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Trade facilitation and global warming: based on cross-country panel data

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This study delves into the intricate interplay between trade facilitation and global warming, emphasising the ramifications of trade facilitation on climate change dynamics. To quantify the effects of trade facilitation on global warming, this research employed both spatial econometric and traditional econometric models, leveraging data spanning 129 countries from 2010 to 2019. The empirical findings reveal a notable direct negative correlation between trade facilitation and global warming. This negative impact arises from optimised resource allocation, the acceleration of green technology development, and the facilitation of industrial green transformation. Intriguingly, the study also indicates an absence of significant spillover effects from trade facilitation on neighbouring regions. Moreover, the relationship between trade facilitation and global warming is linear, devoid of any non-linear associations. A deeper mechanism analysis elucidates that trade facilitation primarily mitigates global warming by reducing carbon emissions and fostering technological innovation, particularly in developed economies. In stark contrast, this impact is less pronounced in developing countries, primarily due to constraints in technology and policy frameworks. This nuanced understanding underscores the importance of context-specific considerations when assessing the environmental implications of trade facilitation. The study culminates in a series of policy prescriptions aimed at bolstering green trade facilitation measures, fostering innovation, enhancing regional cooperation, and formulating policies tailored to the needs of developing countries. These recommendations strive to strike a delicate balance between mitigating global warming and promoting economic growth, thereby illustrating the potential for trade facilitation to serve as a dual catalyst for environmental sustainability and economic prosperity.

KEYWORDS

global warming, sustainable trade policies, technological innovation, trade facilitation, carbon emissions

1 Introduction

In an era marked by the relentless acceleration of globalisation, trade facilitation has emerged as a cornerstone in driving economic efficiency and fostering international market integration. The World Trade Organisation (WTO) delineates trade facilitation as the process of simplifying, modernising, and harmonising trade procedures, encompassing measures like streamlined customs protocols, digitalisation of trade documents, enhanced port efficiency, and the integration of advanced logistics systems. These endeavours markedly diminish trade barriers, decrease transaction costs, expedite cross-border

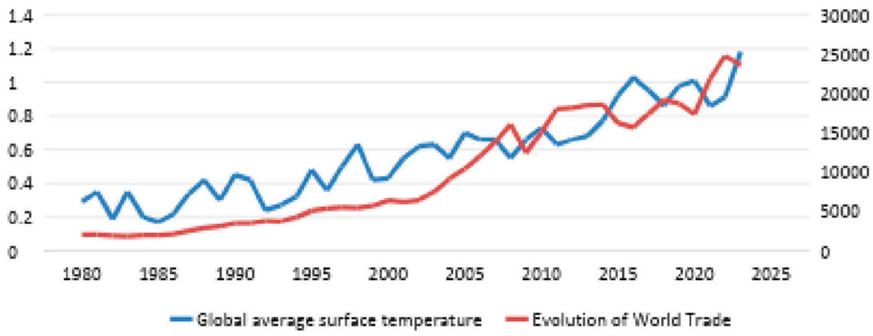

FIGURE 1
Average global surface temperature and development of world trade. (Source: UN Trade and Development (UNCTAD)).

trade flows, and empower enterprises, notably those in developing nations, to tap into global markets with greater efficacy. Consequently, trade facilitation assumes a pivotal role in augmenting industrial expansion, fostering global supply chain integration, and spurring economic growth. However, amidst the undeniable economic advantages of trade facilitation, its ramifications on the environment, particularly with respect to global warming, constitute a critical yet underexplored dimension.

Global warming, primarily induced by anthropogenic greenhouse gas emissions, results in escalating global temperatures, a surge in extreme weather events, and widespread environmental degradation. According to the Intergovernmental Panel on Climate Change (IPCC), global temperatures have already risen by approximately 1.1°C above pre-industrial levels, with further warming posing grave threats to ecosystems, economic stability, and global food security. Given that trade facilitation facilitates the swift movement of goods across borders, it exercises a direct influence on global warming through heightened transportation emissions, expanded industrial production, and altered energy consumption patterns.

While the environmental consequences of trade liberalisation have been exhaustively scrutinised in the extant literature (Bilal and Känzig, 2024), there exists a notable dearth of studies specifically evaluating the role of trade facilitation in shaping the dynamics of global warming. This gap underscores the necessity for a more nuanced examination of how trade facilitation, while bolstering economic prosperity, might inadvertently exacerbate climate challenges, necessitating innovative strategies to mitigate its adverse environmental impacts.

Figure 1 elucidates the intricate interplay between trade development and global warming through visual representation. It portrays the trajectory of global trade volume spanning from 1980 to 2022 alongside the evolution of the global average surface temperature. The blue line in the graph denotes the deviation in global average surface temperature from pre-industrial levels, measured in degrees Celsius, whereas the orange line traces the expansion of world trade, quantified in billions of US dollars. The graphic reveals a striking parallelism: both trade volume and surface temperature have ascended markedly over the past 4 decades. Since the onset of the 1990s, several factors have propelled the rapid expansion of global trade. These include advancements in digital trading platforms, the revolution in containerisation and logistics technology, the conclusion of pivotal trade agreements, and the widespread embrace of trade facilitation measures. This surge in trade activity has occurred concurrently with an unprecedented elevation in global temperatures, prompting concerns that facilitated trade flows might exacerbate environmental degradation.

The concurrent rise of these two trends hints at a potential nexus, where trade facilitation could be a catalyst in global temperature increases, notably by fostering energy-intensive transport networks and industrial production. Nevertheless, the dynamics at play here are multifaceted. Trade facilitation also functions as a conduit for technology transfer, fostering innovation dissemination and promoting the adoption of low-carbon economic strategies. This dual nature underscores the complexity of the relationship between trade development and global warming. Thus, while trade facilitation may indeed contribute to environmental challenges, it simultaneously presents avenues for technological advancements and sustainable practices that could mitigate these effects. The nuanced interplay between these forces necessitates a comprehensive analysis to fully comprehend their implications for global climate patterns.

The intricate nexus between trade facilitation and global warming manifests in a variety of ways, encompassing both detrimental and beneficial ramifications. On one side of the spectrum, trade facilitation augments carbon emissions by accelerating the pace and efficacy of global trade activities. This acceleration fosters heightened production volumes, stimulates a greater demand for freight transportation, and intensifies the reliance on fossil fuel-based logistics. Indeed, according to estimates by the International Transport Forum (ITF), freight transport alone contributes nearly 8% of global carbon emissions. Notably, the maritime, aviation, and trucking sectors—which have experienced substantial growth due to enhanced trade efficiency—are the primary sources of these emissions. Furthermore, the just-in-time supply chains facilitated by trade ease often necessitate more frequent yet smaller shipments, thereby elevating fuel consumption per unit and exacerbating the overall carbon footprint. Additionally, the expansion of trade in energy-intensive sectors, such as manufacturing, petrochemicals, and mining, particularly in emerging economies with nascent regulatory frameworks for emissions control, further accelerates emissions growth.

Conversely, trade facilitation possesses the potential to catalyse technological innovation, propel the adoption of cleaner production methodologies, and facilitate the global dissemination of environmental technologies, thereby contributing to a climate-resilient economic transformation. One of the most significant positive ramifications of trade facilitation lies in its capacity to amplify knowledge spillovers and expedite the diffusion of innovation. By diminishing trade costs and broadening market access, trade facilitation empowers firms in developing nations to integrate advanced environmental technologies, such as renewable energy equipment, carbon capture systems, and energy-efficient industrial processes. This, in turn, contributes to a sustained reduction in emission intensity. Moreover, trade facilitation fosters the global proliferation of low-carbon solutions by decreasing costs and enhancing the availability of technologies like solar panels, wind turbines, and battery storage systems. Additionally, the swift digitalisation of trade processes—through initiatives such as e-Customs, paperless trade, blockchain-based supply chains, and AI-driven logistics optimisation—can markedly decrease waste, augment supply chain efficiency, and diminish the environmental footprint of global trade operations. Smart trade solutions, incorporating IoT-based freight monitoring and automated route optimisation, can further mitigate unnecessary fuel consumption and emissions, rendering global trade more environmentally sustainable. In essence, while trade facilitation does pose certain environmental challenges, its potential to drive technological advancements and foster sustainable practices offers a pathway towards a more climate-friendly economic landscape.

While academia and policymakers have exhibited increasing curiosity regarding the interplay between trade and environmental dynamics, the precise ramifications of trade facilitation on global warming remain largely unexplored. Existing research frequently conflates trade liberalisation with trade facilitation, thereby obscuring the distinct effects of various facilitation measures—such as customs modernisation, digital trade systems, and investments in transport infrastructure—on carbon emissions and climate change. Moreover, the influence of trade facilitation on global warming is contingent upon a multitude of factors, including sector, region, and policy framework, as well as underlying variables like energy sources, industrial structure, and technological prowess.

