Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 18 March 2025
DOI 10.3389/fenvs.2025.1517472

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OPEN ACCESS

EDITED BY
Jiachao Peng,
Wuhan Institute of Technology, China

REVIEWED BY
Paul Terhemba Iorember,
Nile University of Nigeria, Nigeria
Tsung Han Tai,
Shandong University, China

*CORRESPONDENCE
Yiniu Cui,
n15234698731@163.com
Zizhuo Li,
17596979966@163.com
Jingjing Wang,
wangjingjing1115@neau.edu.cn
Shuo Qiao,
17637036386@163.com

RECEIVED 26 October 2024
ACCEPTED 25 February 2025
PUBLISHED 18 March 2025

CITATION
Guo M, Cui Y, Li Z, Wang J and Qiao S (2025) Global carbon emission governance and green trade: the moderating role of political stability and trade diversity.
Front. Environ. Sci. 13:1517472.
doi: 10.3389/fenvs.2025.1517472

Global carbon emission governance and green trade: the moderating role of political stability and trade diversity

Mengyao Guo[1], Yiniu Cui[1]*, Zizhuo Li[1]*, Jingjing Wang[2]* and Shuo Qiao[3]*

[1]Yunnan University, Kunming, Yunnan, China, [2]University of Science and Technology Beijing, Beijing, China, [3]Henan University of Economics and Law, Henan, China

In contrast to traditional trade, green trade fully considers the social costs of production, investment, and export following economic activities, building upon environmental governance and protection. While the promotion of green trade is a historical inevitability, countries must actively foster collaboration in new trade initiatives to meet carbon reduction targets. However, during the process of encouraging the expansion of green trade, there is a risk that countries may further increase their carbon emissions, thereby exacerbating environmental degradation. This study utilizes panel data from G20 countries between 2000 and 2022 to examine the relationship between carbon emissions and green trade through an Ordinary Least Squares regression model, with the primary objective of determining whether green trade increases or decreases carbon emissions. To further explore the moderating role of trade diversity and political stability on the relationship between carbon emissions and green trade, a moderating effect regression model is also employed. Additionally, this paper introduces a quantile regression model to assess the varying impact of green trade on carbon emissions across different quantiles. The study's findings indicate that green trade tends to result in higher carbon emissions. Under conditions of political stability, the potential for green trade to reduce carbon emissions diminishes. Conversely, the positive impact of trade diversification inhibits the positive effects of green trade on carbon emissions. The coefficient of green trade is positive and steadily increases across various quantiles of carbon emissions. At the 0.9 quantile, the association is significantly positive, offering further evidence that green trade could lead to increased carbon emissions. Based on these findings, the paper suggests that a significant reduction in carbon emissions may not be achievable in the near future, and that the path to expanding green trade is both challenging and protracted. Therefore, governments worldwide must carefully implement green trade practices, protect the environment, achieve sustainable economic growth, and promote the rational allocation of resources as prerequisites for the long-term development of the green sector.

KEYWORDS

green trade, political stability, trade diversification, moderating effect regression model, quantile regression model

1 Introduction

As the process of globalization continues to advance, international trade among countries has become increasingly frequent. Many nations are actively engaging in global trade, leveraging their competitive advantages to generate economic benefits and substantially enhancing international economic efficiency (Konisky and Carley, 2021; Cui et al., 2022; Derindag et al., 2023). The expansion of global trade has contributed to a rise in total trade volumes. According to data published by the United Nations, global trade reached $32 trillion in 2022. The growth of global trade has also led to a geographical separation between countries that specialize in production and those that primarily consume. Due to variations in economic development and environmental governance capacities across countries, trade expansion has, in many cases, intensified environmental pollution (Tawiah et al., 2021). Data from the World Bank indicates that global carbon dioxide emissions reached 33.884 billion tons in 2021, marking a 5.6% increase from 2020. In the early stages of trade development, many developing countries—which often serve as the primary production hubs—focus on reducing costs to attract foreign investment and increase their share of global trade. This approach inevitably places additional burdens on the local environment (Carrasco and Tovar-García, 2021). Furthermore, some developed countries may, in the course of trade development, offload their more polluting industries to developing nations, thereby further worsening the environmental conditions in those regions (Tawiah et al., 2021; Falzon, 2023).

Global trade, as a crucial driver of economic development in an interconnected world, not only fosters economic growth but also elevates the risk of increased carbon emissions (Saidi and Omri, 2020). The flourishing of global trade amplifies environmental costs, creating a conflict between trade expansion and environmental sustainability, particularly between developed and developing nations. While trade encourages "environmental improvement" in developed countries through the adoption of new technologies and the promotion of green industrial upgrades, it simultaneously exports carbon emissions and environmental pollution to developing countries, resulting in "environmental degradation" in those regions (Saidi and Omri, 2020; Tawiah et al., 2021).

However, this process can lead to "industrial hollowing out" in developed countries as industries are relocated abroad, potentially causing economic decline that may offset the initial benefits of trade. Meanwhile, developing countries not only suffer environmental degradation, effectively becoming "pollution havens," but also face obstacles in developing high-tech industries. The dominance of high-polluting enterprises hinders their ability to achieve significant qualitative economic advancements (Carrasco and Tovar-García, 2021; Derindag et al., 2023).

At the same time, green trade may also generate a series of negative spillover effects on non-participating countries and the global supply chain. Firstly, countries that do not engage in green trade could face a competitive disadvantage. Due to their inability to meet stringent environmental standards, these countries may see a decline in exports and a loss of market share internationally, which could impede their economic growth (Derindag et al., 2023). Secondly, green trade could trigger carbon leakage, where industries with high pollution and emissions relocate to non-participating countries with less rigorous environmental regulations, thereby avoiding strict environmental policies. This shift could result in increased carbon emissions in those countries (Saidi and Omri, 2020). Furthermore, within the global supply chain, green trade may lead to supply chain restructuring. Countries or companies unable to adapt to the new green standards may find themselves excluded from the supply chain, leading to economic losses and employment challenges (Adedoyin et al., 2021).

The advancement of globalization is indeed an irreversible trend, necessitating that countries engaged in global trade place greater emphasis on the importance of sustainable development. Both developed and developing nations must prioritize the green transformation of trade to ensure the smooth functioning of the global economy while safeguarding the environment. Presently, there is a growing awareness of the significance of transitioning to a green economy and achieving an optimal allocation of resources.

The *Glasgow Climate Agreement*, ratified by the *United Nations Framework Convention on Climate Change* (UNFCCC) in 2021, commits countries to uphold the *Paris Agreement*'s objectives, including limiting the global temperature rise to 1.5°C. In response, nations are actively pursuing these goals by setting national carbon neutrality targets (Konisky and Carley, 2021). For example, China aims to achieve carbon neutrality by 2060 and to peak its carbon emissions before 2030. Similarly, the European Union has implemented various policies, such as the *European Green Deal and the European Climate Law*, with the goal of reaching carbon neutrality by 2050.

In this context, countries are actively promoting the development of green industries, products, and sustainable transportation in alignment with their roles in the global trade chain. This collaborative effort is facilitating the growth of green trade and contributing to carbon reduction (Adedoyin et al., 2021; Derindag et al., 2023). As trade structures evolve in a healthier direction, and as trade restructuring and the division of labor among nations progress (Wang et al., 2024), both developing and developed countries can forge new cooperative relationships. This evolution in trade structures is expected to address issues such as "pollution havens" and "industrial hollowing out," leading to improved outcomes (Balsalobre-Lorente et al., 2022).

