 1 for all years after 2005; otherwise *Post* equals 0. $\ln(SO_2) \times f(t)$ indicates the interaction term of logarithmic form of SO_2 surface concentration of the city where the firm is located from 1990 to 1997 and the third-order polynomial of the time trend.

Main results

Baseline results

Table 2 reports the baseline results of Equation 1 and 3. Column 1) in Table 2 shows that $TCZ \times Post$, as well as city and year fixed effects, are added to Eq. 1. In order to alleviate policy selection bias, we add $\ln(SO_2) \times f(t)$ in column (2), which also contains ownership and industry fixed effect. Firm-level variables are included in column (3), and the industry-level and city-level variables are added in column (4). After adding variables one by one, the coefficients of $TCZ \times Post$ decrease gradually, but they are all significantly positive, which indicates that after the implementation of EPA-TCZ policies, firms in the TCZ cities facing stricter environmental regulations have higher significantly labor income share. From the result of point estimation, the average DID effect of the EPA-TCZ policies is 0.026, showing that compared with the firms in non-TCZ cities, the average labor income share in TCZ cities increases by 2.6%.

Robustness checks

Common trend test. The key assumption of the DID method is the common trend hypothesis, which means that before the implementation of the EPA-TCZ policies, labor income share in TCZ and non-TCZ cities exhibits the same trend. Figure 2 shows the changing trend of the labor income share in TCZ and non-TCZ cities. It can be found that the labor income share declined from 1998 to 2013, which is consistent with the fact that China's labor income share was reducing at the macro level during the same period. In particular, labor income share in TCZ and non-TCZ cities has the similar declining trend before 2005, but after the implementation of the EPA in 2005, the declining trend of labor income share in TCZ cities is alleviate obviously, which reveals that the treatment group and the control group meet the common trend assumption before the implementation of the policy.

In order to furtherly investigate the common trend and dynamic effect, we use the case study to explore the dynamic effect of the EPA-TCZ policies. The equation is as follows:

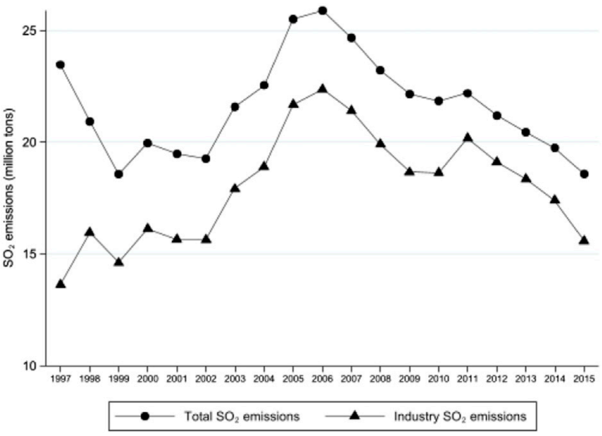

FIGURE 1
SO_2 emissions trend in 1997–2015.

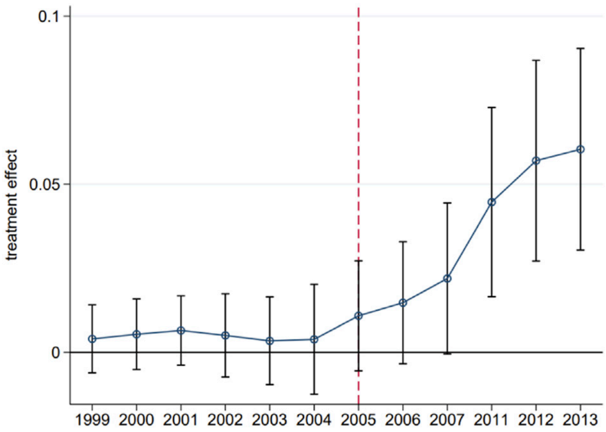

FIGURE 3
Estimated coefficients.

FIGURE 2
Labor income share trend in 1998–2013.

$$ls_{ijt} = \sum_{t=1998}^{2013} \beta_t TCZ_i \times \delta_t + \rho \ln (SO_2)_i \times f(t) + \gamma Z_{ijt} + \alpha_i + \delta_t + \varepsilon_{ijt} \tag{4}$$

β_t represents a series of estimation coefficients from 1998 to 2013, which captures the differences in the labor income share between TCZ and non-TCZ cities before and after the implementation of the EPA policy. As shown in Figure 3, there is no significant difference between the coefficient β and 0 before the occurrence of the EPA policy, and the effect of the policy on labor income share gradually increased after the implementation of the EPA policy in the TCZ cities compared with non-TCZ cities. This not only suggests that the common trend assumption is met, but also indicates environmental policy has a continuous positive effect on labor income share.

Placebo test. In order to ensure a more robust conclusion, with reference to Chetty et al. (2009)'s method, we undertake a placebo test. First, the treatment firms are randomly selected from the full samples, and the other firms are regarded as the control group. Then, we define and calculate the DID dummy. Finally, the DID effect is estimated. The above processes are repeated 500 times, and the distribution of DID coefficients is shown in Figure 4, where β is primarily distributed around 0 and does not reach the real value of 0.026. This reveals that the virtual policy grouping does not have the increasing effect of labor income share, and the placebo test is consistent with expectations. Further, it shows that the increase in labor income share is caused by the EPA policy implemented in 2005.

Alternative samples. Previous studies have shown that after 2005, in order to achieve environmental performance goals, local officials in TCZ cities would rather give up economic growth and take various measures to reduce pollution emissions within their jurisdictions (Chen et al., 2018). Other policies or major events will also affect local governments to make a trade-off between economic growth and pollution emissions after 2005. For example, in order to ensure the air quality during the 2008 summer Olympic Games, local governments may further sacrifice economic growth and require most industrial firms to limit or stop production. The samples of host cities as well as co-host cities are removed to reduce the impact of the major event of the Olympic Games on the results, including Beijing, Shanghai, Tianjin, Shenyang, Qinhuangdao and Qingdao, which are given in columns 1) and 2) of Table 3. We find that β coefficient is still significantly positive, showing that the baseline result is not affected by the major events.

Change the variable definition. Considering that the value of labor income share is between 0 and 1, consistent with the work of Wei et al. (2013), we define the "odds ratio" of *ls* in

TABLE 3 Robustness checks.

Variables	(1) ls	(2) ls	(3) $\ln(\text{ls}/(1-\text{ls}))$	(4) $\ln(\text{ls}/(1-\text{ls}))$
TCZ × *Post*	0.038***	0.025***	0.214***	0.146***
	(0.009)	(0.007)	(0.046)	(0.037)
Control Variables	NO	YES	NO	YES
$\ln(SO_2) \times f(t)$	YES	YES	YES	YES
City Fixed Effect	YES	YES	YES	YES
Year Fixed Effect	YES	YES	YES	YES
Ownership Fixed Effect	NO	YES	NO	YES
Industry Fixed Effect	NO	YES	NO	YES
N	290660	290660	313742	313742
R^2	0.094	0.175	0.095	0.174

Note: Standard errors in parentheses are clustered at the city level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. If the firm is in the TCZ cities, *TCZ* equals one; otherwise, *TCZ* equals 0. *Post* = 1 for all years after 2005; otherwise *Post* equals 0. Control variables include Export, Size, HHI, Unemployment and ln(GDP). $\ln(SO_2) \times f(t)$ indicates the interaction term of the average SO_2 surface concentration of the city where the firm is located from 1990 to 1997 and the third-order polynomial of the time trend.

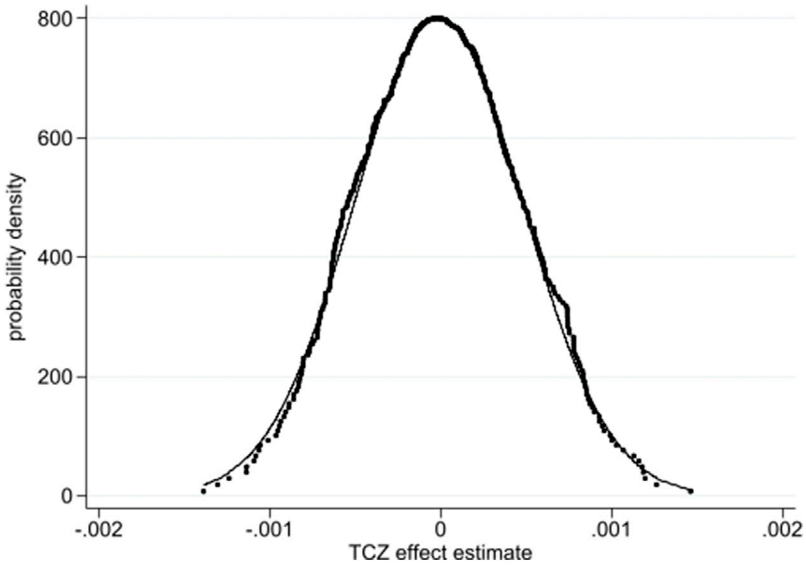

FIGURE 4
Placebo test.

the logistic model as $ln(ls/(1-ls))$, the logarithm of the labor-capital income ratio, which is the dependent variable used in the regression. The estimated results in columns 3) and 4) show that after changing the definition of labor income share, the coefficient of *TCZ* × *Post* is still significantly positive and the point estimation suggests that the labor capital income ratio increases by 15.8% more than the non-TCZ firms, which supports the baseline conclusion.

Mechanism analysis

The main purpose of the TCZ policy is to reduce the emissions of major pollutants such as SO_2 , and the policy effectiveness need to be confirmed before carrying out the mechanism analysis. With $\ln(SO_2)$ as the proxy variable of the environmental regulation level, the EPA-TCZ policy significantly reduces sulfur dioxide emissions after control other variables in columns 2) in Table 4. With the level of

TABLE 4 Mechanism check: "source control" treatments.

Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	ln (SO_2)	**ln (SO_2)**	**ln(K/L)**	**ln(K/L)**	**ln (clean energy)**	**ln (clean energy)**
TCZ × Post	−0.105	−0.167**	−0.103**	−0.147***	0.558***	0.461**
	(0.083)	(0.073)	(0.049)	(0.044)	(0.214)	(0.181)
Control Variables	NO	YES	NO	YES	NO	YES
$\ln(SO_2) \times f(t)$	YES	YES	YES	YES	YES	YES
City Fixed Effect	YES	YES	YES	YES	YES	YES
Year Fixed Effect	YES	YES	YES	YES	YES	YES
Ownership Fixed Effect	NO	YES	NO	YES	NO	YES
Industry Fixed Effect	NO	YES	NO	YES	NO	YES
N	382576	382576	528446	528446	179077	179077
R^2	0.086	0.367	0.150	0.253	0.194	0.257

Note: Standard errors in parentheses are clustered at the city level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. If the firm is in the TCZ cities, *TCZ* equals one; otherwise, *TCZ* equals 0. *Post* = 1 for all years after 2005; otherwise *Post* equals 0. Control variables include Export, Size, HHI, Unemployment and ln(GDP). $\ln(SO_2) \times f(t)$ indicates the interaction term of the average SO_2 surface concentration of the city where the firm is located from 1990 to 1997 and the third-order polynomial of the time trend. Dependent variables in columns (1) and (2) are $\ln(SO_2)$ represented by the logarithmic form of SO_2 emissions. Dependent variables in columns (3) and (4) are $\ln(K/L)$ represented by the logarithmic form of per capita capital. Dependent variables in columns (5) and (6) are ln(clean energy) represented by the logarithmic form of clean energy consumption.

TABLE 5 Mechanism check: "changes in production processes" treatments.

Variables	**(1)**	**(2)**	**(3)**	**(4)**
	ln$(SO_2$ sensity$)$	**ln$(SO_2$ sensity$)$**	$D_{\mathbf{newproduct}}$	$D_{\mathbf{newproduct}}$
TCZ × Post	0.053	−0.001	0.053	-0.001
	(0.032)	(0.023)	(0.032)	(0.023)
Control Variables	NO	YES	NO	YES
$\ln(SO_2) \times f(t)$	YES	YES	YES	YES
City Fixed Effect	YES	YES	YES	YES
Year Fixed Effect	YES	YES	YES	YES
Ownership Fixed Effect	NO	YES	NO	YES
Industry Fixed Effect	NO	YES	NO	YES
N	383513	383513	383513	383513
R^2	0.129	0.435	0.708	0.749

Note: Standard errors in parentheses are clustered at the city level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. If the firm is in the TCZ cities, *TCZ* equals one; otherwise, *TCZ* equals 0. *Post* = 1 for all years after 2005; otherwise *Post* equals 0. Control variables include Export, Size, HHI, Unemployment and ln(GDP). $\ln(SO_2) \times f(t)$ indicates the interaction term of the average SO_2 surface concentration of the city where the firm is located from 1990 to 1997 and the third-order polynomial of the time trend. Dependent variables in columns (1) and (2) are $\ln(SO_2$ sensity$)$ represented by the logarithm of SO_2 generated per unit of output. Dependent variables in columns (3) and (4) are $D_{\text{newproduct}}$ which equals one if the firm has new product output; otherwise it equals 0.

environmental regulation represented by the SO_2 remove rate, the results are significantly positive shown in columns 1) and 2) in Table 6. These results offer evidence that the EPA-TCZ policy is effective at reducing firm-level SO_2 emissions in TCZ cities, which is consistent with the findings of Chen et al. (2018) and Zhang et al. (2020). On this basis, we test the mechanism of the policy on labor income share by identifying abatement strategies.

Firms mainly adopt three abatement strategies: "source control," "changes in production processes," and "end-of-pipe". Under the constraints of environmental policy, if firms adopt "source control" treatments to reduce emissions, they will

TABLE 6 Mechanism check: "end-of-pipe" treatments.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	SO_2 remove rate	SO_2 remove rate	ln(K)	ln(K)	ln(y)	ln(y)	ln(w)	ln(w)
TCZ × *Post*	0.049**	0.044**	−0.003	−0.152***	−0.198***	−0.123***	−0.064**	−0.080***
	(0.021)	(0.020)	(0.050)	(0.047)	(0.051)	(0.035)	(0.029)	(0.023)
Control Variables	NO	YES	NO	YES	NO	YES	NO	YES
$\ln(SO_2) \times f(t)$	YES	YES	YES	YES	YES	YES	YES	YES
City Fixed Effect	YES	YES	YES	YES	YES	YES	YES	YES
Year Fixed Effect	YES	YES	YES	YES	YES	YES	YES	YES
Ownership Fixed Effect	NO	YES	NO	YES	NO	YES	NO	YES
Industry Fixed Effect	NO	YES	NO	YES	NO	YES	NO	YES
N	213212	213212	528443	528443	313742	313742	313742	313742
R^2	0.194	0.223	0.121	0.466	0.287	0.389	0.306	0.376

Note: Standard errors in parentheses are clustered at the city level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. If the firm is in the TCZ cities, *TCZ* equals one; otherwise, *TCZ* equals 0. *Post* = 1 for all years after 2005; otherwise *Post* equals 0. Control variables include Export, Size, HHI, Unemployment and ln(GDP). $\ln(SO_2) \times f(t)$ indicates the interaction term of the average SO_2 surface concentration of the city where the firm is located from 1990 to 1997 and the third-order polynomial of the time trend. Dependent variables in columns (1) and (2) are SO_2 remove rate calculated using the ratio of the amount of SO_2 removed over the sum of SO_2 generation. Dependent variables in columns (3) and (4) are ln(K) represented by the logarithm of fixed assets. Dependent variables in columns (5) and (6) are ln(y) represented by the logarithm of per capita output. Dependent variables in columns (7) and (8) are ln(w) represented by the logarithm of per capita wage.

increase the use of clean energy or use labor instead of capital. Here, we use capital intensity (logarithm of per capita capital, $\ln(K/L)$), and clean energy use as measures of "source control" treatments[3]. The capital intensity effect of the EPA-TCZ policy is presented in columns 3) and 4) in Table 4, which reveal that the strict environmental regulation significantly reduces firm-level capital intensity and significantly increases the labor income share. This suggests that firms adopt the strategy of labor instead of capital in the short term to fight the SO_2 emissions, which is consistent with the conclusion of Zhang et al. (2020) that more labor are allocated to polluted areas. The demand effect of the EPA-TCZ policy on clean energy is provided in column 5) and (6), which demonstrates that improvements in environmental regulation help to enhance clean energy use in firms, implying that the cost effect will work and wages decline as well as labor productivity.

If "changes in production processes" treatments are adopted, firms will increase their R&D investment and improve production technology to reduce generated SO_2 before entering abatement facilities. Referring to Liu et al. (2021)'s practice, the production of SO_2 per unit output is taken as the abatement measurement of "changes in production processes" treatments. In addition, the CIED provides information in firms' innovation behavior, and we take whether a firm has a new product output ($D_{newproduct}$) as another measurement. If the firm has new product output, the value of $D_{newproduct}$ equals one; otherwise it equals 0. In Table 5, the amount of SO_2 produced per unit output (columns 1) and (2)), and $D_{newproduct}$ (columns 3) and (4)) are used as depended variables. The results show that the coefficients of policy variables are not significant, indicating that the environmental regulation does not encourage firms to choose the path of technological innovation to improve production efficiency and reduce pollution emissions, suggesting innovation compensation effect does not exist.

If adopting "end-of-pipe" treatments, firms do not change the production process and SO_2 generated, but only reduce SO_2 emissions by abatement facilities. Here, we use the SO_2 remove rate as the measurement of "end-of-pipe" treatments[4]. Columns 1) and 2) in Table 6 provide the results that EPA-TCZ policy

3 We also find that the use of average sulfur of coal is decreasing after the implementation of EPA policy

4 We also treat the number of abatement facilities as the "end-of-pipe" treatment, and estimate it as the depended variable. The results show that the impact on the number of abatement facilities is not significant, which is consistent with the results obtained by Liu et al. (2021). This may been explained as the demand for abatement equipment and statistics on the number of abatement facilities. Large-scale desulfurization equipment has strong pollutant handling capacity, and firms need a small amount of equipment to meet the abatement requirements. Thus, the amount of equipment needed will not be very significant. In addition, in order to avoid environmental regulation, firms may not report or underreport pollution emissions and abatement treatment

TABLE 7 Heterogeneous effects by workforce types.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	ls	$\ln(K/L)$	$D_{\mathbf{newproduct}}$	SO_2 remove rate	ln(y)	ln(w)
TCZ × Post × highskilled	0.008	−0.096	−0.002	0.064***	−0.039	−0.073**
	(0.008)	(0.063)	(0.009)	(0.023)	(0.039)	(0.028)
TCZ × Post × lowskilled	0.016*	−0.209***	−0.022**	0.060**	−0.191***	−0.167***
	(0.009)	(0.064)	(0.010)	(0.026)	(0.043)	(0.031)
Control Variables	YES	YES	YES	YES	YES	YES
$\ln(SO_2) \times f(t)$	YES	YES	YES	YES	YES	YES
City Fixed Effect	YES	YES	YES	YES	YES	YES
Year Fixed Effect	YES	YES	YES	YES	YES	YES
Ownership Fixed Effect	YES	YES	YES	YES	YES	YES
Industry Fixed Effect	YES	YES	YES	YES	YES	YES
N	45579	95271	95287	61610	45579	45579
R^2	0.185	0.165	0.565	0.216	0.380	0.397

Note: Standard errors in parentheses are clustered at the city level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. If the firm is in the TCZ cities, *TCZ* equals one; otherwise, *TCZ* equals 0. *Post* = 1 for all years after 2005; otherwise *Post* equals 0. Firms in the treatment group are classified into two groups, high-skilled or low-skilled, according to the ratio of high school or above workers for year 2004 (a census year). Control variables include Export, Size, HHI, Unemployment and ln(GDP). $\ln(SO_2) \times f(t)$ indicates the interaction term of the average SO_2 surface concentration of the city where the firm is located from 1990 to 1997 and the third-order polynomial of the time trend. SO_2 remove rate is the ratio of the amount of SO_2 removed over the sum of SO_2 generation. $\ln(K/L)$ represents the logarithmic form of per capita capital. $D_{\text{newproduct}}$ equals one if the firm has new product output; otherwise it equals 0. ln(y) represents the logarithm of per capita output. ln(w) represents the logarithm of per capita wage.

TABLE 8 Heterogeneous effects by ownership.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	ls	$\ln(K/L)$	$D_{\mathbf{newproduct}}$	SO_2 remove rate	ln(y)	ln(w)
TCZ × Post × State-owned	0.020*	−0.213***	−0.009	0.075***	−0.112*	−0.149***
	(0.011)	(0.069)	(0.012)	(0.028)	(0.063)	(0.049)
TCZ × Post × Private-owned	0.005	−0.101	-0.006	0.057**	−0.065	−0.087***
	(0.009)	(0.063)	(0.009)	(0.024)	(0.042)	(0.031)
TCZ × Post × Foreign-owned	0.019	−0.051	0.003	0.070**	−0.032	−0.011
	(0.017)	(0.112)	(0.018)	(0.031)	(0.089)	(0.050)
Control Variables	YES	YES	YES	YES	YES	YES
$\ln(SO_2) \times f(t)$	YES	YES	YES	YES	YES	YES
City Fixed Effect	YES	YES	YES	YES	YES	YES
Year Fixed Effect	YES	YES	YES	YES	YES	YES
Ownership Fixed Effect	YES	YES	YES	YES	YES	YES
Industry Fixed Effect	YES	YES	YES	YES	YES	YES
N	45579	95271	95287	61610	45579	45579
R^2	0.185	0.165	0.565	0.216	0.379	0.397

Note: Standard errors in parentheses are clustered at the city level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. If the firm is in the TCZ cities, *TCZ* equals one; otherwise, *TCZ* equals 0. *Post* = 1 for all years after 2005; otherwise *Post* equals 0. State-owned equals one if a firm is state-owned; otherwise, State-owned equals 0. Private-owned equals one if a firm is private-owned; otherwise equals 0. Foreign-owned equals one if a firm is foreign-owned; otherwise, Foreign-owned equals 0.Control variables include Export, Size, HHI, Unemployment and ln(GDP). $\ln(SO_2) \times f(t)$ indicates the interaction term of the average SO_2 surface concentration of the city where the firm is located from 1990 to 1997 and the third-order polynomial of the time trend. SO_2 remove rate is the ratio of the amount of SO_2 removed over the sum of SO_2 generation. $\ln(K/L)$ represents the logarithmic form of per capita capital. $D_{\text{newproduct}}$ equals one if the firm has new product output; otherwise it equals 0.ln(y) represents the logarithm of per capita output. ln(w) represents the logarithm of per capita wage.

significantly improves SO_2 remove rate, which is consistent with the results obtained by Han et al. (2021).

"End-of-pipe" treatments require firms to enhance investments in abatement facilities and increase labor for the installation, maintenance, and operation of facilities, which will crowd out the investment in production, resulting in a decline in output and lower profits and wages, and leading to changes in the labor income share. The results in Table 6 provide evidence in support of this point, and are shown that environmental regulation have significantly reduced investment in firm-level fixed assets (columns 3) and (4)) and per capita output (columns 5) and (6)), as well as wages (columns 7) and (8)). The point estimates show that compared with those of non-TCZ cities, firm-level outputs in TCZ cities have decreased by 13% and wages in TCZ cities have decreased by 8.3%, which result in labor income share increasing due to the greater decline in output and the smaller decline in wage rigidity.

To summarize, under strict environmental regulation, firms choose "source control" and "end-of-pipe" abatement strategies and labor income share is increased though factor-substitute effect and cost effect.

Heterogeneous analysis

In addition to policies' average effects on the labor income share, we are also concerned about which firms are more vulnerable to environmental policies. Therefore, this paper further discusses the heterogeneous impacts of environmental rules on the labor income share from different skill employment structures and ownership.

Workforce skill. Compared with low-skilled workers, high-skilled labor has higher labor productivity and wages. Under stringent environmental policies, firms may reduce the demand for low-skilled workers in order to reduce costs or carry out technological innovation (Liu et al., 2021). For this reason, the impact of environmental rules on labor income share is different in firms with different skill structures. There is a survey on the employment structure of labor force in China's Economic Census in 2004. Therefore, we will retain the firms in 2004 and match them with other years according to their unique identification codes, and divide the firms in the treatment groups into high-skilled and low-skilled firms according to the median of the proportion of the labor force above the high school level. Table 7 shows that the policies have a positive effect on labor income share and SO_2 remove rate, and have significant negative effects on capital intensity and the possibility of a new product in low-skilled firms, suggesting that environmental regulation reduce the labor income in low-skilled firms with "source control" and "end-of-pipe" treatments through the factor-substitute effect and cost effect.

Ownership. Previous studies have shown that the environmental performance in foreign-owned firms is better than that of domestic firms. Therefore, environmental regulations have little impact on pollution emissions and operations of foreign-owned firms (Dean et al., 2009). In domestic firms, environmental regulation policies have a greater impact on the labor demand of state-owned firms than private firms (Liu et al., 2021). Therefore, environmental policy has heterogeneous impacts on the labor income share within different ownership firms. The results in column 1) in Table 8 show that the policies only significantly increases labor income share in state-owned firms, which use more labor instead of capital strategy and "end-of-pipe" treatments (see column 2) and column 4) in Table 8), through factor-substitute effect and cost effect as shown in column 5) and column (6). The possible explanation is two reasons as follows. On the one hand, strict environmental regulation means that the prices of production factors such as raw materials rise faster than those of labor, thus enabling firms to increase labor input (Bezdek et al., 2008), thereby increasing the labor income share. This is in line with the factor-substitute effect of environmental regulation, so that labor resources are allocated to the area with strict policy implementation (Zhang et al., 2020). On the other hand, in the face of local environmental policies, state-owned firms have greater social responsibilities in employment and pollution reduction.

Conclusion

This study theoretically analyzes the impact mechanisms of environmental regulation on labor income share with different abatement strategies and empirically tests the effects and impact mechanisms of the TCZ policy on labor income share after incorporating EPA policy using matching data from the CIED and the CPED. We find that the policies of EPA-TCZ significantly reduces the emission of sulfur dioxide (SO_2) and increases the labor income share by 2.6%.

Furthermore, we identify the impact mechanisms of environmental regulation on labor income share through firms' abatement strategies. The results demonstrate that under strict environmental policy constraints, firms primarily adopt "source control" and "end-of-pipe" strategies to achieve emission reduction in the short term. When firms choose "source control" abatement, they use clean production factors such as labor and energy, which make the factor-substitute effect and cost effect of environmental regulation act, to increase the labor income share. When firms choose "end-of-pipe" treatments, it requires the investment in abatement facilities and increases labor for the installation, maintenance, and operation of facilities, which will crowd out the investment in production, resulting in a decline in output and lower profits and wages under the cost effect, and leading to increase in the labor income share due to wage rigidity. Moreover, the heterogeneous effects of environmental regulation on labor income share can been found in low-skilled firms and state-owned firms.

This study supplements the literature on the firm-level resource allocation and income distribution effects of abatement strategies. Existing literature have focused on the impact of firms' different abatement strategies ("changes in production processes" and "end-of-pipe") on labor demands (Berman and Bui, 2001; Liu et al., 2021). We find that "source control" treatments are always neglected, which refer that firms reducing emissions at the source of the production process will choose cleaner input factors, such as using labor instead of capital and other polluting factors, which in turn impact the labor income share. In addition, we get that under strict environmental policies, firms tend to select "source control" and "end-of-pipe" treatments, and especially "end-of-pipe" strategy is not a long-term strategy to reduce pollution emissions. Thus, market-oriented environmental policies should be formulated, and may encourage firms to shift to "changes in production processes" treatments that can play an innovative compensation effect in the long term.

This study provides complements to the existing research on the impacts of environmental policies in developed countries. In contract to the policies market-oriented in these countries, the early environmental policies in China are mainly on the form of laws, regulations, and government performance appraisal, which helps to reduce pollution emissions at the cost of reducing production investment and productivity as shown in our results, without fundamentally solving the contradiction between pollution control and growth. This paper provides a new empirical research from developing countries and effective references for the formulation of China's environmental regulation policy.

Future research can compare the impact of differentiated environmental regulation policies (for example, early environmental policies and market-oriented environmental policies, amount control policies and structural control policies) on firms abatement strategies and labor income share. We can consider internalizing the externality of pollution through coordinated decision-making between local governments (Pan and Chen, 2021). Moreover, we can also consider more heterogeneity analysis, such as different industries and regions.

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

YH:Theoretical Analysis, Methodology, Writing-original draft. JZ:Writing-review and editing. JL:Theoretical Analysis, Writing-review and editing. The corresponding author is responsible for ensuring that the statement is correct and agreed by all authors.

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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 economic development under the fiscal decentralization system: Evidence from china

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The literature is still divided on the study of the ecological and economic effects of fiscal decentralization. To clarify the relationship between fiscal decentralization between central and local governments and green economic development in developing countries, we take China as an example to test the impact of fiscal decentralization on green total factor productivity and its mechanism. It is found that fiscal decentralization helps local governments play a greater role in the regional economic system and promotes green economic development. From the perspective of policy synergy, environmental regulation is an enhanced mechanism for fiscal decentralization to promote green economic development. We also find that technological innovation is an important mechanism for fiscal decentralization to promote green economic development. Our study develops the theory of fiscal federalism and affirms the necessity of decentralization system reform in the context of the green economy, which has important theoretical and practical implications.

KEYWORDS

fiscal decentralization, green economy, environmental regulation, technological innovation, China

Introduction

The vast majority of centralized countries are faced with the problem of the distribution and trade-off of powers and responsibilities between central and local governments. Therefore, some countries have been exploring the institutional reforms of the division of powers and responsibilities. However, these reforms may affect economic growth and the ecological environment by adjusting the relationship between the central and local governments. Our study focuses on the impact of fiscal decentralization on the local green economy, which is an interesting and important topic. On the one hand, fiscal decentralization may have an impact on the green economy by affecting the structure and efficiency of local fiscal expenditures. For example, some studies based on incentive theory and public choice theory have found that fiscal decentralization may affect local fiscal expenditures on science and technology and environmental protection as a way to influence the local green economy (Yang et al., 2020). On the other hand, the horizontal competition among local governments around

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economic growth under the decentralization system may also affect the speed and quality of economic growth (Yan et al., 2022). Therefore, the reform of the fiscal decentralization system has the potential to influence the local green economy.

How to promote green economy development through institutional reform is a hot topic (Chen et al., 2022; Qi et al., 2022), and the literature has increasingly focused on the performance of the local green economy under the fiscal decentralization system (Safi et al., 2022). For example, Gao et al. (2022) examined the impact of fiscal decentralization on local carbon productivity based on provincial panel data in China and found that decentralization can leverage the local information advantages of local governments, which is an important institutional guarantee to improve local carbon productivity. Similarly, He (2015) found that fiscal decentralization also promotes an increase in local fiscal expenditures on environmental protection as a way to promote environmental governance. However, more studies have expressed concerns about urban environmental governance under a decentralized system (Cheng and Zhu, 2021; Yuan et al., 2022). For example, Li et al. (2022) examined the impact of fiscal decentralization on environmental pollution from the perspective of haze pollution and found that decentralization reinforces the economic growth preferences of local governments and is a key factor impeding environmental improvement. Qi and Yu (2022) found that decentralization makes it difficult for the central government to effectively constrain the self-interested investment preferences of local governments, which results in serious environmental pollution.

We aim to clarify the impact of fiscal decentralization on the green economy with China as an example. On the one hand, China is a typical centralized country and began the decentralization system reform in 1994. On the other hand, like other developing countries, China is facing severe environmental pressure. In 2021, China's energy output rate was 84% of that of the United States, 57% of that of Germany and 59% of that of Japan. The contribution rate of China's green total factor productivity (GTFP) growth to the overall economic growth is less than 30%, while the contribution rate of OECD countries has reached 60%. Research on China is a reference for other developing countries.

Compared with previous studies, our potential contributions are as follows. First, the ecological and economic effects of fiscal decentralization at the city level have been less explored. We construct urban green economic development indicators by GTFP and examine the impact of fiscal decentralization on the green economy, which makes up for the lack. Second, previous literature has neglected the examination of government policy synergy in the development of the green economy. We put fiscal decentralization and environmental regulation in the same analytical framework, explored the moderating mechanism of environmental regulation, and verified the theoretical viewpoint that multidimensional policies synergistically promote green economic development. Third, we also explore the mechanism of the effect of fiscal decentralization on the urban green economy from the perspective of technological innovation, which provides empirical evidence for understanding the economic and ecological effects of fiscal decentralization.

Literature review

Fiscal decentralization not only affects the supply of regional public goods but also profoundly affects the performance of the government's ecological functions (Weingast, 2009). Fiscal expenditure is the basic way for local governments to support green economic development (Lee, 2011). The rationalization of the economic power structure between central and local governments can effectively give play to the macrostrategic advantages of the central government and the information advantages of local governments, which improves the efficiency of fiscal expenditures (Xu, 2011; Yang et al., 2020). The second generation of fiscal federalism believes that devolving part of the fiscal revenue and expenditure authority to local governments can enhance the sense of responsibility of local governments and improve their fiscal efforts, thus improving fiscal expenditure efficiency (Oates, 1985; Qian and Roland, 1998). Additionally, fiscal federalism theory suggests that local governments can provide public goods more efficiently than the central government in accordance with the conditions of their jurisdictions and the heterogeneous preferences of their residents (Qiao et al., 2008). These arguments provide a theoretical basis for fiscal decentralization promoting urban green economic development.

However, decentralization is not always perfect. Fiscal decentralization may lead to vertical fiscal imbalance and distort local government behavior, which results in negative outputs (You et al., 2019). For example, it has been argued that China's fiscal decentralization system lacks integrity and normativity and negatively affects ecological improvement (Yang et al., 2021). This is due to the irrational design of the fiscal decentralization system that may cause an imbalance in economic structure and the prevalence of local government corruption (Xie et al., 1999; He, 2015; Jia and Nie, 2017). In addition, fiscal decentralization weakens the macrocontrol ability of the central government. When there is no effective supervision mechanism for local governments, fiscal decentralization makes it more difficult for the central government to restrain the behavior of local governments, resulting in self-interested investment preferences of local governments that "emphasize scale over ecology" (Zhang and Zou, 1998).