In light of these conceptual and empirical ambiguities in the existing literature, it is useful to contextualize how this study builds upon and diverges from recent contributions. While the environmental implications of trade-related policies have attracted considerable scholarly attention, existing studies often diverge in focus, methodology, and geographical scope. For instance, Salam et al. (2025) examined the impact of trade and financial development on CO_2 emissions in BRI countries directly connected to China. Their findings underscore the nuanced effects of bilateral trade with China, revealing that exports to China exacerbate emissions, while imports help reduce them, and that financial development is a key driver of environmental degradation. In contrast, Chishti et al. (2023) investigated the asymmetric effects of commercial policies (proxied by import taxes) on consumption-based CO_2 emissions in Pakistan, showing that contractionary trade measures can mitigate emissions, while expansionary ones intensify pollution. Although both studies offer valuable insights into the trade–environment nexus, they are context-specific—focusing on either a multi-country trade corridor (BRI) or a single-country commercial policy environment, and address different dimensions of trade: bilateral trade intensity *versus* domestic policy tools. By comparison, the current study provides a broader, cross-national perspective, using panel data from 129 countries to investigate trade facilitation—a distinct policy dimension characterized by institutional and infrastructural efficiency rather than trade volume or tax measures. Importantly, our findings diverge in key ways: unlike bilateral trade or tariff policies, trade facilitation exhibits a direct negative correlation with global warming, primarily via technology diffusion and industrial upgrading, especially in developed economies. These contextual differences—not methodological contradictions—highlight the multifaceted nature of the trade–environment relationship. By systematically incorporating spatial effects, mediating variables (e.g., carbon emissions and innovation), and heterogeneity across development stages, this study complements and extends the prior literature. It thus contributes a novel empirical layer to ongoing debates by revealing how institutional trade efficiency can serve as a lever for climate mitigation in contrast to volume-based or tariff-centered mechanisms.

To bridge these gaps in understanding, this study endeavours to meticulously dissect the impact of trade facilitation on global warming, emphasising its adverse environmental repercussions and potential catalysis of green innovation. Specifically, by utilising comprehensive global cross-country panel data, we construct a country-level trade facilitation index to address three pivotal inquiries.

1. How does trade facilitation influence global warming?
2. In what ways do carbon emissions and technological innovation mediate the impact of trade facilitation on global warming?
3. What strategic frameworks can be devised to align trade facilitation with global climate objectives, such as the Paris Agreement and Sustainable Development Goal (SDG) 13: Climate Action?

Elucidating the intricate interconnections between trade facilitation and global warming is imperative for devising sustainable trade policies that harmonise economic efficiency with environmental stewardship. By delving into the environmental consequences of trade facilitation, this research offers profound insights into optimising trade policies to foster innovation dissemination, facilitate low-carbon logistics, and promote sustainable industrial paradigms. Through rigorous analysis, we aim to provide a nuanced understanding that transcends simplistic correlations, thereby informing policymakers in their pursuit of balanced and equitable trade strategies.

2 Literature review and hypothesis development

2.1 Literature review

2.1.1 Review of theoretical literature

The environmental Kuznets curve (EKC), the framework addressing the environmental ramifications of trade facilitation (encompassing the pollution haven hypothesis alongside scale, structure, and technological effects), and the theory of global value chains (GVCs) constitute three preeminent and extensively documented theoretical paradigms. The EKC posits that pollution tends to escalate in the nascent phases of economic development yet diminishes as income levels augment and environmental consciousness heightens (Grossman and Krueger, 1995; Stern, 2004). Empirical evidence underscores that trade facilitation, a pivotal driver of economic growth, positions economies at diverse junctures of the EKC trajectory, thereby influencing carbon emissions (Wang et al., 2022). However, the EKC, in isolation, falls short of comprehensively elucidating the environmental repercussions of trade facilitation, necessitating an integrated analysis with the ecological implications of the trade framework (Copeland and Taylor, 2004).

This framework delineates three principal effects of trade facilitation: scale, structural, and technological. Scale effects highlight the augmentation of economic growth through trade facilitation, which fosters production expansion and, consequently, elevated carbon emissions. Structural effects emphasise industrial reconfiguration, where developed economies transition towards high value-added, low-pollution industries whereas developing nations may attract more polluting sectors (Zhang et al., 2017). Technological effects signify the accelerated dissemination of green technologies, enabling the transfer of eco-friendly innovations from developed to developing nations, thereby mitigating carbon emissions (Copeland and Taylor, 2004).

Moreover, the Pollution Haven Hypothesis (PHH) posits that trade liberalisation may prompt the relocation of heavily polluting enterprises to countries with less stringent environmental regulations, exacerbating global carbon emissions. This hypothesis has garnered varying degrees of empirical support across studies conducted in diverse countries and regions (Zhang et al., 2017). Conversely, the GVC theory contends that trade facilitation has catalysed the reconfiguration of global production networks, rendering carbon emissions contingent not merely on individual countries' production activities but also intricately linked to the global division of labour (Peters et al., 2011). Shapiro (2016) observed that trade facilitation has reduced global transportation costs, albeit potentially intensifying carbon emissions from transportation. Zheng and Wang (2021), through their multi-regional input-output analysis, further illuminated that GVC restructuring leads to the intercountry transfer of carbon emissions. While trade facilitation may decrease emissions from carbon-intensive industries by optimising value chain allocation, it may concurrently augment emissions due to an increase in long-distance transportation. In summary, the synergistic integration of the EKC, the environmental effects framework of trade facilitation (encompassing the pollution haven hypothesis and scale, structure, and technological effects), and the GVC theory offers a holistic explanation of the ramifications of trade facilitation on global climate change. This synthesis provides a robust theoretical foundation for empirical research endeavours.

2.1.2 Review of empirical literature

In recent times, the severity of global climate change has escalated, positioning global warming as a pivotal challenge impeding sustainable development worldwide. Concurrently, trade facilitation has emerged as a critical catalyst for global economic growth, exerting intricate influences on global carbon emissions and, consequently, climate change dynamics. Despite this, the existing scholarly corpus on the nexus between trade facilitation and global warming remains sparse. Many studies have primarily concentrated on trade openness, industrial structure, or energy transitions, neglecting the nuanced impacts of trade facilitation measures—such as tariff reductions, enhanced customs clearance efficiency, and optimised global supply chains—on the global climate system. Hence, delving into the mechanisms through which trade facilitation influences global climate change, particularly global warming, assumes significant academic merit and policy relevance. This endeavour not only fills a crucial gap in the existing research landscape but also offers insights that could inform policy interventions aimed at mitigating climate change while fostering economic growth. By scrutinising the intricate interplay between trade facilitation and climate dynamics, we can uncover pathways to promote sustainable development that harmonises economic prosperity with environmental stewardship.

The primary factors contributing to global warming encompass greenhouse gas emissions, alterations in land use, climate patterns, and demographic shifts, notably population aging. Gu's research in 2023 revealed that deforestation dramatically impairs the carbon sequestration capacity, subsequently elevating atmospheric CO_2 levels and intensifying global warming trends. Drawing on data spanning six nations, this study underscores the ramifications of forest depletion on global temperature escalation and underscores the critical significance of sustainable forest management practices in mitigating climate change impacts.

In a systematic review of global greenhouse gas emission dynamics amidst the COVID-19 pandemic, Kumar et al. (2022) observed a notable decline in CO_2 concentrations attributed to the reduction in global economic activity enforced by pandemic-induced lockdowns. This finding indicates that human economic endeavours, particularly industrial production and international trade, serve as pivotal drivers of greenhouse gas emissions. Lehner and Coats' work in 2021 illuminated the intricate relationship between greenhouse gas emissions and the nonlinear alterations within the hydrological climate system, such as shifts in soil moisture and precipitation patterns, which exacerbate global climate instability. While this study underscores the multifaceted nature of climate change, it leaves unaddressed the nuanced impact of trade facilitation on the spatial distribution of carbon emissions. Kenyon and Hegerl (2008) explored the influence of climatic patterns, such as the El Niño–Southern Oscillation (ENSO), on extreme weather events worldwide, concluding that global warming may amplify the frequency and severity of such events. However, this investigation primarily concentrated on natural climatic factors, neglecting the role of international trade in perpetuating global warming. Expanding on these insights, Chen et al. (2024) emphasised that aging populations are disproportionately affected by extreme temperatures amidst global warming. They projected a substantial increase in mortality rates due to both high and low temperatures under warming scenarios of 1.5°C, 2°C, and 3°C. This study underscores the profound implications of demographic shifts on climate change but refrains from delving deeply into the interplay between trade facilitation and carbon emissions. Collectively, these studies paint a comprehensive picture of the multifarious drivers of global warming, yet they reveal gaps in our understanding, particularly regarding the intricate connections between international trade, demographic changes, and their cumulative impacts on climate dynamics. Thus, future research endeavours should strive to bridge these knowledge gaps, fostering a more holistic comprehension of the intricate web linking human activities, environmental changes, and their far-reaching consequences.

In exploring the ramifications of trade facilitation on global warming, Shahbaz et al. (2017) delved into the correlation between trade openness and CO_2 emissions, revealing that trade openness augments CO_2 emissions across both high-income and low-income nations. In contrast, middle-income countries exhibit a reciprocal causal dynamic between these two variables. This research underscores that trade openness may exacerbate the disparities in the global distribution of carbon emissions; however, it neglects to quantify the precise influence of trade facilitation measures—such as tariff reductions and logistics optimisations—on carbon emissions, and by extension, on global warming. Building upon this foundation, Wang et al. (2024) broadened the analytical horizon to assess the impact of trade diversification, encompassing both import and export diversification, on carbon emissions. Their findings underscore that while trade openness generally leads to an increase in carbon emissions, trade diversification, particularly import diversification, acts as a mitigating factor, reducing carbon emissions. Furthermore, the study elucidates that the impact of trade openness on carbon emissions manifests asymmetrically across different emission levels, fostering emissions at lower levels while potentially restraining them at higher levels. Despite providing a more holistic analytical framework, this study too falls short of investigating the nuanced ways in which trade facilitation influences global warming.