However, green trade may also fall short in effectively promoting carbon emissions reduction. The *General Agreement on Tariffs and Trade* (GATT) has indicated that the development of green trade might trigger an increase in other trade costs, potentially leading to new forms of environmental pollution (Liu et al., 2020). Balcilar et al. (2023) noted that, under the framework of green trade, some countries impose environmental taxes, eliminate fossil fuel subsidies, and implement protective policies for green industries. These measures can increase the difficulty of exporting green products and force countries lacking green technology to allocate more fiscal resources during trade (Cui et al., 2023; Kammerer and Ingold, 2023). In this process, green trade may result in a more challenging trading environment, particularly for countries with a scarcity of green industries, which may not benefit from these trends. This situation could also lead these adversely affected countries to increasingly "decouple," contributing to deglobalization and even potential instability in the international political landscape (Dou et al., 2021). In this context, the World

Trade Organization (WTO) and the International Monetary Fund (IMF) have repeatedly stressed the importance of trade liberalization and diversification. They advocate for the reduction of trade barriers, the abandonment of decoupling strategies, and joint efforts to maintain international political stability, thereby further promoting the healthy development of trade (Doğan et al., 2022; Baajike et al., 2024). Only through these measures can the true realization of low-carbon green trade be achieved.

Green trade not only emphasizes the environmental sustainability and diversification of products and transportation modes but also aims to reduce costs and barriers to trade flows between countries during the trading process. It advocates for productive cooperation between developed and developing countries to achieve a more rational utilization of resources (Tawiah et al., 2021). Currently, the WTO has established the *Trade Facilitation Agreement* (TFA) to further encourage the shift toward lower-carbon emissions trading. This agreement supports open trade and promotes trade diversification, (Şanlı and Gülbay, 2023) encouraging countries to move away from a sole reliance on individual products and services (Huang et al., 2023). Through this approach, countries can enhance their competitiveness through diversified trade and allocate more resources and energy toward environmental governance.

Although the primary goal of green trade was to reduce carbon emissions by promoting the circulation of environmental technologies and products, evidence has shown that in certain situations, green trade may actually result in increased carbon emissions (Saidi and Omri, 2020). This outcome has prompted a reevaluation of the effectiveness of green trade implementation, indicating the need to consider additional external factors that influence its environmental impact. In this context, political stability and trade diversification emerge as two crucial moderating factors that can significantly affect the direction and intensity of green trade's impact on carbon emissions. Political stability strengthens the environmental benefits of green trade by ensuring consistent and enforceable policies. Meanwhile, trade diversification helps mitigate the rise in carbon emissions under the green trade framework by optimizing industrial structures and integrating green technologies, thereby reducing dependence on high-pollution industries (Cui et al., 2022). Thus, examining how these two factors moderate the impact of green trade on carbon emissions is essential for a comprehensive understanding of the effectiveness of green trade implementation.

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The existing study on the link between green trade and carbon emissions by researchers includes the following limitations:

Firstly, as a novel concept in trade, current research on green trade is predominantly theoretical and lacks comprehensive, systematic analysis ranging from theoretical frameworks to measurable assessments of its impact on carbon emissions. Additionally, many scholars tend to overemphasize the influence of green trade on global carbon emissions, leading to a biased perspective on their relationship. This often results in regression analyses that do not accurately reflect the true correlation between green trade and carbon emissions (Balcilar et al., 2023).

Secondly, the majority of research on trade-related carbon emissions focuses on the impact of Foreign Direct Investment (FDI) on these emissions (Derindag et al., 2023), yet it fails to explicitly define the term "green trade." However, FDI represents only one aspect of green trade. Without a comprehensive framework for green trade, any depiction of the impact of global trade on carbon emissions will remain incomplete.

Finally, some scholars have highlighted the possibility that green trade might lead to an increase in carbon emissions (Balcilar et al., 2023). These researchers also acknowledge that political instability could trigger another wave of rising carbon emissions. Moreover, they recognize that trade protection policies and an overemphasis on single-track trade development impede the advancement of green trade, which further exacerbates carbon emissions (Adedoyin et al., 2021). However, few scholars have examined the impact of trade diversification and political stability on carbon emissions and green trade. Specifically, the effect of trade diversification and political stability on the relationship between green trade and carbon emissions has been largely overlooked.

In light of this, the following innovations are present in this article:

This article is grounded in theoretical research. After a comprehensive analysis of the potential impacts of green trade on carbon emissions, Ordinary Least Squares (OLS) and quantile regression are employed to further examine the relationship between the two variables. Additionally, this study evaluates the effect of green trade on carbon emissions using data from the Group of Twenty (G20) countries. There are several reasons for focusing on the G20 countries: Firstly, these countries represent 80% of global GDP and 75% of international trade (Erdoğan et al., 2020). As major players in global trade, they include both developed and developing nations, making their data more compelling and widely applicable. Secondly, G20 countries are responsible for 67% of global carbon emissions. Studying these countries can help researchers explore effective policies and measures to reduce carbon emissions through green trade, ultimately contributing to a decrease in global carbon emissions and promoting genuine environmental protection. Lastly, most G20 countries are engaged in regional free trade agreements within their respective groups, making their data particularly relevant for discussions on trade diversification (Huang et al., 2023).

Secondly, green trade primarily focuses on the representation of green products and green services. To address this, the article utilizes the United Nations (UN) Comtrade database and classifies traded goods and services based on the green product list issued by the Asia-Pacific Economic Cooperation (APEC) in 2018 (Kang and Lee, 2021). Using this classification, all categories of goods and services related to "green trade" are systematically summarized, offering a more detailed depiction of green trade. Only through such an approach can the relationship between green trade and carbon emissions be more accurately reflected.

Finally, this article specifically examines the roles of political stability and trade diversification in the context of green trade and carbon emissions. It provides a detailed analysis of how political stability and trade diversification influence these factors, further highlighting the significance of both political stability and trade diversification.

This article presents the OLS regression model to investigate the impact of green trade on carbon emissions, emphasizing the importance of developing green trade and the urgency of achieving carbon neutrality. Additionally, it introduces the moderating effect regression model to examine the interrelationships among political stability, trade diversification, green trade, and carbon emissions, further highlighting the significance of political stability and trade diversification. To explore variations in the effect of green trade on carbon emissions across different levels of the distribution, the article also introduces the quantile regression model.

Accordingly, the structure of this paper is organized as follows: Section 2 presents a literature review and proposes the three hypotheses of the study; Section 3 outlines the research data and methodology; Section 4 presents the empirical analysis; and the final section offers conclusions and policy recommendations.

2 Literature review and hypothesis formulation

2.1 Green trade and carbon emissions

The foundation of green trade lies in environmental regulation and protection, distinguishing it from traditional trade (Kang and Lee, 2021). Additionally, green trade fully incorporates trade costs, which encompass not only the social costs of production, investment, and exports but also the environmental costs that arise from these economic activities. According to the theory of new institutional economics, the lack of clearly defined property rights for environmental and energy resources means that the environmental costs associated with trade cannot be internalized. This results in an inefficient allocation of both social and environmental costs in the pricing of traded products (Kang and Lee, 2021; Can et al., 2022). Consequently, a key focus of green trade is addressing the externalities of trade, specifically the environmental problems that emerge during the trade process (Khan et al., 2020).

As global production activities and trade exchanges continue to increase, the consumption of resources and energy is also rising, significantly impacting the environment (Carrasco and Tovar-García, 2021). The concepts of the "pollution halo" and "pollution haven" form the foundation of current research on green trade and carbon emissions. The pollution halo theory suggests that multinational firms engaging in direct investment in other countries bring advanced production technologies and managerial expertise to the host nation, enhancing its productivity and fostering economic growth (Balcilar et al., 2023). According to the theory of regional specialization in trade, this process enables the host country to upgrade its industrial structure through the adoption of these emerging technologies, leading to reduced energy consumption and subsequently lower environmental pollution and carbon emissions (Wang et al., 2023).