In addition, a growing body of literature pays attention to the impact of fiscal decentralization on technological innovation (Feng et al., 2021). For example, Lin and Zhou

(2021a) argue that the vertical fiscal imbalance caused by decentralization is an important cause of inefficient technological innovation. Yang et al. (2020) found that fiscal decentralization predisposes local governments to a preference for "scale over innovation" in fiscal investment, which inhibits local governments' innovation functions. However, technological innovation is an important support for ecological improvement (Koseoglu et al., 2022). Therefore, some studies have explored the role of fiscal decentralization in affecting ecological performance from the perspective of technological innovation and found that fiscal decentralization leads to the distortion of local government incentives, inhibits the government innovation function, and further inhibits energy performance (Lin and Zhou, 2021b). Drawing on these ideas, we also build a mediating effect model to test whether fiscal decentralization can affect the green economy by influencing technological innovation.

Methodology

Models

We investigate the impact of fiscal decentralization on the green economy by a two-way fixed effect model as in Eq. 1.

$$GTFP_{it} = \alpha_0 + \alpha_1 fisdec_{it} + \alpha_j \sum X_{jit} + \mu_i + v_t + \varepsilon_{it} \quad (1)$$

where $GTFP_{it}$ denotes the GTFP of city i in year t, which is used to measure the level of urban green economy. This is appropriate because GTFP is a composite indicator that captures both economic growth and negative outputs of energy consumption and the environment (Yang et al., 2022). $fisdec$ indicates the degree of fiscal decentralization. X_{jit} refers to a series of control variables that affect urban green economy, including industrial structure and population density and so on. μ_i denotes the city dummy variable and v_t is the year dummy variable. ε_{it} is the error term.

Based on Eq. 1, we continue to construct the models shown in Eqs. 2, 3 to test the mechanism of fiscal decentralization influencing the green economy.

$$innovation_{it} = \beta_0 + \beta_1 fisdec_{it} + \beta_j \sum X_{jit} + \mu_i + v_t + \varepsilon_{it} \quad (2)$$

$$GTFP_{it} = \gamma_0 + \gamma_1 fisdec_{it} + \gamma_2 innovation + \gamma_j \sum X_{jit} + \mu_i + v_t + \varepsilon_{it} \quad (3)$$

If fiscal decentralization has a significant effect on local green economy, that is, if α_1 is significant, then Eqs. 2, 3 are further estimated. If β_1 and γ_2 are simultaneously significant, then fiscal decentralization affects urban green economy by influencing technological innovation; thus, its indirect effect is $\beta_1 \times \gamma_2$. If they are not simultaneously significant, then the indirect effect of technological innovation is not significant.

Variables and data

As mentioned earlier, we use GTFP to characterize the development level of green economy. Wang et al. (2020) proposed a two-period Biennial Malmquist–Luenberger Productivity Index (Biennial MLPI or BML) to measure GTFP. The index can not only solve the problem of infeasible solutions but also take into account technological retrogression. In addition, the previously calculated index also remains robust when the sample years are increased. Therefore, the index is somewhat better than the Global Malmquist–Luenberger Productivity Index (GML). We measure labor input in terms of the number of employed persons, capital input in terms of the real capital stock, and energy input in terms of the city's annual electricity consumption. It is important to note that we use the perpetual inventory method to calculate capital stock. In particular, we set the depreciation rate at 10.96%. Output indicators include both expected output and unexpected output. The expected output is measured by real gross domestic product (GDP), which is converted to GDP in constant prices in 2003 through the GDP deflator. We measure the unexpected output by the emissions of three pollutants produced in industrial production: wastewater, sulfur dioxide and soot.

Fiscal decentralization (*fisdec*) is the core explanatory variable. Similar to Yang et al. (2020), we approximate the level of fiscal decentralization using the proportion of urban per capita fiscally budgeted expenditure to the sum of central, provincial and urban per capita budgeted expenditure.

The level of technological innovation (*innovation*) is our mediating variable. Considering that invention patents have the most innovative value and economic value among all patent types, we use the ratio of invention patent applications to the total population within a city to measure technological innovation.

We also control the following variables. (1) Financial development level (*finance*), measured by the ratio of bank deposits and loan balances to regional GDP. (2) Industrial structure (*indstru*), measured by the proportion of added value of the service industry in GDP. (3) Marketization level (*marketization*), measured by the marketization index of each province as disclosed by Wang et al. (2019). (4) Population density (*population*), measured by the logarithm of population per square kilometer. (5) Local government growth incentive (*goal*), measured by the economic growth targets set by local governments at the beginning of the year. (6) Environmental regulation (*ER*), measured by the frequency of environment-related words in the government's annual work report.

Due to the availability of data, we conduct empirical analysis based on the panel data of 285 cities from 2003 to 2018. The data of invention patent applications are obtained from China's Research Data Platform. The marketization level is obtained from the China Provincial Marketization Index Report. Local

TABLE 1 Statistical characteristics of variables.

Variable	Obs	Mean	Std. Dev.	Min	Max
GTFP	4,560	0.6492	0.2535	0.1337	1.7132
fisdec	4,560	0.2764	0.1254	0.0430	0.8464
innovation	4,560	−0.6548	1.8719	−6.4433	5.1056
ER	4,560	0.0047	0.0024	0.0000	0.0229
finance	4,560	2.1238	1.0419	0.5081	11.1728
indstru	4,560	37.4211	9.0422	8.5800	85.3400
marketization	4,560	6.6387	1.6853	2.3300	11.7100
population	4,560	5.7125	0.9126	1.5476	7.8816
Goal	4,560	9.4874	1.6330	5.0000	15.0000

government economic growth targets and environmental regulation intensity are obtained by the authors according to the annual governments' work reports of each city. Other data are obtained from the China Urban Statistical Yearbook. The statistical characteristics of each variable are shown in Table 1.

Results and discussion

First, we estimate Eq. 1 based on city panel data to examine the effect of fiscal decentralization on the green economy and the results are shown in regressions (1–5) in Table 2. Among them, regression (1) is the result of estimation with only fiscal decentralization as the independent variable. We can see that fiscal decentralization plays a significant role in the development of urban green economy. Regression (2) further incorporates a series of control variables, and the results show that the coefficient of fiscal decentralization remains positive and still passes the significance test of 1%. The above results show that fiscal decentralization promotes urban green economy. This confirms the applicability of fiscal federalism theory in

TABLE 2 Estimation results.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	GTFP	GTFP	GTFP	GTFP	GTFP	Innovation	GTFP
	Benchmark regression	Adding control variables	Adding interactive items of province and year	Estimation after sample deletion	Moderating effect of environmental regulation	Mediating effect of technological innovation	
fisdec	0.3571***	0.4250***	0.3818***	0.4915***	0.3543***	2.1282***	0.4250***
	(0.0527)	(0.0543)	(0.0546)	(0.0582)	(0.0628)	(0.2988)	(0.0543)
innovation							0.0106***
fisdec×ER					13.1615**		(0.0028)
					(5.8906)		
finance		−0.0229***	−0.0037	−0.0245***	−0.0225***	0.0516**	−0.0229***
		(0.0037)	(0.0041)	(0.0042)	(0.0037)	(0.0206)	(0.0037)
indstru		0.0029***	0.0016***	0.0025***	0.0028***	−0.0047**	0.0029***
		(0.0004)	(0.0005)	(0.0004)	(0.0004)	(0.0023)	(0.0004)
marketization		0.0006	−0.0834**	−0.0025	0.0013	0.0860***	0.0006
		(0.0039)	(0.0378)	(0.0042)	(0.0039)	(0.0213)	(0.0039)
population		−0.0149	−0.0047	−0.0213*	−0.0153	0.0450	−0.0149
		(0.0115)	(0.0109)	(0.0125)	(0.0115)	(0.0638)	(0.0115)
Goal		−0.0087***	−0.0261	−0.0103***	−0.0086***	0.0738***	−0.0087***
		(0.0017)	(0.0227)	(0.0018)	(0.0017)	(0.0093)	(0.0017)
ER		4.1966***	3.1089***	3.8274***	0.3200	10.1761**	4.1966***
		(0.8443)	(0.8364)	(0.9001)	(1.9294)	(4.6677)	(0.8443)
Constant	0.9563***	1.0664***	1.6229***	1.1619***	1.0819***	−4.8927***	1.1157***
	(0.0086)	(0.0728)	(0.3184)	(0.0781)	(0.0731)	(0.3740)	(0.0690)
Sobel test						0.0008***	
						(0.0001)	
Observations	4,560	4,560	4,560	4000	4,560	4,560	4,560
R-squared	0.6530	0.6639	0.7638	0.6824	0.6643	0.9250	0.8665

Note: ***, ** and * indicate the significance levels of 1%, 5% and 10% respectively.

promoting decentralization reform and green economy in a large developing country such as China (Tiebout, 1956; Oates, 1985). The development of green economy is inherently dependent on local governments. On the one hand, local governments have a more specialized understanding of the development of green economy in their regions. Fiscal decentralization is conducive to the local information advantages of local governments, which overcomes the information asymmetry between the central government and local governments and guarantees the accuracy and flexibility of fiscal expenditures. On the other hand, fiscal decentralization has a certain incentive effect to stimulate the degree of fiscal effort and responsibility of local governments while expanding their fiscal expenditure authority, which is conducive to improving local fiscal expenditure efficiency on green economy.

The factors affecting green economy are complex and some of them are difficult to quantify precisely. In addition, it is difficult to accurately include all control variables affecting green economy in our regressions. Therefore, the aforementioned estimation results face the problem of missing variables to some extent. We construct the interaction term between year and province where the city is located and add it to Eq. 1 for estimation to alleviate the problem of omitted variables. The results are shown in regression (3). The coefficient of fiscal decentralization is positive at the significance level of 1%, which is consistent with the previous results. In addition, China's provincial capitals, municipalities directly under the central government, and municipalities with independent planning status have special status in regional and even national economic development, and most of them also enjoy special fiscal policies and political resources. Therefore, in regression (4) we exclude the sample of these cities. As seen, the results also affirm the role of fiscal decentralization in the development of green economy.

Existing studies have neglected the environmental institutional context in which fiscal decentralization affects green economy. Fiscal decentralization may have a differential impact on the green economy under different environmental regulation intensities. For this reason, we construct the interaction term between environmental regulation and fiscal decentralization and bring it into Eq. 1 for estimation. The results are shown in regression (5) in Table 2. The coefficient of fiscal decentralization remains significantly positive, while the interaction term is also significantly positive at the 1% level. This is similar to the findings of Song et al. (2018), which provides evidence that fiscal decentralization may better promote green economy under strict environmental regulation policies. Thus, environmental regulation is a reinforcing mechanism for fiscal decentralization to promote green economy and increasing the intensity of environmental regulation can strengthen the role of fiscal decentralization in promoting green economy.

Finally, we estimate Eqs. 2, 3 to examine the mechanism of fiscal decentralization influencing green economy. The results are shown in regressions (6) and (7) in Table 2. Fiscal decentralization can effectively promote technological innovation. This is also consistent with the view of fiscal federalism theory that fiscal decentralization enables local governments to better provide necessary public goods for technological innovation. In addition, technological innovation also plays a significant role in promoting urban green economy, which is also consistent with the mainstream view that technological innovation provides technical support and guarantees for green economy (Yan and Zhang, 2021). Combining the results of the two regressions, it can be judged that fiscal decentralization can promote the development of green economy by promoting technological innovation. In addition, we also conducted a Sobel test, and the results also support the existence of the mediating effect of technological innovation. After controlling for the mediating effect of technological innovation, the coefficient of fiscal decentralization on green economy remains significantly positive. This shows that technological innovation is a partial mediating variable and that fiscal decentralization may also promote urban green economy through other mechanisms.

Conclusion

We investigate the impact of fiscal decentralization on green economy and its mechanism based on panel data from China's cities. As emphasized by the theory of fiscal federalism, fiscal decentralization enables local governments to better perform the functions in the regional economic system and promote urban green economy. From the perspective of policy synergy, environmental regulation is an enhanced mechanism for fiscal decentralization to promote urban green economy. China's city-level environmental and fiscal policies have achieved effective synergy in promoting green economy. We also find that technological innovation is an important mechanism for fiscal decentralization to promote urban green economy. This finding complements studies on the ecological and economic effects of fiscal decentralization. Our study emphasizes the necessity of decentralization system reform in the development of green economy and affirms the applicability of fiscal federalism theory in guiding the practice of decentralization system reform in developing countries, which has important theoretical and practical implications.

Based on the above conclusion, more attention should be given to the role of decentralization system reform in green economic development. On the one hand, fiscal decentralization system reform should be deepened and give local governments greater autonomy in fiscal expenditure. On the other hand, green development requires the coordination of policies in different areas, especially the environmental system. In addition, innovation is an important support for green economic development. The reform of decentralization system should strengthen the incentive effect on technological innovation.

It should be noted that our study also has shortcomings and room for further expansion. For example, we did not include the environmental decentralization system in the analytical framework. Environmental decentralization and fiscal decentralization are two important issues that cannot be ignored in the reform of the decentralization system between the central government and local governments. Considering the synergy of the two types of decentralization systems in the process of promoting green economy is an important issue that needs to be studied in the future. In addition, although we examined the impact mechanism of fiscal decentralization on green economy from the perspective of technological innovation, we failed to exclude the existence of other mechanisms. The diverse mechanisms of the impact of fiscal decentralization on green economy also need to be further clarified in future studies.

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

Conceptualization, YS; Methodology, FL; Data, FL and BW; Writing—original draft preparation, SY; Writing—review and editing, SY and BW; Investigation, SY; Funding acquisition, SY.

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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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Spatial spillover effect of industrial structure upgrading on carbon emission intensity: panel data evidences from Beijing, China

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Applying the panel data of 16 districts in Beijing, China from 2009 to 2020 as the research object, this study measures and analyzes the carbon emission intensity and the level of industrial structure upgrading. Based on the above results, a spatial econometric model is established to analyze the spatial spillover effect of industrial structure upgrading on carbon emission intensity. Conclusions are drawn as follows: (a) In 2009, 2015 and 2020, the carbon emission intensity in most districts of Beijing has decreased, and in some areas even decreased significantly. The upgrading of industrial structure in all districts has been improved (b). According to the results of spatial autocorrelation, the carbon emission intensity in Beijing shows significant positive spatial autocorrelation in 2009 and 2020, while negative spatial autocorrelation in 2015; The upgrading of industrial structure in Beijing shows significant positive spatial autocorrelation in 2009, 2015 and 2020 (c). The regression results of the spatial econometric model show that industrial structure upgrading not only reduces the carbon emission intensity of the region, but also decreases the carbon emission intensity of the surrounding areas.

KEYWORDS

industrial structure upgrading, carbon emission intensity, spatial spillover effect, spatial econometric model, moran scatterplot

1 Introduction

Carbon dioxide emissions and global warming have raised concern in various countries in recent years once again with the increasing number of extreme weather events (Paul and Bhattacharya, 2004). The increase of carbon dioxide emissions led to a series of natural disasters, forcing the countries to jointly call for the reduction of carbon emissions, which puts forward new requirements for national and regional industrial development and thus, promoting industrial development and transformation to become a crucial link in national strategic development (IPCC, 2007). On 22 September 2020, Chinese President Xi Jinping announced to the world at the General Debate of the 75 sessions of the United Nations General Assembly that China will scale up its Intended

Nationally Determined Contribution by adopting more vigorous policies and measures, aiming to peak CO2 emissions before 2030 and achieving carbon neutrality before 2060. As the world's largest energy producer and consumer, China has been actively promoting industrial restructuring and energy structure optimization since the 11th Five-Year Plan period in order to achieve sustainable and high-quality economic development. As the second largest first-tier city in terms of GDP in China, Beijing has experienced a constant evolution of urban function positioning and has the biggest tertiary industry as a proportion of GDP among all Chinese cities. Beijing has played an exemplary role in actively implementing the industrial structure upgrading and emission reduction among Chinese cities. Especially, a large number of enterprises with high pollution and high energy consumption have been closed down or transferred since 2014, achieving the industrial structure upgrading from the industrial economy to the service economy. Meanwhile, Beijing has been actively responding to the call of carbon emission reduction work by the central government and achieved remarkable results in the field. In addition, CO2 emissions are mainly concentrated in urban areas, accounting for 70% of global CO2 emissions. China is the largest carbon emitter in the world, and Beijing, as the capital and first-tier city of China, has attracted great attention from the world. Does the industrial structure upgrading promote the reduction of carbon emission intensity? The empirical research from 16 districts in Beijing may provide a reference for China to achieve the "carbon peaking and carbon neutrality goals" as scheduled, and also for other countries to formulate industrial policies and reduce carbon emission intensity.

On the issue of carbon emission intensity, some scholars have carried out a large number of studies to explore the factors affecting carbon emission intensity from different perspectives. Hanif et al. (2019) conclude that FDI is a significant source of CO2 emissions for developing countries (Hanif et al., 2019). The relationship between economic development level and carbon emission intensity has been frequently discussed. A large number of studies show that the economic development level has a significant impact on carbon emission intensity in China (Li, 2010; Meng et al., 2011; Zhang and Lin, 2012). Auffhammer and Carson (2008) analyze the influencing factors of carbon emission intensity in 25 provinces of China during 1985–2004 and find that there is an inverted U-shaped relationship between carbon emission intensity and per capita GDP in China (Auffhammer and Carson, 2008). (Fan et al., 2007) empirically analyze the influencing factors of carbon emission intensity and reveal that carbon emission intensity in China generally showed a downward trend from 1980 to 2003 (Fan et al., 2007).

In addition, more and more scholars are paying attention to the relationship between industrial structure and carbon emissions since China is in a critical period of industrial structure transformation and upgrading. Plentiful literatures reveal that carbon emissions are closely related to industrial structure, energy structure, and energy intensity. Ang et al. (1998) study the relationship between CO2 emission and industrial energy consumption in China during 1985–1990 by using the logarithmic mean Divisia index (LMDI) method. Their results show a large positive effect associated with the change in industrial production and a large negative effect associated with the change in sectorial energy intensity (Ang et al., 1998). The research results of Zhang (2000) show that, without the policies and measures toward energy conversation, it would be difficult for China to contribute to a significant decline in carbon emission intensity given its economic growth rate (Zhang, 2000). Zhang J. et al. (2018) empirically find that industrial structure optimization can significantly inhibit carbon emissions. Cheng Z. et al. (2018) study the effects of the industrial structure upgrading in China on carbon emission intensity, finding that both the carbon emission intensity in China and the industrial structure upgrading show a significant positive spatial autocorrelation, and industrial structure upgrading reduces the carbon emission intensity of the region (Cheng et al., 2018). Through reviewing the relevant literature, it is found that there are plentiful studies on the influence relation between industrial structure upgrading and carbon emission intensity in China at the national level, but few studies at the urban level. This paper innovatively explores the relation from the perspective of "small scale in big city" to offer a closer look at this field.

Although extensive studies have examined the factors affecting carbon emissions, especially those on the impact of industrial structure on carbon emissions are springing up, there are still some perspectives that remain insufficiently analyzed. The previous literature mostly studies the impact of industrial structure on total carbon emissions rather than carbon emission intensity, which can better reflect the concept of low-carbon economy. Few of the existing literatures have analyzed the relationship between industrial structure upgrading and carbon emission intensity from a spatial perspective. Besides, the existing studies mostly have focused on the relationship between industrial structure and carbon emissions at the provincial level but not considered the relationship between the two at a city level. This article aims to measure and analyze the carbon emission intensity and the level of industrial structure upgrading with appropriate indicators in each district of Beijing and then builds a spatial econometric model to discuss the spatial spillover effect of industrial structure upgrading on carbon emission intensity.

The first section of this paper introduces the research background and current status of relevant research. *Methods* introduces data sources and research methods. Then in *Statistical analysis* we select the relevant data of each district in Beijing to calculate and analyze the carbon emission intensity and industrial structure upgrading level. The next we analyze the spatial correlation and heterogeneity of the two, then study the impact of industrial structure upgrading on carbon emission intensity in Beijing by SDM model. Based on the interpretation of

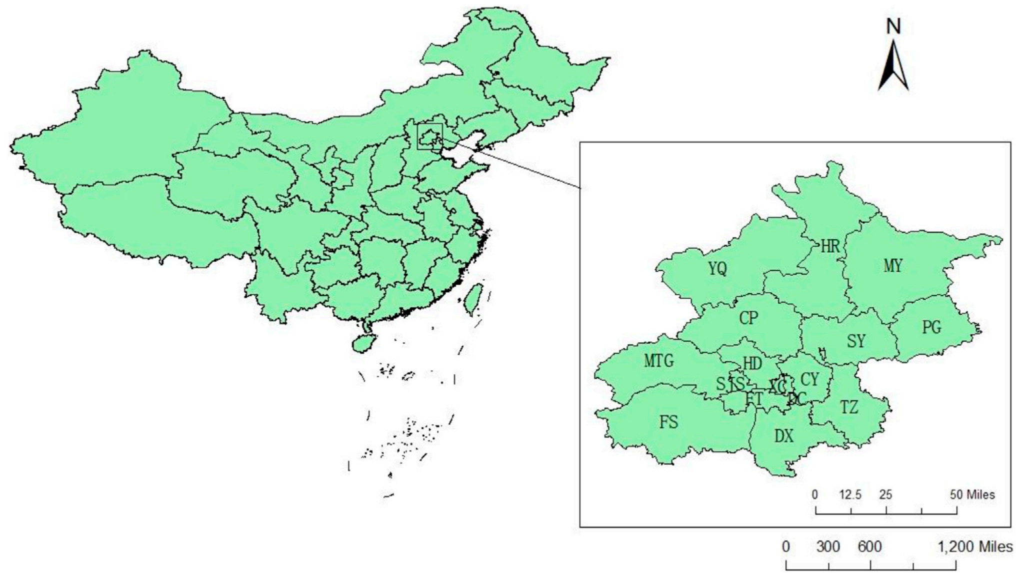

FIGURE 1
Location of each administrative district in Beijing.

the results of spatial analysis, a discussion is presented in *Discussion*. Lastly, the conclusion is summarized and relevant policy recommendations are put forward in *Conclusion*.

2 Methods

2.1 Data sources

Beijing is located in northern China with a population of 21.886 million and an area of 16,410 square kilometers. The per capita GDP in Beijing was 164,200 yuan by the end of 2020, ranking first in China. Our research object is the 16 municipal districts of Beijing from 2009 to 2020 and the original data are collected from *Beijing Statistical Yearbook*[1] (Beijing Municipal Bureau of Statistics and NBS Survey Office in Beijing, 2009–2020) and EPS database[2]. The dependent variable is set as carbon emission intensity and the core explanatory variable is industrial structure upgrading. According to the relevant literatures, investment level, economic development level, consumption level and labor input are the major factors affecting carbon emission intensity. The indicator of investment level is measured by regional actual utilized foreign direct investment/regional GDP (fdi). The indicator of economic development level is measured by per capita GDP (pgdp). The indicator of consumption level is measured by per capita personal consumption expenditure (pcon). And the indicator of labor force is measured by total sum of on-duty employees' wages (lab). Appendix A displays the definitions and descriptive statistics of the above variables. Figure 1 shows the location and administrative boundaries of districts in Beijing. The symbols of 16 districts in Figure 1 are the phonetic initials of each district. The projection method used in Figure 1 is CGCS_2000. The same below.

1 http://tjj.beijing.gov.cn/tjsj_31433/

2 https://www.epsnet.com.cn/index.html#/Index

2.2 Research methodologies

2.2.1 Exploratory spatial data analysis

This study uses spatial autocorrelation to explore the spatial pattern of carbon emission intensity and industrial upgrading. Spatial autocorrelation refers to the statistical correlation between the spatial proximity among observational units and the numeric similarity among their values. In general, the closer the distance, the greater the correlation between the two values. Moran's I and Local Moran Index are usually introduced to measure global and local spatial correlation. The former is a method of global clustering test, which tests the similarity (spatial positive correlation) and dissimilarity (spatial negative correlation) or mutual independence of adjacent areas in the whole research area; The latter is used to test whether similar or different observations have been collected locally. Moran's I index is generally used for global spatial autocorrelation (Moran, 1950). In this study, global Moran's I value is used to analyze the degree of spatial correlation as a whole and the calculation formula is as follows:

$$I = \frac{N}{\sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}} \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}\left(y_i - \bar{y}\right)\left(y_j - \bar{y}\right)}{\sum_{i=1}^{N}\left(y_i - \bar{y}\right)^2} \quad (1)$$

Where N is the total number of districts in Beijing; y_i is carbon emission intensity or industrial structure upgrading index in region i; $\bar{y}$ is the average of carbon emission intensity or industrial structure upgrading index; W is the spatial weight matrix, where adjacent space is 1 and non-adjacent space is 0. The value range of Moran's I is [−1,1], where positive value represents positive spatial autocorrelation, negative value represents negative spatial autocorrelation, and 0 represents spatial uncorrelation. Z-test is usually used to perform statistical tests on Moran's I value results:

$$Z(I) = \frac{I - E(I)}{\sqrt{var(I)}} \quad (2)$$

Where $E(I)$ is the expected value, $var(I)$ is the variance.

Local spatial autocorrelation refers to the Local Moran Index of a region (Pinto et al., 2014), which is used to measure the degree of association between region I and its adjacent regions. Our study applies LISA as a local metric of spatial autocorrelation (Anselin, 1995) to identify clusters and outliers, such as districts which have higher or lower carbon intensity or industrial upgrading values than expected. The accumulation of j in the formula does not involve the district I itself, that is, j ≠i. We use LISA agglomeration map to analyze the characteristics of local agglomeration. LISA agglomeration map consists of four quadrants, namely, the first quadrant, the second quadrant, the third quadrant and the fourth quadrant. The first quadrant (HH) represents the high-value region surrounded by the high-value regions; the second quadrant (LH) represents the low-value region surrounded by the high-value regions; the third quadrant (LL) represents the low-value region surrounded by the low-value regions; and the fourth quadrant (HL) represents the high-value region surrounded by the low-value regions.

$$I_i = \frac{\left(y_i - \bar{y}\right)}{S_y^2}\sum_j\left[W_{ij}\left(y_j - \bar{y}\right)\right] \quad (3)$$

$$S_y^2 = \sum_j\left(y_j - \bar{y}\right)\Big/N \quad (4)$$

Where N is the total number of districts in Beijing; y_j is carbon emission intensity or industrial structure upgrading index in region i; $\bar{y}$ is the average of carbon emission intensity or industrial structure upgrading index; W is spatial weight matrix; S_y^2 is the variance.

2.2.2 Spatial econometric model

This study utilizes mainly spatial regression models, such as Spatial Autoregressive Model (SAR), Spatial Autocorrelation Model (SAC) and Spatial Durbin Model (SDM).

2.2.2.1 Spatial Autoregressive Model (SAR)

The Spatial Autoregressive Model (Anselin, 2013)proposed by Cliff and Ord (1981) is the most widely used method in spatial econometrics (Cliff et al., 1981). Spatial Autoregressive Model is used for examining spatial dependence between dependent variables, mainly considering the interaction between regions with spillover effects, excluding the interaction of independent variables. The formula is as follows:

$$Y = \delta WY + \alpha\tau_N + X\beta + \varepsilon \quad (5)$$

Where Y is the dependent variable of order N×t; X is the independent variable of order N×t; W is the spatial weight matrix; δ is used to measure the degree of interaction between regions; τ_N is the unit vector of order N×t; α is the constant term; Y is the actual value of the dependent variable; β is the unknown parameter variable to be estimated; ε is the stochastic disturbance term; δ is the spatial autoregressive coefficient. If δ is significant, then the variables are spatially correlated; the larger the value of δ is, the more significant the spillover effect is.

2.2.2.2 Spatial Autocorrelation Model (SAC)

SAC model (Dormann C et al., 2007) does not consider the spatial interaction effect among explanatory variables, compared with Spatial Durbin Model. It should be noted that SAC model can only be constructed on the basis of fixed effects model, so the specific calculation formula is as follows:

$$Y = \delta WY + \alpha\tau_N + X\beta + \mu \quad (6)$$

$$\mu = \lambda W\mu + \varepsilon \quad (7)$$

Where μ is the residual vector in the regression; λ is the error spatial autoregression coefficient, which is used to measure the spatial dependence of Y. If λ is significant, then there is spatial correlation in the error term caused by the important factor omitted.

2.2.2.3 Spatial durbin model

The Spatial Durbin Model comprehensively considers both exogenous and endogenous interaction effects, the calculation formula as follows:

$$Y = \delta WY + \alpha\tau_N + X\beta + WX\theta + \mu \quad (8)$$

$$\mu = \lambda W\mu + \varepsilon \quad (9)$$

Where θ is an unknown parameter variable that needs to be estimated (LeSage and Pace, 2009; Yu et al., 2013).

3 Statistical analysis

3.1 Measurement of carbon emission intensity

Carbon emission intensity is calculated according to energy consumption. The formula is as follows:

$$E = ETCE \times EF \times \frac{44}{12} \quad (10)$$

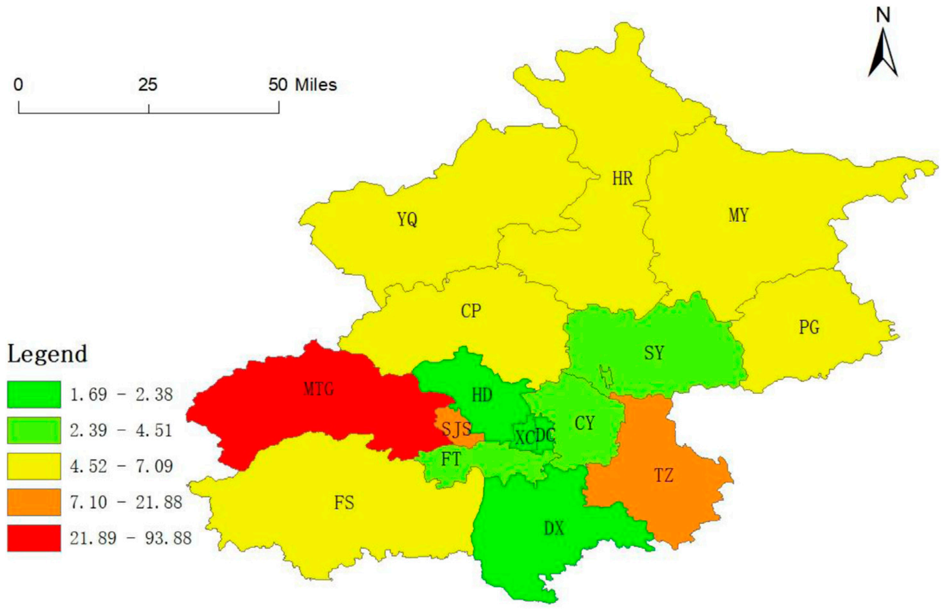

FIGURE 2
Distribution of carbon emission intensity in 2009.

$$c = \frac{E}{GDP} \tag{11}$$

Where E is the total amount of carbon emission, ETCE is energy consumption (standard coal); EF is the transition coefficient between energy consumption and carbon emission intensity; and C is carbon emission intensity. The district-level energy consumption data of Beijing come from *Beijing Regional Statistical Yearbook* (Beijing Municipal Bureau of Statistics). According to the transition coefficient developed by Zheng et al. (2019), EF is 2.204 kg CO2/kg TCE.

3.2 Measurement of industrial structure upgrading

The level of industrial structure upgrading can be evaluated by various indexes, such as Proportional Weight Method of Industrial Structure, Technical Complexity Method and Included Angle Cosine Method. Proportional Weight Method of Industrial Structure is suitable to measure the rationalization process and upgrading process of industrial structure change. Technical Complexity Method has such critical requirements for data that the process is often difficult to implement. Included Angle Cosine Method expresses the improvement degree of industrial structure by studying the angle of geometric vector. According to both data availability and the limitations, this study adopts the method developed by Fu (2010) to measure the industrial structure upgrading. Fu (2010) introduces the angle of three-dimensional vectors in space instead of simple and rough subjective assignment, and his approach has been widely adopted as a main research method by many Chinese scholars. This method is also called "Angle Method of Space Vectors". The first step is to measure the ratio of the output value of primary industry, secondary industry and tertiary industry to GDP as a component of the spatial vectors to form a set of 3-dimensional vectors $X_0 = (x_{1,0}, x_{2,0}, x_{3,0})$. Then we measure the angles between X_0 and the vectors of primary industry, secondary industry and tertiary industry respectively ($X_1 = (1,0,0)$, $X_2 = (0,1,0)$, $X_3 = (0,0,1)$), namely θ_1, θ_2, θ_3:

$$\theta_j = \arccos\left(\frac{\sum_{i=1}^{3}\left(x_{i,j}x_{i,0}\right)}{\left(\sum_{i=1}^{3}\left(x_{i,j}^2\right)^{1/2}\sum_{i=1}^{3}\left(x_{i,0}^2\right)^{1/2}\right)}\right) \tag{12}$$

j = 1,2,3.