Zhang et al. (2020) elucidated that technological progress serves as a pivotal factor in mitigating carbon emission intensity, whereas the influence of industrial structure optimisation appears more constrained. This revelation underscores that, within the framework of trade facilitation, the attainment of carbon emission reductions hinges predominantly on technological innovation, rather than mere industrial restructuring. In a parallel study, Yi et al. (2022) observed that the digital economy indirectly fosters carbon emission reductions by refining the energy mix, with this effect being particularly pronounced in developed regions. However, their exploration of this phenomenon within the context of trade facilitation remained cursory. Furthermore, Cheng et al. (2019) demonstrated that economic growth generally correlates with an increase in carbon emissions. Notably, the emission reduction effect of renewable energy exhibits an inverted U-shaped trajectory across various stages of development. This finding suggests that the deployment of renewable energy in the globalised trade landscape may not sustainably reduce carbon emissions, particularly in high-carbon emitting industries. Such insights add complexity to the narrative surrounding renewable energy's role in mitigating climate change. Additionally, Sun and Huang (2020) delved into the impact of urbanisation on carbon emission efficiency, revealing a nuanced relationship. Initially, urbanisation acts as a catalyst for enhancing carbon emission efficiency; however, beyond a certain threshold of urban development, carbon emissions exacerbate. This study highlighted the dual-edged sword of urbanisation, where its benefits in terms of carbon efficiency are eventually outstripped by increased emissions. Collectively, these studies paint a multifaceted picture of the factors influencing carbon emissions in the context of trade facilitation. Technological innovation emerged as a standout solution, while the potential of industrial restructuring and renewable energy appeared more nuanced and context-dependent. Similarly, urbanisation's impact on carbon emission efficiency underscored the importance of striking a delicate balance between development and environmental sustainability.

Regarding policy instruments, Liu et al. (2021) conducted an examination of the efficacy of carbon tax policies in China, revealing that the imposition of a carbon tax can indeed lead to a decrease in carbon emissions. However, such a measure may concurrently exert a modest adverse effect on GDP. Their study advocates for a moderate tax rate as a strategy to strike a balance between economic growth and emission reduction. Notably, a gap exists in their analysis, as they neglect to delve into the ramifications of carbon taxes on international trade flows. In contrast, Wang et al. (2023) analysed the intricate relationship between income inequality and carbon emission efficiency, uncovering an inverted U-shaped correlation. Their findings suggest that, in the nascent phases of economic growth, income inequality may serve as a barrier to enhancing carbon emission efficiency. Conversely, as income disparities widen, carbon emission efficiency may witness an improvement. This research offers profound insights into the allocation of carbon emissions within the global trading system. Yet, it leaves unexplored the potential of trade facilitation in alleviating the environmental impacts stemming from income inequality. Furthermore, Dong et al. (2022) explored the interplay between the development of renewable energy and carbon emission efficiency, identifying a threshold effect in this dynamic. Their work underscores that renewable energy can effectively mitigate carbon emissions only under conditions of low energy consumption intensity and a mature financial market. This nuanced understanding highlights the conditions necessary for renewable energy to play a pivotal role in carbon reduction strategies. Collectively, these studies provide a multifaceted view of the policy challenges and opportunities in reducing carbon emissions. However, a comprehensive understanding necessitates bridging the gaps identified: examining the international trade implications of carbon taxes, exploring the mitigative potential of trade facilitation, and delineating the precise conditions under which renewable energy can significantly contribute to emission reductions. Such integrations are crucial for developing holistic and effective carbon reduction strategies in the context of global economic interactions and environmental sustainability.

In conclusion, the ramifications of trade facilitation on global warming exhibit a dual nature. On the positive side, it stimulates economic growth and enhances the international division of labour in production, thereby augmenting energy consumption and carbon emissions. Conversely, it also possesses the potential to mitigate the progression of global warming by fostering the dissemination of green technologies, refining the energy mix, and bolstering international collaboration on carbon emission reduction. Nonetheless, contemporary research endeavours are fraught with several notable shortcomings. Primarily, there is a scarcity of studies delving into the mechanisms through which trade facilitation influences global climate change. Secondly, the majority of existing research concentrates on the impact of trade openness on carbon emissions, neglecting the pivotal role of trade facilitation in addressing global warming governance. Thirdly, the measurement of trade facilitation lacks a robust and comprehensive quantification. Hence, this investigation endeavours to quantify trade facilitation and its nuanced effects on global change. Furthermore, it explores strategies to advance trade facilitation while minimising carbon emissions, which strikes a delicate balance between economic growth and environmental sustainability, thereby achieving a harmonious win-win scenario.

2.2 Hypothesis development

The influence of trade facilitation on global warming manifests through various pathways, contingent upon an intricate interplay of factors including trade patterns, modes of transportation, production frameworks, and regulatory policies. On one hand, trade facilitation could exacerbate greenhouse gas emissions by augmenting the overall scale of international commerce. This, in turn, might amplify the demand for long-distance transportation, thereby fostering an environment conducive to the relocation of high-carbon industries (Peng et al., 2024). Conversely, it also holds potential to catalyse the dissemination of eco-friendly technologies, optimising resource allocation and fostering the adoption of low-carbon production techniques. Additionally, enhanced trade facilitation can improve supply chain efficiency, mitigating unnecessary carbon emissions in the process (Cai et al., 2021). The nuanced effects of trade facilitation on global warming are thus contingent upon the specific trade architecture, energy consumption patterns, and the enforcement of environmental regulations across diverse countries and sectors. These factors combined render any definitive conclusion elusive. Instead, the net impact emerges as a complex mosaic, where the promotion of sustainable practices could counterbalance the emissions-inducing tendencies inherent in expanded trade activities. Hence, understanding the multifaceted interactions between trade facilitation and climate change necessitates a holistic perspective that considers both the potential benefits and drawbacks within the broader context of global economic and environmental dynamics. The hypothesis is as follows.

Hypothesis 1a: Trade facilitation may promote global warming.

Hypothesis 1b: Trade facilitation may inhibit global warming.

Trade facilitation exerts a multifaceted influence on global warming, with carbon emissions serving as a pivotal factor in this complex interplay. Specifically, its effects can be analysed from two distinct yet interconnected perspectives. Firstly, trade facilitation may inadvertently amplify carbon emissions, thereby exacerbating global warming. This occurs through several mechanisms. One notable mechanism is the stimulation of international trade, which typically entails an increase in long-distance transportation. Such an expansion not only enhances the volume of goods moved across borders but also tends to rely heavily on fossil fuels, thereby augmenting carbon emissions (Du et al., 2021). Furthermore, trade facilitation can facilitate the global dissemination of high-carbon industries. Accompanying this trend, resource extraction activities and changes in land use, such as deforestation, may diminish the planet's carbon sink capacity. These changes further contribute to the intensification of global warming by reducing the natural sequestration of atmospheric carbon dioxide (Kafy et al., 2023). Conversely, trade facilitation also harbours the potential to mitigate carbon emissions and, consequently, counteract global warming. This beneficial impact arises from several avenues. By enabling the seamless cross-border transfer of clean energy technologies and low-carbon products, trade facilitation can foster the adoption of sustainable practices worldwide. Moreover, it can enhance production and energy efficiency through the dissemination of advanced manufacturing techniques and energy-saving innovations. Lastly, it promotes the sustainable optimisation of global supply chains, ensuring that resources are utilised more judiciously and emissions are minimised throughout the production and distribution processes (Deng et al., 2024). In this nuanced interplay, carbon emissions emerge as a critical moderating factor. They do not merely reflect the direct consequences of trade facilitation but also mediate its overall impact on global warming. Thus, as policymakers navigate the complexities of trade facilitation, they must carefully consider its dual potential—both as a catalyst for carbon emissions and as a conduit for emissions reduction. By doing so, they can harness the transformative power of trade to either exacerbate or mitigate global warming, ultimately steering the planet towards a more sustainable future. The hypothesis is as follows.

Hypothesis 2a: Trade facilitation promotes global warming by affecting carbon emissions.

Hypothesis 2b: Trade facilitation inhibits global warming by affecting carbon emissions.

Trade facilitation promotes technological exchanges and industrial upgrading between countries, which may accelerate the development and diffusion of high-carbon technologies, such as more efficient fossil fuel extraction and utilisation technologies, potentially leading to an increase in total carbon emissions (Chipangamate and Nwaila, 2024). In addition, trade facilitation enhances market competition, making companies more inclined to adopt less costly but carbon-intensive production methods in the short term, thus exacerbating global warming (Bhatia et al., 2024). On the other hand, trade facilitation may also promote technological innovation, such as promoting research and development and the cross-border application of clean energy, carbon capture and storage, energy conservation and environmental protection technologies, improving energy efficiency and optimising the global industrial structure to reduce carbon emissions and thus curb global warming (Yu et al., 2022). Therefore, national innovation may play a moderating role in the impact of trade facilitation on global warming. The hypotheses are as follows.

Hypothesis 3a: Trade facilitation promotes global warming by affecting national innovation.

Hypothesis 3b: Trade facilitation inhibits global warming by affecting national innovation.