However, Carrasco and Tovar-García (2021) emphasize that the majority of carbon emissions today originate from developing countries. This is attributed to their economic and technological backwardness, low productivity, and the dominance of energy-intensive and labor-intensive industries, all of which contribute to the deterioration of local environmental conditions. Therefore, promoting the modernization of the industrial structure in developing nations is a key objective in achieving carbon neutrality. According to Tawiah et al. (2021), developing countries must actively attract investments from high-tech firms, provide local communities with appropriate technological support, and facilitate the upgrading of their industrial structures to promote green development.

Nevertheless, the conclusion of the pollution haven hypothesis suggests the opposite. That is, the majority of foreign direct investment (FDI) merely transfers the low-end segments of businesses from developed to developing countries (Wang et al., 2023). According to the theory of comparative advantage, these highly polluting foreign-owned enterprises are attracted to the low-cost raw materials and cheaper labor in developing countries, where environmental regulations are relatively lenient. To avoid stricter environmental regulations in their home countries, these firms relocate their operations to developing countries with lower costs.

Moreover, the negative impact of green trade on global supply chains is significant and cannot be ignored. Under new green standards, some developing countries and small and medium-sized enterprises (SMEs) may struggle to adapt due to a lack of access to green technologies and financial support. As a result, they face the risk of being excluded from global supply chains (Usman et al., 2024). This exclusion could lead to a loss of market share and competitive advantage in international trade, further deepening inequalities within global supply chains. Developed countries, with their technological and financial resources, can swiftly adapt and dominate the emerging green supply chains. In contrast, developing countries, constrained by limited resources, may become increasingly marginalized, hindering their economic growth (Demiral and Demiral, 2021). Tawiah et al. (2021) highlight that this uneven restructuring of supply chains not only impacts the economic development of developing countries but also compromises the fairness and inclusivity of global green trade.

In this process, due to the lack of sufficient regulatory constraints on corporate behavior and inadequate funding for environmental governance in developing countries (Demiral and Demiral, 2021; Falzon, 2023; Kammerer and Ingold, 2023), these countries not only fail to receive adequate support from foreign high-tech firms but also experience further degradation of their environment, leading to a net loss. Meanwhile, in developed countries, while the relocation of high-polluting enterprises may lead to environmental improvements, the reduction in domestic industries could cause rising unemployment and economic pressure, resulting in a decline in consumer purchasing power (Ajl, 2021; Brown et al., 2023). Consequently, global trade may stagnate, undermining the original goals of carbon reduction policies.

Conversely, some scholars have integrated the conclusions of the two hypotheses mentioned above. The Environmental Kuznets Curve (EKC) theory posits that environmental degradation is an inevitable consequence as trade develops (Agozie et al., 2022). This is because, in the early stages of trade expansion, friction in international cooperation occurs to varying degrees, which partially increases trade costs (Liu et al., 2020). Additionally, each country undergoes a process where pollution initially rises and then declines. In the early stages of economic development, there is often a lack of capital to invest in high-tech industries. Consequently, countries are compelled to foster low-cost but highly polluting businesses to accumulate capital, acquire advanced production technologies, introduce high-tech enterprises, upgrade their industrial structures, and promote local green development (Doğan et al., 2022). During this phase, sacrificing the environment to some extent is unavoidable for the initial growth of the local economy (Balsalobre-Lorente et al., 2022).

However, once a country's economy has developed sufficiently, the principle of sustainable development suggests that people will gradually recognize that economic growth alone is unsustainable, and a healthy, green living environment is essential. At this stage, governments and enterprises will actively promote green industries, collaborate with other nations to establish a new trade paradigm, maintain a healthy trading environment, and jointly protect the environment (Konisky and Carley, 2021). Ultimately, global pollution will decrease, and a true harmony between humans and nature will be achieved.

Agozie et al. (2022) assert that the green transformation of global trade is a lengthy and challenging process. This is because it entails not only the upgrading of production and consumption patterns but also the modernization of transportation systems, human capital, and trade operations, among other areas. Until these aspects are effectively renewed and replaced, there is a risk of unintended consequences, potentially resulting in more severe environmental degradation. The emergence of new environmental challenges or trade barriers is a concern, given the high costs associated with manufacturing green products, the expense of utilizing renewable energy for transportation, and the reluctance of some countries to actively support the development of green industries (Liu et al., 2020; Tian et al., 2022). Consequently, countries must carefully consider the implications when vigorously promoting green trade.

In summary, the reduction of carbon emissions driven by green trade is not an immediate process. At the present stage, many countries have yet to transition away from high-polluting industries for production, which continue to serve as the backbone of economic development in most nations (Demiral and Demiral, 2021; Kammerer and Ingold, 2023). Consequently, regardless of whether the current trade focuses on green products or countries actively promote the use of clean energy, some degree of environmental pollution remains inevitable. Therefore, further research is needed to examine how green trade impacts carbon emissions, as it has the potential to either raise or lower them. Based on this, the study proposes the following hypothesis.

Hypothesis 1: Green trade will increase carbon emissions.

2.2 Political stability, trade diversification and green trade and carbon emissions

The concept of comparative advantage forms the theoretical basis for trade diversification. According to this theory, countries can leverage their unique advantages to engage in global trade in the most efficient way possible (Adedoyin et al., 2021). Within this framework, the context of free trade offers participating countries a more favorable trade environment, facilitating more convenient and diverse trade opportunities (Konisky and Carley, 2021).

In recent years, the increase in trade tariffs and carbon emissions taxes has led to a deteriorating trade environment. As a result, scholars are actively investigating the relationship between political stability, trade diversification, green trade, and carbon emissions (Kang and Lee, 2021; Cui et al., 2024). Unfortunately, this situation not only hampers the effective promotion of green trade but also obstructs the progress of global trade. Moreover, it potentially exacerbates the instability of international politics. Despite the UNFCCC and the *Kyoto Protocol*'s repeated assertions that nations should not use environmental protection as a pretext for trade protection (Kang, 2020; Kang and Lee, 2021), the practice of trade protection.

Liu et al. (2020) and Falzon (2023) highlighted that as public awareness of environmental protection increases, many countries have implemented relevant environmental taxes and policies to curb high energy consumption and restrict production by energy-intensive enterprises. While this has provided some level of protection for the local environment, certain companies and individuals, seeking to evade regulations, have relocated their high-consumption and energy-intensive operations to regions with less stringent environmental oversight. Consequently, this has led to increased pollution in those areas.

At the same time, some countries, aiming to safeguard domestic employment and their economic environment, have restricted excessive trade with numerous other nations, contributing to a trend of deglobalization. This limitation of trade to primarily one direction has intensified trade friction between countries (Rehman et al., 2021). In this process, these nations have compromised the economic interests of others for their own benefit, resulting in elevated trade costs for the countries left out (Dou et al., 2021). Although countries are actively promoting relevant green policies to develop a diversified pathway for recyclable green trade and to foster green development, such unfavorable trade environments are likely to give rise to new forms of environmental pollution (Wang et al., 2023).

The fundamental aim of green trade is to incorporate the concept of sustainable development, facilitating beneficial trade and economic exchanges that simultaneously protect the environment. It emphasizes the vigorous promotion of emerging technologies to foster diversified trade growth among nations, ultimately achieving economic circulation and jointly safeguarding the planet's ecosystem (Kang and Lee, 2021). However, it is clear that the current trajectory of development is diverging from the original objectives of green trade advocates.