The formula of industrial structure upgrading (W) is as follows:

$$W = \sum_{k=1}^{3}\sum_{j=1}^{k}\theta_j \tag{13}$$

3.3 Analysis of carbon emission intensity and industrial structure upgrading level

3.3.1 Calculation of carbon emission intensity

In order to understand the change of carbon emission intensity in each district of Beijing from 2009 to 2020, we conduct analysis on the data of the years of 2009, 2015 and

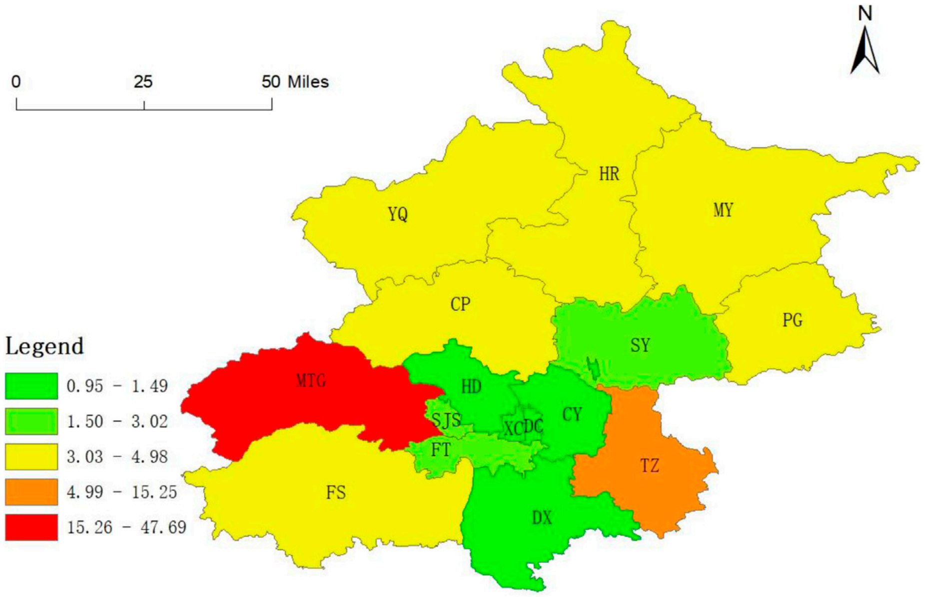

FIGURE 3
Distribution of carbon emission intensity in 2015.

2020. The color changing from green to red in Figures 2–4 indicates the value getting larger. As can be seen from Figures 2–4, the carbon emission intensity of all districts in Beijing was low on the whole, while that of some districts was high, such as Mentougou District, however, with a downward trend. From the perspective of spatial distribution, the carbon emission intensity of Dongcheng District, Xicheng District and its surrounding ones was significantly lower than that of other districts. The districts with higher carbon emission intensity were mainly the outer suburbs of Beijing and the carbon emission intensity of most

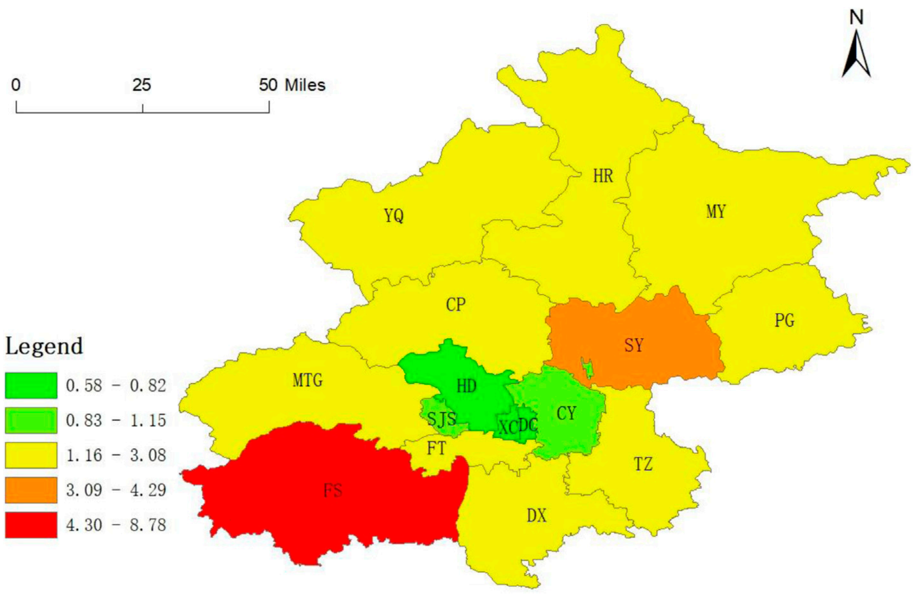

FIGURE 4
Distribution of carbon emission intensity in 2020.

TABLE 1 Carbon emission intensity of each district in Beijing in 2009, 2015 and 2020.

Districts	2009	2015	2020
Dongcheng District (DC)	1.848	1.265	0.823
Xicheng District (XD)	1.693	0.953	0.580
Chaoyang District (CY)	2.987	1.492	0.983
Fengtai District (FT)	4.510	3.022	1.935
Shijingshan District (SJS)	20.491	2.484	1.149
Haidian District (HD)	2.380	1.258	0.666
Mentougou District (MTG)	93.882	47.690	1.864
Fangshan District (FS)	6.457	4.358	8.778
Tongzou District (TZ)	21.877	15.254	2.279
Shunyi District (SY)	3.250	1.936	4.292
Changping District (CP)	6.264	3.553	2.423
Daxing District (DX)	2.202	1.050	2.643
Huairou District (HR)	5.859	3.817	2.314
Pinggu District (PG)	7.093	4.790	3.084
Miyun District (MY)	5.862	4.331	2.785
Yanqing District (YQ)	6.138	4.984	2.504

areas in Beijing was at the medium level. As shown in Table 1, except Fangshan District, Shunyi District and Daxing District, carbon emission intensity of other districts experienced a decline in 2009, 2015 and 2020, among which Mentougou District witnessed the most significant downturn of 92.018. The carbon emission intensity of Xicheng District dropped below 1 for the first time in the year of 2015. And in 2020, the carbon emission intensity of Dongcheng District, Xicheng District, Chaoyang District and Haidian District dropped below 1, with the lowest value of 0.580 in Xicheng District. Besides, Mentougou District recorded the highest carbon emission intensity in 2009 and 2015 and Fangshan District in 2020 in Beijing.

3.3.2 Calculation of industrial structure upgrading level

In order to understand the changes of industrial structure upgrading level in each district of Beijing from 2009 to 2020, we conduct analysis on the data of the years of 2009, 2015 and 2020. In Figures 5–7, the value is getting higher with color from red to green. As can be seen from Figures 5–7, the industrial structure upgrading level of Beijing radiated gradually from the center to the surrounding areas: the closer to the center, the higher the upgrading level; the further to the center, the lower. In general, the industrial structure upgrading of Beijing was on the rise in the 3 years. In 2009, 2015 and 2020, the upgrading level of central areas, such as Dongcheng District, Xicheng District, Chaoyang District, Haidian District, Fengtai District and Shijingshan District was at a high level, while that of surrounding areas was at a low level. As shown in Table 2, the industrial structure upgrading level of each district in Beijing has been improved to some extent in 2009, 2015 and 2020. The industrial structure upgrading level of Dongcheng District has exceeded 7.8 in all 3 years whereas that of Xicheng District exceeded 7.8 for the first time in 2020. Also in 2020, the industrial structure upgrading level of Chaoyang District and Haidian District was between

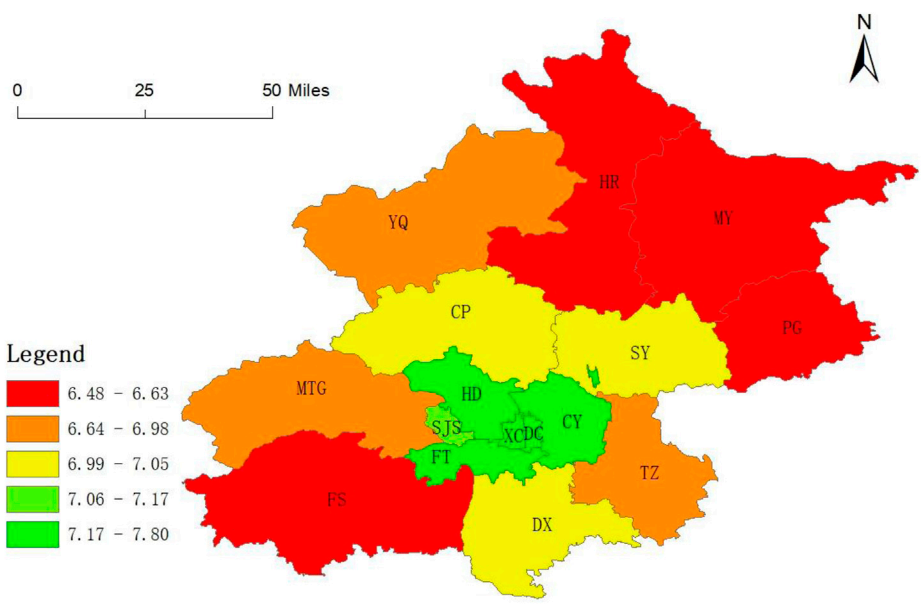

FIGURE 5
Distribution of industrial structure upgrading level of Beijing Districts in 2009.

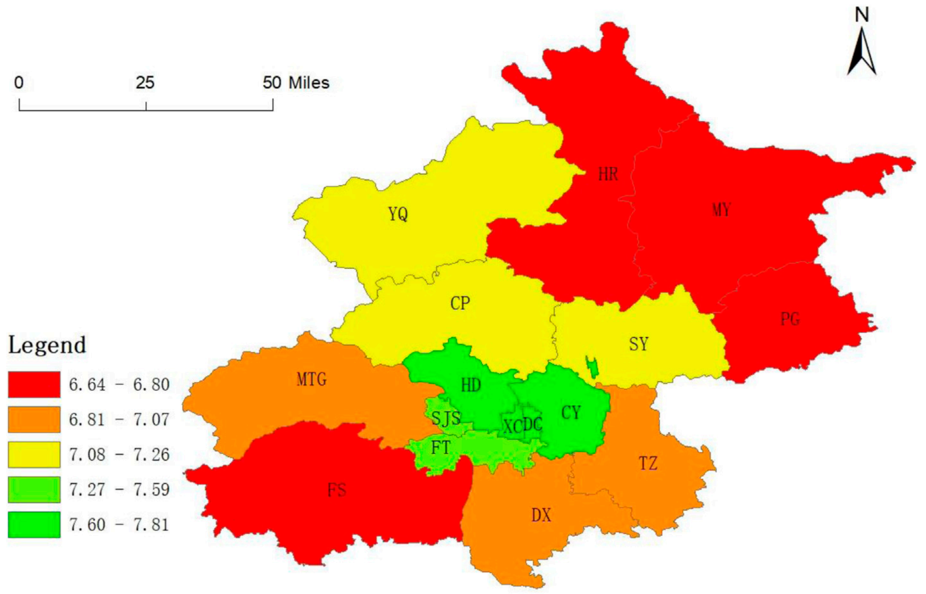

FIGURE 6
Distribution of industrial structure upgrading level of Beijing Districts in 2015.

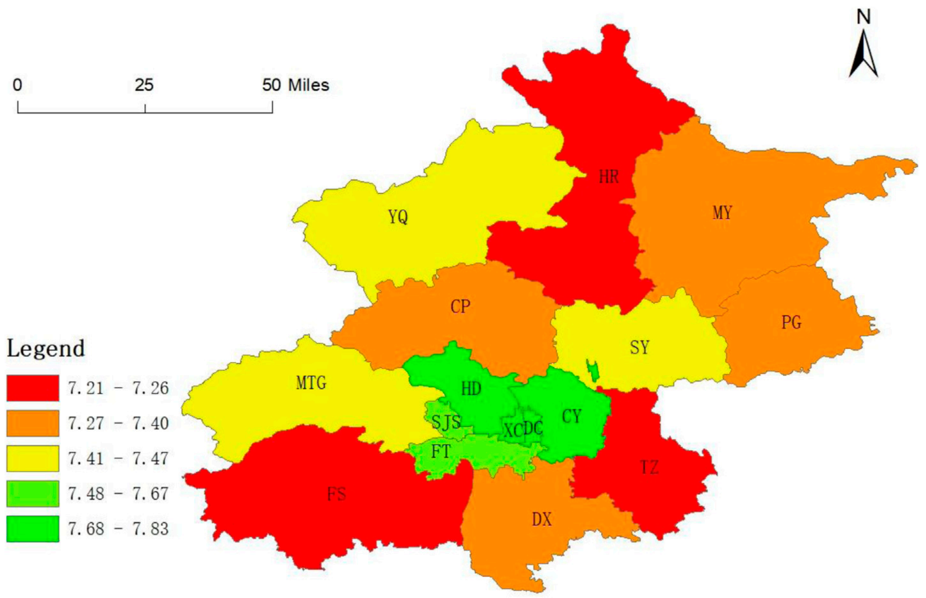

FIGURE 7
Distribution of industrial structure upgrading level of Beijing Districts in 2020.

7.7 and 7.8 while that of Fengtai District and Shijingshan District was between 7.6 and 7.7, which was followed by that of Mentougou District, Shunyi District and Yanqing District, between 7.4 and 7.5; meanwhile the industrial structure upgrading level of Changping District, Daxing District, Fangshan District, Huairou District, Miyun District, Pinggu District and Tongzhou District was lower than 7.4. The results show the significant effect of industrial transformation of each district in Beijing and the industrial structure upgrading level of Beijing has been remarkably improved.

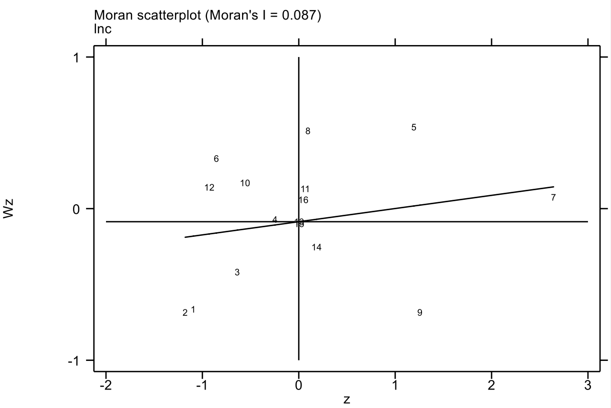

FIGURE 8
Moran scatterplot of carbon emission intensity in 2009.

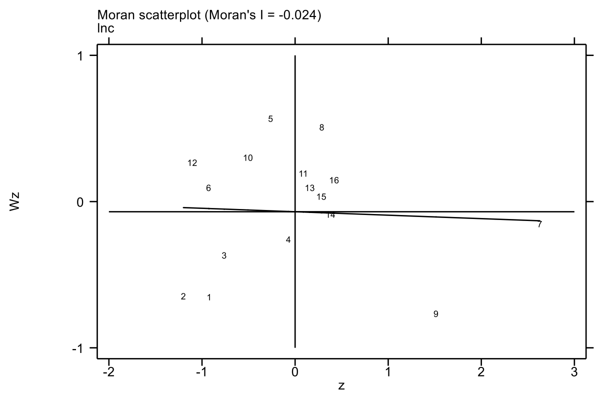

FIGURE 9
Moran scatterplot of carbon emission intensity in 2015.

TABLE 2 Industrial structure upgrading level of each district in Beijing in 2009, 2015 and 2020.

Districts	2009	2015	2020
Dongcheng District (DC)	7.804	7.810	7.829
Xicheng District (XC)	7.741	7.755	7.801
Chaoyang District (CY)	7.727	7.770	7.779
Fengtai District (FT)	7.537	7.587	7.673
Shijingshan District (SJS)	7.165	7.396	7.664
Haidian District (HD)	7.669	7.714	7.767
Mentougou District (MTG)	6.976	7.070	7.468
Fangshan District (FS)	6.601	6.766	7.223
Tongzou District (TZ)	6.961	6.967	7.262
Shunyi District (SY)	7.046	7.189	7.456
Changping District (CP)	7.043	7.259	7.397
Daxing District (DX)	6.999	7.027	7.369
Huairou District (HR)	6.590	6.782	7.209
Pinggu District (PG)	6.635	6.643	7.337
Miyun District (MY)	6.482	6.800	7.370
Yanqing District (YQ)	6.908	7.170	7.437

4 Results

4.1 Analysis of spatial data

This study utilizes Moran scatterplot to explore the spatial agglomeration of carbon emission intensity and industrial structure upgrading in each district of Beijing. The results are shown from Figures 8,–13.

According to our study, the carbon emission intensity of most districts of Beijing was high-high or low-low agglomeration, while that of several districts was high-low or low-high agglomeration. It should be noted that in 2020, the industrial structure upgrading of all the districts was basically high-high and low-low agglomeration. Specifically, in 2009, Dongcheng District, Xicheng District and Chaoyang District were in low-low agglomeration areas, that is, carbon emission intensity of these areas and their neighboring areas was low. Shijingshan District, Mentougou District, Fangshan District, Changping District and Yanqing District were in high-high agglomeration area, that is, these areas and their adjacent areas had higher carbon emission intensity. The carbon emission intensity of Haidian district, Shunyi District and Daxing District was in low-high agglomeration area, that is, the carbon emission intensity of these areas was low but that of neighboring areas was high. The regions such as Tongzhou District and Pinggu District were in the high-low agglomeration area, that is, the carbon emission intensity of these regions was high while the carbon emission intensity of their neighboring regions was low. The change in 2015 was not very obvious compared with that in 2009. It is worth mentioning that the spatial correlation in 2015 was negatively correlated. In 2020, the spatial agglomeration type of each district in Beijing has changed greatly and the agglomeration was obvious, mainly low-low and high-high agglomeration. The carbon emission intensity of Dongcheng District, Xicheng District, Chaoyang District, Shijingshan District and Haidian District was in low-low agglomeration area, that is, the carbon emission intensity of both these areas and their neighboring areas was low. The carbon emission intensity of Fangshan district, Tongzhou District, Shunyi District, Daxing District, Huairou District, Pinggu District, Miyun District and Yanqing District was in high-high agglomeration area, that is, the carbon emission intensity of both these areas and their neighboring areas was high.

Note: the figures representing the districts of Beijing as follows: 1 Dongcheng District, 2 Xicheng District, 3 Chaoyang District, 4 Fengtai District, 5 Shijingshan District, 6 Haidian

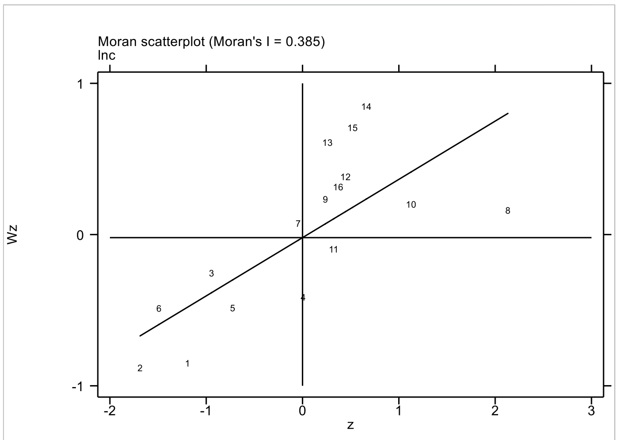

FIGURE 10
Moran scatterplot of carbon emission intensity in 2020.

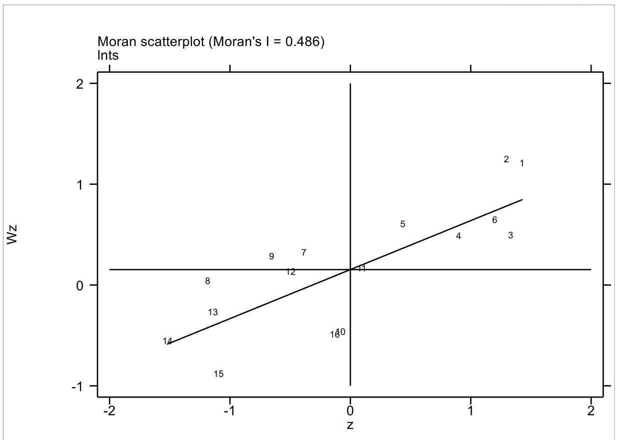

FIGURE 12
Moran scatterplot map of industrial structure upgrading in 2015.

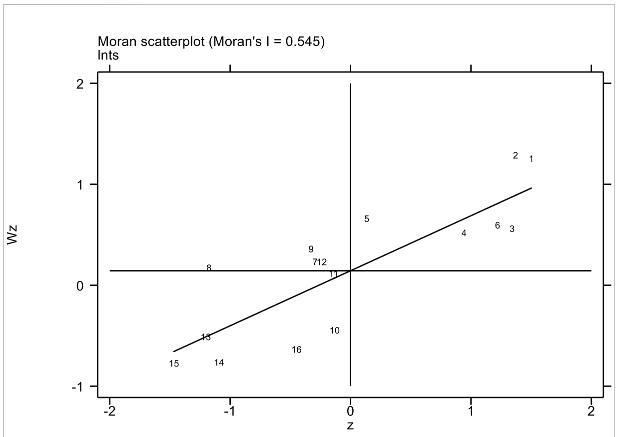

FIGURE 11
Moran scatterplot map of industrial structure upgrading in 2009.

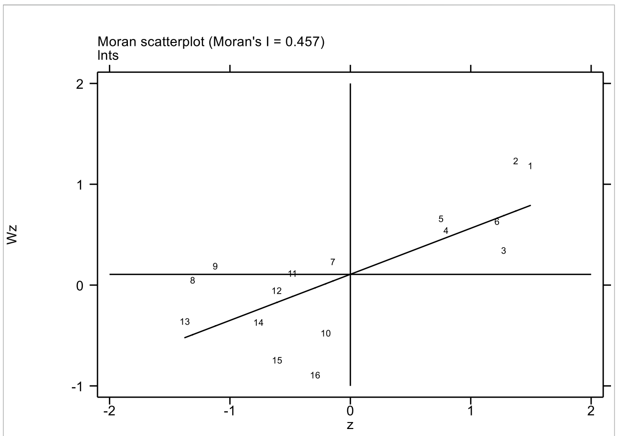

FIGURE 13
Moran scatterplot map of industrial structure upgrading in 2020.

District, 7 Mentougou District, 8 Fangshan District, 9 Tongzhou District, 10 Shunyi District, 11 Changping District, 12 Daxing District, 13 Huairou District, 14 Pinggu District, 15 Miyun District, 16 Yanqing District. The Same below.

Then the spatial agglomeration of industrial structure upgrading in each district of Beijing is analyzed. On the whole, most regions were in the areas of high-high and low-low agglomeration, a few regions were in low-high agglomeration area and no region was in high-low agglomeration area. Specifically, in 2009, Dongcheng District, Xicheng District, Chaoyang District, Fengtai District, Shijingshan District and Haidian District were in high-high agglomeration areas, that is, these areas and their adjacent areas had a high level of industrial structure upgrading; Mentougou District, Fangshan District, Tongzhou District and Daxing District were in low-high agglomeration areas, that is, the industrial structure upgrading level of these areas was lower while that of their neighboring areas was higher. Shunyi District, Changping District, Huairou District, Pinggu District, Miyun District and Yanqing District were in low-low agglomeration area, that is, both these areas and their neighboring areas had a lower level of industrial structure upgrading. In 2015, Mentougou District and Tongzhou District were in low-high agglomeration area, while other areas were in high-high or low-low agglomeration area. In 2020, there was no significant change in the spatial agglomeration of industrial structure upgrading in each district of Beijing since there was no significant change in terms of district and number of districts in each quadrant.

TABLE 3 Estimated results of spatial spillover.

	SDM-FE	SDM-RE	SAC-FE	SAR-FE	SAR-RE
Direct effect					
lnts	−19.524***	−12.710***	−6.069***	−6.553**	−1.302
	(3.468)	(3.686)	(2.079)	(2.597)	(1.859)
lnfdi	−0.111***	−0.095***	−0.139***	−0.117***	−0.102***
	(0.030)	(0.033)	(0.031)	(0.033)	(0.033)
lnpgdp	−1.695***	−0.907**	−2.139***	−2.127***	−0.948***
	(0.405)	(0.363)	(0.382)	(0.424)	(0.299)
lnpcon	0.881	0.614	−1.094**	−0.985	−0.448
	(0.783)	(0.784)	(0.486)	(0.638)	(0.310)
lnlab	−0.154	−0.126	0.076	0.014	−0.082
	(0.445)	(0.244)	(0.455)	(0.491)	(0.192)
Indirect effect					
lnts	18.839***	18.154***	−1.138	1.391*	0.243
	(4.731)	(4.860)	(1.313)	(0.732)	(0.398)
lnfdi	−0.102	−0.097*	−0.027	0.025**	0.022*
	(0.066)	(0.059)	(0.032)	(0.012)	(0.012)
lnpgdp	−0.921	−0.318	−0.390	0.461**	0.205*
	(0.686)	(0.376)	(0.446)	(0.196)	(0.114)
lnpcon	−3.281***	−1.263	−0.197	0.219	0.106
	(0.995)	(0.782)	(0.241)	(0.157)	(0.092)
lnlab	−1.123	0.336	0.010	−0.003	0.019
	(0.782)	(0.295)	(0.151)	(0.111)	(0.043)
Total effect					
lnts	−0.685	5.444***	−7.207***	−5.162**	−1.059
	(3.499)	(1.985)	(2.712)	(2.121)	(1.520)
lnfdi	−0.213***	−0.192***	−0.166***	−0.092***	−0.080***
	(0.066)	(0.051)	(0.050)	(0.027)	(0.026)
lnpgdp	−2.616***	−1.226***	−2.530***	−1.666***	−0.742***
	(0.611)	(0.265)	(0.578)	(0.352)	(0.241)
lnpcon	−2.400***	−0.649**	−1.291**	−0.766	−0.342
	(0.556)	(0.277)	(0.618)	(0.508)	(0.233)
lnlab	−1.277	0.210	0.086	0.010	−0.063
	(0.823)	(0.208)	(0.562)	(0.390)	(0.153)

***, ** and * represent significance at 1%, 5% and 10% confidence level respectively; Standard deviations are shown in brackets.

4.2 Analysis of spatial spillover effect

4.2.1 Estimated results of spatial spillover

Columns 2 to 6 of Table 3 show the estimation results of fixed effect by Spatial Durbin Model, random effect estimation by Spatial Durbin Model, fixed effect estimation by Spatial Autocorrelation Model, fixed effect estimation by Spatial Autoregressive Model, and random effect estimation by Spatial Autoregressive Model respectively. The spatial weight matrix used for the estimated results in the table is Spatial Adjacency Matrix (Queen Adjacency). The same below.

In the five spatial models, the regression coefficient of the direct effect of industrial structure upgrading on carbon emission intensity is negative and significant at different levels, indicating that the industrial structure upgrading in a certain region has a significant inhibitory effect on the local carbon emission intensity. In terms of indirect effect of the five models, those of SDM-FE, SDM-RE and SAR-FE models are positively significant at different levels, indicating that the industrial structure upgrading in neighboring areas has a significant promoting effect on local carbon emission intensity. In terms of total effect, that of the five models presents positive or negative significance, indicating that the industrial structure upgrading levels of local and neighboring areas influence local carbon emission intensity at the same time, and the actual impact should be judged by the specific levels of the two.

TABLE 4 Model selection test.

Test methods	Statistic	*p* Value		
LR-spatial lag	45.81	0.0000		
Wald-spatial lag	259.48	0.0000		
Model	obs	df	AIC	BIC
SDM-FE	192	12	174.6039	213.6938
SAC-FE	192	8	204.1507	230.2107

Investment level and economic development level have similar effects on carbon emission intensity, therefore this study only selects investment level for analysis. In the five models, the direct effect of investment level on carbon emission intensity is significantly negative at the significance level of 1%, indicating that the increase of investment level has a significant inhibitory effect on local carbon emission intensity. The indirect effect of investment level on carbon emission intensity has both positive and negative coefficients in the five models and the significance level is not obvious, indicating that the improvement of investment level in neighboring areas has no obvious effect on the carbon emission intensity in this region. The total effect of investment level on carbon emission intensity is negative in the five models and passed the significance level test, indicating that investment level has a significant inhibitory effect on local carbon emission intensity under the combined influence of local and neighboring areas.

Among the five models, the direct effect of consumption level on carbon emission intensity is significantly negative

TABLE 5 Robustness test results.

	Economic geographic matrix	Distance matrix	Inverse distance matrix
Direct effect			
lnts	−4.650	−7.974**	−6.417*
	(2.907)	(3.521)	(3.795)
lnfdi	−0.073**	−0.114***	−0.108***
	(0.029)	(0.033)	(0.033)
lnpgdp	−2.628***	−2.097***	−2.223***
	(0.432)	(0.452)	(0.434)
lnpcon	−0.443	−0.549	−0.447
	(0.610)	(0.714)	(0.775)
lnlab	−0.405	0.178	−0.355
	(0.488)	(0.505)	(0.526)
Indirect effect			
lnts	−22.44***	0.569	2.019
	(4.938)	(3.629)	(3.612)
lnfdi	−0.0339	−0.122**	−0.080
	(0.063)	(0.061)	(0.055)
lnpgdp	0.493	0.399	1.607***
	(0.814)	(0.480)	(0.514)
lnpcon	0.126	−0.470	−0.430
	(0.908)	(0.844)	(0.823)
lnlab	−1.974**	1.248	2.097***
	(0.967)	(0.775)	(0.761)
Total effect			
lnts	−27.09***	−7.404***	−4.398**
	(5.587)	(2.446)	(2.092)
lnfdi	−0.107	−0.236***	−0.188***
	(0.071)	(0.062)	(0.050)
lnpgdp	−2.135**	−1.699***	-0.616
	(0.987)	(0.551)	(0.445)
lnpcon	−0.318	−1.020	−0.877*
	(1.213)	(0.699)	(0.489)
lnlab	−2.379**	1.427*	1.742***
	(1.014)	(0.808)	(0.633)

only in SAC-FE model, and there is no significant effect in other models. In term of indirect effect, only in the SDM-FE model consumption level has a significantly negative effect on carbon emission intensity, while in the other models it has no significant effect. In term of total effect, the regression results of all the five models show that the influence coefficient of consumption level on carbon emission intensity is negative and is significant only in SDM-FE, SDM-RE and SAC-FE models.

The direct effect, indirect effect and total effect of labor input level on carbon emission intensity are not significant in the regression results of the five models and there are both positive and negative regression coefficients, indicating that the improvement of labor input level in both local and neighboring regions has no obvious inhibitory effect on local carbon emission intensity.

4.2.2 Model selection test

After the regression results of five spatial econometric models shown in Table 3, we conduct a model test to select the model suitable for this study. Fixed-effect models are more suitable since the research objects of spatial econometrics are mostly uninterrupted Spatio-Temporal data. Therefore, this study selects from SDM-FE, SAR-FE and SAC-FE econometric models and the test results are shown in Table 4. First, we use the LR test and Wald test to select between SDM-FE and SAR-FE. The test results reject the null hypothesis that SDM could degenerate into SAR, indicating that SDM-FE should be chosen out of the two. Then we make choice between SDM-FE and SAC-FE by AIC and BIC information criteria. The results show that both the AIC value and BIC value of SDM-FE are less than the estimated value of SAC-FE. Therefore SDM-FE is more suitable for this study.

4.2.3 Robustness test

Since the regression results of the spatial econometric model are largely influenced by the spatial weight matrix, the robustness test is carried out by replacing the spatial weight matrix. The above results are obtained based on the Adjacency Space Weight Matrix. In order to prove the reliability of the conclusion, this study uses economic geographic matrix, distance matrix and inverse distance matrix for model estimation. The economic geographic matrix is calculated based on the per capita GDP of each district in Beijing in 2020. The distance matrix and inverse distance matrix are calculated with Euclidean Distance. As shown in Table 5, the direct effect, indirect effect and total effect of the core explanatory variables are significant, which is consistent with the conclusion above and the control variables do not change significantly, proving that the conclusion of this study is reliable.

5 Discussion

Based on the panel data of each district in Beijing from 2009 to 2020, this study measures and analyzes the carbon emission intensity and industrial structure upgrading. On this basis, control variables are added to analyze the spatial spillover effect of industrial structure upgrading on carbon emission intensity, and the research conclusions are as follows:

First, the carbon emission intensity and industrial structure upgrading of each district in Beijing showed an obvious spatio-temporal evolution pattern from 2009 to 2020. The spatial distribution of carbon emission intensity and industrial structure upgrading in 16 districts of Beijing are shown in Figures 2,–7. More specifically, in the 3 years of 2009, 2015 and 2020, the carbon emission intensity in most areas showed a downward trend, indicating that Beijing has achieved phased results in carbon emission reduction. The carbon emission intensity dropped remarkably in some districts, indicating that the carbon emission reduction reform in Beijing has achieved significant results. The industrial structure upgrading level in all districts has been improved to some extent, indicating that the industrial transformation in China has also achieved remarkable results. From the perspective of space, both the carbon emission intensity and the industrial structure upgrading of Beijing showed a radial pattern of development. The areas with low carbon emission intensity in Beijing were mainly agglomerated in Dongcheng District, Xicheng District and their adjacent districts. Then the carbon emission intensity gradually increased towards the surrounding areas. The industrial structure upgrading of Beijing had similar distribution characteristics as carbon emission intensity with radial pattern: the central area was better than the surrounding ones. Through the analysis of data of these three years, it can be inferred that all of the districts of Beijing have been constantly reducing carbon emissions and optimizing the industrial structure.

Second, spatial spillover regression results show that the local industrial structure upgrading has significant inhibitory effect on local carbon emission intensity; the industrial structure upgrading in neighboring areas plays a significant role in decreasing local carbon emission intensity; the industrial structure upgrading levels of local and neighboring areas influence local carbon emission intensity at the same time and the actual impact should be judged by the specific levels of the two. The improvement of local investment level and economic development level has a significant inhibitory effect on local carbon emission intensity, while the improvement of neighboring investment level and economic development level has no obvious effect on local carbon emission intensity. The increase of local consumption level has no obvious inhibitory effect on local carbon emission intensity, while the increase of neighboring consumption level has a significantly negative effect on local carbon emission intensity. The direct effect, indirect effect and total effect of labor input level on carbon emission intensity are not significant in the regression results of the model and there are both positive and negative regression coefficients, indicating that the improvement of local and neighboring labor input level has no obvious inhibitory effect on local carbon emission intensity. According to the analysis results of spatial spillover effect, the influence of industrial structure upgrading on carbon emission intensity in Beijing varies among the districts and presents obvious spatial spillover effect.