3 Methodology and data

3.1 Method

To delve into the intricate interplay between trade facilitation and global warming, this study undertakes an initial evaluation of the inherent spatial dependence in the nexus between trade dynamics and global temperature variations. Prior to specifying the econometric framework, we embarked on a spatial autocorrelation analysis employing Moran's I index, aiming to ascertain whether indicators of trade facilitation and global temperature display patterns of spatial clustering. A significant Moran's I score serves as an indicator of robust spatial interconnectedness, necessitating the application of spatial econometric methodologies to capture cross-border effects that may elude traditional regression models. This preliminary assessment is pivotal, as it ensures that our empirical endeavour adequately integrates geographical factors, mitigates estimation biases, and enhances the precision of our research findings. Furthermore, by acknowledging the spatial dimension of these interactions, we not only adhere to the rigors of empirical analysis but also pave the way for a more nuanced understanding of the intricate web linking economic activities, such as trade facilitation, with environmental phenomena like global warming. This spatial perspective acts as a corrective lens, revealing nuances that might otherwise remain obscured in analyses confined to conventional regression frameworks. Thus, our approach not only refines methodological rigor but also contributes to the theoretical discourse by illuminating the complex, spatially contingent relationships within the broader domain of environmental economics.

Given the established presence of spatial dependence, we adopt the spatial Durbin model (SDM) as our principal analytical framework. Our rationale for selecting the SDM stems from its capacity to encapsulate both the spatial lags of dependent and independent variables, thereby offering a more holistic evaluation of both direct and indirect effects. Direct effects constitute the ramifications of trade facilitation on a country's environmental outcomes. Conversely, indirect effects manifest as spillover effects that extend to neighbouring countries. These spillover effects propagate through diverse channels, such as supply chain integration, production relocation, and technology diffusion, all of which have the potential to profoundly influence cross-border temperatures. The integration of these spatial lags within the SDM allows for a nuanced understanding of how trade facilitation not only impacts a country's immediate environment but also triggers ripple effects across geographical borders. These indirect effects, akin to ripples in a pond, emanate from economic activities and propagate through interconnected supply chains, production shifts, and technological advancements. In essence, the SDM serves as a lens through which the intricate web of interactions that shape cross-border environmental conditions can be dissected, thereby advancing the understanding beyond mere contiguous impacts to encompass broader spatial dynamics.

A detailed comparison with alternative spatial models underscores the distinctive merits of the SDM. Spatial Lag Models (SLM) predominantly focus on elucidating spatial dependence within the dependent variable, yet they overlook the influence that a country's independent variables exert on the environmental conditions of neighbouring countries. While SLMs are instrumental in capturing spatial feedback loops, they neglect the significant impact of policy variables and trade facilitation measures across diverse regions. Conversely, Spatial Error Models (SEM) assume that spatial dependence is confined solely to the error term, suggesting that unobservable factors underlie spatial interactions. However, SEM's inability to explicitly model the spatial transmission mechanisms of trade facilitation undermines its capacity to encapsulate the dynamic and policy-induced nature of economic-environmental interdependencies. This limitation renders SEM less adept at capturing the intricate web of relationships that are driven by both observable policies and latent spatial factors. In this context, the SDM emerges as a more comprehensive framework. It not only acknowledges the spatial spillovers in the dependent variable but also integrates the effects of independent variables across borders, thereby offering a nuanced understanding of how trade facilitation and policy measures propagate through space. This holistic perspective is crucial for formulating policies that can effectively mitigate adverse environmental impacts while fostering economic growth.

Conversely, Spatial Durability Modelling offers a framework that is not only more adaptable but also theoretically fortified, explicitly accounting for the spatial interdependencies between dependent and independent variables. In the context of this research, this feature assumes paramount importance, given that the ramifications of trade facilitation on global warming do not manifest instantaneously but rather unfold progressively over time. Spatial durability models stand out as potent instruments for delineating the intricate interplay between economic activities and environmental sustainability. They possess the capability to aptly seize both direct and delayed effects, thereby enhancing the analytical depth. By seamlessly amalgamating spatial and temporal dimensions, spatial durability models provide deeper insights into the mechanisms through which trade-related policies exert influence on environmental consequences at a global juncture. This integration facilitates and broadens the nuanced understanding of the multifaceted relationships at play. The formal representation of Equation 1 is as follows:

$$Warm_{it} = \gamma W \times TradeF_{it} + \alpha TradeF_{it} + \vartheta M \times Z_{it} + \varphi_i + \omega_t + \varepsilon_{it} \quad (1)$$

where M denotes the regional adjacency matrix, reflecting the nation adjacency relationships. γ is the spatial lag coefficient, α and ϑ are the coefficients of independent variables and control variables, respectively. φ_i and ω_t account for the fixed effects of region and year, respectively, while ε_{it} is the error term. In this model, $Warm_{it}$ indicates the average temperature level in country i in year t.

If trade facilitation did not have a spatial spillover effect on global warming, this paper would change the empirical model from a spatial econometric model (1) to a two-way fixed effect model (2).

$$Warm_{it} = \alpha_0 + \alpha_1 TradeF_{it} + Z_{it} + \varphi_i + \omega_t + \varepsilon_{it} \quad (2)$$

3.2 Variable description

Dependent variable: $Warm_{it}$ represents the average surface temperature level in the country for that year, which is used to measure the impact of climate warming. In our methodological approach, we drew inspiration from the research conducted by

TABLE 1 Trade facilitation development indicator System.

Level 1 indicator	Level 2 indicator	Direction
Infrastructure Development	Road infrastructure construction	+
	Railway infrastructure construction	+
	Port infrastructure construction	+
	Aviation infrastructure construction	+
Government Regulations	Unconventional payments and bribery	-
	Prevalence of tariff barriers	-
	Transparency of decision-making	+
	Government regulations Efficiency of dispute resolution	+
	Independence of the judiciary	+
	Government regulatory burden	-
Financial Services	Availability of financial services	+
	Ease of access to credit	+
	Availability of risk capital	+
Internet Penetration	Internet penetration rate	+

Hansen et al. (2025). Specifically, we employed the annual average surface temperature data sourced from the World Bank's Climate Change Knowledge Portal to quantify the extent of climate warming across various countries. This portal serves as a comprehensive global climate data repository, amalgamating and disseminating historical climate data alongside predictive models curated by esteemed institutions like the Global Climate Observing System and the World Meteorological Organisation. These datasets encompass a spectrum of climate variables, including temperature, precipitation, and extreme weather events. Within the context of the study, the annual average surface temperature data from this portal was strategically chosen as the pivotal metric for assessing climate warming. This selection was driven by the need to ensure the authority and comparability of our data sources, thereby providing robust data foundations for the empirical analyses that follow. The adoption of this approach not only aligned with established practices in climate research but also enhanced the reliability and generalisability of the findings, much like how a meticulous artist selects their paints to bring a canvas to life.

Independent variable: Referring to Cong et al. (2025), this paper used principal component analysis (PCA) to construct a national trade facilitation index ($TradeF_{it}$) to comprehensively and accurately measure the development level of trade facilitation in various countries. PCA serves as a sophisticated dimensionality reduction technique, transforming a multitude of highly correlated variables into a smaller set of uncorrelated principal components. This process aims to preserve as much information as feasible within the data, ultimately facilitating the reduction of variable dimensionality and enhancing the validity and interpretability of subsequent data analyses. The merits of PCA are multifaceted and can be elucidated as follows: PCA mitigates the issue of multicollinearity among diverse indicators, thereby bolstering the stability of regression analyses. By decreasing the correlation among variables, PCA ensures that the statistical models derived from these variables are more robust and less prone to errors induced by collinear relationships. Furthermore, PCA accomplishes dimensionality reduction through data compression, effectively pruning redundant information. This leads to a more concise and efficient index construction process, as only the most significant components are retained. Such compression not only simplifies the data structure but also facilitates more streamlined and insightful data analysis. Lastly, PCA ensures an objective contribution of each indicator to the final index. This is achieved by assigning weights based on the variance contribution rate inherent in the data, rather than relying on subjective assessments. This approach elevates the objectivity and reliability of the measurement results, as it aligns the significance of each indicator with its actual influence on the overall dataset. In essence, PCA emerges as a potent tool in the realm of data analysis, not only in streamlining complex datasets but also enhancing the accuracy and trustworthiness of the insights derived from them. By addressing multicollinearity, reducing dimensionality, and ensuring an objective weighting system, PCA contributes significantly to the advancement of data-driven research and decision-making.

In this research endeavour, a comprehensive set of core variables pertinent to trade facilitation was selected in Table 1. These variables encompassed indicators across four pivotal dimensions: infrastructure construction, government regulations, financial services, and internet penetration. Ensuring that the data emanated from authoritative sources and that the indicators were representative of their respective domains was paramount. Subsequently, these variables were standardised to nullify the influence of units and orders of magnitude, thereby facilitating comparisons. Proceeding further, we delved into the computation of the covariance matrix for the variables, from which we extracted eigenvalues and eigenvectors. This statistical analysis served as a cornerstone for selecting the principal components. Specifically, the leading few principal components that collectively explained the largest proportion of variance were identified. The determination of the weight assigned to each principal component was grounded in its variance contribution rate, ensuring that the methodology was robust and reflective of the data's underlying structure. Ultimately, leveraging the principal component scores, the Trade-F index was formulated for each country. This index provides a nuanced and objective lens through which the level of trade facilitation could be assessed, encompassing infrastructure quality, regulatory environments, financial services accessibility, and information technology sophistication. In this way, this study not only aggregates complex data into a manageable metric but also offers a sophisticated tool for policymakers and researchers to evaluate and compare trade facilitation across nations.