Harrison (2010) and Ajl (2021) argue that environmental governance has, in some cases, become a tool for political leverage by developed countries, where global influence grants priority over environmental stewardship. At this stage, environmental governance has transformed from a purely ecological concern into a political one. Some countries, seeking to gain an advantageous position in the international political and economic landscape, engage in trade protectionism under the guise of environmental preservation. In doing so, they disregard the interests of other nations and distort international trade by arbitrarily adjusting tariffs (Ajl, 2021; Böhringer et al., 2021; Falzon, 2023). Consequently, the international political climate has become increasingly turbulent (Şanlı and Gülbay Yiğiteli 2023). It is evident that only a stable political and economic environment can effectively support green trade and unite global efforts to collectively address environmental challenges. Jiang et al. (2022) emphasize that nations enacting trade protection laws must adopt a long-term perspective on economic growth, and these countries can only prioritize carbon emissions reduction against a backdrop of stability, security, and peace.

Green trade currently has a delayed impact on reducing carbon emissions. In fact, it may exacerbate environmental issues in the early stages of the green economy's development. Given that mutual cooperation can help reduce carbon emissions, governments from various nations should convene to discuss how green trade can be advanced (Dou et al., 2021; Tian et al., 2022). Consequently, Chen et al. (2023) and Falzon (2023) highlight that only through the collective efforts of countries, utilizing healthy and appropriate methods to foster cooperation, actively maintaining international political stability, and ensuring a stable global economic environment, can more emerging technologies and talents be engaged in building the pathway to green development, ultimately achieving carbon reduction goals and creating a better global environment. Based on this, countries need to reduce current trade barriers, maintain political stability, and return to a state of free trade. Thus, the following Hypothesis 2 is proposed in this paper.

Hypothesis 2: Political stability acts as a moderating factor in the relationship between green trade and carbon emissions. Specifically, as the political climate becomes more stable, countries may reduce the negative impact of green trade on carbon emissions.

Indeed, according to relevant theories of classical economics, the diversified development of trade can only be truly promoted under the conditions of free trade. This, in turn, encourages the growth of the green economy and facilitates a genuine reduction in carbon emissions. Dai and Du (2023) suggest that governments must champion free trade to support the varied growth of green trade, especially since the current development of green products remains limited, and the influence of low-carbon sectors is relatively weak. Consequently, economically developed nations should actively assist developing countries in economic growth by helping them cultivate high-tech talent, fostering the development of diverse trade, and establishing themselves as leading nations. This support is crucial as most developing nations lack the technological expertise and talent required to drive the growth of green trade (Jiang et al., 2022). According to Wang et al. (2023), trade liberalization incentivizes countries to produce more environmentally friendly goods, fosters the diversified development of green sectors, and promotes varied trade growth. Furthermore, encouraging diverse trade can help nations better manage environmental challenges.

In conclusion, only by vigorously promoting diversified trade development can governments find truly suitable trading methods amid globalization, further develop green industries tailored to their countries, upgrade their industrial structures, position their countries advantageously in global trade, and achieve benign trade competition (Dai and Du, 2023). Baajike et al. (2024) point out that increasing trade barriers and advocating deglobalization will only cause a country to "derail" from the global economy, accelerating its economic decline. At the same time, the WTO also emphasizes that trade diversification and environmental protection, along with the interests of all countries, are not contradictory; they are complementary and mutually reinforcing. A favorable trade environment is essential to promote diversified trade development among countries, thereby achieving a rational allocation of resources and fostering harmonious coexistence between humans and nature. Therefore, this paper proposes Hypothesis 3.

Hypothesis 3: The impact of green trade on carbon emissions is moderated by trade diversification. Specifically, as nations diversify their trade, the positive effect of green trade on carbon emissions decreases, and in this context, green trade can ultimately have a negative impact on carbon emissions.

3 Methodology and data

3.1 Methodology

3.1.1 OLS panel regression model construction

To verify the above hypothesis, this paper first constructs a basic linear model (OLS) to explore the impact of green trade on carbon emissions. The model is represented as Equation 1:

$$\mathrm{pco2}_{it} = a_0 + \beta_1 \ln gt_{it} + \beta_2 ln\,\mathrm{labor}_{it} + \beta_3 ln\,fdi_{it} + \beta_4 reenergy_{it} + \beta_5 pgdp_{it} + \varepsilon_{it} \tag{1}$$

In Equation 1, i represents the region, t represents the year; $lngt_{it}$ is the core explanatory variable, representing green trade; $\mathrm{pco2}_{it}$ is the explained variable, representing carbon emissions; *lnlabor* represents total labor force; $lnfdi$ represents foreign direct investment; $reenergy$ represents renewable energy consumption; $pgdp$ represents *per capita* GDP; $\beta_1 \sim \beta_5$ represents the variable coefficients; a_0 represents the constant term; ε is the random error term.

3.1.2 Construction of a moderating effect regression model

This study builds a moderation effect regression model to investigate the moderating effects of trade diversification and political stability on the impact of green trade on carbon emissions. This work centralizes the interaction terms to remove collinearity between the terms and their components, hence improving the robustness and interpretability of the model estimate. In particular, as seen in Equations 2, 3:

$$pco2_{it} = a_0 + \beta_1 lngtt_{it} + \beta_2 lnpoli_{it} + \beta_3 lngtt_{it} * lnpoli_{it} + \beta_4 ln\,labor_{it} + \beta_5 ln\,fdi_{it} + \beta_6 reenergy_{it} + \beta_7 pgdp_{it} + \varepsilon_{it} \quad (2)$$

$$pco2_{it} = a_0 + \beta_1 lngtt_{it} + \beta_2 tradep_{it} + \beta_3 lngtt_{it} * tradep_{it} + \beta_4 ln\,labor_{it} + \beta_5 ln\,fdi_{it} + \beta_6 reenergy_{it} + \beta_7 pgdp_{it} + \varepsilon_{it} \quad (3)$$

In Formula 2, 3, i represents the region and t represents the year; $pco2_{it}$ is texplained variable, representing carbon emissions; $lngtt_{it}$ is the core explanatory variable, representing green trade; $lnpoli$ is political stability; $tradep$ is trade diversification; $lnlabor$ represents total labor force; $lnfdi$ represents foreign direct investment; $reenergy$ represents renewable energy consumption; $pgdp$ represents *per capita* GDP; $\beta_1 \sim \beta_7$ represents variable coefficient; a_0 represents the constant term; ε is the random error term.

3.2 Variable description and data source

3.2.1 Explained variable

The term "carbon emissions" describes how human activity releases carbon molecules like carbon dioxide (CO_2) into the atmosphere. The primary causes of these emissions include land use changes, industrial production processes, deforestation, and the combustion of fossil fuels including coal, oil, and natural gas. Because carbon emissions raise the atmospheric concentration of greenhouse gases, which causes abnormal climatic shifts and global warming, they are one of the main drivers of climate change. In order to quantify carbon emissions ($pco2$), the United Nations (UN) Comtrade database is used to pick the *per capita* carbon emissions of G20 nations, drawing on the methodologies of Cui et al. (2022) and data availability.

3.2.2 Core explanatory variable

For the measurement of green trade ($lngt$), drawing from the methods of Kang and Lee (2021), Kang (2020), initially distinguishes between green industries and non-green industries, and extracts trade patterns related to green products and related green services. Ultimately, green trade is derived. Specifically, this study utilizes the United Nations (UN) Comtrade database, categorizes trade goods and services of G20 countries according to the green product list released by the Asia-Pacific Economic Cooperation (APEC) in 2018, and summarizes all categories of goods and services involving "green trade" based on this classification to obtain the total volume of green trade for G20 countries.