However, this study has two limitations. First, this study takes the districts of Beijing as the research object which does not take into account the influence of surrounding provinces and cities on Beijing. And it is impossible to exclude these influencing factors from the study. Second, the impact of industrial structure upgrading on carbon emission intensity in each district of Beijing from 2009 to 2020. However, there is impact difference in different development stages and this study does not conduct in-depth discussion on this impact difference.

6 Conclusion

In response to the global climate change, it is a vital challenge for China to coordinate economic development, industrial transformation and environmental protection on its way to “carbon peaking and carbon neutrality goals”. Beijing is the center of scientific and technological innovation and the leading area of the reform and development of industrial structure in China. To some extent, the development of the industrial structure of Beijing can represent the reform direction of other regions in China in the future. The industrial structure upgrading and the optimization of carbon emission intensity in Beijing have important reference significance for China to achieve the goal of “carbon peaking and carbon neutrality goals”. Based on the above analysis results, suggestions are proposed as follows:

First, the carbon emission intensity and industrial structure upgrading of Beijing have a fair development condition. In 2020, the carbon emission intensity of most districts in Beijing is below 3, and the industrial structure upgrading level of them is above 7.2. It is worth mentioning that the carbon emission reduction in Mentougou District from 2009 to 2020 is remarkable, and other cities may use the experience of this district for reference in policy-making. Therefore, it is necessary to continuously develop low-carbon technologies and promote scientific and technological innovation of traditional energy industry, thus effectively promoting the green and low-carbon transformation of the industry and improving the use efficiency and economic value of energy. For the surrounding areas of Beijing, the policymakers should put focus on optimizing the industrial structure through promoting clean production and changing the energy consumption structure dominated by high consumption and high pollution, then they can achieve the goal of the substantive transformation of economic growth mode. For the central area of Beijing, the cultivation and development of emerging industries and circular economy should be continued, realizing the green and low-carbon growth goals with equal emphasis on quality and efficiency.

Second, each district in Beijing should continue to speed up the pace of transformation and upgrading of industry. On the one hand, the transformation and upgrading of traditional industries should be encouraged to improve the industry efficiency so that the “low energy consumption-high output” can be achieved as soon as possible. Meanwhile, it is necessary to speed up the formation of knowledge- and technology-intensive industry, such as the strategic emerging industries and high technology industries. On the other hand, investment in scientific and technological research and development should be increased to improve the current energy structure. In this way, the optimization of industrial structure of Beijing can be facilitated to drive the reduction of carbon emission intensity through a coupling effect.

Third, the government of Beijing should fully play the role of macro-control and match each district with specific carbon reduction policies according to the regional economic development and industrial structure level. At the same time, the spatial interaction of carbon intensity should also be considered to achieve a reasonable and orderly pattern of central area driving the development of surrounding areas. In this way, the completion of “carbon peaking and carbon neutrality goals” can be effectively guaranteed while developing the economy.

Data availability statement

The descriptive statistics of the original data presented in the study is included in the appendix of the paper. For further inquiries, please contact the corresponding author.

Author contributions

BS: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing—original draft, Writing—review and editing, Visualization, Supervision. RW: Methodology, Formal analysis, Data curation, Writing—original draft, Writing—review and editing. RZ: Conceptualization, Formal analysis, Investigation, Writing—original draft, Writing—review and editing, Visualization, Supervision. ZZ: Literature retrieval, writing-original draft.

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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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Appendix

TABLE A1 Appendix A is Variable declaration.

Types of variables	Variables	Symbol	Variable declaration
Dependent variable	Carbon emission intensity	c	Calculated by formula (Zhang, 2000) and (Cheng et al., 2018)
Core explanatory variable	Industrial structure upgrading	ts	Calculated by formula (Moran, 1950) and (Pinto et al., 2014)
Control variables	Investment level	fdi	Measured by actual utilized fdi/regional GDP
	Economic development level	pgdp	Measured by GDP per capita
	Consumption level	pcon	Measured by per capita consumer spending
	Labor input	lab	Measure with on-duty worker gross wages

TABLE B1 Appendix B is Statistical description of variables.

Variables	Obs	Mean	Std.Dev	Min	Max
Lnc	192	1.206	0.987	−0.545	4.542
lnts	192	1.980	0.055	1.869	2.058
lnfdi	192	3.122	1.112	−0.702	5.691
lnpgdp	192	11.124	0.724	9.969	13.034
lnpcon	192	10.159	0.359	9.378	10.944
lnlab	192	5.391	1.322	2.871	8.138

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Does fiscal decentralization curb the ecological footprint in pakistan?

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This paper offers a new indulgence to the present literature by integrating the role of fiscal decentralization (FD) in affecting ecological footprint (EF). So, this study considered the effect of FD on EF in the existence of energy consumption (EC), technological innovation (TI), gross domestic product (GDP), and trade openness (TOP) from 1990 to 2018 in Pakistan. We employ econometric methods like Bayer & Hanck cointegration, fully modified ordinary least squares, dynamic ordinary least squares, and canonical cointegration regression for empirical analysis. Moreover, the frequency domain causality test is used to conclude the causal impact of FD, EC, TI, GDP, and TOP on EF. The regression results disclose that EC, GDP, and TOP boost EF in Pakistan; however, FD and TI promote the sustainability of the environment by reducing EF. Besides, the frequency causality outcomes indicate that FD, EC, TI, GDP, and TOP have insinuations for EF in the long term. As a policy recommendation, this research suggests that Pakistan could successfully integrate strategies to increase ecological quality by allowing the lower level of government to utilize eco-friendly technological innovations.

KEYWORDS

fiscal decentralization, ecological footprint, FMOLS, DOLS, pakistan

1 Introduction

Since the World Earth Summit in Kyoto, Japan, in 1997, developing a sustainable atmosphere has become a major global concern. The meeting emphasized the importance of protecting our earth from worldwide environmental catastrophe. Roughly 80% of the planet's population resides in a nation that is beset by significant environmental challenges. Due to substantial economic advancement and affluence, human living requirements and well-being have soared substantially in recent generations (Majeed et al., 2021; Adebayo, 2022a; Adebayo et al., 2022; Ali et al., 2022; Kirikkaleli et al., 2022). This stresses the ecosystem, leading to pollution, biodiversity deterioration, and environmental disparity (Ahmed & Wang, 2019). As a result, developing and attaining long-term environmental goals has risen to the pinnacle of the critical global list.

Among these initiatives, some authorities and academics think fiscal decentralization (FD) is an impactful way to reduce emissions; they argue that FD can stimulate a "race to the top" between local authorities by creating greater ecological guidelines in order to generate eco-friendly environments and, as a result, less pollution in damaged regions (Mu, 2018; Chen and Chang, 2020). However, in current years, there has been an emergent risk of the influence of FD on environmental performance (Khan et al., 2021). Advocates of this viewpoint assume that FD will precipitate a "race to the bottom" wherein local authorities will reduce their environmental guidelines in order to draw foreign businesses, thereby increasing pollution. These conflicting findings have caught the attraction of academics in the link between FD and environmental sustainability.

Therefore, the research's main goal is to examine the impact of FD on environmental sustainability in Pakistan. Decentralization in Pakistan looks to be regarded as either a curse or a cure or an augmentation to the nation's already massive pressures or a remedy for all wrongs (Shahzad and Younus 2018). Pakistan is an Islamic country ruled by the 1973s Constitution of Pakistan. The national government accumulates the majority of the nation's earnings and then redistributes it among the various governmental strands of national and provincial administrations to rectify both horizontal and vertical fiscal imbalances. According to the 1973 constitution, the National Finance Commission (NFC) creates prudent and honest resource allocation decisions between the national and provincial authorities (Asghar, 2016). Nevertheless, the NFC did not always deliver indisputable grants, and the fiscal resource allocation process did not always perform admirably. Pakistan, on the other side, is presently experiencing macroeconomic imbalances, as well as a current account deficit, rising unemployment, and rising prices. Under these circumstances, efficient FD is anticipated to be a productive tool for achieving long-term economic development, macroeconomic consistency, and enhanced environmental conservation.

This study gives a fresh perspective on FD and environmental sustainability in the case of Pakistan. To the best of our understanding, there appears to be a research discrepancy in the context of Pakistan. Notwithstanding the study of Li et al. (2021), this study employed ecological footprint (EF) as an alternative to ecological performance. Due to the widespread use of carbon dioxide (CO_2) emissions as a measure, the existing literature has been criticized for neglecting to grasp all facets of a sustainable environment. This indicator has recently been called into the discussion because it is not inclusive, as the individual's effect on the atmosphere is not studied. As a result, the emphasis has shifted to EF as an advanced measure (Charfeddine & Mrabet, 2017; Bello et al., 2018; Alola et al., 2019; Chunling et al., 2021). The EF integrates the two principles to confront the harm triggered instigated by human actions on the ground level as well as the destruction caused by unsolicited usage of all of the earth's natural resources (Zahra & Badeeb 2022). Likewise, the current investigation also provides a deeper understanding of the roles of TI, GL, and GDP as substantial factors of EF. Besides, by applying contemporary time-series estimation methodologies to explore the impact of FD on EF, this research specifically adds to the literature. Furthermore, policymakers, climate activists, and public representatives will benefit from the study's findings, which offer better knowledge as well as vital information, effects, and proof of ecological safety.

The subsequent section covers the theoretical model, data, and methods. The third section discusses the outcomes founded on the methods employed. The last section designates the conclusion and prospect policy outline.

2 Theoretical model, data, and methods

2.1 Theoretical framework and model

To study the effect of FD on EF in the presence of control factors like EC, TI, GDP, and TOP during 1990–2018, the empirical equation is exhibited as:

$$\ln EF_t = \alpha_0 + \alpha_1 \ln FD_t + \alpha_2 \ln EC_t + \alpha_3 \ln TI_t + \alpha_4 \ln GDP_t + \alpha_5 \ln TOP_t + \varepsilon_t \tag{1}$$

where EF shows ecological footprint, FD is fiscal decentralization, EC denotes energy consumption, TI means technological innovation, GDP stands for gross domestic product, and TOP signifies trade openness. Ln demonstrates the natural log, ε symbolizes the error term, and t shows the time period.

FD increases the adequate allocation of confined resources by lowering the expense of providing local public products and improving the effectiveness of government spending. Local authorities may offer more beneficial public facilities with the incisive benefit of local desires under the FD mechanism. There are two distinct perspectives on FD that influence the atmosphere. The first one is the race to the top strategy, and the second is the race to the bottom strategy (Ji et al., 2021). The race to the top strategy encourages FD in the system, which helps to regulate or cut pollution levels in the environment. Besides, this process expedites sustainable development by strengthening economic performance, better utilization of fiscal resources, robust institutional performance, and normalization of environmental degradation externalities. Focusing on this strategy, FD is anticipated to have an adverse effect on EF, $FD_t < 0$. Most markets rely on industry sectors in the race to the bottom framework. These sectors are more polluting the atmosphere, with poor institutional quality, poor environmental laws, and easing constraints to attract foreign funding in order to establish extra-economic prosperity. This type of framework encourages the utilization of nonrenewable energy, which raises the intensity of pollution in the environment. In this situation, we anticipate that FD will have a favourable impact on EF, $FD_t > 0$. Furthermore, the EC is included in the model. A rise in EC due to the unneeded use of fossil fuels for growth

TABLE 1 Data description.

Variables	Description	Units	Data source
EF	Ecological footprint	global hectares per capita	GFN
FD	Fiscal decentralization	Percentage of provincial government expenditures to the total government expenditures	SBP
EC	Energy consumption	kg of oil equivalent per capita	WDI
TI	Technological innovation	the number of patent applications submitted each year	WIPO
GDP	Gross domestic product	Constant 2010 US Dollars	WDI
TOP	Trade openness	% of GDP	WDI

elevates pollution, culminating in a decrease in ecological performance (Yang et al., 2020a; Adebayo, 2022b; Qayyum et al., 2022; Yang et al., 2022). As a result, if the association between EC and EF is positive, we propose $EC_t > 0$. Technological innovations could have an effect on the environment by introducing energy improvements and energy-efficient facilities (Yang et al., 2021). Therefore, we assume $TI_t < 0$ if the association between TI and EF is negative. According to Qayyum et al. (2021) and Yang et al. (2020b), economic progress is the basic cause for rising contamination heights because GDP is reliant on heavy energy usage, which exponentially degrades environmental reliability. As a result, we anticipate $GDP_t > 0$ if the association between GDP and EF is positive. Lastly, trade could have harmful effects on the environment due to the use of extensive amounts of carbon-emitting capabilities and substantial transportation usage (Antweiler et al., 2001; Fan et al., 2020; Fareed et al., 2022). So, we suppose $TOP_t > 0$ if the connection between TOP and EF is positive. The sources of data, meanings, and variable units used in Equation (1) are shown in Table 1. Figure 1 portrays the estimation flow diagram used in this study.

2.2 Methodologies

2.2.1 Unit root test

Before a cointegration process is conducted, the sequence of the integration must often be acknowledged by probing the unit root test. The global transition occurs during our study period, resulting in structural breaks. Unit root indicators that do not correspond to structural breaks may produce unsatisfactory outcomes. Hence, the Zivot and Andrews (2002) unit root technique is used to evaluate the stationary attributes of the variables and single structural breaks. The Zivot and Andrews unit root approach is superior to others because it considers structural breaks when evaluating the stationarity level.

2.2.2 Cointegration test

Bayer & Hanck's (2013) procedure is applied following the stationarity affirmation to examine the cointegration association between the study elements. By combining several different test results, such as those of Engle and Granger (1987), Johansen (1991), Peter Boswijk (1994), and Banerjee et al. (1998), this newly customized cointegration approach offers a more proper findings. The following are Fisher's calculations for the Bayer & Hanck strategy:

$$EG - JO = -2\left[\ln\left(P_{PG}\right)+\ln\left(P_{JO}\right)\right] \quad (2)$$

$$EG - JO - BO - BDM = -2\left[\ln\left(P_{PG}\right)+\ln\left(P_{JO}\right)+\ln\left(P_{BO}\right)+\ln\left(P_{BDM}\right)\right] \quad (3)$$

The possible scores for each of the aforementioned cointegration tests are P_{EG}, P_{IO}, P_{BO}, and P_{BDM}. The creation of Fisher statistics determines the cointegration of the underlying factors.

2.2.3 Long-run estimates

To detect the long-run influence of FD on EF in Pakistan, with EC, TI, GDP, and TOP as controlled variables. We use the fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS), and canonical cointegration regression (CCR) techniques correspondingly. Phillips and Hansen (1990) developed the semi-parametric technique FMOLS to address the correlation issue, emphasizing that the approach is completely impartial and reliable asymptotically. Likewise, CCR, a process equivalent to FMOLS founded by Park (1992), is exploited to probe cointegration patterns in a sequence in which the sequence of the stationarity is I (1). The main difference between the FMOLS and CCR approximation strategies is that the FMOLS tends to focus on both data and variable transition. In contrast, the CCR centres on data modification (Wu et al., 2018). The DOLS procedure incorporates leads and lags to compensate for simultaneity and tiny sample bigotry. Both DOLS and FMOLS methodologies address the issue of endogeneity and serial correlation by interacting with disorderly parameters (Yildirim & Orman, 2018).

2.2.4 Breitung and Candelon causality

In addition, to check the causal effects of FD on Pakistan's EF and other factors at various frequency ranges. The frequency-domain causality test of Breitung and Candelon (2006) is utilized in this research. This methodology is built on

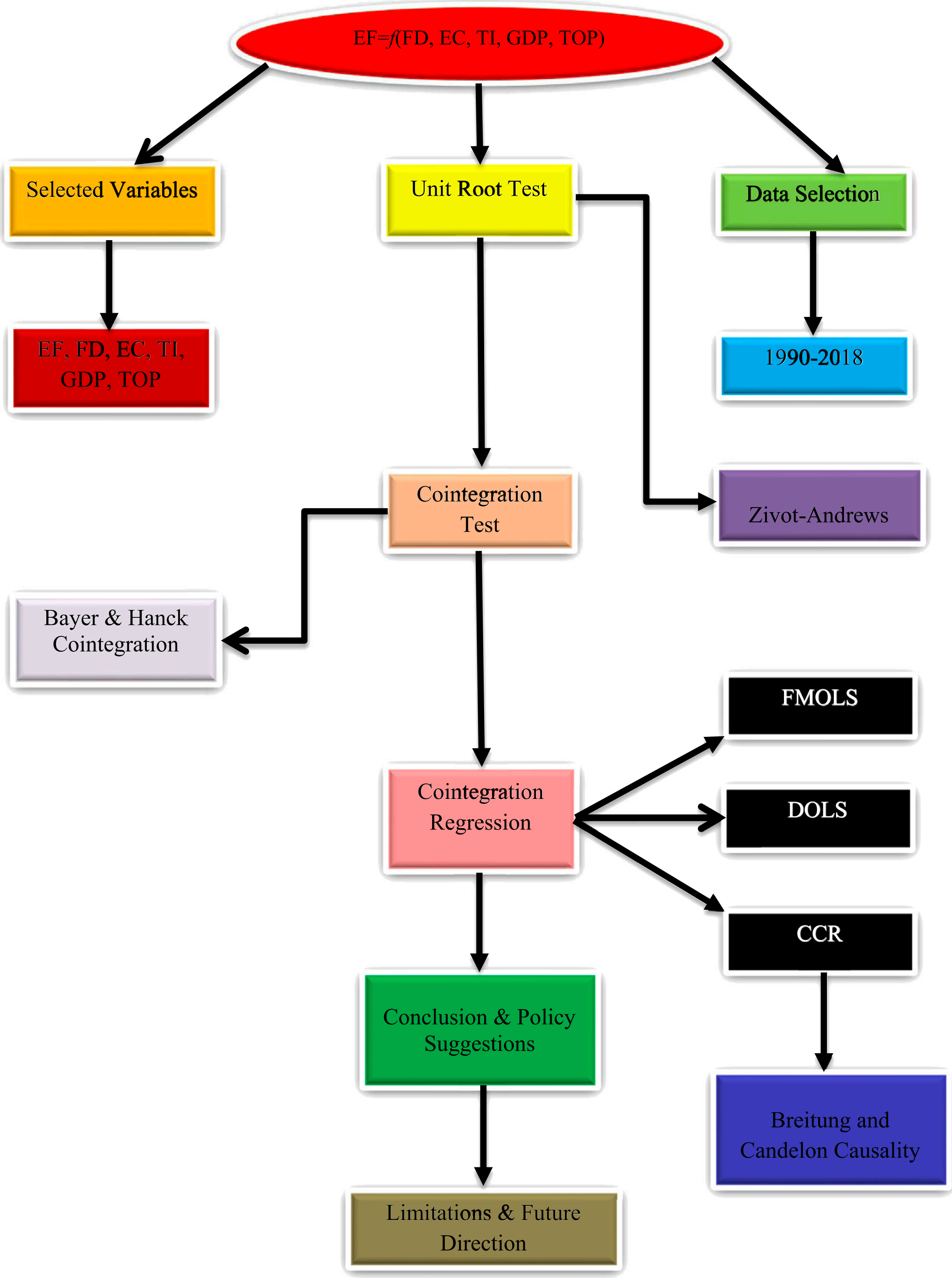

FIGURE 1
Flow diagram of the analysis.

primary investigation conducted by Geweke (1982) and Hosoya (1991). The decisive difference between time-domain and frequency-domain strategies, according to Odugbesan and Adebayo (2020), is that the time-domain approach uncovers a certain change within a time set, while the frequency-domain procedure embodies the

TABLE 2 Unit root test results.

Variables	At level		At first difference	
	Test statistic	Time break	Test statistic	Time break
Level				
EF	-1.3221	1999Q2	-5.9711***	1993Q2
FD	-1.8291	2002Q1	-5.7644***	2000Q2
EC	-2.3474	1997Q2	-6.9702***	1994Q2
TI	-1.5416	1991Q4	-6.0117***	1998Q1
GDP	-2.1017	1993Q2	-5.6017***	2002Q2
TOP	-1.0502	1995Q4	-5.2119***	2001Q4
Critical value				
1%	-5.34			
5%	-4.93			
10%	-4.58			

*** display significance at 1% levels.

TABLE 3 Results of bayer and hanck cointegration.

	Fisher statistics	Fisher statistics	Cointegration
	EG-JO	EG-JO-BO-BDM	
EF = *f* (FD, EC, TI, GDP, TOP)	16.9931	28.4764	
	Critical value	Critical value	
5%	10.576	20.143	

density of distinctive adjustments inside a time sequence (Ali & Kirikkaleli, 2021).

3 Results and discussions

This paper intends to study the effects of FD on Pakistan's environmental sustainability. As a first stage in estimating the model, the stationarity attributes of the data are examined by employing the Zivot and Andrews test for unit root. The unit root process has been used to determine a series of stationary factors resembling a structural break. As can be seen in Table 2, the unit root approach shows that none of the factors are stationary at the level. Besides, after the first difference, all of the elements become stationary.

The current study also uncovers the cointegration properties of parameters by utilizing the combined Bayer and Hanck cointegration test. Table 3 summarises the Bayer and Hanck test's findings. At the 5% significance level, the outcomes specify that long-term cointegration continues between EF, FD, EC, TI, GDP, and TOP.

Results from Table 4 denote that FD reduces EF by 0.182% in FMOLS, 0.195% in DOLS, and 0.188% in CCR. It infers that many ecological safety recommendations, like fiscal expenditures and environmental expenditures, are also executed through FD. According to the results, FD is linked with much more optimized and efficient monetary and fiscal practices, which may improve atmosphere sustainability via committed legitimacy. Wang & Lei (2016) contended that better FD enhances the ecological atmosphere because local authorities can devote more capably than the federal government due to the data benefit. These

TABLE 4 Long-run results.

Variables	FMOLS	DOLS	CCR
FD	-0.1821*** (0.0032)	-0.1951*** (0.0009)	-0.1879*** (0.0071)
EC	0.2621*** (0.0021)	0.2949** (0.0413)	0.2748** (0.0214)
TI	-0.1591*** (0.0000)	-0.1782*** (0.0003)	-0.1967*** (0.0009)
GDP	0.2277*** (0.0075)	0.2537** (0.0145)	0.2726** (0.0361)
TOP	0.2811** (0.0352)	0.3027* (0.0619)	0.2968** (0.0247)
Constant	-2.2152*** (0.0000)	-2.3992*** (0.0000)	-2.4118*** (0.0000)
R^2	0.9314	0.9422	0.9488
Adjusted R^2	0.9521	0.9328	0.9247

*, **, and *** show significance at 10, 5, and 1% levels, correspondingly.

TABLE 5 Results of Frequency domain causality test.

Direction of causality	Long-term		Medium-term		Short-term	
	$\omega_i = 0.01$	$\omega_i = 0.05$	$\omega_i = 1.00$	$\omega_i = 1.50$	$\omega_i = 2.00$	$\omega_i = 2.50$
FD →EF	5.5414* (0.0615)	5.6558* (0.0821)	0.1019 (0.4401)	0.1451 (0.8178)	0.1944 (0.4391)	0.1647 (0.7144)
EC→EF	6.6583** (0.0411)	6.7655** (0.0357)	6.9421** (0.0414)	6.8421** (0.0151)	2.2443 (0.4577)	2.6048 (0.2148)
TI→EF	8.8475** (0.0351)	8.9578** (0.0269)	0.5221 (0.7787)	0.5437 (0.3775)	0.5838 (0.4717)	0.6050 (0.6288)
GDP→EF	9.8474*** (0.0005)	10.0877*** (0.0000)	5.8226** (0.0411)	5.9942** (0.0442)	0.2214 (0.6724)	0.2588 (0.7337)
TOP→EF	7.5871** (0.0394)	7.7993** (0.0412)	0.2181 (0.4711)	0.2655 (0.52175)	0.1488 (0.7941)	0.1915 (0.6988)

The values within () show the *p*-value. → Specifies the path of causality. *, **, and *** specify significance at 10, 5, and 1% levels, correspondingly. SIC, defines the lag lengths for the VAR models.

outcomes are analogous to those of Tufail et al. (2021) and Yuan et al. (2022). Overall, present estimates indicate that FD can be utilized as a productive tool to reduce EF. The empirical findings of the study show that FD decentralisation enhances ecological quality. Therefore, for ecological sustainability, a higher level of FD is necessary. As a result, it is crucial to explain roles at various stages of authority to attain the goal of lower pollution successfully.

As per the EC outcomes, a 1% increase in EC raises EF by 0.262, 0.295, and 0.275%, respectively. Energy creation from fossil resources noticeably worsens environmental performance in Pakistan by raising pollution. Our findings are akin to those of Yang et al. (2021) and Shabir et al. (2022). It is hard to ignore the use of energy for a higher quality atmosphere because it is a necessary component of economic progression. Economic evolution raises the energy requirements by establishing new industries or expanding established ones, resulting in a rise in the country's pollution levels. Besides this, there is an urgent consideration to establish clean and advanced energy sources in order to reduce pollution without negatively impacting the ecosystem or economic progress.

The coefficient values of TI had a negative indication, implying a pollution-mitigation impact. A 1% rise in TI substantially lowers EF by 0.159, 0.178, and 0.197%, respectively. Implementing eco-friendly, greener technologies to increase energy efficiency is the most effective way to address environmental contamination. Environmental innovation is a strategy for promoting economic expansion and advancement while preventing ecological deterioration and biodiversity loss. Numerous empirical investigations have found that energy technology advancement is shifting toward greener and more innovative energy sources (Du et al., 2019). Similarly, Cantner et al. (2019) have revealed that factories and government entities are now creating significant financing for research and development to obtain workable remedies in sustainable and clean energy to acquire greener economic development and the atmosphere. Our findings undermine the conclusions of Chunling et al. (2021) and Awosusi et al. (2022), who contended that TI utilizes energy sources to strengthen economic operations, which increases rather than decreases EF.

Table 4 also demonstrates that a 1% augmentation in GDP will lead to a 0.228, 0.254, and 0.273%, respectively, rise in EF. This demonstrates how growing GDP is preceded by surging EF in Pakistan. It must be mentioned that an expansion in a nation's GDP amplifies a powerful push on the atmosphere, and ongoing and inadequate consumption of natural resources in a region further damages environmental protection. So, the rate of EF will ultimately surge. This indicates that as the GDP upswings, countries will move their concentration to more industries, further hovering demand for high energy usage. Because of the high demand for consumption, the industry's use of nonrenewable energy is increasing. This type of energy usage is hazardous and inevitably raises the level of EF. The outcomes corroborate those of Kalmaz and Kirikkaleli (2019), Ji et al. (2021), Abid et al. (2022), and Akadiri et al. (2022).

Furthermore, at a 1% statistical level, TOP is positively connected to EF. The value of TOP denotes that a one percent rise in TOP raises EF by 0.281, 0.303, and 0.297%, respectively. The TOP outcomes are consistent with the findings of Danish et al. (2018) and Hashmi et al. (2020); they affirm the authenticity of a substantial relationship between TOP and environmental quality. The results revealed that the level of economic advancement is spreading due to the scale effect, which may exacerbate environmental pollution. The manufacturing of pollution-intensive goods causes more pollution. In recent times, the investigation of driving force has confirmed that trade density is the main factor in expanding emissions events (Wu et al., 2005).

A frequency-domain causality technique is utilized in this paper to assess the causal association among variables (see Table 5). The outcomes show that FD, TI, and TOP emit EF in the long term. Besides, EC and GDP contribute to EF in both the long and medium term. Hence, any policy change in FD, EC, TI, GDP, or TOP has aftermaths for EF in the long term. Similarly, any plan modification in EC and GDP also affects EF in the medium term.

4 Conclusion and policy recommendations

Given the ongoing dialogue over the reasons for environmental deterioration, this paper backs to the present literature by probing the effect of FD on the EF in the existence of EC, TI, GDP, and TOP in the case of Pakistan from 1990 to 2018. The econometric strategies provide significant results: i) all parameters are integrated to the same order of I (1); ii) long term cointegrating associations exist among variables; iii) FD and other control variables such as EC, TI, GDP, and TOP are crucial elements in the context of ecological footprint; iv) an increase in FD, and TI decrease EF in Pakistan; v) EC, GDP, and TOP are unfavorable for environmental performance; vi) there is confirmation of a long term causality between FD and EF, EC and EF, TI and EF, GDP and EF, TOP and EF.

Regarding policy concerns, this research implies that Pakistan could effectively incorporate policies to boost ecological performance by permitting a lower level of government. As a result, confirmation of duties at various stages of government is required to attain the energy-saving capabilities of fiscal spending. Moreover, an enhancement in technological innovation can help reduce ecological footprint efficiently; therefore, it is essential to pay attention to environment-conscious, highly developed innovations that transform economic development contributing factors aside from nonrenewable energies and toward green and clean energy sources. These eco-friendly developments have far-reaching ramifications for the environment and climate change. Besides that, economic structures in Pakistan must be amended to promote innovation.

Future work on Pakistan should concentrate on other combinations of accessible factors relating to fiscal decentralization and environmental quality. In addition, in the case of Pakistan, the future could also concentrate on determining the threshold level of FD that optimizes economic development. Another issue is that we only utilized Pakistan as a test example. In the upcoming investigation, the study's results can be applied to different groups of nations, like the G20.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

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

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Fiscal decentralisation and green total factor productivity in China: SBM-GML and IV model approaches

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This paper uses the SBM-GML model to measure and evaluate green total factor productivity based on the panel data of 30 provinces and cities in China from 2012 to 2018. It examines the impact of different dimensions of financial decentralisation on green total factor productivity. The research results show that: 1) green total factor productivity in China is improved year by year and better in central and western regions; 2) the decentralisation of fiscal revenue and expenditure significantly weakens the increase of green total factor productivity in provincial level; 3) fiscal decentralisation inhibits green total factor productivity in central and western regions with regional heterogeneity; 4) local government competition affects the relationship between fiscal decentralisation and green total factor productivity, weakens the negative effect of fiscal decentralisation on green total factor productivity. Finally, the study aims to promote green total factor productivity and sustainable development from the perspective of financial decentralisation. This paper expands the literature and evidence of financial decentralisation on green total factor productivity and offers suggestions for governments and policymakers working toward sustainable development.

KEYWORDS
financial decentralization, green total factor productivity, sustainable development, local government competition, SBM-GML model

Introduction

Since the tax sharing reform in 1994, the financial relationship between the central and local governments in China has changed substantially, the core of which is economic and political power centralisation. On the one hand, economic decentralisation has mobilised local governments to develop the economy vigorously (Feltenstein and Iwata, 2005) so that local governments have more substantial economic decision-making power than other countries. It led to the "Chinese miracle" of sustained rapid growth (Lu et al., 2014; Weingast, 2014; Sun et al., 2017). On the other hand, the central government has greater power in local officials' promotion, and the assessment of economic indicators such as GDP growth triggers the short-sighted local governments to pursue GDP growth blindly and ignore green development (You, 2011; Cheng et al., 2013; Chen et al., 2017), leading to environmental problems such as air pollution. To certain extent, financial decentralisation plays a crucial role in sustainable development (Yuan et al., 2015; Kuai et al., 2019).

Regarding revenue decentralisation, local governments mainly obtain financial revenue from the public budget, tax and non-tax income (Arkin and Slastnikov, 2007; Han and Kung, 2015; He, 2015). In expenditure decentralisation, local governments allocate financial resources through investment in infrastructure construction (Jia et al., 2014; Tang et al., 2019). Thus, expenditure decentralisation restricts green and sustainable development. In recent years, China's central government has established a green total factor productivity-oriented mechanism, requiring local governments to pursue high-quality and sustainable development, and has made remarkable achievements in the green industrial development along the Yangtze River Economic Belt (Chu et al., 2019; Li et al., 2021). However, research on the impact of fiscal decentralisation on green total factor productivity in China is scarce from the perspective of income and expenditure decentralisation (Zhang et al., 2017). So, under the Chinese fiscal decentralisation system, what will be the impact of decentralisation of fiscal revenue and expenditure on the green total factor productivity? Is there regional heterogeneity in its impact? What is the corresponding mechanism of action? This paper examines the "green" consequences and influence mechanism of financial decentralisation in a sample of 30 provinces and cities in China from 2012 to 2018.

The possible contributions in this paper are: 1) to study the "financial decentralisation and green total factor productivity relationship" controversy, this study constructs the SBM-GML model that measures green total factor productivity. Regarding fiscal revenue decentralisation, the fiscal expenditure decentralisation dimension system examines the influence of financial decentralisation on green total factor productivity. This study enriches the financial decentralisation and sustainable development in developing countries literature. 2) To further consider the regional heterogeneity, this study divides the eastern, central and western regions to investigate their role and relationship between fiscal decentralisation and green total factor productivity, deepening the understanding of the regional heterogeneity of the "green" consequences under the fiscal decentralisation. 3) To explore the influence path of fiscal decentralisation on green total factor productivity from the perspective of local government competitions.

Literature review

Fiscal decentralisation refers to the central government empowering local governments in debt arrangement, tax management, and budget implementation (Zhang and Zou, 1998). It reflects labour division and financial power transfer between the central and local governments (Labonne, 2013). As the green movement needs financial support, fiscal decentralisation might impact sustainable development (Kuai et al., 2019). The previous financial decentralisation and sustainable development literature can be sorted into two branches. The first branch of literature is about research on the relationship between fiscal decentralisation and environmental protection, and the second is about the impact of fiscal decentralisation on green total factor productivity.