The design of this indicator system meticulously ensures a comprehensive evaluation of each country's trade facilitation level, encompassing diverse facets. Notably, infrastructure construction stands as a fundamental prerequisite for trade facilitation, spanning road, railway, port, and aviation domains. These indicators assess respective transportation capacities in land, maritime, and air transport, thereby exerting a direct influence on the efficiency of goods circulation and serving as the linchpin for the seamless operation of international trade. Regarding governmental regulations, a conducive policy environment is pivotal in mitigating trade barriers, fostering market transparency, and bolstering investor confidence. This encompasses metrics such as non-conventional payments and bribery (indicating governmental integrity), the prevalence of tariff barriers (quantifying trade impediments), the transparency of decision-making (measuring policy formulation openness), the efficiency of governmental regulations in dispute resolution (evaluating the legal system's responsiveness to trade disputes), judicial independence (assessing judicial impartiality), and the regulatory burden (measuring administrative regulation's impact on trade activities). Collectively, these indicators mirror the nation's trade policy facilitation, regulatory efficacy, and legal environment. Financial services play an indispensable role in facilitating international trade, with indicators encompassing financial service accessibility (evaluating the ease of access for businesses and individuals), credit availability (measuring the accessibility of financing for enterprises), and venture capital availability (indicating the financial ecosystem that nurtures innovation and business growth). These indicators reflect the financial system's maturity and influence the facility of trade financing and cross-border investments. Furthermore, Internet penetration, a crucial indicator of information infrastructure reach, underscores a country's competitiveness in e-commerce and cross-border trade facilitation. The data for all indicators is sourced from the Global Competitiveness Report (GCR), with values ranging from one to seven for most indicators (Internet penetration spans from 1 to 100), ensuring data authority and comparability. The National Trade Facilitation Index was constructed through the application of PCA to weigh the aforementioned indicators, effectively circumventing the subjective bias inherent in manually assigned weights. This approach offers a more scientific measurement of each country's trade facilitation level, thereby enhancing the accuracy and robustness of the evaluation framework.

Z_{it} represents a set of control variables. The intricate relationship between trade facilitation and global warming is contingent upon a myriad of economic and structural factors, each weaving a complex tapestry of influence. Initially, economic development stands as a pivotal determinant in shaping a nation's environmental footprint. Advanced economic stages are frequently paralleled by augmented industrial endeavours, heightened energy consumption, and augmented greenhouse gas emissions—all contributing to an upward trajectory in surface temperatures. Paradoxically, economic expansion can also catalyse investments in clean technologies and the formulation of environmental policies, serving as buffers against temperature escalation (Ferreira et al., 2020). To quantify this dimension, this study adopts gross domestic product (GDP) *per capita* as a fundamental metric, mirroring *per capita* economic output and its ramifications on climate change dynamics. Furthermore, foreign direct investment (FDI) exerts a profound impact on economic structure and energy utilisation patterns, ultimately influencing national temperature trends. The influx of FDI propels industrial growth, infrastructure augmentation, and technological advancements, which may either exacerbate or ameliorate temperature increases, contingent upon the host country's energy sources and environmental benchmarks (Li et al., 2022). To dissect the role of FDI in climate-induced economic transformations, this study incorporated the proportion of FDI in GDP as a strategic control variable.

Additionally, remittances (denoted as *Remit*) influence household income and consumption paradigms, indirectly modulating surface temperatures. Heightened remittance inflows typically result in augmented energy demand, infrastructure expansion, and carbon emissions, potentially intensifying temperature fluctuations. Conversely, remittances can also fortify climate adaptation strategies by financing investments in renewable energy and sustainable infrastructure, thereby fostering resilience (Mills, 2023). To encapsulate this role, this study utilised remittances as a percentage of GDP (remittances/GDP) as a control variable, illuminating its significance in shaping climate-related economic endeavours. Moreover, government spending (denoted as *Govern*) exhibits both direct and indirect ramifications on national temperature trends. Elevated government expenditures can finance environmental protection policies, renewable energy ventures, and climate adaptation initiatives, effectively mitigating temperature increases. However, large-scale infrastructure and industrial investments may exacerbate carbon emissions, thereby intensifying warming trends (Akorede et al., 2012). To address this, this study integrated government spending as a percentage of GDP (government spending/GDP) as a critical control variable.

Energy consumption (*Energy*) emerges as a fundamental determinant of temperature change, directly influencing greenhouse gas emissions and heat generation. Nations with elevated *per capita* energy consumption often face more severe climate impacts, particularly when their energy mix heavily relies on fossil fuels. Nevertheless, these adverse effects can be mitigated through enhanced energy efficiency and the transition to clean energy sources (Wu et al., 2023). To evaluate the role of energy use in temperature dynamics, this study employed *per capita* energy consumption as a pivotal control variable. Lastly, exports of goods and services (denoted as *Export*) exert an influence on national temperature levels by modulating production intensity and energy

TABLE 2 Descriptive statistics.

Variables	Sample size	Mean	Standard deviation	Minimum	Maximum
Warm	1,290	17.938	8.252	−4.61	29.76
TradeF	1,290	0.401	0.117	0.179	0.731
GDP	1,290	16,833.78	21,845.36	210.24	123,678.7
FDI	1,290	5.258	17.138	−117.37	279.36
Remit	1,290	4.301	6.350	0.000	43.77
Govern	1,290	16.195	5.387	3.59	40.55
Energy	1,290	2,773.969	3,030.247	205.62	19,987.58
Export	1,290	42.026	27.810	5.17	206.41

consumption. High export rates may lead to intensified industrial activity and emissions, thereby exacerbating surface temperature increases. Conversely, trade can also catalyse technology transfer and the adoption of energy-efficient practices, thereby mitigating climate-related impacts (Yana and Ramakrishnan, 2023). To delve into this aspect, this study incorporated exports of goods and services as a percentage of GDP (exports/GDP) as a strategic control variable. By meticulously incorporating these control variables—economic development, FDI, remittances, government spending, energy use, and exports—this study undertook a holistic analysis of the multifaceted factors that influence global warming. This nuanced examination not only elucidates the complex interplay between economic activities and climate change but also offers insights into potential policy interventions aimed at fostering sustainable development amidst the ongoing climate crisis.

Considering the accessibility of relevant data, this study was grounded in a comprehensive panel data set encompassing 129 countries spanning the years from 2010 to 2019. The foundational sources for these data were the esteemed World Bank statistical database and the authoritative WTO database. Table 2 provides a detailed overview of the descriptive statistics for the entire sample, meticulously summarising the key characteristics of the dataset.

4 Empirical results and analysis

4.1 Impact of trade facilitation on global warming

4.1.1 Correlation test

This comprehensive analysis delves into the interplay between trade facilitation and global warming, employing a rigorous spatial autocorrelation analysis facilitated by the computation of a global Moran's I index. This index was derived using a spatial adjacent weight matrix, ensuring precision in our methodological approach. The findings presented in Table 3 elucidate the spatial correlation dynamics between the two phenomena. Over the span from 2009 to 2019, the Moran's I index for trade facilitation exhibited a consistent upward trajectory, achieving statistical significance in each year (p-value <0.01). Notably, the index rose from 0.249 in 2009 to 0.377 in 2019, revealing a discernible trend towards heightened spatial agglomeration in trade facilitation across the globe. This evolution signifies a diminishing disparity in trade facilitation levels among various regions, reflecting a robust spatial correlation. Furthermore, this spatial agglomeration effect has progressively intensified over the long-term horizon. Based on the results, as trade facilitation became increasingly integrated spatially, the differences among regions narrowed, fostering a cohesive global landscape in this domain. This convergence not only highlights the interconnected nature of international trade but also suggests potential pathways through which global warming might be influenced by these spatial dynamics. Thus, the analysis contributes to a nuanced understanding of the spatial dimensions of trade facilitation and their implications for global warming, paving the way for further exploration and informed policymaking.

In recent years, the Moran's I index for global warming has exhibited notable spatial autocorrelation, evidenced by a p-value below 0.01. Notably, the magnitude of this index is typically lower compared to that observed for trade facilitation. This finding underscores the presence of spatial agglomeration in global warming, albeit its intensity being relatively subdued. Despite the moderate nature of this spatial agglomeration effect, it nevertheless demonstrates a discernible spatial correlation among regions. This correlation may intricately intertwine with regional environmental policies, the ramifications of climate change, and the overarching trajectory of global climatic shifts.

4.1.2 The results of the regression of trade facilitation on global warming

Prior to model estimation, it is imperative to ascertain the nature of spatial correlation via the Lagrange multiplier (LM) test. This step is crucial for deciding between the SEM and SLM. Table 4 presents a compelling picture, where all test methodologies—encompassing LM-spatial lag, Robust LM-spatial lag, and LM-spatial error, among others—exhibited statistical significance at the 1% level, with P-values universally at 0.000. This unanimous significance underscores the prominent presence of spatial correlation across diverse testing scenarios. Consequently, the data unmistakably point to a notable spatial effect within the model, necessitating a deeper dive into identifying an apt spatial model configuration.

The application of the Wald test and the likelihood ratio (LR) test was instrumental in assessing the feasibility of reducing the SDM

TABLE 3 Spatial correlation test between trade facilitation and global warming.