The green product list published by APEC includes several categories: (1) Agriculture and agricultural products: such as green agricultural products, environmentally friendly agricultural production methods, etc.; (2) clean energy: which includes energy from the sun, wind, water, and other renewable sources; (3) Environmental services: such as environmental protection, pollution control, sustainable development consulting, etc.; (4) Green building materials, energy-efficient building techniques, and other forms of sustainable construction and building materials; (5) Low-carbon transportation vehicles and transportation services: including electric vehicles, public transportation systems, environmentally friendly logistics, etc.; (6) Water-saving technologies and products: such as efficient water-saving equipment, water resource management systems, etc.; (7) Environmental products and environmental technologies: including environmental equipment, environmental technology services, etc.

3.2.3 Moderating variables

(1) Political stability refers to the effective safeguarding of authority of a government in a country or region, with the political system demonstrating durability and predictability. There are no large-scale social upheavals, political turmoil, or internal conflicts, and the government is capable of effectively managing domestic affairs and maintaining social order. This stability is typically characterized by widespread recognition of government legitimacy, the inheritance and exercise of political power within legal and institutional frameworks, citizens enjoying basic rights and freedoms, and the political system being less susceptible to threats from illegal or violent means (Ajl, 2021). For the measurement of political stability ($lnpoli$), this paper emphasizes the stability and security of the international political environment. Due to limited data availability, the paper selects the percentage of political stability and terrorism-free indicators of G20 countries to measure political stability, with data sourced from the United Nations (UN) Comtrade database.

(2) Trade diversification refers to the involvement of multiple different trading partners and product types in the economic activities of a country or region. In such cases, the economy engages in trade and transactions with multiple countries as well as involves in exchange of various products or services, rather than relying on a single source of trading partner or product. For the measurement of trade diversification ($tradep$), This study builds the Herfindahl-Hirschman Index (HHI) of trade for G20 nations based on the methodology of Data is sourced from the United Nations (UN) Comtrade database and the Wind database. Specifically:

First, calculate the HHI of trade for the G20 countries:

$$Herfindal_{it} = \sum_{p=1}^{n} \left(\frac{X_{ipt}}{X_{it}} \right)^2$$

Where, i、 p and t represent the country, green products, and time respectively. X_{ipt} is the total trade value of product p for the country i in year t, and X_{it} is the total trade value for the country i in year t. The sum of squares of the ratio of each product's trade value to the nation's overall trade value is the HHI of green trade for the G20. In other words, the more diverse the products used for import and export, the smaller the HHI, indicating a more diversified range of products used for trade in that country. Products are classified according to the Standard International Trade Classification (SITC).

Next, in order to better reflect the degree of trade product diversification, this paper uses the reciprocal of the HHI to measure the level of trade diversification among G20 countries.

$$tradep_{it} = \frac{1}{Herfindal_{it}}$$

3.2.4 Control variable

(1) Total labor force (*ln*labor): The complete population of a certain area or nation who is able to work and is either employed or willing to work is referred to as the total labor force. It is typically used to measure the scale of labor resources and the level of activity in the labor market of a region or country. An increase in the total labor force can involve more people in environmental protection activities. However, considering that the development of environmental protection requires high-tech talents, an excessive labor force will to some extent increase carbon emissions. Therefore, this paper selects the total labor force as a control variable.

(2) Foreign Direct Investment ($lnfdi$): The term "foreign direct investment" describes the financial contributions made by citizens or businesses from one area or nation to businesses, assets, or projects in another, along with their involvement in some aspects of administration and operation. This form of investment typically involves multinational corporations or individuals making capital investments on an international scale, aiming to gain profits or control, and it is characterized by its long-term and sustained nature. Taking into account the external effects of foreign investment on the environment, using the quantity of foreign direct investment as the measure and employing foreign direct investment as a control variable.

(3) Renewable energy consumption ($reenergy$): The entire quantity of renewable energy used in a certain area or nation during a given time frame is referred to as the consumption of renewable energy. Energy from naturally replenishing sources, such as sun, wind, hydroelectric, geothermal, and other forms of energy, is referred to as renewable energy. A area or nation's use of renewable energy, as well as its effects on sustainability and the environment, may be assessed by measuring the amount of renewable energy used. This study chooses the use of renewable energy in G20 nations as a control variable since it can lessen environmental harm and, to some extent, ameliorate carbon emissions.

(4) Per capita GDP ($pgdp$): It is vital to consider how growth in economy affects carbon emissions. According to Cui et al. (2022), economically developed areas will be better equipped to deal with environmental problems and encourage the decrease of carbon emissions. Of these, a nation's *per capita* GDP is a stronger indicator of its economic health. The Gross Domestic Product (GDP) of a nation or area divided by the total population of that nation or region is referred to as *per capita* GDP. It is a crucial measure for gauging a nation's or region's degree of economic growth. A greater *per capita* GDP often denotes a comparatively higher economic level of that nation or territory. This metric is typically used to compare the economic circumstances across different countries or regions. Per capita GDP is therefore used as the control variable in this study.

3.2.5 Brief summary

To more intuitively observe each variable, this paper presents the composition and sources of the variables in tabular form. The specific details are shown in Table 1 below.

3.3 Descriptive statistics

Studying the impact of green trade on carbon emissions in G20 countries is of great significance. These countries represent the majority of the global economy and trade, and their environmental policies and green trade practices have a decisive impact on global climate change and the achievement of carbon reduction goals. By analyzing the implementation effects of green trade in these countries, we can reveal the complex relationships between trade structure, environmental policies, and carbon emissions, providing a reference for countries to develop more effective green trade policies, thereby promoting the global economy's transition towards a low-carbon and sustainable future. The G20 countries include: Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, Saudi Arabia, South Africa, South Korea, Turkey, the United Kingdom, the United States, and the European Union.

Since the world political landscape was rather steady throughout this time, data from 2000 to 2022 was used. Against this backdrop, countries actively promoted the development of globalization, leading to rapid growth in international trade. Thus, it would be more beneficial to carry out empirical study on green trade and carbon emissions at this time in order to better understand how the two are related to one another as well as the moderating function that political stability has in this connection. Additionally, during this period, trade between countries became more frequent, and the diversification of trade would have a more pronounced moderating effect on green trade and carbon emissions. The data for various variables mainly come from the Wind database and the United Nations (UN) Comtrade database. To ensure the scientific rigor and accuracy of the empirical analysis, and to minimize the impact of variable heteroscedasticity, this study logarithmically transformed absolute values such as green trade, political stability, trade diversification, total labor force, foreign direct investment, renewable energy consumption, and *per capita* GDP. Descriptive statistics for each variable are shown in Table 2.

4 Results and discussion

4.1 Data stability test

In order to ensure data stationarity, this study first performed panel cointegration and unit root tests, the results of which are displayed in Table 3.

(1) All variables passed at least one of the Hadri and Fisher unit root tests, suggesting that the variables chosen are appropriate;
(2) The Pedroni test is significant, suggesting that the variables have stable long-term associations, allowing panel regression to be performed.

4.2 OLS regression, moderating effect regression and quantile regression

OLS regression is used in this study to investigate the connection between carbon emissions and green trade. The reason for choosing

TABLE 1 Variable composition and description.