In the first branch of literature, many documents have analysed and examined the influence of financial decentralisation on environmental protection, which is mainly reflected in the concept of service promotion and weakening. On the one hand, the empirical evidence of He (2015), Khan (2020), and Ran et al. (2020) supported the notion that fiscal decentralisation positively impacts environmental protection. He (2015) took the per-capita discharge of "three wastes" (water, gas, and solid) as the environmental pollution measurement index and examined the impact of China's financial decentralisation on environmental pollution at the provincial level. They found that financial decentralisation played a positive role in promoting environmental governance. Khan (2020), based on the Organization for Economic Co-operation and Development (OECD) country data from 1990 to 2018, examined the impact of fiscal decentralisation on sustainable development and found that financial decentralisation and ecological innovation have promoted renewable energy consumption and reduced the use of non-renewable energy. Ran et al. (2020) used the panel data of 30 provinces and cities in China from 2005 to 2016 to study the relationship between environmental decentralisation and carbon emissions and found that environmental decentralisation has a significant governance effect on carbon emissions.

On the other hand, fiscal decentralisation reduces fiscal and environmental protection financial resources, relaxes the supervision of highly polluting enterprises, and negatively impacts environmental quality. West and Wong (1995) showed that financial decentralisation crowded out investment in public services and adversely impacted social welfare. Yang (2016) found that fiscal decentralisation was not always beneficial and affected the green development of the secondary industry. Pan et al. (2020) found that financial decentralisation negatively affected environmental protection in central and western China, despite a weak impact.

In the second branch of literature, scholars focused on the relationship between fiscal decentralisation and green production and efficiency, but they also had contradictory findings. First, fiscal decentralisation may not be conducive to green production and development. Xie et al. (1999) studied the impact of fiscal decentralisation on the United States public expenditure and concluded that financial decentralisation was not conducive to the significant growth of public expenditure and implied a negative impact on green ecological projects. Li et al. (2022) integrated the ecological environment into green total factor productivity and empirically found that green total factor productivity was driven by technical efficiency, and financial decentralisation weakened the improvement of green production efficiency. On the other hand, Song et al. (2018) examined the impact of fiscal decentralisation on green total factor productivity in 11 provinces and cities in the Yangtze River Economic Belt between 2000 and 2015. They concluded that fiscal decentralisation increased green total factor productivity at the provincial level. Third, there were different phrases in financial decentralisation's impact on green behaviour. Elheddad et al. (2020) found a non-linear relationship between fiscal decentralisation and green behaviours such as energy consumption. Finally, to further understand the relationship between fiscal decentralisation and green total factor productivity, Konisky (2010), Hong et al. (2019), and Yang et al. (2020) proposed to analyse the "competition to the end" of local governments.

As an essential aspect of sustainable development, comprehensive discussion about the relationship between fiscal decentralisation and green total factor productivity, the relationship between the two is still controversial, and the research on the influence mechanism is relatively scarce. Based on the previous literature, this study utilised the SBM-GML model to construct a green total factor productivity index and systematically examined the influence of Chinese fiscal decentralisation on green total factor productivity under fiscal revenue and expenditure decentralisation. It also analysed the mechanism of a local government competition to study the relationship between fiscal decentralisation and green total factor productivity.

Measurement models and data

SBM-GML model

Model setting

This study estimates green efficiency (GTFP) by using Data envelopment analysis (DEA). It is a non-parametric technical efficiency analysis method to compare multiple input-output systems (Sueyoshi et al., 2016). DEA method can quantify the results of index data to evaluate the results of production efficiency more objectively (Tyteca, 1996). The output of green total factor productivity mainly includes environmental emissions such as water, gas, and solid, which constitutes unexpected output. On this basis, the SBM model is used to study the relationship between input, production, and pollution problems and better solve the problem of insufficient efficiency evaluation (Tone and Tsutsui, 2010). The Formula 1 shows the SBM model:

$$\begin{aligned} \min \rho &= \frac{1-\frac{1}{m}\sum_{i=1}^{m} S_i^-/x_{ik}}{1+\frac{1}{q1+q2}\left(\sum_{r=1}^{q2} S_r^+/y_{rk}+\sum_{t=1}^{q2} S_t^b/b_{rk}\right)} \\ X\lambda + S^- &= x_k \\ Y\lambda + S^+ &= y_k \\ B\lambda + S^b &= b_k \\ \lambda, S^-, S^+ &\geq 0 \end{aligned} \tag{1}$$

In Formula 1, m represents the number of DMU input elements, q_1 represents the number of classes corresponding to expected output, and q_2 represents the number of types corresponding to an unexpected result. x_{ik} represents the input element of green total factor productivity, y_{rk} represents the expected output element of green total factor productivity, and b_{rk} represents the unexpected output element of green total factor productivity. In contrast, Si^-, Sr^+, and S_t^b represent the slack variables corresponding to information, desired outcome, and surprising result. λ is a constant vector. The greater the efficiency value of the objective function, the higher the efficiency of the DMU.

SBM model is the basis for us to calculate green efficiency. Compared with other models, the SBM model has transitive and global characteristics, which avoids the problem that linear programming has no feasible solution when calculating efficiency (Oh, 2020). Next, this research constructed the Global Malmquist Luenberger (GML) index model. The index of green efficiency is constructed through the GML model, as shown in the formula (2):

$$GML_t^{t+1} = \frac{1+\overline{D_0^G}\left(x^t, y^t, b^t; y^t, -b^t\right)}{1+\overline{D_0^G}\left(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1}\right)} \tag{2}$$

In Formula 2, $\overline{D_0^G}$ represents the global directional distance function, x represents the input element of green total factor productivity, y represents the expected output element of green total factor productivity, and b represents the unexpected output element of green total factor productivity. t is a time variable, t represents the current period, and $t+1$ represents the next period. In addition, the specific input and output factors of green total factor productivity are shown in Table 1.

Variables

Many methods help measure the green total factor productivity of sustainable development: the parameter method (Yao and Li, 2010), DEA-Malmquist (Fare et al., 1997), Shephard-Malmquist (Wang Q. et al., 2019). We used the SBM-GM index to measure the level of green production at China's provincial level. Based on the SBM-GM model, input factor variables and output factor variables are selected, respectively.

TABLE 1 Input and output variables based on the SBM-GML model.

Input factor variables	Output factor variables
Annual number of employees in the region	Real GDP (expected)
Average annual balance of net fixed assets in the region	Wastewater discharge (unexpected)
Total regional energy consumption	Exhaust emissions (unexpected)
	Solid waste emissions (unexpected)

(Source: China Statistical Yearbook and China Environmental Statistical Yearbook).

Li and Lin (2016) suggested that the production input factors of Chinese provinces include labour, capital and energy. Thus, this study chose the annual number of employees in the region, the annual average balance of net fixed assets, and the region's total energy consumption. Concerning output factor variables, in addition to GDP, China's production brought wastewater, gas and solid waste. Adopt the practice of (Wang Y. et al., 2019), the expected output is the actual regional GDP, while the non-expected output is wastewater, gas, and solid waste discharge. Table 1 introduces the input and output variables under the SBM-GML model.

Instrumental variable model (IV model)

Model setting

The IV model, which lags the first explanatory variable, is used to examine the impact of fiscal decentralisation on green sustainable development at the provincial level in China. The IV model needs to select a variable as the instrumental variable of the explanatory variable in the model and estimate the corresponding parameters together with other variables in the model. The model overcomes the errors of missing variables and measurement errors, and the choice of lagging explanatory variables as instrumental variables has specific applicability (Bellemare and Carnes, 2015). Accordingly, Formula 3 constructed the instrumental variable model:

$$GTFP_{i,t} = \beta_0 + \beta_1 Fisde_{i,t-1} + \beta_2 Controllers_{i,t} + Year + Province + \varepsilon_{i,t} \tag{3}$$

Among them, GTFP represents green efficiency, FID represents fiscal decentralisation, Controller represent other control variables affecting green total factor productivity, the year is the annual effect, and the province is the regional effect of 30 provinces and cities in China. ε is a random disturbance term, i represents 30 individual provinces and cities, and t represents time.

Variables

The dependent variable of this study is green efficiency (GTFP): Under the condition of sustainable development, energy, like labour, capital, and other factors, also has the characteristics of scarcity, compensation, and direct participation in production activities, so green total factor productivity considering the input of production factors and the consumption of energy resources can measure the effect of sustainable development. Based on the variable measurement method of Fang et al. (2020), this study adopts the SBM-GML model to evaluate green total factor productivity.

The academic community of financial decentralisation is mainly based on fiscal revenue decentralisation (Lin and Zhou, 2021) and fiscal expenditure decentralisation (Cheng et al., 2019). To avoid the estimation bias caused by a single index measure, this study integrates the financial decentralisation practices, which focuses on the calculation method of Kassouri (2022), and measures the fiscal revenue decentralisation (FIRD) and fiscal expenditure decentralisation (FIED) separately. Following Wang et al. (2020), Qiu et al. (2021), and Zhuo et al. (2022), control variables include economic development level (EDEL), industrial structure (INDS), foreign direct investment (FDI), population density (POD). The independent variable includes fiscal decentralisation (FID), as this study intends to investigate the impact of different financial decentralisation scenarios on green production efficiency.

Economic development level (EDEL): As both the resource consumption situation and the concept of sustainable development will constantly evolve with the change of the economic development stage, the matching green production behaviour will also undergo adaptive adjustment. Per-capita GDP is used as an indicator to measure economic development.

Industrial structure (INDS): In addition to economic development, the industrial structure is another economic factor closely related to green production behaviour. Industrial structure determines the type and intensity of energy consumption and affects green production efficiency. As the "factory of the world," adjusting its industrial structure and eliminating the "three high" (high pollution, high energy consumption, and high emission) industries have become one of the essential means of competition for local governments. We introduce the control variable of industrial structure and use the ratio of the secondary industry's added value to the regional GDP as the calculation method of industrial structure.

Foreign direct investment (FDI): two competitive conclusions can introduce the impact of foreign direct investment on regional green production efficiency. Weakening concept, foreign investment introduced by provinces of developing countries may be the major projects to undertake industrial transfer, dragging the overall green total factor productivity (Wang et al., 2020). The other is to promote a concept; namely, foreign investment may bring advanced production technology and green concept, promote regional green production

TABLE 2 Variable definitions

Variable		Variable symbol	Variable declaration
Dependent variable	Green total factor productivity	GTFP	Green total factor productivity was assessed comprehensively using the SBM-GML model
Independent variable	Fiscal revenue decentralisation	FIRD	Per capita fiscal revenue in regional budget/(per capita fiscal revenue in regional budget + per capita fiscal revenue in central budget)
	Fiscal expenditure decentralisation	FIED	Per capita fiscal expenditure in the regional budget/(per capita fiscal expenditure within the regional budget + per capita fiscal expenditure in the central budget)
Control and regulation variables	Economic development level	EDEL	GDP per capita
	industrial structure	INDS	The added value of the secondary industry/regional GDP
	Foreign direct investment	FDI	Ln (regional actual utilisation of foreign direct investment)
	Population density	POD	Ln (number of regional permanent resident population/area of urban administrative division)
	Local government competition	LOCP	Total regional import and export volume/regional GDP
	Year	Year	Set the year virtual variable, this year take 1, otherwise take 0
	Provincial variables	Province	Set up virtual variables for the 30 provinces and cities involved in China

(source: China Statistical Yearbook and China Financial Statistical Yearbook).

efficiency improvement (Qiu et al., 2021). The region's utilised foreign direct investment logarithm measures the control variable.

Population density (POD): denser areas are associated with more frequent human and industrial activities, which lead to increased pollutant emissions affecting green total factor productivity (Zhuo et al., 2022). In order to control the potential impact of regional industrial and commercial activities on green total factor productivity, the population density was introduced, and the ratio of the number of permanent residents to the area of urban administrative divisions was expressed in logarithm.

Regulated variable

Local government competition (LOCP): Foreign investment can bring impetus to regional economic growth, so attracting foreign investment has become an essential manifestation of local government competition (Sun and Wang, 2014). In the case of free trade, it may stimulate the competition level of local governments, improve regional trade environment with administrative orders (Fan et al., 2019), and bring about changes in green production efficiency. The adjustment variable is expressed by the proportion of total imports and export to regional GDP. Table 2 is the definitions and descriptions of each variable.

Sample selection and data source

Due to the lack of data in the Tibet Autonomous Region, Hong Kong, Macao, and Taiwan, thus to select 30 provinces and cities in China. At the same time, in June 2019, the Chinese central government officially issued the Regulations on the Central Ecological and Environmental Protection Supervision Work, implementing the ecological and environmental protection supervision system, and setting up a full-time supervision agency. Considering the central government will strengthen ecological and environmental protection supervision after 2018, it may affect the inter-provincial green total factor productivity. In order to eliminate the possible impact of non-financial decentralisation on the green total factor productivity of China's provinces, we choose the research period from 2012 to 2018, with a total of 7 years. The data used in this paper are from the website of the China National Bureau of Statistics, China Statistical Yearbook, China Financial Statistical Yearbook, China Environmental Statistical Yearbook, and other official authorities. A few missing values were interpolated for 210 observations to complement the balanced panel data.

Data analysis

Descriptive statistics

Table 3 shows the descriptive statistics of the main variables. The mean GTFP of the green total factor productivity of the dependent variable is 1.027, the minimum value is 0.716, and the maximum value is 1.628, indicating some differences in the sustainable development performance among the 30 provinces and cities in China. In addition, Table 4 gives the data description of input and output variables of green total factor productivity, and the results based on measurement software are shown in Table 5. According to the green total factor productivity measurement index of China's provinces from 2012 to 2018,

TABLE 3 Descriptive statistics of the main variables.

Variable	Sample size	Mean value	Standard deviation	Minimum	Maximum
GTFP	210	1.027	0.111	0.716	1.628
FIRD	210	0.517	0.121	0.327	0.835
FIED	210	0.860	0.037	0.793	0.937
EDEL	210	1.608	0.413	0.679	2.641
INDS	210	0.439	0.083	0.186	0.577
FDI	210	3.686	1.793	-2.215	6.016
POD	210	0.489	0.757	0.008	4.182
LOCP	210	0.267	0.297	0.017	1.441

TABLE 4 Input and output variables of green total factor productivity.

Variable type	Variable	Sample size	Mean value	Standard deviation	Minimum	Maximum
Input variables	The annual number of employees in the region (ten thousand people)	210	936.556	798.569	66.537	4585.192
	Average annual balance of net fixed assets in the region (million yuan)	210	17228.053	11474.002	1883.422	55202.720
	Total regional energy consumption (ten thousand tons)	210	14922.178	8822.078	1687.980	40581.000
Output variables	Real GDP (million yuan)	210	24535.848	18925.084	1893.540	97277.770
	Wastewater discharge (ten thousand tons)	210	235141.344	183574.296	21953.030	938261.100
	Exhaust emissions (ten thousand tons)	210	150.523	101.203	9.533	450.005
	Solid waste emissions (ten thousand tons)	210	22194.367	18682.985	697.675	91684.590

most of the green total factor productivity is higher than 1, the overall performance is improved year by year, and the eastern region is better than the central and western regions.

Among the independent variables of financial decentralisation, the average FIRD is 0.517, and the standard deviation is 0.121, indicating a certain amount of fiscal revenue decentralisation in the 30 provinces and cities in China. The other independent variable, FIED decentralisation, is 0.860, with a minimum value of 0.793 and a maximum value of 0.937, indicating the different characteristics of fiscal expenditure decentralisation in the sample. Regarding control variables, the average economic development level (EDEL) and the industrial structure (INDS) of the 30 provinces and cities were 1.608 and 0.439 each, indicating that the sample region has a specific scale of per-capita GDP and the added value contribution of the secondary industry. The average FDI and POD are 3.686 and 0.489, respectively, which have the economic implication of foreign investment with a certain proportion and the economic implication of a large overall population density. As a regulatory variable, the average LOCP is 0.267, and the standard deviation is 0.297, showing the reality that different local governments have competition. In general, the descriptive statistical results are consistent with the financial and development reality at the provincial level in China. Finally, before the standard regression, we also did the variable correlation coefficient analysis, which showed that most variables' correlation coefficient was less than 0.5, the variance expansion factor was less than 10, and no obvious collinearity problem was observed.

Benchmark test and heterogeneity analysis

Based on the model (3), the whole-sample benchmark regression and heterogeneous regression analysis were performed, and the results are shown in Table 6. Column (1) ~ (2) examines the impact of fiscal revenue and expenditure decentralisation on green total factor productivity in 30 provinces and cities in China, and columns (3) ~ (6) examines the role of fiscal decentralisation on green total factor productivity from the perspective of regional heterogeneity. From the regression results, columns (1) and (2) suggest that the decentralisation of fiscal revenue and fiscal expenditure that constitute the two dimensions of financial decentralisation is significantly negative, indicating that both the decentralisation of fiscal revenue and fiscal expenditure generally suppresses green total factor

TABLE 5 China provincial green total factor productivity (GTFP) in 2012–2018.

Province	2012	2013	2014	2015	2016	2017	2018	Mean
An Hui	1.202	0.985	0.999	0.985	0.969	1.052	1.052	1.035
Bei Jing	1.316	1.039	1.068	1.030	1.040	1.144	1.259	1.128
Fu Jian	0.873	0.999	1.006	0.975	0.989	1.087	1.194	1.018
Gan Su	1.129	0.958	0.968	0.955	0.914	1.002	1.013	0.991
Guang Dong	0.844	0.950	1.053	0.899	0.808	1.136	1.212	0.986
Guang Xi	1.212	0.974	1.003	0.979	0.980	1.029	0.948	1.018
Gui Zhou	1.113	0.979	1.019	0.966	0.994	1.017	1.013	1.014
Hai Nan	0.802	0.923	1.250	0.763	1.056	1.145	1.083	1.003
He Bei	1.204	0.957	0.980	0.977	0.953	1.080	1.084	1.034
He Nan	1.215	1.009	1.054	1.023	1.004	1.121	1.149	1.082
Heilong Jiang	1.001	0.945	0.974	0.982	0.966	0.980	1.006	0.979
Hu Bei	1.246	0.989	1.025	0.991	1.031	1.146	1.125	1.079
Hu Nan	1.144	0.980	1.021	0.987	1.002	1.096	1.092	1.046
Ji Lin	0.821	1.017	1.034	0.990	0.973	1.070	0.951	0.979
Jiang Su	1.370	1.064	1.094	1.075	1.056	1.162	1.279	1.157
Jiang Xi	1.193	0.993	1.001	0.988	0.969	1.031	1.040	1.031
Liao Ning	0.716	1.001	1.020	0.994	1.008	0.820	0.932	0.927
Inner Mongolia	0.754	0.989	0.966	0.939	0.970	0.992	0.887	0.928
Ning Xia	1.106	1.009	0.980	0.968	0.988	1.031	1.072	1.022
Qing Hai	1.142	1.000	1.000	1.000	0.943	1.060	1.000	1.021
Shan Dong	1.120	1.042	1.105	1.033	1.002	1.088	1.114	1.072
Shan Xi (Jin)	1.084	0.927	0.920	0.912	0.927	0.966	1.172	0.987
Shan Xi (Shan)	0.902	1.002	1.012	0.973	0.924	1.014	1.053	0.983
Shang Hai	0.826	1.014	1.049	1.007	1.032	1.163	1.370	1.066
Si chuan	1.306	1.010	1.013	0.988	1.011	1.087	1.153	1.081
Tian jin	1.259	0.962	1.027	0.991	0.982	1.137	1.628	1.141
Xin jiang	1.107	0.938	0.935	0.953	0.903	0.962	1.020	0.974
Yun nan	0.831	1.000	1.024	0.968	0.968	0.981	1.017	0.970
Zhe jiang	0.964	1.039	1.066	1.040	1.036	1.163	1.168	1.068
Chong Qing	0.802	1.012	1.048	1.007	1.009	1.016	1.029	0.989
Mean	1.053	0.990	1.024	0.978	0.980	1.059	1.104	1.027

productivity. The heterogeneity regression of the sub-samples shows that, only the estimated coefficient of column (4), column (6), fiscal revenue decentralisation FIRD(-1) and fiscal expenditure decentralisation FIED(-1) was significantly negative, with-1.155 and-2.898 each. The estimated coefficients of columns (3) and columns (5) are negative but insignificant. The above shows a regional heterogeneity in the influence of fiscal revenue and expenditure decentralisation on green total factor productivity in 30 provinces and cities in China, and it is more evident in the central and western regions.

In fact, under China's rapid economic development and fiscal decentralisation system arrangement, local governments in central and western provinces often earn less revenue than expenditure, which quickly leads to local governments paying excessive attention to economic development (Tranter, 2011), which harms green total factor productivity. In addition, compared with eastern China, the Midwest province's overall economy is underdeveloped, sustainable development consciousness is relatively weaker, and local government fiscal spending is more inclined to choose immediate economic benefits projects (Song et al., 2020). Deficiencies in green production advocacy and supervision make the Midwest in the sub-sample regression of fiscal revenue and expenditure decentralisation of green total factor productivity inhibition more significant.

Mechanism test results and analysis

As China's economy transforms and upgrades to high-quality development, the central government increases the assessment and supervision and constraints on the green

TABLE 6 Results of benchmark regression and heterogeneity regression.

Variable name	Full sample		Sub-sample			
	GTFP in 30 provinces		East GTFP	Midwest GTFP	East GTFP	Midwest GTFP
	(1)	(2)	(3)	(4)	(5)	(6)
FIRD (-1)	-0.334* (-1.89)		-0.687 (-0.55)	-1.155** (-2.57)		
FIED (-1)		-0.942*** (-2.60)			0.398 (0.15)	-2.898** (-2.00)
EDEL	0.132** (2.31)	0.115*** (2.62)	0.707 (1.34)	0.284* (1.70)	0.564 (1.13)	0.275 (1.60)
INDS	-0.085 (-0.66)	-0.072 (-0.62)	-3.729** (-2.04)	0.041 (0.09)	-3.574 (-1.97)	-0.100 (-0.23)
FDI	-0.000 (-0.01)	-0.012 (-1.59)	-0.058 (-1.28)	-0.005 (-0.29)	-0.069 (-1.51)	-0.008 (-0.49)
POD	0.024 (1.10)	0.022 (1.17)	-0.751 (-0.70)	-1.034 (-0.32)	-0.604 (-0.57)	-3.060 (-0.94)
Constant	1.069*** (12.34)	1.770*** (5.99)	2.231 (1.13)	1.264*** (5.58)	1.466 (0.50)	3.550*** (2.92)
Year	control	Control	control	control	control	control
Province	control	Control	control	control	control	control
Observations	210	210	70	140	70	140
Adj R-squared	0.242	0.254	0.431	0.262	0.428	0.245

Note: (1) * * *, * * and * indicate significance levels of 1, 5 and 10%, respectively, the same below; (2) all in brackets are the two-tailed T values after cluster processing of provincial level standard robust error, the same below; (3) eastern sub-samples include Hebei, Beijing, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Fujian, Hainan, and other provinces and cities are divided into Midwest sub-samples.

development of local governments. Since 2012, the central government has released the "12th Five-year" comprehensive work plan for energy conservation and emission reduction. Energy Conservation and Emissions Reduction Comprehensive Work Plan Energy Conservation and Emissions Reduction Comprehensive Work Plan put environmental protection and green development as the critical assessment criteria of local officials' promotion, which may even be a "one vote veto". Local governments will strengthen the environmental protection and green development (Pan et al., 2020) and not just focus on GDP growth. In addition, at another level of local government competition, investment attraction is also one of the critical assessment tasks that local governments need to accomplish. In the context of the diminishing margin of financial support in recent years, an excellent ecological environment and sustainable production are all necessary means to attract high-level foreign investment while accelerating the competition of local governments in creating a green production atmosphere and encouraging green development behaviour (Yang et al., 2020). Thus, local government competition weakens the negative effect of fiscal decentralisation on green total factor productivity.

Based on the model (3), this paper include the regulatory variable of local government competition LOCP. It examines the potential role of local government competition in the relationship between fiscal decentralisation and green total factor productivity through FIRD (-1) * LOCP and FIED (-1) * LOCP transfer items. It shows that the local government competition regulation has improved the adverse effect of fiscal revenue decentralisation on green total factor productivity. In the mechanistic test results presented in Table 7 Column (1), the influence of FIRD (-1) on green total factor productivity GTFP is significantly negative. However, with local competition LOCP as the adjustment variable, after the FIRD (-1) * LOCP of local government competition is introduced in the regression equation, the estimated coefficient is positive at 1%.

Similarly, column (2) FIED (-1) * LOCP, after introducing fiscal expenditure decentralisation to compete with local

TABLE 7 Results of mechanism testing.

Variable name	GTFP	
	(1)	(2)
FIRD (-1)	-0.423* (-1.88)	
FIED (-1)		-1.441*** (-3.41)
LOCP	-0.501*** (-3.51)	-1.425* (-1.81)
FIRD (-1)*LOCP	0.900*** (4.20)	
FIED (-1)*LOCP		1.568* (1.69)
EDEL	0.111* (1.74)	0.154*** (3.14)
INDS	0.131 (0.72)	-0.044 (-0.41)
FDI	0.007 (1.75)	-0.015* (-1.94)
POD	-0.074** (-2.29)	0.010 (0.52)
Constant	1.056*** (9.82)	2.162*** (6.30)
Year	Control	control
Province	Control	control
Observations	210	210
Adj R-squared	0.360	0.274

 10.3389/fenvs.2022.989194

TABLE 8 Results of robustness testing.

Variable name	GTFP	
	Fixed effect model regression	Random effect model regression
	(1)	(2)
FIFD	-1.368*** (-3.30)	-0.416*** (-2.70)
EDEL	0.244*** (3.46)	0.152*** (3.74)
INDS	0.669** (2.36)	0.028 (0.23)
FDI	-0.034* (-1.84)	-0.003 (-0.41)
POD	0.805 (1.20)	0.031* (1.75)
Constant	0.890** (2.44)	1.014*** (12.44)
Year	Control	uncontrolled
Province	Control	uncontrolled
Observations	210	210
Adj R-squared	0.364	0.109

governments, has an estimated coefficient of 1.568 and is significant at 10%. It shows that the local government competition improves the relationship between fiscal expenditure decentralisation and green total factor productivity. To sum up, local government competition weakens the negative role of fiscal decentralisation on green total factor productivity.

Robustness test

The robustness test is a series of tests to investigate and evaluate the reliability of conclusions, and its purpose is to ensure that the research conclusions do not change with alternative indicators and model transformation (Ajmi et al., 2015). In order to ensure the reliability of the above conclusions, we also conducted a series of robustness tests from the perspective of variables and model robustness. First, change the variable. Cheng et al. (2021) measure financial decentralisation from the perspective of financial freedom, with the degree of financial freedom (FIFD) of revenue and expenditure decentralisation as the core independent variable, and the provincial fiscal revenue divided by the provincial financial expenditure is used to measure the regression, and the conclusion is unchanged. Secondly, change the model and regress again. In order to avoid possible estimation bias in the model setting, we refer to the practice of Qian et al. (2019) and regress based on the fixed effect model and random effect model, respectively. As shown in Table 8, no matter whether the fixed effect model or the random effect model is used, the core conclusions of this paper have not changed fundamentally.

Discussion

Implications to theory

"High growth and high pollution" in developing countries have caused substantial waste of resources and environmental pollution, motivating these countries to implement sustainable development solutions in recent years. Likewise, green total factor productivity factors have aroused scholars' interest. Some studies shed light on environmental regulation, foreign direct investment, technological progress, etc., but they ignore the impact of fiscal decentralisation on green total factor productivity. This paper uses China as an example to study the relationship between fiscal decentralisation and green productivity and its impact by using SBM-GML and IV Model. This study not only improves the traditional DEA model, but also adopts the SBM-GML model with more transitive and global characteristics to measure green total factor productivity. Moreover, the empirical results enrich the literature on whether and how fiscal decentralization affects sustainable development in developing countries, and help scholars understand the "black box" of fiscal decentralization and green total factor productivity from the perspective of regional heterogeneity and local government competition.

Implications to policy

According to the green efficiency results in Chinese provinces from 2012 to 2018, the eastern region is better than the central and western regions, meaning better economic development might lead to higher green efficiency. While policy makers may consider environmental protection outcomes from pollutants such as CO and NOx, they seldom consider the issues from the input-output analysis. This study offers them alternative views on these issues when they review the effectiveness of environmental policies. The results can also be generalised to other policy issues as most policy makers simply consider the output (outcomes) but ignore the inputs when implementing different policies. Besides, the study results imply that win-win economic and environmental development co-exists when we perceive the environmental issues from green efficiency perspectives.

Good economic development is a crucial factor in achieving environmental friendly outcomes. Given the unbalance green efficiency in China with better performance in wealthier parts of China, it informs policy makers in China that apart from spending money on controlling environmentally friendly facilities, they should also spare extra efforts on research and development. Adopting clean energy require a lot of financial resources to a certain extent. Technology like hydrogen used for buses at present, for example, requires research grants for many years. Thus, public finance and expenditures for achieving co-economic and environmental developments require government officials' wisdom.

Limitations and future research directions

Similar to previous research, this paper has some limitations, which need further study in the future. First, this paper takes wastewater discharge, exhaust emission and solid waste discharge as output variables. Given that many different types of water and air pollutants are undesired outputs, future research might consider these. Second, we focus on the relationship and the mechanism between fiscal decentralisation and green productivity in China. The scope can be expanded to other countries in the future based on worldwide data. Since data transparency is one of the global smart cities' movements, big data analysis and data that covers a more extended period may be another future direction. Finally, other models like system dynamics (Mao et al., 2015) might be used to study how changes in some of these factors affect green efficiency. New forecasting and machine learning models (Li et al., 2018) can be used to forecast the changes, bringing practical ideas to policy makers and governments.

Conclusion and discussion

The study found that: 1) the overall green total factor productivity has improved year by year and the eastern region is better than the central and western regions. 2) the overall financial decentralisation has significantly weakened the green total factor productivity increase. 3) From the two dimensions of fiscal revenue decentralisation and fiscal expenditure decentralisation. Detailed investigation of the impact of fiscal decentralisation on sustainable development. 4) From the perspective of regional heterogeneity, we find that the inhibitory influence of fiscal decentralisation on green total factor productivity is more evident in the central and western regions. 5) Taking local government competition as the potential mechanism between fiscal decentralisation and green total factor productivity, the local government competition weakens the negative effect of fiscal decentralisation on green total factor productivity.

The study's conclusion is helpful to enrich the discussion of "the relationship between fiscal decentralisation and green total factor productivity" and provide ideas for China to reform fiscal decentralisation and the development of green science. The policy recommendations in this paper are: 1) Continue to promote the reform of the fiscal decentralisation system. In the existing Chinese-style financial decentralisation, the local government's financial and administrative power is fully matched, which is one of the main reasons financial decentralisation shows an inhibitory effect on green total factor productivity. In the future, the reform of the financial decentralisation system should be further strengthened, and clarify the role between the central and local governments. At the same time, the financial power relationship between the governments below the provincial government deepens the implementation of the concept of green development, strengthens the authority of project approval and financial funds, and promotes the improvement of green total factor productivity; 2) Pay attention to regional heterogeneity, and give full play to the role of fiscal decentralisation in sustainable development according to local conditions. The relatively developed economy of eastern China has considerable financial power and little room for sustainable development and green total factor productivity improvement. The central and western regions are in the process of rapid transformation. It is essential to improve the green sustainable development level and further increase green production, environmental protection supervision, and management personnel. Appropriate restrain and standardise local governments' behaviour and power use, establish and perfect the green production management system; 3) Improve local government and officials' assessment mechanism, and entirely abandon local officials' improper decision-making behaviour "only GDP theory." It is necessary to strengthen the weight of environmental governance and green development governance in the promotion criteria of local officials, increase the incentives of local governments, deepen the level of local government competition, and actively promote the positive regulatory effect of local government competition to enhance the green total factor productivity.

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

XZ: Original writing, Editing and Revise paper. RL: Original writing, Editing and Revise paper, Data curation. XL: Data collection. FH: Editing and Revise paper. MW: Data analysis. YQ: Data analysis. JX: Data collection. WL: Language editing and proof.

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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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Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.989194/full#supplementary-material

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Spatiotemporal impact of the COVID-19 pandemic lockdown on air quality pattern in Nanjing, China

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In response to the COVID-19 outbreak, severe steps have been taken to control its rapid spread by countries globally. A nationwide lockdown was executed at the end of January 2020 in China, which resulted in a significant change and an improvement in air quality patterns. In this study, the objectives were to assess the spatiotemporal impact of the COVID-19 lockdown on air quality in Nanjing, China. The present study researched the six air pollutant parameters, namely, PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3. The data were divided into six periods, P1–P3: pre-lockdown, during lockdown, and after lockdown periods, P4–P6: 2017–19 (same dates of lockdown). The results reveal that during the COVID-19 control period, a significant drop and an improvement in air quality were observed. According to our findings, the PM_{10}, $PM_{2.5}$, SO_2, NO_2, and CO concentrations were reduced by -33.03%, -35.41%, -21.26%, -39.79%, and -20.65%, respectively, while the concentration of O_3 significantly increased by an average of 104.85% in Nanjing. From the previous 3 years to lockdown variations, PM_{10} (-40.60%), $PM_{2.5}$ (-40.02%), SO_2 (-54.19%), NO_2 (-33.60%), and CO (23.16%) were also reduced, while O_3 increased (10.83%). Moreover, compared with those in the COVID-19 period, the levels of PM_{10}, SO_2, NO_2, CO, and O_3 increased by 2.84%, 28.55%, 4.68%, 16.44%, and 37.36%, respectively, while $PM_{2.5}$ reduced by up to -14.34% after the lockdown in Nanjing. The outcomes of our study provide a roadmap for the scientific community and local administration to make policies to control air pollution.