Year	Trade facilitation		Global warming	
	Moran's I	P-value*	Moran's I	P-value*
2009	0.249***	0.000	0.105***	0.000
2010	0.278***	0.000	0.098***	0.000
2011	0.286***	0.000	0.093***	0.000
2012	0.295***	0.000	0.087***	0.000
2013	0.306***	0.000	0.088***	0.000
2014	0.308***	0.000	0.082***	0.000
2015	0.318***	0.000	0.085***	0.000
2016	0.326***	0.000	0.080***	0.000
2017	0.337***	0.000	0.085***	0.000
2018	0.369***	0.000	0.081***	0.000
2019	0.377***	0.000	0.088***	0.000

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

TABLE 4 Model selection test.

Test method	Statistical value	P-value
LM-spatial lag	109.670***	0.000
Robust LM-spatial lag	121.330***	0.000
LM-spatial error	78.309***	0.000
Robust LM-spatial error	3.249***	0.000
Wald-spatial lag	15.852***	0.000
LR-spatial lag	17.030***	0.000
Wald-spatial error	30.040***	0.000
LR-spatial error	80.310***	0.000
Hausman test	56.70***	0.000

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

to a simpler spatial lag or spatial error model. The findings presented in Table 4 reveal that both statistical tests achieved significance at the stringent 1% level (notably, the Wald statistic for the spatial lag component stood at 15.852, with a corresponding P-value of 0.000). These results reinforce the intricate nature of the SDM and suggest that it cannot be distilled into either of the aforementioned simpler models. Consequently, the SDM retains its validity and applicability within the context of our analysis. Moreover, to discern between a random effects model and a fixed effects model, the Hausman test was employed. The outcome of this test, characterised by a statistic of 56.70 and a highly significant P-value of 0.000, provides compelling evidence against the null hypothesis favouring a random effects model. This statistical robustness led us to conclude that a fixed effects model is more appropriate. Therefore, the ultimate choice of model is the SDM incorporating double fixed effects. This decision underscores the complexity and nuanced nature of the spatial relationships inherent in the data, necessitating a sophisticated modelling approach to capture these dynamics accurately.

Table 5 presents the spatial econometric outcomes of trade facilitation (denoted as TradeF) in relation to global warming. When examining direct effects, the coefficient of TradeF stands at −0.022, achieving statistical significance at the 1% level. This underscores a negative direct influence of TradeF on global warming, suggesting that TradeF can substantially diminish its detrimental effects by decreasing environmental costs associated with trade, refining resource allocation strategies, and fostering the adoption of green technologies. This outcome aligns with Hypothesis 1b, which posits that TradeF can ameliorate global warming, particularly by fostering the green transformation of industries, facilitating the implementation of low-carbon technologies, and enhancing overall sustainability. In terms of indirect effects, the spillover coefficient of TradeF was −0.025, albeit non-significant. This implies that TradeF's impact on other regions may be marginal or even negligible, lacking a discernible spillover effect. The dynamic effects corroborate the static findings, reinforcing the notion of TradeF's negative direct impact on global warming. Specifically, considering the total dynamic effect, the coefficient for TradeF was −0.006, indicating a continued significant negative influence on global warming in the long run. This demonstrates that, as time progresses, TradeF's mitigation of global warming becomes increasingly pronounced, thereby promoting sustainable climate development. Collectively, these findings imply that TradeF alleviates global warming primarily through direct channels, with its sustained negative impact being globally significant, particularly in advancing green transitions and sustainable development. However, in select instances, TradeF may lack a substantial spillover effect. These insights underscore the multifaceted role of TradeF in shaping the environmental landscape, emphasising its potential to foster a more sustainable future while acknowledging limitations in its broader regional impacts.

Given the insubstantial spillover effects of trade facilitation on global warming, this paper undertakes a revised assessment of its impact employing Equation 2. Our analysis, presented in Table 6, meticulously considers the negligible spillover implications. Upon examining the outcomes derived from the fixed-effect model, a nuanced picture emerges: across various regression models (I, II, III, and IV), the coefficient associated with trade facilitation (TradeF) consistently registers as negative, and attains statistical significance in select models. This finding underscores a potential inverse relationship between trade facilitation and global warming, albeit with variations in its statistical robustness across different specifications.

Specifically, in Column I, the coefficient of trade facilitation stands at −0.077, achieving statistical significance at the 1% level. This signifies a negative direct impact of trade facilitation on global warming, implying that advancements in trade facilitation may contribute to mitigating global warming trends. The underlying rationale for this negative effect lies in trade facilitation's potential to alleviate environmental stress through enhanced resource allocation efficiency and accelerated adoption of green technologies. Transitioning to Column II, the coefficient adjusts slightly to −0.069 yet maintains its statistical significance. This observation underscores the persistence of trade facilitation's notable negative influence on global warming, even after

TABLE 5 Spatial econometric results on the impact of the trade facilitation and global warming.

Variable	Direct effect	Indirect effect	Total effect	Dynamic direct effect	Dynamic indirect effect	Dynamic total effect
TradeF	−0.022***	−0.025	−0.054***	−0.045***	−0.271	−0.006***
	(0.004)	(0.674)	(0.003)	(0.008)	(0.245)	(0.001)
L.Warm				−0.050***	0.012	−0.008***
				(0.010)	(0.007)	(0.001)
ρ			0.034			0.003
			(0.039)			(0.048)
σ_e^2			0.022***			0.794***
			(0.006)			(0.007)
Control variable	YES	YES	YES	YES	YES	YES
Country	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES

Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors are within parentheses. and represent Spatial rho and Variance sigma2_e, respectively.

accounting for various confounding variables. To delve deeper into the potential for a non-linear relationship between trade facilitation and global warming, the squared term of trade facilitation was incorporated in Columns III and IV. Intriguingly, despite the coefficients of trade facilitation and its squared term displaying opposite signs, the significance of trade facilitation diminishes. This result further corroborates that the impact of trade facilitation on global warming does not adhere to a non-linear pattern. In synthesising these findings, it becomes evident that the evolution of trade facilitation has, to a certain extent, acted as a brake on the progression of global warming. This revelation underscores the multifaceted benefits of trade facilitation, extending beyond economic gains to encompass environmental sustainability.

4.1.3 Robustness checks

To enhance the reliability of the benchmark results, this study employed a quintet of rigorous robustness testing methodologies. Specifically, these include variable substitution, truncation of the sample period, placebo tests, the utilisation of the generalised method of moments (SYS-GMM). In addition, endogeneity issues were addressed through the application of two-stage least squares (2SLS). These multifaceted approaches collectively scrutinised the robustness of the benchmark findings from diverse angles. Each of these techniques served a unique purpose: variable substitution assessed the sensitivity of the results to alternative specifications, truncation of the sample period examined the consistency of the findings over different time horizons, and placebo tests gauged the impact of spurious correlations. SYS-GMM was leveraged to mitigate potential biases arising from endogeneity and serial correlation in panel data, while 2SLS provided a robust solution to address endogeneity directly. By integrating these diverse methodologies, the study not only verified the benchmark results but also fortified their credibility. This comprehensive approach ensured that the conclusions drawn were not contingent upon any single assumption or data characteristic, thereby presenting a more resilient and generalisable understanding of the phenomenon under investigation.

In the context of robustness testing, the initial examination involved substituting the variable in question. Specifically, while the benchmark regression model relied on a trade facilitation index formulated through principal component analysis, the robustness test employed an alternative index derived by the entropy method. This method of variable substitution served as a crucial means to ascertain the consistency of the trade facilitation impact on global warming across diverse methodological constructions. Upon scrutinising the data presented in Table 6, specifically column V, it became evident that when the entropy method-constructed index was utilised for regression analysis, the results continued to indicate a statistically significant negative effect of trade facilitation on global warming. The coefficient, valued at −0.094, underscored the robustness of the findings obtained from the baseline regression model. This consistency not only reinforced the reliability of our initial conclusions but also highlighted the robustness of our methodological approach in capturing the intricate relationships between trade facilitation and global warming.

The second robustness test entailed truncating the sample period, specifically by narrowing the scope of years analysed from 2010 to 2019 to 2010–2017. This approach was designed to mitigate potential biases associated with any particular period. The findings presented in Table 6, column VI, revealed that the adverse influence of trade facilitation on global warming persisted as statistically significant within this truncated timeframe, exhibiting a coefficient of −0.036. Notably, this evidence underscored that the reduction in the sample period did not appreciably alter the directionality or statistical significance of the benchmark findings. Consequently, this observation fortified the robustness of the impact that trade facilitation exerts on global warming.

TABLE 6 Spatial econometric results on the impact of the trade facilitation and global warming.