Variable name	Variable definition	Variable composition	Variable significance	Data sources
carbon emissions (*pco2*)	Emissions of carbon compounds such as carbon dioxide (CO_2) generated by human activities	Per capita carbon emissions of G20 countries	Carbon emissions are one of the main causes of global climate change	United Nations (UN) Comtrade database
green trade (ln gt)	Trade patterns related to green products and related green services	Summarize all goods and services categories related to "green trade" in G20 countries according to the green product list published by the Asia-Pacific Economic Cooperation (APEC)	Assess and measure a country or region's ability to comply with sustainable development and environmental standards in international trade	United Nations (UN) Comtrade database; The list of green products released by the Asia-Pacific Economic Cooperation (APEC) in 2018
political stability (lnpoli)	The authority of a country or region's government is effectively guaranteed, and the political system has durability and predictability	The percentage indicator of political stability and non terrorism in G20 countries measures political stability	Assessing the impact of a country or region's political environment on its green trade development and environmental policy implementation	United Nations (UN) Comtrade database
trade diversification (tradep)	The economic activities of a country or region involve multiple different trading partners and product types	Constructing a trade Herfindahl index for G20 countries to measure trade diversification	Measuring the breadth of a country or region's export products and market diversity	United Nations (UN) Comtrade database; Wind database
total labor force (lnlabor)	The total number of people in a specific region or country who are able to participate in labor and are currently working or willing to work	Total labor force of G20 countries	The increase in the total labor force can enable more people to participate in environmental protection	United Nations (UN) Comtrade database
foreign direct investment (lnfdi)	Residents or businesses in one country or region invest funds into businesses, assets, or projects in another country or region	Foreign Direct Investment in G20 Countries	Foreign investment has a certain external impact on the environment	United Nations (UN) Comtrade database
renewable energy consumption (reenergy)	The total amount of renewable energy utilized by a specific region or country within a certain period of time	Renewable energy consumption of G20 countries	Can help evaluate the progress and development level of a region or country in renewable energy utilization	United Nations (UN) Comtrade database
per capita GDP (pgdp)	The GDP of a country or region divided by its total population	Per capita GDP of G20 countries	One of the important indicators for measuring the level of economic development of a country or region	United Nations (UN) Comtrade database

TABLE 2 Descriptive statistics.

Variable	Obs	Mean	Min	Max
pco2	340	8.042	0.984	19.469
Lngt	340	23.645	20.546	26.27
lnpoli	340	3.692	1.56	4.546
tradep	340	0.719	0.29	1.108
lnlabor	340	17.794	15.962	20.476
lnfdi	340	24.928	20.92	28.767
reenergy	340	13.958	0	50.05
Pgdp	340	25,313.2	710.509	70,219.47

OLS regression in this paper is based on the following reasons: Firstly, the OLS model is highly interpretable and convenient to compute. The basic principle of the OLS model is to obtain the best fit line by minimizing the squared difference between the predicted and actual values, which makes it easier for us to explain the meaning of the regression coefficients. Additionally, the OLS model has a closed-form solution, and parameter estimates can be quickly obtained through simple matrix operations without the need for complex algorithms or substantial computational resources. Secondly, the OLS model has good statistical properties. Under the assumptions of the classical linear regression model (such as linear relationship, homoscedasticity, no autocorrelation, normal distribution of error terms, etc.), the OLS estimator is the Best Linear Unbiased Estimator (BLUE). This means that the OLS estimator has the smallest variance among all linear unbiased estimators. Therefore, under the assumed conditions, its expected value equals the true parameter value. Lastly, the OLS model has broad applicability and is easy to diagnose and correct. OLS regression performs well with large samples and can provide reliable estimates even with a large sample size.

Therefore, given the context of panel data on G20 countries in this paper, using the OLS model will be more helpful in analyzing the impact of green trade on carbon emissions. The fixed effects model was chosen and Hausman tests were performed in the manuscript prior to OLS regression. The OLS model developed in this work is regarded as scientifically sound because of the improved goodness of fit that was achieved with the fixed effects model.

TABLE 3 Data stability test.

Unit root test		Lngt	Lnlabor	Lnfdi	Reenergy	pgdp	Tradep
FISHER	Inverse chi-squared	71.4993***	38.567	75.459***	40.851	72.054***	70.434***
	Inverse normal	−3.509***	0.429	−3.108***	1.625	−2.796***	−2.071**
	Inverse logit t	−3.431***	0.381	−3.502***	1.892	−2.933***	−2.235**
	Modified inv. Chi-squared	3.522***	−0.16	3.965***	0.095	3.584***	3.403***
HADRI	z	6.995***	5.741***	-	7.717***	5.945***	7.254***
Unit Root Test		lnpoli	pco2				
	Inverse chi-squared	44.294	37.083				
FISHER	Inverse normal	−0.149	1.543				
	Inverse logit t	−0.272	1.48				
	Modified inv. Chi-squared	0.722	−0.326				
HADRI	z	7.806***	6.856***				
Panel cointegration test					statistic	statistic	
Pedroni		Modified Phillips-Perron t			4.2263	0.0000	
Pedroni		Phillips-Perron t			−3.9747	0.0000	
Pedroni		Augmented Dickey-Fuller t			−2.963	0.0015	

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

At the 5% significance level, Table 4 (1) shows a substantial positive association (coefficient of 0.647) between carbon emissions (pco2) and green trade ($lngt$), suggesting that green trade raises carbon emissions. Granted, green commerce encompasses a broad spectrum of products and associated services, and in its infancy it might not succeed in meeting carbon reduction targets. The following are the current causes of the rise in carbon emissions from green trade: Firstly, in order to build green industries, nations must heavily engage in the search for new energy sources, the application of cutting-edge technology, and the development of highly skilled laborers. All of these activities will eventually result in increased energy consumption and carbon emissions. Secondly, the new energy sources replacing oil and coal are difficult to find, and the production costs are relatively high for current technologies, which will also cause some environmental damage in the process. At the same time, the technologies and methods for recycling emerging energy and products are limited. If countries blindly promote the use of these green products, the waste generated from the production and use of these green products will not be effectively treated, leading to a new round of pollution to our earth, thereby increasing more carbon emissions. Finally, the green transportation methods advocated by many scholars at present are bound to increase longer transportation distances and transportation costs, which will instead have a negative impact on the environment and increase carbon emissions. Therefore, hypothesis 1 is confirmed.

Simultaneously, empirical findings demonstrate that, at the 1% significance level, the total labor force (*lnl*abor) has a substantial positive correlation (coefficient of 0.027), suggesting that a rise in the labor force will encourage carbon emissions. According to the marginal cost theory, there is a limit to the total labor force needed by society. If the total labor force exceeds this limit, society will incur additional costs to manage the surplus labor force, inevitably increasing social burden and carbon emissions. Furthermore, at the 5% significance level, there is a substantial positive association between foreign direct investment ($lnfdi$) and carbon emissions (coefficient of 0.215), suggesting that rising foreign direct investment will lead to rising carbon emissions. This is because some enterprises receiving foreign direct investment tend to choose countries with low production costs and environmental costs for investment. These recipient countries mostly have low technological levels and low production efficiency, and can only develop labor-intensive, highly polluting enterprises. Even if these enterprises consciously protect the environment, provide advanced technology to the recipient country, and actively cultivate high-quality local talents, the insufficient productivity of the recipient country will inevitably increase the local environmental burden and carbon emissions when introducing foreign direct investment. This is unavoidable. In addition, the use of renewable energy ($reenergy$) shows a strong negative correlation (coefficient of −0.06) at the 1% significance level, suggesting that it will reduce carbon emissions. Since most carbon emissions come from the use of oil and coal, if countries can better utilize renewable energy, it will effectively reduce global emissions of gases and waste and achieve carbon emission reduction goals. Finally, at the 1% significance level, *per capita* GDP ($pgdp$) exhibits a significant negative association with a coefficient of −0.000, suggesting that it will decrease carbon emissions. Per capita GDP does, after all, indicate a nation's strength both economically and technologically. A nation's technical and inventive levels are directly correlated with its *per capita* GDP. As a result, more expertise and technology will be available to support the growth of green sectors, which will ultimately advance environmental protection and reduce carbon emissions.

TABLE 4 OLS regression and moderating effect regression results.