KEYWORDS
COVID-19, lockdown, air quality, air pollution, Nanjing

1 Introduction

A novel disease later named coronavirus disease 2019 (COVID-19) was first identified at the end of 2019, in Wuhan, China. Due to this contagious disease, a health emergency had been declared by the World Health Organization all around the world (World Health Organization 2020). More than 210 countries had been affected by COVID-19 within 6 months (Wang C et al., 2020). According to a report, about 18,354,342 were affected by the COVID-19 pandemic on 5 August 2020 (World Health Organization 2020). To control the rapid spread of this virus, forced restrictions and control measures were implemented by many countries and nations (McMahon 2020). In this scenario, the air quality significantly improved during the lockdown time. For instance, during the COVID-19 pandemic lockdown period, a sharp drop in air pollution was noticed in several areas and regions all around the world shown by satellite images (Holcombe and O'Key 2020). The lockdown is vital to the public health response to COVID-19, and it has also brought unexpected benefits for the environment (Abdullah et al., 2020; Bhatti et al., 2022a).

Many studies reported that due to these restrictions, a remarkable reduction was found in the concentrations of almost all air pollutants around the globe (Bao and Zhang 2020; Li at al., 2020; Zambrano-Monserrate and Ruano 2020). For instance, according to Berman and Ebisu's study (2020), due to the COVID-19 pandemic lockdown, a significant decline was reported in the concentration of $PM_{2.5}$ (11%) and NO_2 (26%) in the United States. Shakoor et al. (2020) reported that during the COVID-19 pandemic lockdown, the concentrations of CO, NO_2, and $PM_{2.5}$ were decreased by 19%, 37%, and 1.1%, respectively, in the United States. Their results demonstrate that the concentrations of CO, NO_2, SO_2, $PM_{2.5}$, and PM_{10} were decreased by 27%, 39%, 18%, 18%, and 38%, respectively, in China. Another study illustrates that in India and China, the lockdown measures brought positive impacts and decrease in $PM_{2.5}$ and NO_2 concentrations, to be reduced by an average of 65%, 66%, and 45%, 37%, respectively (Agarwal et al., 2020). Meanwhile, it is evident by the study of Sharma et al. (2020) that during the COVID-19 pandemic lockdown period, due to shut down and strict restrictions, an improvement in air quality levels was observed. Their results indicate that during the lockdown period, the concentrations of PM_{10}, $PM_{2.5}$, NO_2, and SO_2 decreased by 24–44%, 23–58%, 30–64%, and 35–70%, respectively. According to Zambrano-Monserrate et al. (2020) just after the execution of lockdown, the concentrations of $PM_{2.5}$ and NO_2 were significantly reduced. Another study identified the reduction in pollutant emissions along the Yangtze River Delta using satellite and observed data. The study finds that the water-soluble ions (WSI) were decreased during lockdown and pollutant levels also followed a reduction during the lockdown period (Wang et al., 2021a; Wang et al., 2021b). A similar study is carried out to observe the change of urbanization during COVID-19, and it was observed that pollutant levels in larger cities are more than that in smaller cities (Shen L et al., 2021). Air pollution results in Brescia also show a similar decrease in air pollutants due to lockdown restrictions. A study shows that despite the reduction in emission sources during the lockdown period, which allowed to reach a significant reduction of NOx emissions, the PM levels did not have a similar trend if the annual (not the mean in 3 years) decrease of PM is considered (Bontempi et al., 2022).

To prevent the large-scale spread of the COVID-19 pandemic, China was the first country to carry out a nationwide lockdown to shut down all essential activities such as transportation, educational institutions, markets, and commercial and industrial activities at the end of January 2020 (Tian et al., 2020; Wang Y et al., 2020). Many researchers found that during this period, China found a new pattern of air quality (Chu et al., 2020; Xu et al., 2020; Zheng et al., 2020). Compared to 2017–19, in 366 urban areas and territories across China, the concentrations of particulate matter with an aerodynamic diameter of <10 and 2.5 μm, SO_2, NO_2, and CO were decreased, while the concentrations of O_3 increased (Chen et al., 2020). Due to the reduced economic activities and energy consumption in China during the COVID-19 pandemic, NO_2 concentration was significantly reduced, as reported by NASA (NASA 2020). Meanwhile, concentrations of PM_{10}, $PM_{2.5}$, and NO_2 also decreased during the lockdown period, while those of SO_2 and O_3 increased in Hangzhou, China. During the COVID-19 pandemic lockdown in northern China, reduced economic, social, and industrial activities resulted in substantial improvement in air quality (Wang L et al., 2020).

Our study assessed the six air pollutant parameters (PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3) in Nanjing, using daily average data obtained from nine monitoring sites. During the COVID-19 pandemic, our study determined the impact of lockdown and discovered new findings and substantial changes in the selected air pollutant parameters. Compared with a number of studies related to COVID-19, our study provides better results with a new pattern (Agarwal et al., 2020; Anil and Alagha, 2020; Islam et al., 2020; Kumar et al., 2020; Singh and Chauhan 2020; Aamir et al,. 2021; Borhani et al., 2021; El-Sheekh and Hassan 2021; Shen N et al., 2021). The objective of the current study was to 1) evaluate the spatiotemporal impact of the COVID-19 lockdown measures on air quality in different time periods, 2) determine the variation, and 3) find out the air pollutant concentrations from the previous 3 years to the lockdown period. The study provides valuable materials and new findings for the scholars and local bodies to make policies to improve and control air pollution.

The remainder of the article is organized as follows: section 2 presents the study area, air quality data, study period, data analysis, and the model. Section 3 presents the results and discussion. Section 4 discusses the conclusions.

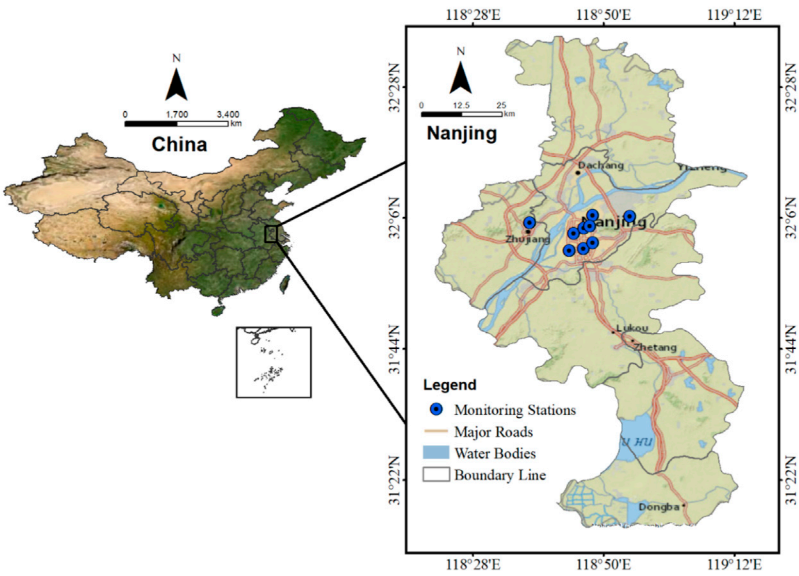

FIGURE 1
Geographical location and the air pollution monitoring sites in Nanjing.

2 Materials and methods

2.1 Study area

Nanjing, the capital of Jiangsu Province, is one of the most economic hubs of the Yangtze River Delta (YRD) with a large population and well-developed industrial and manufacturing zones. Due to rapid development in different sectors, the city has been facing extreme air pollution in recent years (Zu et al., 2017). Nanjing lies between latitude 31°14′ and 32°37′ and longitude 118°22′ and 119°14′ with 11 districts that can be divided into three regions, urban, rural, and suburban, covering an area of 6596 km^2. With a density of 8500 people/km^2, the population of Nanjing was approximately 8.34 million according to 2019. The city has four distinct seasons having a subtropical monsoon climate (Nanjing Municipal Government 2018). The main and vital industries in Nanjing are automobile, electronics, steel smelting, and petrochemical.

Presently, a total of nine monitoring stations are working to monitor and record air pollutant concentrations in Nanjing, and their locations are shown in Figure 1.

2.2 Air quality data and study period

To assess the impact of nationwide lockdown on air pollution, daily average concentrations of the six air pollutants, namely, PM_{10} (particulate matter with diameters of ≤10 μm), $PM_{2.5}$ (particulate matter with diameters of ≤2.5 μm), SO_2 (sulfur dioxide), NO_2 (nitrogen dioxide), CO (carbon monoxide), and O_3 (ozone) were collected from the Nanjing Environmental Monitoring Centre. A total of nine monitoring stations are working to collect and record air pollutant concentrations in Nanjing. According to the Technical Regulation for Selection of Ambient Air Quality Monitoring Stations of China, these nine monitoring stations belong to different areas that are Xianlin, Pukou, Xuanwuhu, Ruijinlu, Caochangmen, Maigaoqiao, Zhonghuamen, Shanxilu, and Aotizhongxin. In our study, the data were divided into six periods, pre-lockdown: 11 November 2019 to 24 January 2020 (75 days), lockdown period: 25 January 2020 to 8 April 2020 (75 days), post-lockdown: 9 April 2020 to 22 June 2020 (75 days), P4–P6: same dates of lockdown in 2017, 2018, and 2019.

2.3 Data analysis

In this study, summary statistics were calculated during the study period for different variables. This study investigates variations in concentrations of air pollutants in multiple periods as described in the abovementioned lines. In our analysis, the net difference and percentage change were also examined. Box plots were generated to represent the concentrations of these pollutants during the study period. In addition, during the lockdown period, to investigate the relationships between the air pollutants, linear regression analysis was performed.

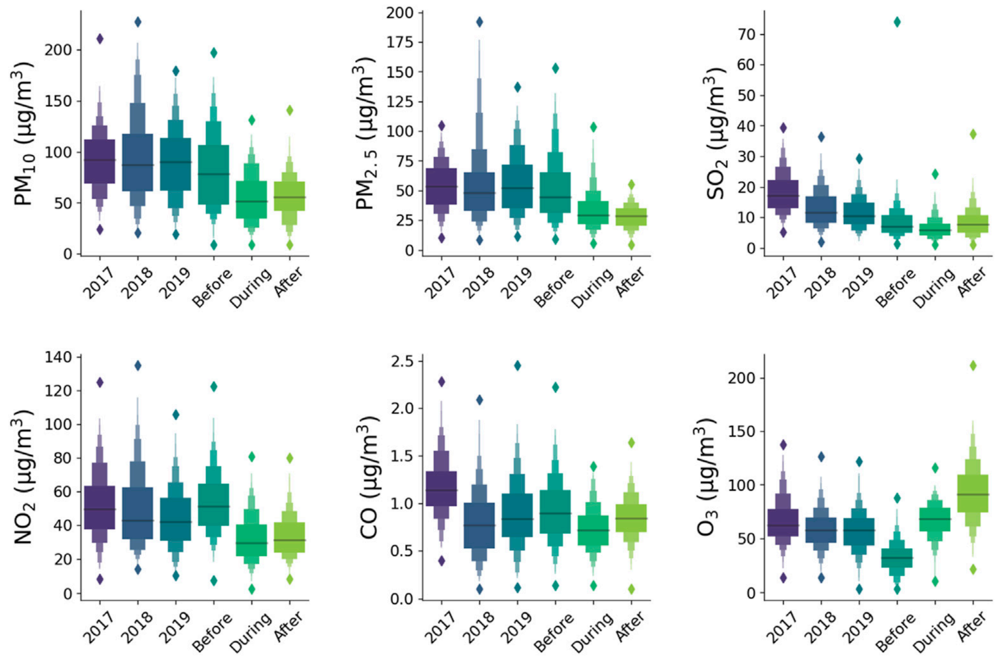

FIGURE 2
Daily average concentrations of PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3 during the all-study periods in Nanjing.

2.4 HYSPLIT model

The backward trajectories were calculated to study the transport pathways of air mass reaching Nanjing using the NOAA HYSPLIT model (https://ready.arl.noaa.gov/HYSPLIT.php). The model is widely used in atmospheric research and pollution process analysis. The backward trajectories were plotted to identify the sources of air mass in the three periods, pre-LD, active-LD, and post-LD in Nanjing. These trajectories were analyzed for 72 h, starting every 6 h each day. Stein et al. (2015) discussed the details of the HYSPLIT model.

3 Results and discussion

3.1 Understanding the pattern of particulate matter

Due to the large-scale spread of the COVID-19 pandemic, the Government of the People's Republic of China imposed a lockdown in late January 2020. Consequently, pollution levels during the lockdown period across the country have significantly reduced. According to many studies, a sudden decrease in pollutant concentrations was observed all around the world (Abdullah et al., 2020; Bao and Zhang 2020; Li et al., 2020; Zambrano-Monserrate and Ruano 2020; Bhatti et al., 2022b). The concentration patterns of particulate matter and variations are shown in Figure 2 and Tables 1, 2, 3. Our results demonstrate that compared to the pre-lockdown period, a notable reduction in the concentrations of particulate matter was observed in Nanjing, China. According to the obtained results, the concentrations of PM_{10} and $PM_{2.5}$ reduced by −33.03% and −35.41%, respectively, during the COVID-19 lockdown period in Nanjing. According to the study by Shakoor et al. (2020), an approximately 38 and 18% reduction in the concentrations of PM_{10} and $PM_{2.5}$ were recorded, respectively, during the lockdown period in China. Another study stated by Berman and Ebisu (2020) revealed that during the COVID-19 pandemic lockdown period in the United States, there was a decline in $PM_{2.5}$ concentration (11%). In urban areas and regional areas, road dust, transportation, and industrial and construction activities are the main and important sources of particulate matter. The reduction in these sources caused a massive decrease in the concentrations of particulate matter in many areas during the COVID-19 pandemic lockdown (Mor et al., 2021). In addition, the study showed that the concentrations of PM_{10} and $PM_{2.5}$ decreased by -15.50% and -32.77%, respectively, from pre- to post-periods in Nanjing. In these findings, the reduction in the concentration of $PM_{2.5}$ was higher than that of PM_{10}.

Our results demonstrate that in comparison to last year (2019), PM_{10} and $PM_{2.5}$ concentrations showed decreasing trends, reduced by an average of -39.23% and -41.10%,

TABLE 1 Daily average concentration and variation of pollutants in different time periods in Nanjing.

Pollutants	Before lockdown	During lockdown	Avg. before and during lockdown	After lockdown	Variation (during and before lockdown)		Variation (after lockdown and avg. of before and during lockdown)	
					Net	%	Net	%
PM_{10} Max	197.33	131.57	164.45	140.64	−65.76	−33.32	−23.81	−14.48
Min	81.5	54.58	68.04	56.13	−26.92	−33.03	−11.91	−17.50
Avg	9.1	8.77	8.94	9.29	−0.33	−3.63	0.355	3.97
$PM_{2.5}$ Max	153.29	103.56	128.43	54.95	−49.73	−32.44	−73.48	−57.21
Min	50.97	32.92	41.95	28.2	−18.05	−35.41	−13.75	−32.77
Avg	8.9	5.52	7.21	4.14	−3.38	−37.98	−3.07	−42.58
SO_2 Max	74	24.27	49.14	37.32	−49.73	−67.20	−11.82	−24.05
Min	8.23	6.48	7.36	8.33	−1.75	−21.26	0.98	13.26
Avg	1.3	1.13	1.22	1.04	−0.17	−13.08	−0.175	−14.40
NO_2 Max	122.26	80.86	101.56	80	−41.4	−33.86	−21.56	−21.23
Min	53.25	32.06	42.66	33.56	−21.19	−39.79	−9.10	−21.32
Avg	7.58	2.42	5	8.46	−5.16	−68.07	3.46	69.20
CO Max	2.23	1.39	1.81	1.64	−0.84	−37.67	−0.17	−9.39
Min	0.92	0.73	0.825	0.85	−0.19	−20.65	0.03	3.03
Avg	0.14	0.14	0.14	0.1	0	0.00	−0.04	−28.57
O_3 Max	87.79	115.71	101.75	211.25	27.92	31.80	109.50	107.62
Min	32.76	67.11	49.935	92.18	34.35	104.85	42.25	84.60
Avg	3.63	10.62	7.125	21.92	6.99	192.56	14.80	207.65

respectively. Compared with the last 3 years (2017–19), Nanjing experienced a high reduction in the concentrations of PM_{10} and $PM_{2.5}$ by −40.60% and −40.02%, respectively. It can be seen that PM_{10} and $PM_{2.5}$ showed similar decreasing trends in this period. A similar pattern was evident by Chen et al. (2020) compared to the corresponding years (2017–19), and the concentrations of particulate matter (PM_{10}, $PM_{2.5}$) showed a diminishing tendency during the COVID-19 pandemic lockdown period in China. Furthermore, Mahato et al. (2020) reported that during the lockdown period, a significant improvement in the particulate matter was recorded as compared to the previous 3 years (2017–19) in megacity Delhi, India. Islam et al. (2020) found that PM_{10} and $PM_{2.5}$ showed a momentous drop from last year (2019) to the lockdown period in Bangladesh. Due to the execution of lockdown in different areas and regions of the world, all essential activities were stopped, such as transportation, construction, and educational, cultural, and industrial activities, which caused a fall in air pollutant levels.

Moreover, compared with the lockdown period, a slight increase in PM_{10} concentration (2.84%) was found, while in contrast, $PM_{2.5}$ showed a decreasing trend (−14.34%) after the lockdown period in Nanjing. Compared with the lockdown period, the increase in PM_{10} concentration can be attributed to the increase in transportation and industrial and construction activities after the lockdown (Mor et al., 2021). In comparison to the preceding 3 years (2017–19), a substantial reduction in PM concentrations was seen after the COVID-19 pandemic lockdown in Nanjing. The results indicate that compared with those in the last 3 years (2017–19), PM_{10} and $PM_{2.5}$ showed decreasing trends, reduced by an average of −38.91% and −48.62%, respectively. We can observe that the reduction ratio in $PM_{2.5}$ concentration is greater than that of PM_{10}. In summary, a drastic drop and an improvement in PM concentration indicate that the COVID-19 pandemic lockdown measures have a considerable impact on changing and improving PM concentration in Nanjing.

3.2 Sulfur dioxide

The results demonstrate that during the lockdown period due to the COVID-19 pandemic, the concentration of SO_2 decreased by −21.26% as compared to that of the pre-lockdown period in Nanjing. The SO_2 concentration pattern is shown in Figure 2, and variations in SO_2 during the study period are presented in Tables 1–3. Coal, diesel, power plants, vehicular traffic, and

TABLE 2 Daily average concentration and variation of pollutants during 2017–20 in Nanjing.

Pollutant	2017	2018	2019	Avg. of 2017–2019	2020	Variation (2020 and 2019)		Variation (2020 and avg. of 2017–19)	
						Net	%	Net	%
PM_{10}									
Max	210.75	227.25	179.25	205.75	131.57	−47.68	−26.60	−74.18	-36.05
Avg	91.84	93.99	89.81	91.88	54.58	−35.23	−39.23	−37.30	-40.60
Min	24	21	19.37	21.46	8.77	−10.6	−54.72	−12.69	-59.13
$PM_{2.5}$									
Max	104.67	192	137.13	144.60	103.56	−33.57	−24.48	−41.04	−28.38
Avg	53.86	54.9	55.89	54.88	32.92	−22.97	−41.10	−21.96	−40.02
Min	10.24	8.4	11.38	10.01	5.52	−5.86	−51.49	-4.49	−44.84
SO_{2z}									
Max	39.5	36.3	29.38	35.06	24.27	−5.11	−17.39	−10.79	−30.78
Avg	18.17	12.9	11.37	14.15	6.48	−4.89	−43.01	−7.67	−54.19
Min	5.33	2	1	2.78	1.13	0.13	13.00	−1.65	−59.30
NO_2									
Max	124.83	134.7	105.79	121.77	80.86	−24.93	−23.57	−40.91	−33.60
Avg	51.53	49	44.33	48.29	32.06	−12.27	−27.68	−16.23	−33.60
Min	8.54	14.3	10.42	11.09	2.42	−8	−76.78	−8.67	−78.17
CO									
Max	2.28	2.09	2.45	2.27	1.39	−1.06	−43.27	−0.88	−38.86
Avg	1.17	0.8	0.88	0.95	0.73	−0.15	−17.05	−0.22	−23.16
Min	0.4	0.1	0.12	0.21	0.14	0.02	16.67	−0.07	−32.26
O_3									
Max	137.71	126.53	121.88	128.71	115.71	−6.17	−5.06	−13.00	−10.10
Avg	66.34	58.46	56.86	60.55	67.11	10.25	18.03	6.56	10.83
Min	13.92	13.85	3.17	10.31	10.62	7.45	235.02	0.31	2.97

industrial and manufacturing activities are the main sources of SO_2 (Lu et al., 2013). During the lockdown period, these types of activities reduced significantly, which resulted in a decline in SO_2 concentration. Shakoor et al. (2020) reported similar findings that the concentration of SO_2 decreased by 18% during the lockdown period, compared to the pre-lockdown period in China. Another study documented by Sharma et al. (2020) witnessed that during the lockdown period, SO_2 showed a declining trend as compared to that in the pre-lockdown period. Additionally, the results indicated that compared with the pre- and during-lockdown periods, the city found an increasing trend in SO_2 concentration (13.26%). Meanwhile, compared with last year (2019) (same dates of lockdown), a significant decreasing trend was observed in SO_2 concentration by approximately −43.01%. According to Wang Y et al. (2020) and Islam et al. (2020), compared to last year (2019), SO_2 concentration has decreased during the lockdown period in China and Bangladesh. Mahato et al. (2020) also found similar results that in comparison to the last year, SO_2 concentration was reduced during the said time period in Delhi, India.

The current study found that in comparison to the previous 3 years (2017–19), SO_2 showed a high decreasing trend of approximately −54.19% in Nanjing as shown in Table 2. We can observe that in these findings, the reduction spell in the concentration of SO_2 was greater than that of the previous 3 years than last year (2019) in the city. According to Chen et al. (2020), compared to the last 3 years (2017–19), SO_2 concentration has reduced in China. Similar results were reported that compared to the last 3 years during the said time period, SO_2 concentration was decreased in megacity Delhi, India (Mahato et al., 2020). Our results indicate that the concentration of SO_2 increased by 28.55% from the active- to post-lockdown period, while compared with the last 3 years 2019–17 (same time frame of lockdown), the SO_2 concentration showed a declining trend (-41.12%) after the lockdown period in Nanjing (Table 3). Overall, the results revealed that the COVID-19 pandemic lockdown has noteworthy impacts on changing and

TABLE 3 Daily average concentration and variation of pollutants in different time periods in Nanjing.

Pollutant	2017	2018	2019	Avg. of 2017–2019	During lockdown (2020)	After lockdown	Variation (after and during lockdown)		Variation (after lockdown and avg. of 2017–19)	
							Net	%	Net	%
PM_{10}										
Max	210.75	227.25	179.25	205.75	131.57	140.64	9.07	6.89	−65.11	−31.65
Avg	91.84	93.99	89.81	91.88	54.58	56.13	1.55	2.84	−35.75	−38.91
Min	24	21	19.37	21.46	8.77	9.29	0.52	5.93	−12.17	−56.70
$PM_{2.5}$										
Max	104.67	192	137.13	144.60	103.56	54.95	−48.61	−46.94	−89.65	−62.00
Avg	53.86	54.9	55.89	54.88	32.92	28.2	−4.72	−14.34	−26.68	−48.62
Min	10.24	8.4	11.38	10.01	5.52	4.14	−1.38	−25.00	−5.87	−58.63
SO_2										
Max	39.5	36.3	29.38	35.06	24.27	37.32	13.05	53.77	2.26	6.45
Avg	18.17	12.9	11.37	14.15	6.48	8.33	1.85	28.55	−5.82	−41.12
Min	5.33	2	1	2.78	1.13	1.04	−0.09	−7.96	−1.74	−62.55
NO_2										
Max	124.83	134.7	105.79	121.77	80.86	80	−0.86	−1.06	−41.77	−34.30
Avg	51.53	49	44.33	48.29	32.06	33.56	1.5	4.68	−14.73	−30.50
Min	8.54	14.3	10.42	11.09	2.42	8.46	6.04	249.59	−2.63	−23.69
CO										
Max	2.28	2.09	2.45	2.27	1.39	1.64	0.25	17.99	−0.63	−27.86
Avg	1.17	0.8	0.88	0.95	0.73	0.85	0.12	16.44	−0.10	−10.53
Min	0.4	0.1	0.12	0.21	0.14	0.1	−0.04	−28.57	−0.11	−51.61
O_3										
Max	137.71	126.53	121.88	128.71	115.71	211.25	95.54	82.57	82.54	64.13
Avg	66.34	58.46	56.86	60.55	67.11	92.18	25.07	37.36	31.63	52.23
Min	13.92	13.85	3.17	10.31	10.62	21.92	11.3	106.40	11.61	112.54

diminishing SO_2 concentration during the study period in Nanjing.

3.3 Nitrogen dioxide

The NO_2 concentration patterns are shown in Figure 2, and variations in NO_2 are presented in Tables 1–3. Generally, NO_2 is released from vehicular emissions, fossil fuels, natural fires, lightning, and soils (Reddy et al., 2012). The results of our study demonstrate that compared with the lockdown period, a sizeable decline was observed in NO_2 concentration by approximately -39.79 in Nanjing. This reduction in NO_2 concentration could be attributed to the reduced industrial and vehicular emissions during the lockdown period in Nanjing. The most momentous similarity with our results is from the study by Shakoor et al. (2020) that the NO_2 concentration was reduced by −39% during the lockdown period in China. Another study documented by Agarwal et al. (2020) also supported our results that during the COVID-19 control period, NO_2 levels decreased by −37%, in China. According to Bao and Zhang (2020) during the lockdown period, a significant decline was observed in NO_2 concentration in many areas and regions across China. All of these findings support our results that NO_2 concentration was reduced during the lockdown period in Nanjing. In addition, our findings demonstrate that after the lockdown, NO_2 concentration decreased by approximately -21.32% in comparison to the pre- and during-lockdown periods in Nanjing. The reduction ratio in NO_2 was quite lower after the lockdown than during the pre- and during-lockdown periods and during the lockdown in comparison to the pre-lockdown period.

The results indicate that compared with the last year (2019), there was a marked decline in NO_2 concentration, to -27.68%, during the lockdown period, while in comparison to the previous 3 years (2017–19), NO_2 has been reduced by up to -33.60%. Chen et al.

(2020) reported that in comparison to the last year (2019), NO_2 showed a declining trend during the lockdown period in China. Islam et al. (2020) also found that compared to the last year (2019), an approximately 35–45% reduction in NO_2 concentration has been observed in Bangladesh. According to Fu et al. (2020), in comparison to the last 5 years (2015–19), NO_2 concentration was at its lowest level during the lockdown period, and while compared with the last year (2019) measurements, NO_2 was reduced by approximately 34.7% in North China. Another study revealed that compared to the last 3 years (2017–19), NO_2 was reduced significantly during the lockdown period in Delhi (India) (Mahato et al., 2020). Our results demonstrate that compared with the lockdown period, there was a slight increase in NO_2 concentration by 4.68% after lockdown while compared to the last 3 years (2017–19), and NO_2 has been reduced by an average of -30.50% in Nanjing. The increasing spell in NO_2 concentration after lockdown compared with the lockdown period could be attributed to the winter–summer change (Ghosh et al., 2017). In summary, the results show that the COVID-19 pandemic lockdown and forced restrictions have a momentous impact on changing and upgrading Nanjing's air pollution.

3.4 Carbon monoxide

CO is mainly a colorless gas emanated from biofuel burning, vehicular emission, agricultural waste burning, and combustion of fossil fuels (Hasnain et al., 2021). Figure 2 shows the concentration pattern of CO, and variations in CO are presented in Tables 1–3. According to our findings, from pre to during lockdown, CO levels decreased by approximately -20.65% in Nanjing. This reduction in CO concentration can be attributed to the restriction on transportation and industrial activities during the COVID-19 control period. According to Sulaymon et al. (2021), during the lockdown period, the concentration of CO reduced in Wuhan, China. A significant decrease in CO concentration was also observed from pre to active lockdown in Delhi, India (Mahato et al., 2020). Compared with the pre and lockdown periods, CO showed an increasing trend after the lockdown period. The results reveal that the increase in the concentration of CO was 3.03% after the lockdown. This shows that the increase in CO levels was due to regular actions such as transportation and industrial activities after the lockdown.

The results demonstrate that compared with last year (2019), the city experienced a sizeable decline in the levels of CO. During this window of time, the reduction in CO was −17.05% in Nanjing. Islam et al. (2020) reported that during the lockdown phase, CO exhibited a declining trend compared with the previous year in Bangladesh. Moreover, compared with the last 3 years, the concentration of CO decreased a significant level. We found a remarkable change and decrease in CO concentration by up to −23.16% in Nanjing. It can be noted that the declining value in the concentration of CO was higher in the previous 3 years to the COVID-19 control period than in the last 1 year to the COVID-19 period. A study reported by Hasnain et al. (2021) supports our findings, which indicates that from the previous 3 years to the lockdown period, the concentration level of CO has decreased. Furthermore, the concentration of CO showed an increasing trend from the lockdown period to the post-lockdown period, which increased by approximately 16.44%. Compared with the previous 3 years, CO presented an opposite pattern, to be decreased by up to −10.53% in Nanjing. The results suggest that the COVID-19 lockdown has a large impact on CO concentration.

3.5 Ozone

In the analysis of O_3, compared with the pre-lockdown period, we found a significant increase in O_3 levels during the COVID-19 period in Nanjing. The results indicate that from pre to during the lockdown periods, the levels of O_3 increased by up to 104.85%, and while compared with the pre and during the lockdown periods, the rising value in the concentration of O_3 was 84.60% in Nanjing. Figure 2 shows the concentration pattern of O_3, and variations in O_3 are presented in Tables 1–3. Previously, it has been reported that during the lockdown period, the concentration level of O_3 increased in China (Fu et al., 2020; Hasnain et al., 2021). Another study documented by Islam et al. (2020) showed that during the COVID-19 period, O_3 concentration decreased in Bangladesh.

O_3 is mainly emitted from sunlight, volatile organic compounds (VOCs), and nitrogen oxides (NOx) (Lal et al., 2020). Compared with last year (2019), O_3 showed a similar trend, to be increased by an average of 18.03% in Nanjing (Table 2). From the previous 3 years to the lockdown period, our study showed that the increasing value for O_3 was 10.83%. According to Fu et al. (2020), during the lockdown period, O_3 levels increased in Guangxi, South China compared with that in the previous 4 years. During the lockdown period in Wuhan, Sulaymon et al. (2021) reported that O_3 concentration was increased. Compared to last year (2019), the increasing spell in the concentration of O_3 was greater than in the previous 3 years to the lockdown period in Nanjing.

Moreover, our results reveal that the concentration of O_3 continuously increased during the lockdown period to post-lockdown period in Nanjing. The decreasing value during this period was 37.36% while compared with the last 3 years to the post lockdown period, and O_3 levels increased by approximately 52.23%. It should be noted that in opposition to other pollutants, O_3 is the only pollutant that showed an increasing trend during the all-study periods in Nanjing. Previously, it was reported by Hasnain et al. (2021) that during the post-lockdown period, the concentration of O_3 had increased. The results suggest that from the COVID-19 control period to the post-lockdown period, the increase in the concentration of O_3 was due to the winter–summer change.

3.6 Backward trajectory analysis

The backward trajectories were plotted to trace the sources of air masses during the pre-LD, active-LD, and post-LD periods in

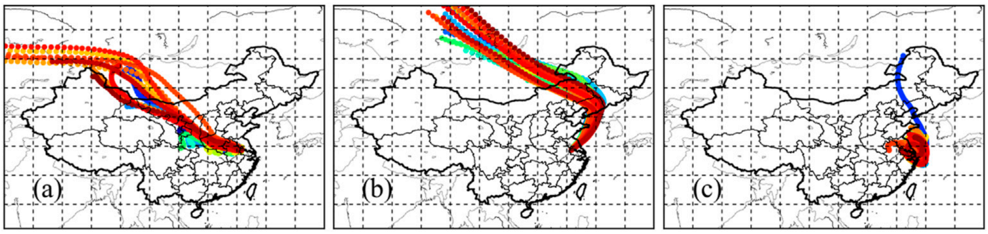

FIGURE 3
HYSPLIT backward trajectories over Nanjing **(A)** pre-lockdown, **(B)** during the lockdown, and **(C)** post-lockdown.