Variable	Baseline results				Robustness check									
	Fixed effect				Alternative variable		Shorten 2 years		Placebo test		SYS-GMM		Endogenous	
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
TradeF	−0.077***	−0.069***	−0.028***	−0.469	−0.094***	−0.113***	−0.071***	−0.036***	0.019	0.005	−0.051***	−0.027***	−0.067***	−0.039***
	(0.003)	(0.004)	(0.008)	(0.470)	(0.002)	(0.000)	(0.001)	(0.002)	(0.014)	(0.040)	(0.001)	(0.001)	(0.000)	(0.004)
$TradeF^2$			0.082***	0.032***										
			(0.006)	(0.001)										
Constant	1.170***	1.224***	1.023***	1.304***	1.431***	1.664***	1.314***	1.562***	1.129***	1.101***			1.582***	1.562***
	(0.005)	(0.002)	(0.006)	(0.004)	(0.003)	(0.005)	(0.008)	(0.002)	(0.009)	(0.000)			(0.006)	(0.002)
L. Warm											0.015***	0.203*		
											(0.000)	(0.121)		
Sargan test												0.247		
AR (1)												0.000		
AR (2)												0.763		
DWH														70.27 ($p = 0.000$)
Shea's Partial R^2														0.7632 (*Trade-F*)
Control variable	NO	Yes	NO	Yes	NO	Yes	NO	Yes	NO	Yes	NO	Yes	NO	Yes
Country	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Note: Refer to notes in Table 5.

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The placebo test constituted the third pivotal methodology employed to discern and mitigate the influence of extraneous, random factors. By simulating a hypothetical scenario devoid of any correlation to the actual research variables, it validated the significance of the benchmark results. In the study conducted by Cong et al. (2025), this test was strategically utilised to deepen the exclusion of random interference. A perusal of Table 6 (column VII) revealed that the placebo test elucidated an insignificant impact of trade facilitation on global warming, with a positive coefficient of mere 0.005. This outcome underscored the failure of the placebo test to introduce noteworthy interference, thereby reinforcing the robustness and reliability of the benchmark findings. In essence, the placebo test served as a robust check against the noise of randomness, ensuring that the underlying relationships under investigation remained pristine.

The SYS-GMM constituted the fourth and pivotal approach designed to tackle the inherent endogeneity challenges in dynamic panel data analysis. This methodology meticulously incorporated the lagged effects of trade facilitation, thereby enabling a more precise capture of its ramifications on global warming. Upon scrutinising the results presented in Table 6, specifically column XII, it became evident that within the framework of the SYS-GMM model, the coefficient associated with trade facilitation stood at −0.051, maintaining a robust significance level of 1%. This finding underscored that, even after accounting for dynamic effects and endogeneity, the adverse influence of trade facilitation on global warming persisted and remained statistically notable. This observation not only reinforced the validity of the initial benchmark results but also imparted a sense of robustness to our analytical framework. In essence, by leveraging the SYS-GMM approach, the understanding of the intricate relationship between trade facilitation and global warming was fortified, demonstrating how dynamic panel data analysis can be refined to address complex endogenous issues. This nuanced exploration not only enriches the theoretical discourse but also provides empirical support for policy interventions aimed at mitigating the detrimental effects of trade on climate change.

Ultimately, this paper employed the two-stage least squares (2SLS) methodology to tackle the issue of endogeneity, utilising the lagged first-order term of trade facilitation as an instrumental variable. This approach enabled a more precise evaluation of the effects of trade facilitation on global warming by mitigating potential biases stemming from endogeneity. As illustrated in Table 6 (column XIV), upon employing this instrumental variable, the coefficient associated with trade facilitation was found to be −0.039, retaining statistical significance at the 1% level. This finding reinforced our confidence that addressing the endogeneity concern does not alter the directionality or statistical significance of the baseline results, thereby fortifying the robustness of our analysis.

In conclusion, the benchmark results had been rigorously validated through five comprehensive robustness tests, affirming their reliability and consistency. Specifically, the application of the replacement variable method, truncation of the sample period, the conduct of a placebo test, the utilisation of the generalised moment estimation technique, and the addressing of endogeneity issues collectively reinforced the significant negative correlation between trade facilitation and global warming. These findings underscored that the robustness of trade facilitation's impact persists across diverse methodological constructions, temporal scales, and analytical frameworks. Furthermore, the enduring and persistent nature of its adverse effects on global warming became evident, painting a comprehensive picture of its long-term implications.

4.1.4 Mechanism analysis

Drawing upon the findings presented in Table 7, this paper delved into the ramifications of trade facilitation on global warming, examining two primary impact mechanisms: carbon emissions and national innovation. The empirical analysis undertaken sought to ascertain whether trade facilitation influenced global warming by inducing alterations in carbon emissions or fostering enhancements in national innovation. Herein lies a nuanced exploration of the mechanism analysis results. Firstly, the mechanism through which trade facilitation might affect carbon emissions was considered. By facilitating smoother and more efficient trade flows, countries may experience an increase in economic activity, potentially leading to heightened energy consumption and, consequently, elevated carbon emissions. This mechanism posits a direct link between trade facilitation and global warming, as augmented emissions exacerbate climate change. Secondly, we turned our attention to the role of national innovation in mediating the relationship between trade facilitation and global warming. Enhanced trade facilitation can stimulate technological advancements and innovative practices, which in turn may contribute to the development of more environmentally friendly technologies. Such innovations could potentially mitigate the adverse effects of trade-induced carbon emissions, thereby acting as a countervailing force against global warming. Transitioning smoothly between these two mechanisms, it becomes evident that the net impact of trade facilitation on global warming is a complex interplay between increased carbon emissions and the potential for innovation-driven mitigation. The empirical results offer insights into the relative strength and direction of these effects, guiding further research and policy interventions aimed at balancing economic growth with environmental sustainability. In conclusion, the intricate relationship between trade facilitation, carbon emissions, and national innovation emerges as a pivotal theme in understanding the multifaceted impacts on global warming. This analysis underscores the necessity for comprehensive policy frameworks that not only harness the benefits of trade facilitation but also address the associated environmental challenges, fostering a symbiotic relationship between economic progress and climate resilience.

The examination of the carbon emission mechanism revealed a pronounced inverse impact on the influence of trade facilitation (denoted as TradeF) in relation to global warming, thereby corroborating hypothesis H2b. Specifically, in Model III, the coefficient of the interaction between carbon emissions and trade facilitation (denoted as Co2*Trade-F) stood at −0.016, marking statistical significance at the 1% level. This finding underscored the pivotal role of the carbon emission mechanism. In essence, trade facilitation can indirectly reduce the carbon footprint of nations by refining resource allocation, augmenting production efficiency, and fostering the adoption of low-carbon technologies. This intricate mechanism underscores how trade facilitation contributes to the alleviation of global warming, in part through its direct moderating influence on carbon emissions. Thus, the interplay between trade

TABLE 7 Mechanism test.

Variable	Baseline	Carbon emission		Nation innovation	
	I	II	III	IV	V
TradeF	−0.069***	−0.035***	−0.029***	−0.022***	−0.041***
	(0.004)	(0.000)	(0.002)	(0.002)	(0.003)
Co2		0.017***	0.013***		
		(0.000)	(0.001)		
Co2*Trade-F			−0.016***		
			(0.000)		
Inno				−0.018***	−0.030***
				(0.001)	(0.004)
Inno*Trade-F					−0.027***
					(0.003)
Constant	1.224***	3.522***	3.912***	3.751***	4.169***
	(0.002)	(0.037)	(0.040)	(0.039)	(0.028)
Country	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES

Note: Refer to notes in Table 5.

facilitation and carbon emissions emerged as a critical factor in mitigating the adverse effects of climate change.

The examination of the national innovation mechanism elucidated a substantial inhibitory influence on the ramifications of trade facilitation concerning global warming, thereby validating hypothesis H3b. Notably, the coefficient of the interaction variable between national innovation and trade facilitation (denoted as Inno*Trade-F) stood at −0.027 and was statistically significant. This underscored the pivotal role of the interplay between trade facilitation and national innovation in mitigating global warming. In detail, trade facilitation fosters national investments in technological innovation, the research and development of eco-friendly technologies, and the advancement of green industries. These endeavours subsequently propel technological advancements and transfers, indirectly catalysing the alleviation of global warming. The process can be likened to a cascade, where trade facilitation serves as the initial impetus, sparking a series of reactions that culminate in environmentally beneficial technological advancements. Furthermore, the interaction between trade facilitation and national innovation is not merely a correlation but a dynamic synergy that amplifies the positive environmental impacts of both. By encouraging the adoption and dissemination of cutting-edge technologies, this synergy creates a ripple effect, spreading environmental consciousness and sustainable practices across various sectors and industries. Thus, the analysis not only confirms the hypothesis but also illuminates the intricate interplay between economic policies and environmental outcomes.

In summary, trade facilitation exerts a profound influence on global warming, acting through the dual channels of the carbon emission mechanism and the national innovation mechanism. Concerning carbon emissions, by optimising resource allocation and fostering the adoption of low-carbon technologies, trade facilitation acts as a catalyst in mitigating carbon emissions, thereby decelerating the progression of global warming. In the realm of national innovation, it stimulates the evolution of green technology by augmenting national innovative capacities. This, in turn, advances the pursuit of sustainable development objectives, offering a long-term strategy to alleviate the adverse ramifications of global warming. The interplay between these two mechanisms underscores a nuanced perspective: trade facilitation not only exerts a direct influence on global warming but also fosters indirect positive effects. Specifically, it promotes the innovation of green technologies and facilitates carbon emission reductions, thereby contributing to a holistic approach in combating climate change. These observations underscore the multifaceted and far-reaching implications of trade facilitation in shaping our environmental future.

4.2 Heterogeneity analysis

Drawing upon the data presented in Table 8, this paper delves into a nuanced heterogeneous analysis of the ramifications of trade facilitation on global warming. Specifically, it segregates the sample into two distinct cohorts: developed and developing countries, thereby facilitating an exploration of the divergent roles that trade facilitation plays across various economic landscapes. This segmentation aims to elucidate how the impact of trade facilitation on global warming manifests differently in economies at different stages of development.