	(1)	(2)	(3)
lngt	0.647**	0.993***	0.709**
	(0.248)	(0.304)	(0.273)
lnpoli	-	−10.153**	-
	-	(4.351)	-
centpol	-	0.453**	-
	-	(0.192)	-
tradep	-	-	−10.166***
	-	-	(1.3)
centtrade	-	-	−2.439***
	-	-	(0.883)
lnlabor	3.729***	3.775***	3.729***
	(0.862)	(0.947)	(0.792)
lnfdi	0.215**	0.256**	0.074
	(0.092)	(0.102)	(0.086)
reenergy	−0.06***	−0.06***	−0.068***
	(0.013)	(0.013)	(0.012)
pgdp	−0.000**	−0.000**	−0.000***
	(0.000)	(0.000)	(0.000)
Id	yes	yes	yes
year	yes	yes	yes
_con	−71.287***	−46.918**	−65.332***
	(15.152)	(20.389)	(14.725)
N	340	340	340
Adj.R-sq	0.976	0.977	0.981

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

The above study leads to the conclusion that trade diversification and political stability both somewhat offset the carbon emission-reducing benefits of green trade. In order to investigate the moderating effects of political stability and trade diversification, this research presents a moderating effect regression and includes interaction factors between political stability and green trade as well as between trade diversification and green trade. Tables 5 (2) and (3) present the findings. Table 5 (2) shows that political stability ($lnpoli$) has a substantial negative correlation at the 5% level, with a value of −10.153. Simultaneously, the interaction term between political stability and green trade ($centpol$) has a significant positive connection at the 5% level, with a value of 0.453, which is less than the coefficient of green trade on carbon emissions in the OLS model. This indicates that a more stable international environment will facilitate joint environmental governance among countries, leading to carbon emission reduction. Furthermore, when political stability increases, the incentive impact of green trade on carbon emissions diminishes. Therefore, hypothesis 2 is confirmed. Only under conditions of peaceful and mutually beneficial international environments can enterprises and individuals have the confidence to engage in green production and consumption. Then and only afterwards will nations be able to concentrate on environmental problems and encourage the growth of the green sector.

At the 1% significance level, trade diversification ($tradep$) has a substantial negative correlation with a coefficient of −10.166, as shown in Table 5 (3). Furthermore, with a value of −2.439, the interaction term between trade diversification and green trade ($centtrade$) exhibits a significant negative connection at the 1% significance level. This suggests that trade diversification can lower carbon emissions and that, as trade diversifies, the influence of green trade on carbon emissions will change from being one of promotion to restriction. In other words, in an environment of open trade, countries can significantly suppress carbon emissions through green trade while promoting trade diversification. Therefore, hypothesis 3 is confirmed. Indeed, in the process of promoting trade diversification, countries will identify their strengths and weaknesses in the green trade chain, which will help strengthen communication and cooperation among countries, collectively address obstacles in promoting green trade development, achieve complementarity of advantages, resource integration, and truly realize the concept of carbon neutrality.

This research also presents a quantile regression model, choosing the 0.1–0.9 quantiles to assess the influence of green trade on carbon emissions. This allows for a more thorough examination of the effects of green trade on carbon emissions at various quantiles. In contrast to ordinary least squares regression, quantile regression simultaneously calculates the regression coefficients at various quantiles in addition to concentrating on determining the dependent variable's mean. Put differently, it offers a more thorough and adaptable approach to data analysis, assisting us in comprehending how the dependent variable varies under various circumstances (Koenker and Bassett, 1978). Table 5 presents the regression findings.

The OLS regression results are consistent with the quantile regression results from Table 5, which indicate that all of the green trade ($lngt$) coefficients are positive and exhibit a pattern of progressive increase from low to high quantiles. Moreover, it exhibits a significant positive correlation when carbon emissions (pco2) reach the maximum emission value (at the 0.9 quantile), with a coefficient of 0.593. This indicates that the promotional effect of green trade on carbon emissions is not significant at the middle and low quantiles due to lower carbon emissions. A reasonable explanation is that when carbon emissions are low, the global environmental conditions are relatively good, and the negative impact brought by green trade is not very pronounced, as the natural environment itself can purify the pollution of these gases and wastes. Green trade, however, significantly increases carbon emissions at higher quantiles. This is because, at this point, the environment in various countries has already suffered serious damage and pollution due to increased production activities, resulting in a substantial accumulation of carbon emissions from sacrificing the environment for economic achievements. The self-healing ability of the environment has been lost. If countries want to promote green production and achieve sustainable development through trade at this stage, it will inevitably lead to further environmental damage in the early stages of development.

TABLE 5 Quantile regression results.

	Quantile 0.1	Quantile 0.3	Quantile 0.5	Quantile 0.7	Quantile 0.9
lngt	0.254	0.137	0.294	0.256	0.593*
	(0.265)	(0.286)	(0.28)	(0.362)	(0.342)
lnlabor	3.343**	2.767**	2.384	1.888	0.702
	(1.516)	(1.403)	(1.741)	(2.424)	(2.538)
lnfdi	0.228*	0.079	0.052	0.016	−0.045
	(0.136)	(0.094)	(0.097)	(0.112)	(0.112)
reenergy	−0.07**	−0.074**	−0.083*	−0.097***	−0.088**
	(0.033)	(0.033)	(0.041)	(0.032)	(0.039)
pgdp	0.000	0.000	0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Id	yes	yes	yes	yes	yes
year	yes	yes	yes	yes	yes
_con	−61.919**	−46.248*	−42。236	−31.512	−17.256
	(26.806)	(23.703)	(29.06)	(39.736)	(41.902)
N	340	340	340	340	340

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

At this point, the ecosystem no longer has the capacity to heal itself very well, and the encouragement of green trade will result in a sharp rise in carbon emissions. Governments all throughout the world are likewise faced with this conundrum (Demiral and Demiral, 2021): the current environmental issues on Earth are extremely severe. If industrial restructuring is not carried out to achieve green development, these high-polluting and energy-consuming enterprises will further damage the environment, and humanity will eventually lose its Earth home. However, in the process of seeking new energy and new production methods, due to the limitations of existing technologies and Earth's resources, it will generate more environmental costs, which is undoubtedly adding insult to injury to the already heavily polluted environment. Therefore, governments worldwide need to work together to shoulder the responsibility of protecting the environment, promoting the development of the green industry at minimal costs, forming an efficient and low-pollution green trade model, and achieving carbon neutrality goals.

4.3 Robustness test and endogeneity test

4.3.1 Robustness test

Due to the presence of autocorrelation, heteroscedasticity, and cross-sectional dependence in the data, this paper employs the FGLS and PCSE methods to make corrections for such issues, with the results shown in Table 6 (1a) and (1b). The regression results of PCSE and FGLS are largely consistent, proving that the construction of the regression results is reasonable. Secondly, to verify the robustness of the results, this paper selects a replacement of the main regression variable for a robustness test, substituting carbon emissions (pco2) with total CO_2 emissions (*lnco*2). The regression results are shown in Table 6 (2). The results indicate that green trade and total CO_2 emissions have a significant positive correlation at the 1% significance level, with a coefficient of 0.141, implying that green trade increases carbon emissions. This is consistent with the OLS regression results, confirming the robustness of the model.

TABLE 6 Robustness test.

Variable	(1a) PCSE	(1b) FGLS	(2)	(3)
lngt	0.647**	0.647***	0.141***	0.693***
	(0.318)	(0.232)	(0.03)	(0.248)
lnlabor	3.479***	3.479***	0.827***	2.922***
	(0.616)	(0.807)	(0.106)	(0.907)
lnfdi	0.215**	0.215**	0.041***	0.212**
	(0.097)	(0.086)	(0.011)	(0.091)
reenergy	−0.06***	−0.06***	−0.013***	−0.056***
	(0.009)	(0.012)	(0.002)	(0.013)
pgdp	−0.000**	−0.000**	0.000	−0.000**
	(0.000)	(0.000)	(0.000)	(0.000)
industrial	-	-	-	−0.039*
	-	-	-	(0.021)
_cons	−71.387***	−71.387***	−5.594***	−61.988***
	(9.441)	(14.185)	(1.858)	(15.875)

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

Furthermore, as the further development of industries in various countries also affects local carbon emissions (Cui et al., 2024), this paper additionally incorporates the control variable of value-added

TABLE 7 Endogeneity test.