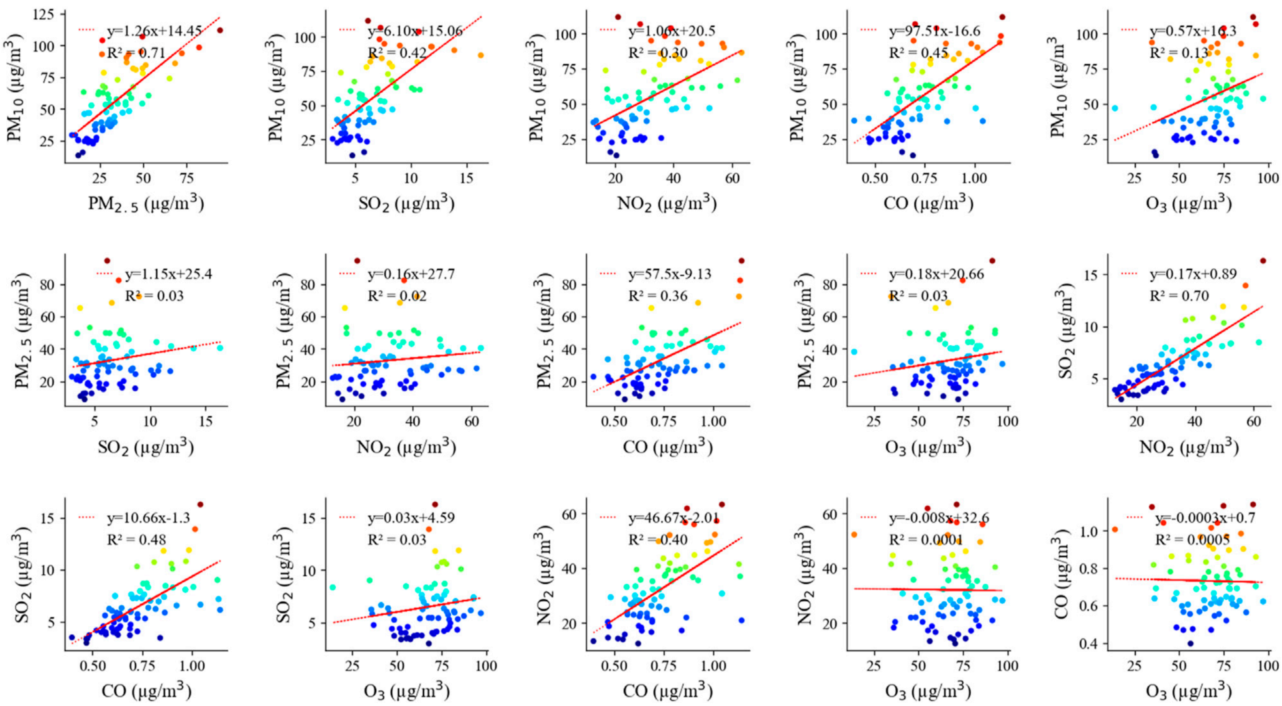

FIGURE 4
Co-relationships between air pollutants during the lockdown period in Nanjing.

Nanjing (Figure 3). The backward trajectories were analyzed for 72 h, starting every 6 h each day. We can see that during the pre-LD period, the trajectories originated from Siberia and passed through Mongolia and northwestern China. During the active-LD period, the air mass comes from the northwest of Mongolia and passed through the Liaoning Province before arriving in Nanjing. During the post-LD period, the air mass comes from Inner Mongolia and passed near the Beijing–Tianjin–Hebei (BTH) region and the East China Sea before reaching Nanjing. The air masses that are coming from Mongolia and passing near the Liaoning Province and the BTH region affect the air quality of Nanjing. The HYSPLIT model reveals the influence of long-range transport of air mass over Nanjing.

3.7 Co-relationships between air pollutants

The correlations between the daily average concentration of air pollutants in Nanjing during the lockdown period are shown in Figure 4. There was a significant correlation between PM_{10} and $PM_{2.5}$ (r = 0.71), while there was also a strong correlation between PM_{10} and SO_2 (r = 0.42), with NO_2 (r = 0.30). The results show that the strong correlation between PM_{10} and $PM_{2.5}$ can be attributed to mutual pollution sources. The correlation between PM_{10} and CO was (r = 0.45), and O_3 (r = 0.13). In contrast to the correlation between PM_{10}, SO_2, and NO_2, during the lockdown period, a weak correlation was observed between $PM_{2.5}$ and SO_2 (r = 0.04) with NO_2 (r = 0.01). $PM_{2.5}$ concentration showed a positive correlation with the concentration of CO (r = 0.36), with O_3 (r = 0.03). Moreover, SO_2 was highly correlated with NO_2 (r = 0.70), SO_2 with CO (r = 48), and SO_2 with O_3 (r = 0.03) during the lockdown period in Nanjing. This strong correlation between SO_2 and NO_2 reveals that it was due to their reduced mutual pollution sources during the lockdown period in the city. The concentration of NO_2 was significantly correlated with CO concentration (0 = 0.40), while there was no correlation between NO_2 and O_3 and CO with O_3. The results indicate that the concentration of CO was positively correlated with all other pollutants except with O_3, while the concentration of O_3 showed weak or no correlation with other pollutants. It suggests that the concentration of O_3 increased with the reduction in the concentrations of other pollutants during the lockdown period in Nanjing.

4 Conclusions

In general, a pronounced improvement in air quality was observed during the COVID-19 pandemic lockdown period in Nanjing. In order to evaluate the impact of the COVID-19 pandemic lockdown measures on air pollution, this is an excellent opportunity to work in this direction in different parts of the world. In this study, the effects of the COVID-19 pandemic lockdown on air quality were examined using daily average data for the six air pollutants in Nanjing. The results illustrate that compared to the pre-lockdown period, all the air pollutants showed a remarkable decline during the lockdown period, except for O_3 in Nanjing. Among these pollutants, the concentrations of PM_{10} and $PM_{2.5}$ were significantly decreased by an average of -33.03% and -35.41%, respectively. Among other pollutants, compared with the pre-lockdown period, SO_2 (−21.26%), NO_2 (−39.79%), and CO (-20.65%) were also reduced, while O_3 levels significantly increased (104.85%) during the lockdown period. Among the selected pollutants, PM_{10}, SO_2, NO_2, CO, and O_3 increased by 2.84%, 28.55%, 4.68%, 16.44%, and 37.36%, respectively, while $PM_{2.5}$ was the only pollutant that increased by an average of 14.34% after the lockdown period. The study revealed that compared with the last year (2019) (same time frame of lockdown), a significant drop and reduction in all pollutants were observed, while O_3 showed an increasing trend. Overall, except for O_3, a substantial decrease in all air pollutants was found during the lockdown period in Nanjing. The results of this research will be helpful for the local bodies of the city and the Chinese administration to develop rules and regulations to improve and upgrade air quality in the future.

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.

Author contributions

SF: conceptualization, methodology, data curation, writing—original draft, writing—review and editing, visualization, project administration, and funding acquisition; RAW: data curation, writing—original draft, writing—review and editing, and visualization; AHH: conceptualization, methodology, data curation, writing—original draft, writing—review and editing, supervision, resources, project administration, and funding acquisition; AAH: data curation, writing—original draft, and writing—review and editing; UAB: investigation, data curation, writing—original draft, writing—review and editing, supervision, resources, and project administration; EE: investigation, data curation, and 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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Exploring the impacts of China's water resource tax policies: A trade-off between economic development and ecological protection

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The reform of water resource tax policies is an important measure in the process of China's green economic transformation. Therefore, improving the accuracy of tax policy impact prediction is crucial for policymakers to make correct decisions. This study focused on the water resource tax policies composed of water resource tax and water pollution tax. A water computable general equilibrium (WCGE) model extended from the traditional computable general equilibrium model was proposed to simulate the impacts of policy changes and determine the optimal tax rate range. Water self-purification capacity and agricultural subsidies were first considered in water computable general equilibrium, providing a simulation–evaluation method that could support the analysis of policy alternatives from a more realistic perspective. The results indicated that water resource tax and water pollution tax synergistically promote water conservation and water pollution reduction, and the negative impact on the economy when they are raised together is lighter than that when the tax burden is raised alone. The water resource tax not only has the best water-saving effect but also has the greatest negative impact on the economy. Technological progress has the best effect in reducing water pollution and is also conducive to reducing the adverse impact of tax increases on the economy. Taxation can also improve social welfare, and the optimal tax rate level is the combination that water resource tax is 4 Yuan/m3, and the water pollution tax is in the range of 5.6–8.4 Yuan/pollution equivalent. The results demonstrate the positive role of government in environmental governance and provide a scientific basis for policymakers to adjust the direction of policy reform, strengthen the collaborative design of water tax policies, and select the optimal tax rate level. Also, solutions of water computable general equilibrium could provide in-depth analysis of the trade-offs between violation risk and system benefits and generate more reliable results by reproducing actual situations. Moreover, the water computable general equilibrium model constructed in this study is also applicable to analyze other types of policies.

KEYWORDS

water resource tax system, water computable general equilibrium model, economic operation, social welfare, environmental effect, optimal tax rate

1 Introduction

Water pressure has been one of the severe environmental stress and socio-economic challenges the world is facing (Wang J et al., 2022). The China Sustainable Development Strategy Report pointed out that two-thirds of China's 669 cities are facing water shortages, and many provinces and cities are in the range of extreme water shortage in the internationally recognized standard (Qin Y et al., 2015). There are also a series of problems such as inefficient use, difficult development, and heavy pollution in addition to the shortage of available water resource (Li H et al., 2022). The "Environmental Performance Index 2020 Report" released by Yale University evaluated 180 countries around the world, and China ranks 54th in the drinking water safety index and 67th in the comprehensive water resource index (Hu et al., 2022). The safety of water resource and the effect of water environment governance are far behind those of neighboring and developed countries, which have irreversible and serious impacts on people's health, economic development, and social life. Various water management policies have been implemented to alleviate these problems (Ray et al., 2022). Hotelling (1931) first put forward the theory that resource tax policy is an effective tool to control the speed of resource consumption. Therefore, the establishment of resource tax policies is an important part of the ecological strategies of various countries. Ekins (1999) proved that many European countries have been increasing the proportion of environmental taxes and fees so as to enable the government to address resource externalities that are difficult for the market to solve due to the environmental pollution caused by the producers in the production process. China has also begun to gradually promote the construction of a water resource tax system, particularly including water resource tax and water pollution tax, to protect water resource from two aspects: resource conservation and pollution control (Wang S et al., 2022; Zhao et al., 2022). Since the water resource tax policies are closely related to factors such as economic development, technological progress, and dynamic correlation between various industries and the complex non-linear coupling relationship between these factors, they should be comprehensively depicted by a model from a systematic perspective. Those all make it extremely difficult to accurately predict and analyze the impacts of tax policies. Meanwhile, as water resource is the basic means of production, water tax policies will inevitably affect all aspects of the economy, society, and environment, directly or indirectly (Amaranto et al., 2022). Human activities are susceptible to changes in water tax policies, and if the impacts of tax policies are not adequately predicted and assessed, policies often fail to achieve the desired goals and may even exacerbate problems such as water scarcity, water pollution, or socio-economic instability (Mehrazar et al., 2020). Therefore, the use of predicting tools to accurately reveal and assess the impacts of alternative policies is an urgent need to enable policymakers to make informed decisions and formulate sound policies.

The objective of this study is to analyze the impacts of water resource tax policies on the economy, social welfare, and environment and determine the optimal tax rate level using the constructed WCGE model, which could comprehensively characterize the complex relationship between water resource tax policies and economic system. This study first takes the water self-purification capacity and agricultural subsidies into account so as to enhance the accuracy of the assessment of policy changes. The study expands the research scope that was limited to a single tax, and its focus on the natural properties of resources inspires research on policies relating to resources. The findings also help policymakers fully understand the impacts of policies and constitute appropriate ways to achieve desired goals.

The remainder of this article is organized as follows: In Section 2, we review the existing literature and discuss each contribution. In Section 3, the water resource tax system composed of water resource tax and water pollution tax is defined, and the impact mechanism of water tax policies from the perspective of market and government is introduced. In Section 4, the water resource and water pollution are integrated into the WCGE model, and 10 scenarios are set and simulated. Based on the simulation results, in Section 5, we analyze the impacts of water resource policies, and the optimal tax rate combination is inferred with the goal of balancing economic development and environmental protection. Following that, Section 6 provides the findings and discussion and puts forth several corresponding policy suggestions. Finally, the conclusions are provided in Section 7.

2 Literature review

Many scholars evaluate the policy effects of environmental taxes (Abdullah and Morley, 2014; Oueslati, 2015; Freire-Gonzalez and and Puig-Ventosa, 2019) and resource taxes (Liu et al., 2018; Xu et al., 2018) using various methods. With the gradual refinement of research into specific tax items, many studies on water resource tax policies focus on water resource tax and water pollution tax, evaluating whether they can play the role of environmental protection and how to improve them from the perspective of legislation. Some scholars believe that levying water resource tax can increase exports, effectively reduce water consumption in high-water-consuming industries (Yang et al., 2020), improve water-use efficiency, and save water in production, but it decreases the output of regional agricultural sectors (Wang et al., 2015). In addition, the transfer payment of water resource tax can reduce the welfare loss caused by taxation (Wu et al., 2021). The water pollution tax has a significant effect of reducing pollution emissions, but it will have a negative impact on the macroeconomy and industrial output in the short and long terms. Therefore, a tax rebate system is required to reduce the negative impact of taxation on economic growth (Wen et al., 2012). Some scholars believe that although the water tax policies will have a negative impact on the economy, it is still within an acceptable range (Shi et al., 2019). Although the tax increases the cost of enterprises in the short term, it helps enterprises to adjust production technology and increases the application of clean technology, which can enhance the competitiveness of enterprises, promote sustainable economic development, and improve environmental quality in the long run (Gao and Yin, 2016; Zhou et al., 2019). At the same time, it is necessary to subsidize industries that are less able to bear tax changes (Wang et al., 2011). Ren (2020) emphasizes the fair orientation of water resource tax policies from the perspective of legislation and believes that the tax burden should be reasonably determined, and a special fund should be established to subsidize industries with low energy consumption and low pollution. In addition, there are some viewpoints that China's current water resource tax policies generally have problems such as excessive regional differences in tax rates (Ma and Li, 2019), not enough low tax burden to cover the cost of environmental governance (Zeng et al., 2019), and insufficient constraints on corporate behavior (Gen and Masuil, 2019; Sicho and Fan., 2020). Tang and Ming, (2018) pointed out that the minimum limit of taxation should be appropriately increased, and punitive levy clauses should be added to achieve the basic effect of using tax to control pollution.

In summary, existing research works provide useful references for the reform of the water resource tax policies, but there are still some issues that need to be further studied. 1) The research content is limited to the discussion of the implementation effect and improvement direction of a single tax on water resource tax or water pollution tax, and there is a lack of in-depth and comprehensive analysis of the water resource tax system composed of these two taxes. Separating the two types of taxation will inevitably ignore the comprehensive effects that these two taxes will have on the economy, society, and environment, resulting in overlapping tax burdens and biasing the research conclusions. 2) Water resource tax policies are implemented nationwide and involve various industries and multiple interests in the economic system. However, the scopes of existing research works are limited to a region or only focus on a certain industry, ignoring the complex impact that tax reform have on macroeconomic operations. Therefore, the effects of water taxation policies should be discussed from a systematic perspective, considering the correlation between various industries and entities. 3) There is a lack of systematic research that combines qualitative analysis and quantitative methods to study issues such as how to determine a reasonable tax rate level, how to coordinate the promotion of water resource tax policies, and what impacts tax policy adjustment will have on the economy, society, and environment. To the best of our knowledge, there is no such study describing the relationship between water resource tax policies and industries from a macroperspective and comprehensively analyzing the policy impact of water resource tax and water pollution tax so as to determine a reasonable level of tax rate combination. These are the objectives of this study.

3 Theoretical foundation

The core manifestations of the water resource tax system are water resource tax and water pollution tax, focusing on different aspects of water resource governance under the framework of the ecological tax system composed of resource tax and environmental tax. The water resource tax is a tax on the behavior of withdrawing water resource and implements the principle of "user pays." In 2016, China introduced water resource into the scope of resource tax collection on a pilot basis. At present, the expansion of water resource tax has become the main trend (Liu et al., 2018; Ma and Wang, 2021). The water pollution tax has been implemented nationwide since 1 January 2018 under the framework of environmental tax, following the principle of "polluter pays." The production of products bears the water resource tax when using water resource, and the water pollution tax is levied along with the discharge of water pollutants in the production process. The water resource tax aims to save water resource at the beginning, and the water pollution tax is to suppress the discharge of water pollutants. These two complement each other and constitute a complete water resource tax system. The tax system changes the cost of products by introducing a price signal and imposes positive or negative incentives on various stakeholders, thereby regulating the behavior of the main body. The essence is that the government adjusts the production methods of enterprises with the help of market laws and guides the transformation of the green economy (Chen, 2019).

Under the influence of the market, it is assumed that there is a sound factor price formation mechanism. Water resource tax and water pollution tax are levied in the production process, and both should be included in the commodity value. The water resource tax reflects the scarcity of resources, and the water pollution tax serves as the price compensation for environmental losses in the process of water use, as shown in Figure 1. Water resource is incorporated into the production factors as the basic means of production; taxation increases the cost of production, and the producer bears part of the tax burden. At the same time, part of the tax burden is passed on to the downstream, the price of

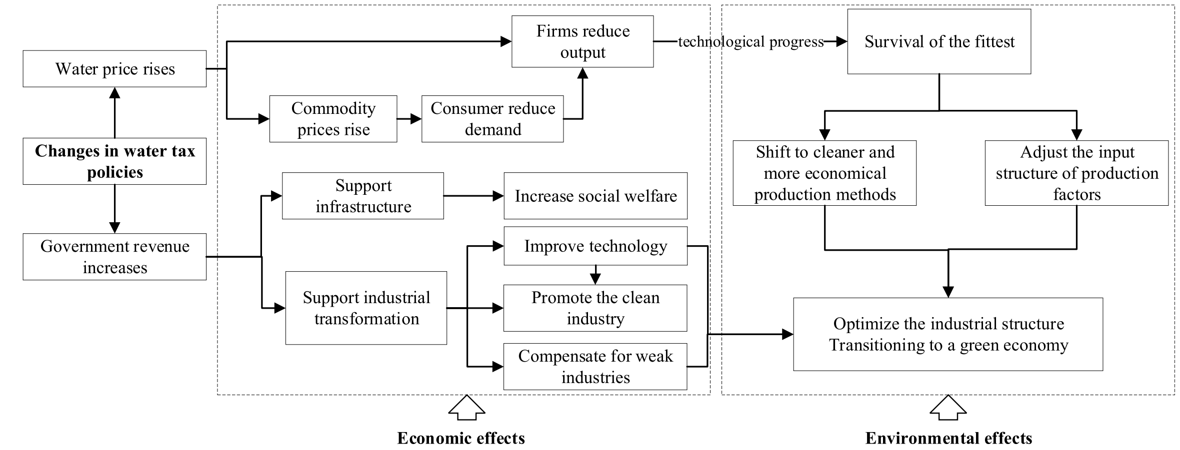

FIGURE 1
Price transmission mechanism of the water resource tax system.

downstream commodities increases, and the tax burden is finally transmitted to consumers in the price of resource products, thereby reducing consumer demand. Under the combined influence of cost pressure and demand decrease, producers reduce output, resulting in a loss of output and a decrease in GDP. However, in order to improve their own competitiveness, some producers would strive to reduce costs, such as reducing the discharge of water pollutants and increasing the efficiency of water resource utilization by improving production technology, while some enterprises with insufficient innovation ability would withdraw, thus making the overall economy shift to a greener economic development approach. In general, the water tax system could restrain the development of industries with high water consumption and high pollution, thus optimizing the industrial structure, but the taxation would have a negative impact on the economy.

Under the influence of the government, water resource tax and water pollution tax can increase the government's revenue, which can be uniformly allocated by the government. The water environment can be improved by devoting substantial financial resources to technology development or incentivizing enterprises that introduce environmentally friendly technologies. Moreover, the government can improve the infrastructure to augment the capital flow (Jahanger et al., 2022). The government uses transfer payments to drive investment and consumption, supports infrastructure construction to increase social welfare, promotes the development of clean industries, and subsidizes agriculture that is less tax bearing in order to ensure a stable economic transformation. Therefore, taxation enables governments to take full advantage of their positive effects on economic, social, and environmental regulation, thereby contributing to the achievement of desired objectives of water resource tax policies.

4 Methodology

4.1 Theory of computable general equilibrium

The theory of the computable general equilibrium model (CGE) began with the general equilibrium theory model proposed by Walras (1874), which takes the economic system as a whole, emphasizes the role of various departments and variables of the economic system, and covers the various components of the national economy and all aspects of the economic cycle. According to Walras's view, all markets reach equilibrium under the adjustment of the price mechanism eventually. Therefore, when the economic system is subjected to external shocks, the economic entities in the system make decisions and interact with each other in accordance with the principle of maximizing interests, and adjust to a new equilibrium state through the optimal allocation of resources. Therefore, the CGE model can more accurately describe the interaction between water tax policy changes and other economic sectors and reveal the interrelationship within the economic system. It is a method to study the relationship between various sectors of the national economy on the basis of input–output analysis.

Conducting impact simulations of policies is a strength of the CGE model. Different from the traditional methods such as trend extrapolation and pattern recognition that rely entirely on historical data, the CGE model belongs to the structural school in the economic model. It depicts the supply and demand balance between various departments and markets of the economic system by establishing a set of non-linear mathematical equations. The simulation model of the regional economy is constructed based on the parameters of each subject in the region. The changes of policies are exogenous as impact variables, and the equations are solved following the optimizing conditions such as cost minimization and benefit maximization. From these variables obtained under the conditions of market clearance and economic equilibrium, the changes of indicators of the economy can be comprehensively and effectively simulated and predicted, so that we can perform in-depth analyses on the application of polices and provide a sufficient understanding of the formulation, evaluation, and implementation of policies.

As the CGE model can effectively describe the linkages between various departments after the economic system is subjected to specific external shocks and macropolicy adjustments, it is widely used in the simulation and analysis of macro policies related to economy, energy, resources, and environment with its scientific theoretical basis and flexible simulation capabilities (Sancho, 2010; Lin et al., 2018; Li et al., 2020; Lin and Wu, 2021), as well as for water resource tax policies. There are many ways to deal with water resource in the model, such as taking water resource as constraints for production or consumption (Xie and Saltzman, 2000; Yan and Zhou, 2010), but this method cannot reflect the cost of water resource, and the price transmission mechanism does not work as well. Hassan and Thurlow (2011) incorporated water resource as an intermediate input into the model, but they were unable describe the substitution relationship between water resource and other production factors. The approach adopted by most of the current studies is to incorporate water resource as an initial factor into the constant elasticity of substitution (CES) production function (Liu et al., 2012; Jonas et al., 2014). Some studies also incorporate water resource as a sector into the model and analyze the macroeconomic impact of changes in water prices by establishing the relationship between the water sector and other sectors (Xia and Huang, 2006; Qin et al., 2012).

4.2 Data

4.2.1 The construction of the social accounting matrix

The social accounting matrix (SAM) table of water resource uses the 2018 China Input–Output Table as the main data source and is compiled with reference to the 2019 China Statistical Yearbook, Finance Yearbook of China in 2019, 2018 China Eco-Environmental Statistical Yearbook, 2018 China Water Resource Bulletin, *etc.* In view of the need for research on industries with high water consumption and high pollution, food and tobacco, paper industry, textile industry, wood-processing industry, and chemical products are listed separately as water pollution industries. On the basis of the three major industry division standards of agriculture, industry, and service industry and four production departments including agriculture, water pollution industries, and other industries and services are established.

4.2.2 The value of water and other parameters

The water pollution tax is levied only on producers and operators, and the water resource in the model is production water, constituting three basic production factors together with labor and capital. First, the value of water resource needs to be determined, and then, the total value of production factors in the input–output table is allocated proportionally among labor, capital, and water resource. Because the water resource tax is levied at the water withdrawal stage, the total amount of water used for production in each industry is used as a constraint, and the direct water consumption coefficient (fresh water) of each department is used to calculate the fresh water directly consumed by producing the products of the corresponding value, which is taken as the taxable amount of water resource tax (Researching Group of Chinese Input-Output Association et al., 2007). Since the shadow price of water resource is based on the full and rational utilization and effective allocation of resources, it can reflect the scarcity of resources, environmental costs, and the relationship between market supply and demand and can objectively measure the value of water resource. Therefore, the shadow price of water resource is calculated as the water price to obtain the value of water resource (Liu et al., 2009). Finally, the total factor value is divided proportionally among the three factors consisting of water resource, labor, and capital.

To determine the value of water pollution tax, the total amount of various water pollutants published in the "2018 China Ecological Environment Statistics Annual Report" is allocated according to the proportion of different water pollutant discharges in various departments (Qin, 2014). Then, the tax rate is multiplied by the pollution equivalent value converted from water pollutants as the amount of water pollution tax. Due to the different sources of data in the SAM table, the direct cross-entropy method is used to calibrate the SAM matrix (Wang et al., 2021). The main elastic parameters of the model are shown in Table 1, which are mainly estimated with reference to the relevant research works of Wu et al. (2021b) and Qin C et al. (2015).

4.3 Basic assumption

In line with the expansion trend of water resource tax, it is assumed that the water resource tax is levied nationwide, with all water-using industries as taxpayers, and constant returns to scale is also assumed in the production function. The behavior of producers and consumers in a perfectly competitive market follows profit maximization and utility maximization principle, and the clearing of the factor market and the equilibrium of the product market are ultimately achieved.

TABLE 1 Main elastic parameters of the model.

Sector	Agriculture	Water pollution industry	Other industries	Service
Elasticity of substitution for the QA	0.3	0.3	0.3	0.3
Elasticity of substitution for the QVA	0.8	0.8	0.8	0.8
Elasticity of substitution for the QLK	0.6	0.6	0.6	0.6
Elasticity of substitution for Armington	3	2.5	2.5	2.5
Elasticity of substitution for CET	4	3.5	3.5	3.5

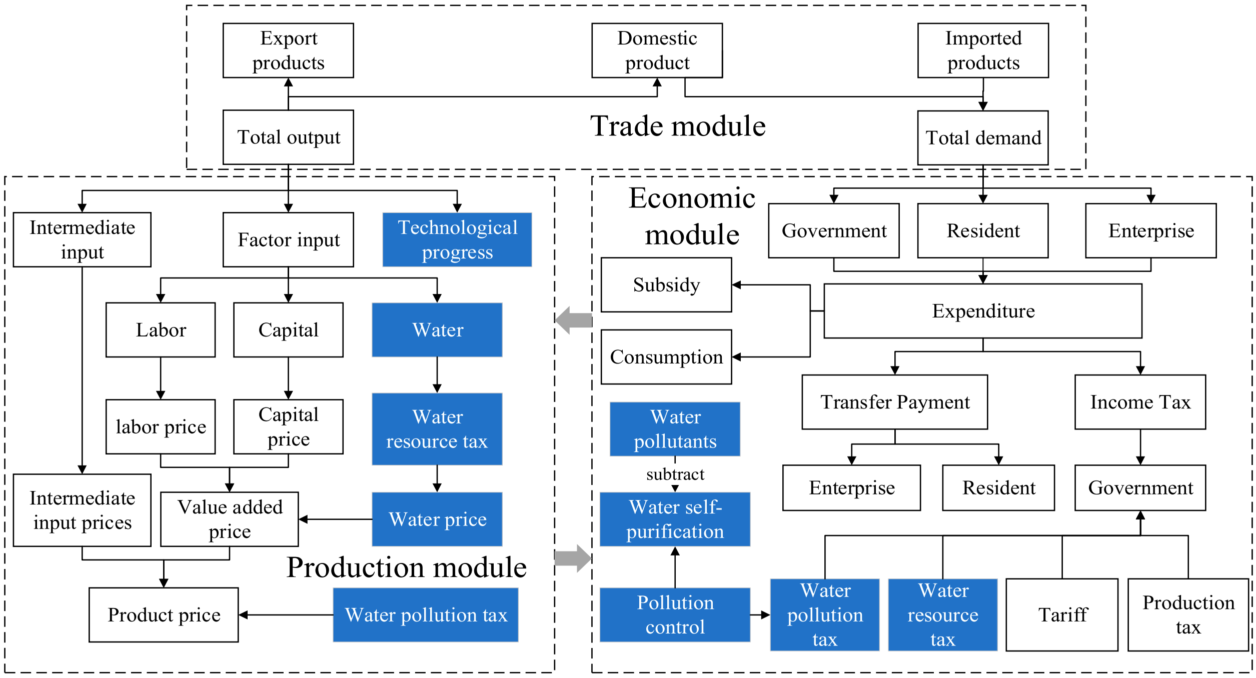

FIGURE 2
Basic structure of the WCGE model.

4.4 Framework of the water computable general equilibrium model

In order to evaluate the economic and environmental effects of water taxation policies, the WCGE model is constructed. Water resource, like labor and capital, is the resource that needs to be used in the production process; therefore, the model assumes that production factors include capital, labor, and water resource. The model mainly includes the production module, trade module, price module, economic subject module, water pollution tax module, and equilibrium and macro closure module. The logical relationship between the modules is shown in Figure 2. The production module is the basic module of the model. It describes the process of the production factor producing goods based on the production function. The produced goods are linked to the international market through the trade module. According to the Walrasian general equilibrium theory, domestic commodity supply is equal to domestic commodity demand, which consists of government consumption, resident consumption, and enterprise investment. The economic module describes the flow of funds among these economic entities. The water resource tax and water pollution tax implemented by the government affect the factor input of producers through the price mechanism and ultimately affect the industry output, household income, water consumption, and water pollutant emissions.

Based on the aforementioned theoretical analysis, the water resource tax, as a factor tax, increases the price of water resource,

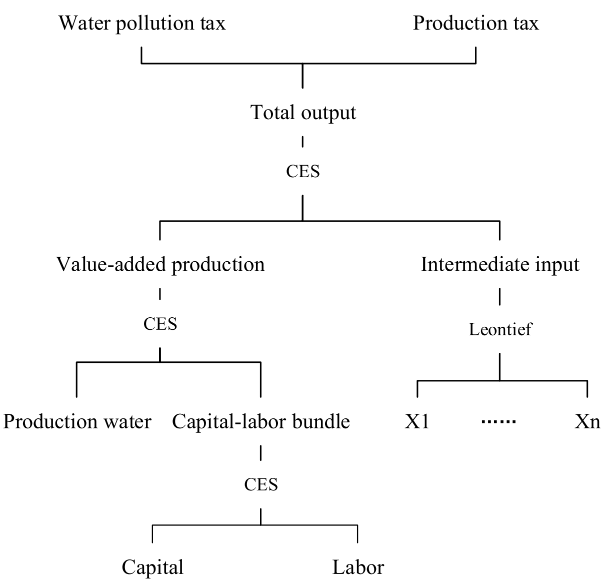

FIGURE 3
Diagram of the production module.

especially affects the production process in economic operation, and indirectly affects the amount of water resource used. The water pollution tax follows the principle of "polluter pays," which is levied on the pollutant discharge behavior in the production process and is added to the value of the output product. This tax and other taxes are jointly managed by the government, and the goals of environmental governance and tax compensation are achieved through transfer payments and government consumption. The main modules presented are those expanded according to research needs, which are the production module, water pollution tax module, economic subject module, and equilibrium and macroclosure module. The rest can refer to the standard CGE model (Zhang, 2017; Lin and Wu, 2021; Zhang et al., 2022). The equations and variables are listed in Supplementary Material.

4.4.1 Production module

The CES production function is used to describe the behavior of producers, and three layers of nested CES production functions are established according to research needs. The first layer of nesting describes the substitution relationship between labor and capital, and the second layer of nesting describes the relationship between capital–labor and water resource. The third level of nesting describes the substitution relationship between water resource–capital–labor and intermediate inputs (see Figure 3).

4.4.2 Water pollution tax module

The pollutants in China's wastewater are mainly COD and NH3-N, which are converted to pollution equivalent value together with other pollutants, and the discharge of water pollutants (QEM_a) is calculated according to the pollution discharge intensity (θ_a) of each industry in the model:

$$QEM_a = \theta_a \bullet QA_a. \tag{1}$$

In addition to the participation of human activities in water pollution control, the natural attributes of water resource endow the water body with self-purification ability, and it also reduces the impact of water pollution to a certain extent. After entering the water body, the concentration of pollutants gradually decreases because of the physical and chemical changes such as precipitation, dilution, mixing, and redox. The biochemical oxygen demand (BOD5) degradation coefficient is used as an indicator of self-purification ability to measure the rate of water decomposing pollutants. Because the degradation coefficient varies with temperature, the annual average water temperature of 14°C in China is taken as the standard temperature (Wang et al., 2020). Therefore, water pollution control is a combination of water self-purification and government investment governance. The formulas are

$$QGM_a + QWM_a = QEM_a, \tag{2}$$

$$QWM_a = BOD_5 \bullet QEM_a, \tag{3}$$

where QGM_a is the government pollution control amount, QWM_a is the water self-purification amount, and BOD_5 is the water pollution degradation coefficient. The amount of water pollution tax is calculated and levied in the form of a specific amount to represent the water pollution tax rate. The water pollution tax is:

$$\begin{aligned} Tpollution_a &= tpol_a \bullet QGM_a = tpol_a \bullet (QEM_a - QWM_a) \\ &= tpol_a \bullet (1 - BOD_5) \bullet QEM_a \end{aligned} \tag{4}$$

4.4.3 Economic entity module

Under the conditions of an open economy, residents' income comes from labor remuneration, investment returns, and government transfer payments. The income of the enterprise comes from the capital gains from the factor market and the transfer payment from the government. In addition to the flow of capital gains to enterprises and residents, there is also a part of the flow to foreign countries, so the foreign income includes capital gains and imports. Government revenue comes from taxes.

$$\begin{aligned} YG = \sum_a \left[tvat_a \bullet QA_a \bullet PA_a \bullet PW_a \bullet QWD_a + Tpollution_a\right] \\ + ti_h \bullet YH + ti_{ent} \bullet YENT + TM \bullet EXR \end{aligned} \tag{5}$$

In the aforementioned formula, YG, YH, and $YENT$ refer to government income, resident income, and corporate income, respectively. ti_h and ti_{ent} represent the resident income tax rate and corporate income tax rate, respectively. TM represents the tariff. EXR represents the exchange rate. For the sake of tax fairness, agriculture is included in the scope of taxation, but considering that it occupies a basic position in the national economy and is in a weak link, the government will subsidize it through transfer payments and other methods after taxation to support its smooth transition to a green industry. Therefore, government expenditure mainly includes government purchases CG and transfer payments to residents $transfr_{hg}$, investment in enterprises $transfr_{entg}$, and subsidies to the agricultural sector $transfr_{agrg}$. The equation is expressed as

$$EG = CG + transfr_{hg} + transfr_{entg} + transfr_{agrg}. \quad (6)$$

The government's balance of payments is the government's net saving. In actual operation, the government mainly affects the allocation of social resources and various elements through tax revenue, government purchases, transfer payments, and other fiscal revenue and expenditure activities so as to realize its publicity and coercive power.