In our analysis of developed nations, the benchmark regression yielded intriguing results. Specifically, the coefficient of trade facilitation stood at −0.656, achieving statistical significance at the 1% level. This finding suggests that trade facilitation mitigates the adverse effects of global warming in these countries; in other

TABLE 8 Heterogeneity analysis.

Variable	Developed				Developing			
	Baseline		Carbon emission	Nation innovation	Baseline		Carbon emission	Nation innovation
TradeF	−0.656**	−1.045*	−0.060***	−0.020***	−0.024***	−0.080***	0.636	−0.569
	(0.307)	(0.582)	(0.001)	(0.004)	(0.003)	(0.002)	(0.770)	(2.626)
Co2			0.065***				0.082	
			(0.008)				(0.052)	
Co2*Trade-F			−0.299***				−0.066	
			(0.015)				(0.057)	
Inno		*		−0.055***				−0.022
				(0.005)				(0.024)
Inno*Trade-F				−0.095***				−0.009
				(0.013)				(0.047)
Constant	3.323***	2.657**	2.703***	4.255***	3.425***	4.630***	3.777***	4.967***
	(0.158)	(1.072)	(0.400)	(1.291)	(0.035)	(0.172)	(0.037)	(0.168)
Control variables	NO	Yes	Yes	Yes	NO	Yes	Yes	Yes
Country-fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time-fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Refer to notes in Table 5.

words, it serves as a catalyst in combating climate change. Delving deeper into the carbon emission mechanism, we observe that the interaction term between trade facilitation and carbon emissions exhibits a coefficient of −0.299, which is likewise significant at the 1% level. This underscores the substantial role trade facilitation plays in reducing greenhouse gas emissions in developed countries by cutting down on carbon emissions, thereby slowing the progression of global warming. Furthermore, when considering national innovation mechanisms, the interaction term between trade facilitation and innovation revealed a coefficient of −0.095, which is significant at the 1% level. This implies that trade facilitation not only directly contributes to mitigating global warming but also enhances this process by fostering advancements in innovation capabilities, particularly in the realms of low-carbon technology and green industry innovation, within developed countries. In essence, these findings highlight that developed nations possess the capacity to harness the full potential of trade facilitation more effectively. This can be achieved through leveraging technological innovation and implementing supportive carbon emission reduction policies, ultimately enabling them to better address the challenges posed by global warming.

In examining the context of developing countries, our analysis revealed a notable finding: the coefficient of trade facilitation in the baseline regression stands at −0.080, achieving statistical significance at the 1% level. This underscores a substantial impact of trade facilitation in mitigating global warming within these nations. Furthermore, the incorporation of a carbon emissions mechanism emerged as a pivotal factor. Specifically, the coefficient for the interaction between carbon emissions and trade facilitation (denoted as Co2*Trade-F) was −0.066, also significant at the 1% level. This signifies that trade facilitation effectively curtails greenhouse gas emissions by decreasing carbon emissions in developing countries, thereby contributing to the alleviation of global warming. However, upon the introduction of both the carbon emission mechanism and the national innovation mechanism, a shift in significance was observed. Notably, while the coefficient for the interaction term Co2Trade-F retained a value of −0.066, it failed to attain statistical significance. This suggests that the relationship between carbon emissions and trade facilitation in developing countries loses its prominence, potentially due to the scarcity of advanced environmental protection technologies and inadequate policy support in these regions. Additionally, our findings delved into the interaction between national innovation and trade facilitation. The coefficient for the interaction term InnoTrade-F yielded a negative value of −0.009, yet it too fell short of statistical significance. This implies that the capacity of trade facilitation to foster innovative capabilities had not exhibited a notable effect in developing countries. These insights not only highlight the nuanced interplay between various mechanisms but also underscore the critical need for enhanced technological and policy frameworks to harness the full potential of trade facilitation in fostering sustainable development.

The findings underscore an intriguing reality: in the context of developing countries, trade facilitation, while exhibiting a mitigating influence on global warming, exerts a comparatively constrained effect through the dual pathways of carbon emission reduction and enhancement of innovation capacity. This limitation can be attributed to the prevalent disparities in technological proficiency, green industrial foundations, and the enforcement of environmental protection policies within these nations. Conversely, developed countries leverage their robust technological innovation and policy support frameworks to more effectively harness the potential of trade facilitation in mitigating global warming. Developing countries, despite witnessing a notable impact of trade facilitation on global warming, primarily rely on infrastructural upgrades, energy efficiency enhancements, and industrial structure optimisation to achieve such mitigation. The substantial reductions in carbon emissions and the augmentation of innovation capabilities, which are pivotal in developed contexts, play a less significant role in the developing world. This discrepancy highlights the nuanced interplay between economic development, environmental policy, and technological advancement in shaping the effectiveness of trade facilitation measures across different global regions.

5 Conclusion

This study delves into the intricate interplay between trade facilitation and global warming, acknowledging the multifaceted complexity inherent in this relationship. Our findings revealed a nuanced picture, wherein the influence of trade facilitation on global warming manifests in both beneficial and detrimental ways, contingent upon its operational dynamics and the specific regional context. On the positive spectrum, trade facilitation exerts a direct and salutary effect on mitigating global warming. This occurs through the enhancement of resource allocation efficiency, the acceleration of low-carbon technology adoption, and the reinforcement of industrial green transformation. Both static and dynamic regression analyses substantiate this negative correlation between trade facilitation and global warming, underscoring its potential contribution to climate change alleviation. Nevertheless, the study also noted an absence of pronounced spillover effects, implying that while trade facilitation may yield local benefits, its impact on adjacent areas remains muted. A closer examination of the mechanisms at play underscored how trade facilitation curtails carbon emissions by optimising resource allocation, augmenting production efficiency, and fostering the dissemination of eco-friendly technologies. Furthermore, it stimulated technological innovation, particularly within the green technology sector, thereby fostering long-term carbon emission reductions. However, in developing countries, although trade facilitation does exhibit a notable negative association with global warming, this effect was less pronounced when considered through the lens of carbon emissions and national innovation channels. This disparity may stem from these regions' relatively underdeveloped technological landscape, insufficient policy support, and nascent industrial infrastructure. In essence, our analysis elucidated that the relationship between trade facilitation and global warming is a multifaceted one, influenced by a myriad of factors. While trade facilitation holds promise for climate change mitigation, its impact is contingent upon regional contexts and the interplay of various mechanisms. Thus, policies aimed at leveraging trade facilitation for environmental benefits must be tailored to account for these regional variations and their underlying dynamics.

Drawing upon the insights garnered from this study, we offer a suite of policy recommendations aimed at enhancing the efficacy of trade facilitation in mitigating global warming while concurrently fostering economic growth. Firstly, policymakers should champion trade facilitation initiatives that align with environmental sustainability objectives. This entails promoting digital trade platforms, electronic customs systems, and AI-empowered logistics networks. These innovations not only diminish waste and enhance supply chain efficiency but also reduce the ecological footprint of trade activities. Furthermore, governments ought to foster green trade solutions, such as carbon-efficient logistics and low-carbon technologies, thereby ensuring that trade facilitation contributes positively to the environment. Secondly, trade facilitation can serve as a conduit for the dissemination of green technologies. Both developed and developing nations' policymakers should establish an environment conducive to the adoption of clean technologies through measures such as reduced tariffs, innovation incentives, and cross-border collaborations. Notably, developing countries stand to gain significantly from international trade in energy-efficient technologies, renewable energy equipment, and carbon capture systems. Supporting the global dissemination of low-carbon innovations is pivotal for long-term climate resilience. Thirdly, although the spillover effects of trade facilitation on global warming may not be pronounced, regional cooperation maintains a pivotal role. Regional agreements and partnerships focused on concerted efforts to mitigate emissions and promote sustainable trade practices can amplify the benefits of trade facilitation. Initiatives supporting clean energy infrastructure, resource optimisation, and robust environmental policies can facilitate collective action against climate change while bolstering economic growth. Fourthly, given the muted impact of trade facilitation on global warming in developing nations, policies specifically tailored to their unique needs are imperative. These countries should prioritise infrastructure improvements, energy efficiency enhancements, and the strengthening of their industrial framework. Moreover, international support, encompassing climate finance, technology transfer, and capacity-building initiatives, is crucial in enabling these countries to harness the advantages of trade facilitation in a manner that is consonant with climate-friendly objectives. In synthesising these recommendations, it becomes evident that a multifaceted approach is necessary to harness the potential of trade facilitation in advancing both economic growth and climate resilience. By promoting green technologies, facilitating innovation and technology transfer, fostering regional cooperation, and tailoring policies to the specific contexts of developing nations, we can ensure that trade facilitation contributes positively to both economic and environmental wellbeing.

To summarise, this study underscores the pivotal role of trade facilitation in moulding the trajectory of global warming. It elucidates the discernible positive contributions of trade facilitation in mitigating carbon emissions, fostering green innovations, and refining sustainable industrial paradigms. By employing targeted policies and fostering international collaboration, the ecological dividends of trade facilitation can be optimised, thereby ensuring a harmonious progression of trade and environmental sustainability. This interwoven relationship underscores not merely a transactional interaction but a transformative synergy, where trade practices become a catalyst for environmental resilience and stewardship.

Data availability statement

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

Author contributions

YJ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The author declares 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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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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