Variable	(1)2SLS	(2)
lngt1	-	0.867***
	-	(0.239)
lngt	1007415***	-
	(374,348.2)	-
lnlabor	−820929.1*	2.897***
	(465,071.9)	(0.892)
lnfdi	75,005.43	0.188**
	(46,082.19)	(0.09)
reenergy	−2,885.447	−0.054***
	(7,583.182)	(0.012)
pgdp	−5.678	−0.000*
	(6.934)	(0.000)

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

by industry for a robustness test. The regression results are shown in Table 6 (3), and it can be seen that the results are largely consistent with the OLS results, further proving the stability of the model.

4.3.2 Endogeneity test

Endogeneity refers to the correlation between the explanatory variables and the error term, which leads to bias and inconsistency in OLS estimates. Common sources of endogeneity include bidirectional causality, omitted variables, and measurement errors. To address the issue of endogeneity and ensure the accuracy of the econometric analysis in this paper, we employed the two-stage least squares method (2SLS) and used the lagged one-period value of green trade to examine endogeneity. The results are shown in Table 7 (1) and (2). It can be seen that the results in Table 7 (1) and (2) are consistent with the OLS regression results. Therefore, the regression results in this paper have strong robustness.

5 Conclusion and policy implications

This study utilizes the United Nations (UN) Comtrade database to classify trade goods and services of G20 countries according to the green product list released by the Asia-Pacific Economic Cooperation (APEC) in 2018. Based on this classification, all categories involving "green trade" are summarized to determine the total volume of green trade among G20 nations. Simultaneously, this study introduces OLS regression model, moderating effect regression model, and quantile regression model. It looks at how green trade affects carbon emissions using panel data from G20 nations covering the years 2000–2022. The study investigates how trade diversification and political stability affect the link between carbon emissions and green trade. Moreover, it makes use of quantile regression models to investigate the ways in which green trade affects carbon emissions at various quantiles.

The following is shown by the research findings of this study: Firstly, green trade will lead to higher carbon emissions; second, when political stability increases, green trade's potential to promote lower carbon emissions will diminish. Furthermore, when trade diversifies, the positive impact of green trade on carbon emissions will become a suppressive effect; Lastly, on quantiles ranging from low to high carbon emissions, the coefficient of green trade is positive and shows a gradually increasing trend, with a significant positive correlation at the 0.9 quantile of carbon emissions, further demonstrating that green trade promotes carbon emissions.

Due to the complex and diverse international situation, the range of goods and services covered by green trade is extensive. When engaging in green trade, countries are bound to incur increased trade costs and environmental damage due to the development of green industries, implementation of green transportation, and pursuit of clean energy. However, countries should not forsake the construction of the global green trade chain for the sake of their own interests, making decisions that not only harm their own national image but also disrupt the economic interests of other countries. To support the growth of the green sector as a whole, nations should band together and work together. Admittedly, the momentum of globalization is irreversible, so countries must actively maintain the current peace situation under the premise of international political and social stability. By implementing an open and free trade policy and collaborating with other countries to diversify the development of the green trade route, only then can the goal of carbon neutrality be truly achieved.

Only by ensuring the diversified development of trade can countries find the path of green development suitable for their own countries during the development of green trade. This is the only approach to mitigate the conflict between environmental preservation and economic growth and to grow the economy at the same time. Due to the increasingly severe environmental pollution, governments of various countries also need to work together to promote relevant environmental protection policies. Moreover, they should cautiously promote and use emerging technologies and new energy sources to ensure the protection of the environment as much as possible while developing green industries. It will take time and effort to build the green trade, and reducing carbon emissions will not happen overnight. Therefore, governments everywhere must prioritize environmental preservation, accomplish economic circular growth, encourage resource allocation that is sensible, and cautiously engage in green trade activities in order to achieve long-term green development.

In light of the aforementioned results, this article makes the following recommendations:

(1) Strengthen the supervision and standard setting of green trade products. Given the trend that green trade has shown to increase carbon emissions in this study, it is recommended that national governments and international organizations strengthen the supervision of green trade products and establish stricter environmental standards and certification mechanisms to ensure that "green products" truly have low-carbon attributes. Through rigorous certification and review mechanisms, it is possible to effectively prevent green trade products from generating significant carbon emissions during their production and transportation processes. Countries

should develop and refine green product standards based on their own industrial structure and environmental capacity, in conjunction with international best practices, to ensure that "green products" meet low-carbon requirements throughout their entire life cycle (from production to consumption). For example, a product carbon footprint certification could be introduced, requiring green products to meet strict carbon emission standards during production and transportation. Additionally, countries should work through international organizations (such as the WTO, UNEP, etc.) to promote the international harmonization of green product standards, preventing varied national standards from creating "green trade barriers." By unifying standards, the cost of compliance for businesses can be reduced, thereby promoting the free flow of green products globally.

(2) Enhance political stability to optimize the environmental benefits of green trade. This article indicates that political stability can mitigate the effect of green trade in promoting carbon emissions. Therefore, governments should focus on improving domestic political stability and enhancing governance structures and policy enforcement to better manage and regulate the environmental impact of green trade. International organizations can also provide relevant technical support and policy guidance to help politically unstable countries strengthen their environmental governance. Additionally, governments should encourage public and non-governmental organization participation in environmental oversight, establishing smooth channels for public participation and reporting, allowing all sectors of society to jointly monitor the implementation of green trade. By introducing social supervision, it is possible to effectively compensate for the shortcomings in government oversight and ensure that green trade policies are truly implemented.

(3) Promote trade diversification to curb the growth of carbon emissions. The results of this article show that trade diversification can turn the promotional effect of green trade on carbon emissions into a suppressive effect. Therefore, countries should actively promote the diversification of trade structures and encourage the import and export of more low-carbon and environmentally friendly products, avoiding dependence on a single high-carbon product. At the same time, countries should use policy tools such as tariff reductions and subsidies to encourage the import and export of low-carbon products and technologies, reducing reliance on high-carbon products. For example, zero tariffs can be imposed on imported low-carbon technologies and environmental protection equipment, encouraging companies to adopt advanced environmental technologies and reduce carbon emissions in the production process. Since G20 countries hold a significant position in global trade, during international trade negotiations, countries may consider diversified trade cooperation, including multilateral trade agreements, technology transfers, and financial support, to help developing countries enhance their green trade levels, thereby achieving more significant carbon emission reductions on a global scale.

(4) Implement differentiated emission reduction policies for countries with different carbon emission levels. According to the results of the quantile regression model in this article, green trade has varying impacts on countries with different carbon emission levels, and its promoting effect is more significant at higher carbon emission quantiles. Therefore, policymakers should design differentiated green trade policies for countries or regions with different carbon emission levels. For example, for countries with high carbon emissions, there should be stricter control over high-carbon products, encouraging the import of low-carbon green products while reducing dependence on the export of high-carbon products.

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

MG: Investigation, Resources, Writing–original draft. YC: Conceptualization, Formal Analysis, Project administration, Visualization, Writing–review and editing. ZL: Investigation, Methodology, Writing–review and editing. JW: Data curation, Methodology, Validation, Writing–review and editing. SQ: Formal analysis and Validation.

Funding

The author(s) declare that financial no support was received for the research, authorship, and/or publication of this article.

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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