4.4.4 Equilibrium and macroclosure module

Factor market equilibrium means that factor demand equals supply. It is assumed that capital is fully used, and labor and water prices are exogenous based on China's economic conditions. The supply of labor and water is determined by the model endogenously and finally reaches an equilibrium state where factor supply equals demand.

Product market equilibrium refers to the balance of product supply and demand in the domestic market, that is, market clearing:

$$QQ_c = QINT_c + QH_c + QG_c + \overline{QINV_c}. \quad (7)$$

In the aforementioned formula, QQ_c refers to the commodities on the domestic market, $QINT_a$ refers to the intermediate input, QH_c refers to the total consumption of residents, QG_c refers to the total government consumption, and $\overline{QINV_c}$ refers to the investment of various departments. It is assumed that investment, government consumption, and government saving are endogenous. Under the condition of fixed exchange rate, foreign balance of payments and foreign savings are endogenous. The investment-saving equilibrium means that the total investment is equal to the total saving of each subject, and the equation is

$$EINV = (1 - mpc)\bullet(1 - ti_h)\bullet YH + ENTSAV + GSAV + EXR\bullet FSAV + WALRAS. \quad (8)$$

In the aforementioned formula, mpc refers to the residents' marginal propensity to consume, YH refers to residents' income, $ENTSAV$ refers to corporate savings, $GSAV$ refers to government savings, and $FSAV$ refers to foreign savings.

Adding $WALRAS$ can verify the correctness of the model, and the variable is 0 in the state of investment-saving equilibrium.

4.5 Policy scenarios

Four main policy scenarios are set based on research purposes: baseline scenario, water resource tax policy change, water pollution tax policy change, and changes in both water tax policies. On this basis, the factor of technological progress is comprehensively considered. China's current water resource tax system generally has problems such as excessive regional differences in tax rates (Hassan and Thurlow, 2011) and low tax burdens (Fang et al., 2016). In order to highlight the differences in economic, social, and environmental effects under different tax burden levels, the rates of water pollution tax are divided according to the degree of economic development. Due to the prominent environmental problems in Beijing, Tianjin, and Hebei, the high regional tax rate is not applicable to the whole country. Therefore, with reference to the current tax rates of Shanghai, Jiangsu, Liaoning, Jilin, Jiangxi, Shaanxi, and other provinces and cities, it is assumed that the water pollution tax rate is set at three levels: the benchmark tax rate of 1.4, 7, and 8.4 Yuan/pollution equivalent. The optimized water resource tax is set to three tax levels: the benchmark tax rate of 2, 3, and 4 Yuan/cubic meter. Since fiscal policy plays the role of water environment governance by leading technological progress (Li S et al., 2022), the technological progress is considered as a variable factor. The simulated scenarios are shown in Table 2. The economic and environmental effects of changes in water taxation policies are quantitatively simulated from three aspects: water resource tax, water pollution tax, and technological progress. According to China's 14th Five-Year Plan, by 2025, the total amount of COD and NH3-N emissions will drop by 8%. It is believed that technological progress will play a role in reducing water pollution discharge, which is manifested as a decrease of 8% in the water pollution discharge intensity coefficient compared to the baseline scenario.

5 Model result interpretation

5.1 Model correctness test

Before interpreting the experimental results, we set $WALRAS$ and $GDPCHK$ to first verify the correctness of the model with reference to the diagnostic test applied by Lin (2022b). As the WCGE model contains multiple markets and eventually all markets reach the equilibrium state, the value of the Walras dummy variable should be 0 or the minimum value

TABLE 2 Instructions of simulation scenarios.

Scenario name	Description	Policy implications
Baseline scenario		
S0	Water pollution tax: 1.4 Yuan/pollution equivalent Water resource tax: 2 Yuan/m3	
Changes in water pollution tax		
S1A	Water pollution tax: 7.0 Yuan/pollution equivalent Water resource tax: 2 Yuan/m3	Tax burden raising
S1B	Water pollution tax: 8.4 Yuan/pollution equivalent Water resource tax: 2 Yuan/m3	Tax burden raising
S1C	Water pollution tax: 8.4 Yuan/pollution equivalent Water resource tax: 2 Yuan/m3 Water pollutant treatment efficiency increased by 8%	Tax burden raising + technological progress
Changes in water resource tax		
S2A	Water pollution tax: 1.4 Yuan/pollution equivalent Water resource tax: 3 Yuan/m3	Tax burden raising
S2B	Water pollution tax: 1.4 Yuan/pollution equivalent Water resource tax: 4 Yuan/m3	Tax burden raising
S2C	Water pollution tax: 1.4 Yuan/pollution equivalent Water resource tax: 4 Yuan/m3 Water pollutant treatment efficiency increased by 8%	Tax burden raising + technological progress
Changes in both water tax policies		
S3A	Water pollution tax: 7 Yuan/pollution equivalent Water resource tax: 3 Yuan/m3	Tax burden raising
S3B	Water pollution tax: 7 Yuan/pollution equivalent Water resource tax: 4 Yuan/m3	Tax burden raising
S3C	Water pollution tax: 7 Yuan/pollution equivalent Water resource tax: 4 Yuan/m3 Water pollutant treatment efficiency increased by 8%	Tax burden raising + technological progress

if the model setting is correct. This study also verifies the correctness of the new model through different GDP-accounting methods. We calculate nominal GDP by using the income method (return on labor + return on capital + government income-subsidies to agriculture) and expenditure method (government consumption + resident consumption + investment + net export), and then let one subtract another. Theoretically, the value obtained must also be 0 or minimum in each scenario.

Usually, if there are errors in the commodity or value flow in the model setting, the Walras dummy variable will deviate significantly from 0. Therefore, before analyzing the model, we first need to consider whether errors are embodied in the setting of the model. We need to pay attention to the value of the Walras dummy variable in each scenario (Figure 4). The results show that the value of Walras basically fluctuates under 0.00001. In addition, the model calculates the annual nominal GDP of each scenario by the expenditure method and income method and finds the

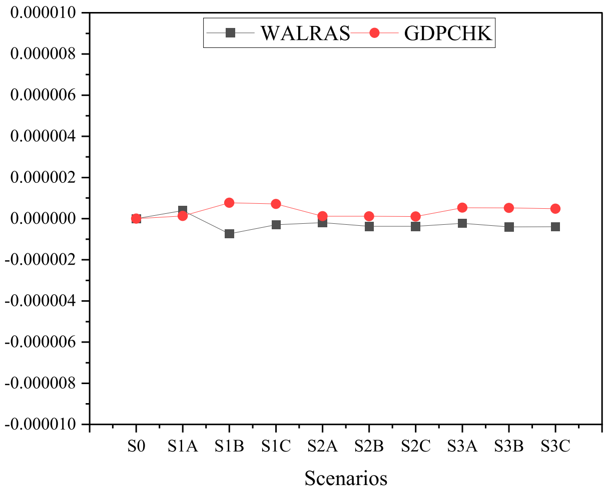

FIGURE 4
Values of WALRAS and GDPCHK.

TABLE 3 Variation of economic indicators under different scenarios (%).

Index		GDP	PGDP	Total output	Total investment
Changes in water pollution tax	S1A	−0.02784	0.19646	−0.057203	0.106808
	S1B	−0.03484	0.19646	−0.071182	0.133450
	S1C	−0.03148	0.19646	−0.064350	0.120666
Changes in water resource tax	S2A	−0.79844	0.98232	−0.811939	0.720104
	S2B	−1.39975	1.66994	−1.422753	1.276890
	S2C	−1.39929	1.66994	−1.421581	1.274954
Changes in both policies	S3A	−0.82026	1.08055	−0.856661	0.807629
	S3B	−1.42071	1.76817	−1.465276	1.363698
	S3C	−1.41856	1.76817	−1.460729	1.354833

differences (Figure 4). If the model is set correctly, usually, the value is also a number close to 0. The results show that the difference (GDPCHK) fluctuates under 0.00001, which is very close to 0, confirming the correctness of the model itself.

5.2 Economic effects of water tax policies

5.2.1 Impact on economic development

The level of economic development is measured by GDP, PGDP, total output, and total investment. Under the impact of policy changes, the changes of various economic indicators relative to the baseline scenario are shown in Table 3. As the tax burden of water resource tax and water pollution tax increases, GDP decreases compared with the baseline scenario, PGDP increases, and the total output of various departments decreases, while the total investment increases. The increase of water pollution tax (S1) has less impact on economic development, basically stable at below 0.2%, while increasing the water resource tax (S2) has a more obvious impact on economic development. This is due to the fact that the water resource tax is broader than the water pollution tax and has a far-reaching impact on the economy. The effect of raising the water resource tax and water pollution tax (S3) at the same time on economic development is higher than the case of raising the two separately, but lower than the superposition of the effects when the two are raised to the corresponding level, indicating that the two kinds of taxes can coordinate with each other, and increasing the tax burden at the same time can not only reduce the negative impact on the economy when the tax is raised alone but also reduce the pressure of departments to increase investment to stimulate economic growth.

The increase in the tax burden leads to an increase in the price of water resource, an increase in PGDP, a weakening of consumers' purchasing power, a decrease in output by producers under cost pressure and a decrease in demand on the consumer side. The output sector suffers losses and GDP decreases. Also, all sectors need to increase investment to stimulate economic growth. However, under the same tax burden level, adding technological progress can make the GDP rebound slightly and reduce the negative impact of tax policy changes on the economy. At the same time, technological advances also ease investment pressures.

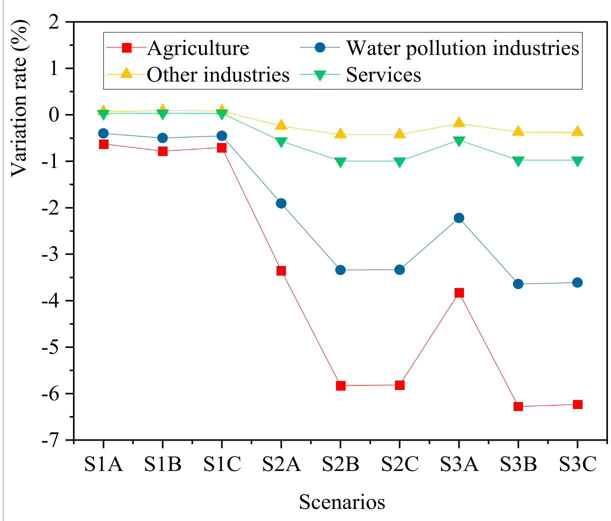

FIGURE 5
Output variation of different industries under different scenarios (%).

5.2.2 Impact on the industrial structure

Changes in the water tax policies can effectively adjust the industrial structure (Figure 5). The increase of water resource tax and water pollution tax can reduce the output of agriculture

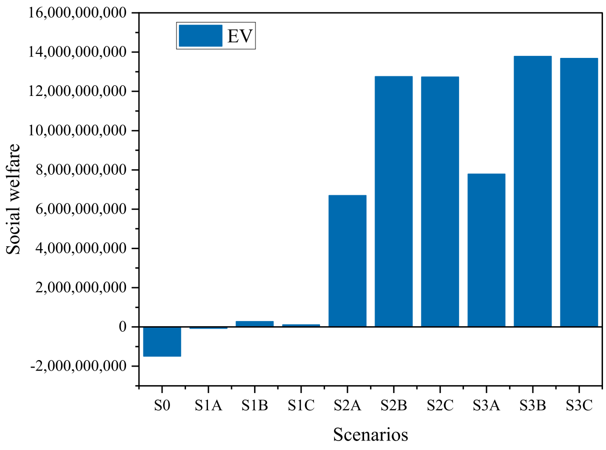

FIGURE 6
Social welfare under different scenarios.

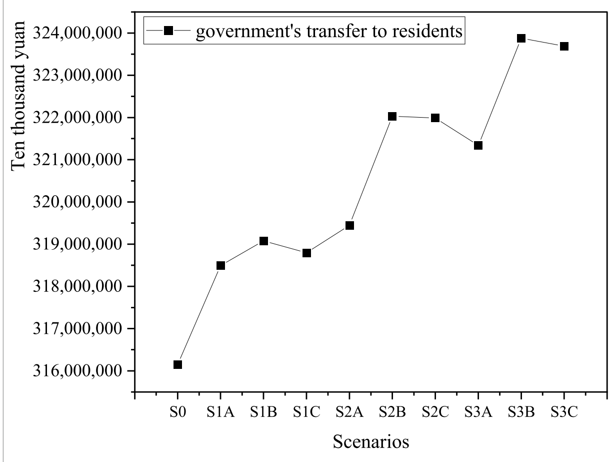

FIGURE 7
Amount of government transfers to residents (ten thousand Yuan).

and water pollution industries. Among them, the increase of water resource tax has more obvious inhibition on the two industries, indicating that water resource tax plays a more significant role in adjusting the industrial structure. In other industries and services, the output increases when the water pollution tax is increased, and technological progress decreases the magnitude of the change, while in the case of higher water resource tax, the output decreases due to higher costs, and technological progress also decreases the output. Compared with raising water pollution tax or water resource tax alone, the negative effects of raising both water pollution tax and water resource tax on the output of various industries are weakened, which is consistent with the result that the synergy of the two can reduce the negative impact on the economy. In terms of industry comparison, the negative impact of agriculture and water pollution industries is significantly stronger than that of other industries and services, while other industries and services also show a positive effect of increased production under the scenario of increased water pollution tax. The negative impact of taxation on these two industries is only shown in the scenario of increasing water resource tax, and the change is significantly lower than that of agriculture and water pollution industries, indicating that the output of industries with high water consumption and high pollution have been largely suppressed, while other industries and services have been less affected, and there is even room for industrial growth. The reason is that agriculture and water pollution industries have a larger demand for water resource and discharge of water pollutants. Higher price of water resource and the cost of emission reduction increase the cost of production, and producers pass on the tax cost to consumers in the sales price to ensure normal operation of production activities, resulting in a reduction in consumer demand and a reduction in the production scale. Conversely, other industries and services have rigid demands on water resource and are less affected by changes in water prices. Therefore, the collection of water resource tax and water pollution tax can effectively inhibit the further expansion of high-pollution and high-water-consuming industries and promote agriculture and water pollution industries to improve the efficiency of water resource utilization and reduce water pollution discharge.

5.2.3 Impact on social welfare

The Hicksian variable is used to analyze the social welfare after the policy shock (Dong et al., 2018), and the implicit function solution method is used to calculate the equivalent change EV, so that the changes in residents' welfare levels under the policy shock can be measured in monetary units. It can be seen from Figure 6 that the increase in tax burden is conducive to increasing social welfare, and the contribution of water resource tax to social welfare is particularly obvious. This is due to the fact that the water resource tax has a wider scope and a larger volume than the water pollution tax, which can increase more revenue for the government, and the increase in the tax enables the government to fully play its macro-control role.

The government makes overall arrangements for the use of taxes, and the income of enterprises and residents can be increased by raising total investment (Table 3) and transfer payments (Figure 7). Government's subsidies to residents increase with the increase of taxation. In this process, various social securities are promoted, and residents' income increases, thereby driving the improvement of social welfare.

TABLE 4 Water pollutant variation of each industry under different scenarios (%).

Sectors		Agriculture	Water pollution industry	Other industries	Service
Changes in water pollution tax	S1A	−0.625009	−0.399979	0.072932	0.028867
	S1B	−0.779806	−0.499195	0.090943	0.035919
	S1C	−8.649093	−8.415481	−7.924276	−7.970061
Changes in water resource tax	S2A	−11.082062	−9.755123	−8.221760	−8.520944
	S2B	−13.358200	−11.074324	−8.390456	−8.915443
	S2C	−20.280997	−18.182707	−15.720240	−16.202608
Changes in both policies	S3A	−18.600972	−17.239940	−15.516142	−15.820454
	S3B	−20.671966	−18.442274	−15.673667	−16.184435
	S3C	−26.982424	−24.943120	−22.424029	−22.891330

TABLE 5 Water demand variation of different industries under different scenarios (%).

Sectors		Agriculture	Water pollution industry	Other industries	Service
Changes in water pollution tax	S1A	−0.579279	−0.310457	0.101376	0.053359
	S1B	−0.722801	−0.387468	0.126461	0.066498
	S1C	−0.654030	−0.350533	0.114420	0.060214
Changes in water resource tax	S2A	−2.703605	−2.851418	−2.744252	−2.788620
	S2B	−4.164725	−4.369810	−4.220160	−4.282198
	S2C	−4.164144	−4.369509	−4.220261	−4.282251
Changes in both policies	S3A	−2.737138	−2.869089	−2.738461	−2.785569
	S3B	−4.190689	−4.383298	−4.215724	−4.279862
	S3C	−4.188048	−4.381925	−4.216176	−4.280098

5.3 Environmental effects of policy mix

5.3.1 Impact on water pollution reduction

As can be seen from Table 4, compared with the baseline scenario, the water pollutant emissions of agriculture and water pollution industries have decreased in all other scenarios. As for other industries and services, water pollutant emissions will only be reduced under the scenario of technological progress and higher water resource tax. It shows that technological progress is a key factor in promoting emission reduction in these two industries. In the absence of technological progress and the increase of water pollution tax, these two industries can only increase production to achieve economies of scale, thereby making up for the increase in production costs, so water pollutants increase instead of decrease. However, when the water resource tax is raised, the water resource tax increases the price of factors, and the tax scale is larger than the water pollution tax, which has a more obvious impact on the production cost, prompting enterprises to adjust the way of water use and improve the efficiency of water resource utilization, thereby indirectly achieving the emission reduction effect. At the same time, the emission reduction effect achieved by raising the water resource tax and the water pollution tax is higher than the superposition of the effects when the two are raised to the corresponding level, indicating that the emission reduction effect under the high tax burden is better than that of the low tax burden, which highlights the importance of using the tax pressure to motivate enterprises to transform to cleaner production methods as soon as possible.

It should be noted that technological progress has played a breakthrough and leading role in water pollution reduction. After adding the technological progress factor, the discharge of water

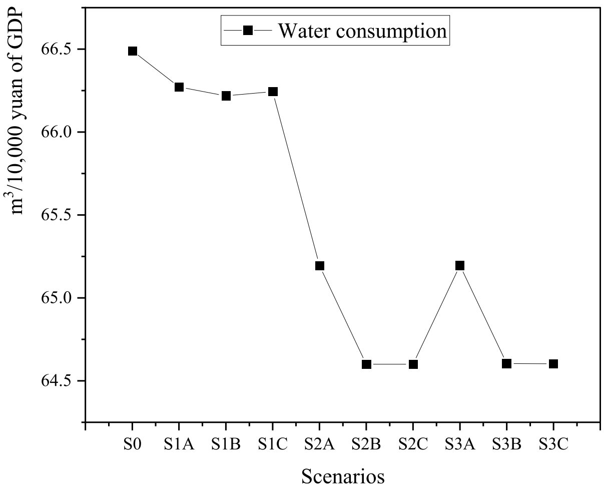

FIGURE 8
Water consumption per 10,000 Yuan of GDP (m3).

pollutants in the four sectors has dropped significantly, even reversing the trend of increasing discharge of water pollutants in other industries and services under the scenario of increasing water pollution tax. The emission reduction effect of all industries included in the four sectors is close to or even more than 8%, which shows an extremely ideal pollution reduction effect, and can also make up for the negative impact of taxation on the economy. Therefore, in order to truly achieve water pollution reduction, in addition to rationally designing the water resource tax system, it is necessary to pay more attention to technological innovation so as to accelerate the green transformation of industries and reduce pollution emissions from traditional industries.

5.3.2 Impact on resource protection

From Table 5, it can be seen that the increase of water pollution tax has gradually reduced the water resource demand of agriculture and water pollution industries, while the water resource demand of other industries and services has increased slightly, and the total scale of water resource demand has decreased, indicating that the increase of water pollution tax is beneficial to water resource conservation. With the increase of water resource tax, the water demand of all industries has fallen sharply, indicating that water tax is a powerful tool to protect water resource.

The water consumption per ten thousand Yuan of GDP is used to measure the water-use efficiency (Yao and Liu, 2021; Zhong et al., 2020), which is the ratio of total water consumption to GDP (Figure 8). It can be seen that water consumption decreases in all tax-increasing scenarios, indicating that water-use efficiency has increased, and the most significant way to save water is to increase water resource tax, illustrating that leverage of taxes prompts enterprises to adopt production methods with higher efficiency.

In the scenario of raising the water pollution tax, technological progress can mitigate the impact of policy changes on industry water demand. While in the scenarios of increasing the water resource tax and the two tax policies changing together, the role of technological progress is relatively weak, indicating that compared with technological progress and water pollution tax, water resource tax is more effective in water resource conservation. As for other industries and services, raising water pollution tax alone will prompt enterprises to consume more water resource to reduce pollution, failing to achieve the purpose of protecting water resource. However, as a factor tax, water resource tax has a wider range of impacts and has a stronger impact on economic development. If water resource tax is to be used as a tool to protect water resource, it is necessary to carefully control the level of tax burden to avoid overly severe shocks to various industries.

5.4 Optimal tax rate combination

In order to calculate the optimal tax rate, so that the water resource tax system can not only play the role of saving water resource and reducing water pollution but also minimize the negative impact on economic output, referring to the method of Zeng et al, (2019), the formula is set as follows:

$$\mu = a\bullet(\Delta y) - b\bullet(\Delta e) - (1 - a - b)\bullet(\Delta r). \quad (9)$$

Among them, a, b, and $1 - a - b$ are the relative weights of pollution reduction, resource protection, and economic development, respectively. Δe is the proportion of water pollutant reduction, Δr is the proportion of water consumption reduction, and Δy is the degree of negative impact on economic development, including GDP, import, and export. In order to calculate the optimal tax burden standard, 8% technological progress is used as the benchmark condition in the set scenarios. The purpose of the research is consistent with the government's goal of emphasizing economic recovery and development, giving higher weight to economic development. Table 6 shows the combination of water resource tax and water pollution tax that can achieve the targets of water saving and emission reduction and have the least negative impact on economic output when the values of a are 0.7 and 0.8.

According to Table 6, when the water resource tax is 4 Yuan/m3, the indices are better than other scenarios under the same water pollution tax level. The tax rate combination that can achieve the optimal government tax target is 4 Yuan/m3 for water resource tax, and 5.6–8.4 Yuan/pollution equivalent for water pollution tax. Compared with Tang Ming's result (2018b) that the optimal tax rate for water pollution tax is four times the current tax rate (5.6 Yuan/

TABLE 6 Optimization of tax objectives.

Water resource tax/Yuan/m3	Water pollution tax/Yuan/pollution equivalent	a = 0.7	a = 0.8
2	4.2	0.001326	-0.000130
	5.6	0.001860	−0.000260
	7	0.002890	0.000010
	8.4	0.003655	0.000145
3	1.4	0.002445	0.005255
	4.2	0.003205	0.004595
	5.6	0.004635	0.005465
	7	0.005365	0.005535
	8.4	0.005360	0.004740
4	1.4	0.002825	0.006175
	4.2	0.004250	0.006250
	5.6	0.004945	0.006255
	7	0.005375	0.006125
	8.4	0.006070	0.006130
5	1.4	0.001655	0.004645
	4.2	0.003745	0.005455
	5.6	0.003475	0.004525
	7	0.004870	0.005330
	8.4	0.005965	0.005935
6	1.4	−0.000780	−0.001834
	4.2	0.000023	0.000005
	5.6	0.000023	0.000004
	7	0.000023	0.000004
	8.4	−0.034205	−0.044595

pollution equivalent), the estimated range of water pollution tax is higher. This is because the model assumes that the water pollution tax would be used by the government for water pollution control, but according to statistics, the government's annual investment in water pollution control is much higher than the actual amount of water pollution tax collected. Only cities with high tax rates, such as Beijing and Tianjin, can make up for government investment in water pollution control, and their tax burdens are in the range of 12–14 Yuan/pollution equivalent, which are higher than the estimated tax rate. Other regions have lower tax burdens due to restrictions on the level of economic development. This result is also consistent with Tang Ming, indicating that cities with higher economic development levels are also more scientific in tax rate setting.

6 Discussion

6.1 Findings and inferences

Due to the extensive and complicated impacts of water resource tax policies, analyzing the impacts of these policies before implementation would be critical for policymakers to make informed decisions. The results of this research could enable local authorities to implement specific water tax policies according to the actual conditions and development needs.

Contrary to the empirical result obtained by Mustafa Kamal (2021) that "fiscal policy significantly increases environmental pollution," this study finds that the water resource tax and water pollution tax synergistically promote the reduction of water pollutants and the conservation of water resource. Compared with a single policy, the combination of the two can reduce the negative impact of separate implementation on economic growth and social welfare and can more significantly exert the environmental effect of water saving and emission reduction. Due to the large amount of water resource tax, it can promote water conservation and waste reduction more effectively, but will have a more significant negative impact on the economy. Raising the water pollution tax is also beneficial to inhibit water waste and pollution emissions.

Due to the different degrees of reliance on water resource in different industries, the implementation of water tax policies and the increase in tax burden will have a strong inhibitory effect on agriculture and water-polluting industries, while other industries and services will be less affected, indicating that taxes force the industries with high water consumption and high pollution to reduce the production scale and promote the rationalization of the industrial structure.

Previous studies by scholars have found that increasing water prices, restricting water consumption in high-water-consuming industries, and increasing tax burdens will all have negative impacts on economic and social welfares (Yan and Zhou, 2010; Shi and Shen, 2016; Chen, 2019; Wu et al., 2021), but the results of this study showed that the water resource tax system can not only achieve the target of water saving and emission reduction but also improve social welfare under the condition of ensuring economic stability if two taxes could be co-designed. Although the imposition of water resource tax and water pollution tax will cause output loss in the production sector, resulting in negative impacts on the economy driven by the role of the market, the tax policies enable the government to fully play its role in improving social welfare through transfer payments. The water resource tax system has unique advantages in achieving a win–win situation between economic development and environmental protection.

The research proves that the water resource tax system is an effective tool for water saving and emission reduction, but its negative impact on the economy is also significant. Therefore, the optimal tax rate is calculated considering government's emphasis on economic development. The results show that when the water resource tax is 4 Yuan/m3, and the water pollution tax is in the range of 5.6–8.4 Yuan/pollution equivalent, the effects of water resource tax system are better than other scenarios, and that result is consistent with Zeng et al. (2019), who believes that the optimal balance of environment and economy can be reached when water pollutants tax is 5.6 Yuan/pollution equivalent. The setting is also in line with the tax rate range, which is currently implemented in China: regions can choose the water pollution tax rate applicable to the region within the range considering the economic development and the ability to bear the tax rate. However, the current water pollution tax and water resource tax in various regions have the problem of low tax rates. So the tax cannot play the role of constraining enterprises to change their production methods, and it is difficult for the tax to play the effect of pollution control and water saving.

Moreover, this study agrees with the conclusion of previous research (Atif et al., 2022) that technological progress is the most effective element of water environment governance, and technological innovation can reduce negative economic consequences. Through technological innovation and updating, the cost pressure caused by tax increases on enterprises can be alleviated, and enterprises can transform into cleaner production methods. So, technological innovation is an effective way to ensure a balance between economic and ecological well-being.

According to the analysis results of this study, the impact of the reform of the water resource tax system on economic development is within an acceptable range, which provides a basis for the regional tax coordination design and tax rate determination, according to the actual needs of economic development and water resource governance.

6.2 Policy implications

As the study assesses the impacts of water resource tax policies in China, we hope that the findings can also have some policy implications. According to the previously discussed results, nationwide recommendations to the policymakers can be noted. First, the water resource tax system is a favorable tool to achieve the goal of green economy transformation while ensuring social welfare. In this process, governments should play a leading role and use water taxation for infrastructure construction, thereby enhancing social welfare and improving the water environment. Second, the collaborative design of the two taxes should be strengthened since water resource tax and water pollution tax can synergistically promote water saving and emission reduction and can reduce the negative impact on the economy and society. Third, as the current tax burden is very low to fully compensate for the pollution and water resource shortage caused by economic development, water pollution tax, and water resource tax should be appropriately raised to facilitate enterprises to reduce pollution and waste. Fourth, more importance should be attached to technological progress, which can not only achieve good ecological governance results but also reduce the negative impact of taxation on the economy. We should increase our support for the development of high-tech industries, improve the level of agricultural modernization, and urge enterprises to improve wastewater treatment technology and convert to water-saving equipment. Fifth, since taxation will have a negative effect on economic operation, the reform of the water resource tax system should be flexibly adjusted according to the specific circumstances of economic development such as downturn, recovery, and prosperity. Tax promotion should be coordinated with corresponding tax incentives and subsidies to ensure that the system reform can be completed smoothly.

6.3 Model comparisons and limitations

Compared with other evaluation models, the advantages of the WCGE model are as follows: 1) it has a solid economic foundation, and through the depiction of the interrelationship between economic subjects including governments, enterprises, and residents, a complete analytical framework has been formed, which can quantitatively measure the multiple impacts of macro policies on social and economic development; 2) multiple sectors and multiple markets can be described at the same time, considering the price and quantity relationship of economic entities when the economic constraints are met under the balance of supply and demand, and the portrayal of economic behavior is more complex, which has practical significance; and 3) it has a flexible theoretical framework, which can be enriched according to the needs of research, and with the increase of model complexity, its interpretation, reduction, and prediction of reality will be more accurate. Therefore, applying CGE models can increase the accuracy of policy effect predictions and the model is widely applicable in the study of other resource policies. Meanwhile, the WCGE model also considers the natural properties of water resource and the reality that agriculture is in a weak link in China's industrial structure, so the model first takes into account the self-purification capacity of water resources and government subsidies for agriculture. Therefore, WCGE constructed in this study could generate more reliable results through incorporating various industries and multiple entities based on input–output and reproducing actual situation, and its focus on the natural properties of water resource could also inspire other research on resource policies.

The research also comes with two main limitations and needs to be further improved. First, the CGE model is a favorable tool for policy evaluation; however, multi-scenario forecasts rely on the data of the base year. Since China's input–output table is released every 5 years, the main source of data at present is the China's input–output table of 2018. Data with different base periods may lead to different simulation results. Second, due to the difference in water resource endowment and regional industrial planning, and different ways of using water in regions, a multi-regional model with a more complex structure should be developed in further research.

7 Conclusion

As water resource is the basic means of production and water resource tax policies are closely related to economic development and human lives, especially water resource tax, which China currently only levies in pilot cities, assessing the impacts of changes in these policies accurately is crucial to ensure the tax policies that are appropriately designed and implemented so as to achieve the desired goals of resource conservation and environmental governance while avoid emerging severe socio-economic problems. To analyze the impacts of water tax policies composed of water resource tax and water pollution tax, the WCGE model that first considers water self-purification capacity and agricultural subsidies was constructed, coupled with the water resource SAM table that was compiled based on the 2018 input–output table of China. Water resource and water pollution are added into the WCGE model as production material and contaminants, respectively, in the production process. The model constructed in this study is also applicable to the study of other policies, and its focus on the natural properties of resources and their ability to reproduce actual situations can inspire other research on resource policies. The reliable results of the in-depth analysis of the impacts of water resource tax policies enrich the theory of the water resource management, contribute to further studies of water resource tax policies, and provide references for the determination of the tax burden rate and the appropriate design and implementation of the tax system combination in practice. With a better understanding of the policy impacts on economy, society, and environment, the local authorities could constitute the most appropriate ways to validate the implementation of water tax policies, according to the reality of regional needs.

Future challenges may involve establishing a multi-regional model in water to simulate the impacts of policies in detail considering the development and water availability, while decision-making procedures at the level of the different localities would constitute one of the most appropriate ways to validate the implementation of the tax policies, according to their needs and perceptions of the region. When discussing the environmental taxation, we must not forget to evaluate its impacts in a balanced way, considering risks and benefits, that is, the trade-off between economic development and environmental protection. We, therefore, believe that the results in this study will inspire future research on water management.

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

CX: Conceptualization, Supervision, Writing—review and editing, Funding acquisition FG (corresponding author): Conceptualization, Methodology, Visualization, Writing, Revising—original draft. AW: Final critical revision 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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.982085/full#supplementary-material

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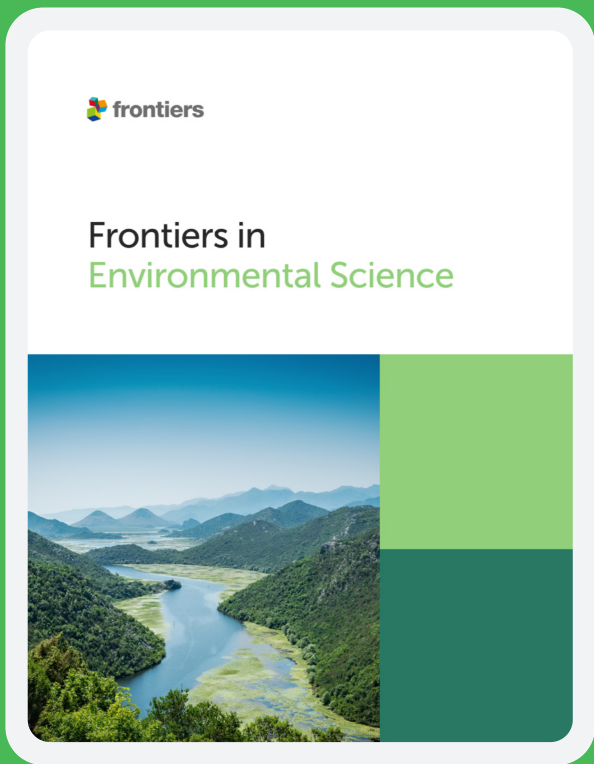

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