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Decoding the environmental effects of green finance, renewable energy, financial development, and globalization through quantile on quantile and wavelet coherence analysis

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Abstract

This study investigates the complex and nonlinear interplay between green finance, financial development, renewable energy consumption, globalization, and Vietnam's ecological footprint during 2000–2021. The original annual data were transformed into quarterly frequency using the quadratic match-sum approach to enable robust dynamic analysis. Advanced methodologies are employed based on quantile-dependent and non-linear behaviors, including quantile-on-quantile regression and wavelet coherence analysis, to uncover dynamic interactions across different time periods and quantiles. Key findings indicate that while renewable energy consumption consistently and significantly reduces the ecological footprint, particularly in high-impact scenarios, the effects of green finance are varied, showing a positive correlation with environmental strain at lower quantiles. Financial development exhibits an inverted U-shaped relationship, transitioning from initial environmental pressure to subsequent mitigation as the system matures. In contrast, globalization has persistently intensified ecological pressure, with adverse impacts becoming increasingly severe in recent years. Based on these results, this study provides actionable policy implications, including expanding green finance frameworks, prioritizing rapid adoption of renewable energy, aligning financial development with sustainability objectives, and integrating robust environmental safeguards into globalization initiatives. These evidence-based insights are essential for guiding Vietnam toward balancing sustainable economic growth with environmental protection.

Keywords Green finance, Renewable energy, Financial development, Globalization, Quantile-on-quantile, Wavelet coherence

1 Introduction

Environmental sustainability is a vital global goal for protecting natural resources and ensuring the well-being of present and future generations. The achievement of the United Nations Sustainable Development Goal (SDG), notably SDG-13, which focuses on climate action, highlights the importance of global efforts to mitigate climate change and strengthen resilience [1]. The international community's succeeding Conferences of the Parties (COP), such as COP28 and the most recent COP29, have strengthened these pledges by establishing more aggressive targets for carbon emission reductions, adaptation methods, and financial mobilization for sustainable ecosystems. This study fits into this global agenda by focusing on environmental sustainability via the lenses of green finance, renewable energy, financial development, and globalization, with the goal of supporting effective policy frameworks that are aligned with these worldwide objectives. The findings from Vietnam, an emerging economy facing a critical economic-environmental trade-off, offer transferable lessons for other rapidly industrializing nations in ASEAN and beyond. The study's importance lies in providing the first comprehensive, non-linear, and time-frequency-aware empirical evidence on the interaction of these key variables in this crucial regional context.

Environmental degradation, driven by the rapid increase in carbon emissions, has become one of the primary challenges of the 21st century [2]. The consequences of this environmental crisis are far-reaching, including a higher frequency of extreme weather events, rising sea levels, loss of biodiversity, and diminished agricultural productivity [3, 4]. As environmental threats escalate, governments, scholars, and industries globally are prioritizing sustainable development to harmonize economic growth with ecological preservation [5]. This ambition is seen in the commitments of emerging economies, where stringent climate regulations aligned with the Paris Agreement have stimulated initiatives to transition to a low-carbon economy [6]. This global agenda, however, must be understood in the context of escalating environmental degradation, where the gap between international commitments and on-the-ground realities has become increasingly evident. Vietnam, as ASEAN's leading CO_2 emitter, has committed to peak emissions by 2030 and carbon neutrality by 2050 under the Paris Agreement [7]. The government has pledged to peak emissions by 2030 and achieve carbon neutrality by 2050. Nonetheless, the trade-off between economic advancement and environmental sustainability remains a significant policy concern [8].

In response to the escalating environmental and climate issues, professionals, scholars, and policymakers have proposed several strategies to enhance environmental sustainability. Allocating resources to environmentally sustainable initiatives represents one of the most significant methods to utilize green funding for altering environmental outcomes [9]. Empirical research highlights its effectiveness in fostering environmental technology innovation and reducing ecological footprints, particularly in developing economies where such policies provide substantial ecological benefits [10, 11]. According to Mehroush, et al. [12], green finance significantly reduces dependence on non-renewable resources and promotes ecological sustainability, thereby improving the financial feasibility of renewable energy initiatives. The imperative of transforming industries to conform to ecological realities, with green finance facilitating this transition towards sustainable growth. Concerns around greenwashing, governance inefficiencies, and varying legal frameworks underscore the imperative for transparent metrics and stringent oversight to ensure that green financing produces tangible environmental advantages [13]. This study highlights the necessity for rigorous standards to ensure genuine green transformation in enterprises, especially in low-competition environments. Green finance, in this regard, emerges as a powerful driver for environmental reform [14]. Shi and Shao [15] delineate the challenges facing green financing, highlighting that governments can enhance transparency and effectiveness via coordinated worldwide efforts.

Using renewable energy is an important part of keeping the environment healthy. Many studies have demonstrated that it might help the environment by making us less reliant on fossil fuels. A complete evaluation of the environmental effects of renewable infrastructure is needed since they might have a big effect on how land is used, how much water is used, and how resources are taken out [16, 17]. Renewable technology might meet more than half of the world's energy demands by 2050 and lower carbon emissions at the same time. They may, however, have a significant detrimental effect on the environment during their manufacturing and usage, which is why more study is needed [18].

Financial development functions as a catalyst for economic growth but exhibits contradictory environmental effects. At the early stage, it may exacerbate ecological degradation by encouraging energy-intensive enterprises. Over time, though, robust financial systems with strong institutions can channel green investment and improve environmental efficiency, consistent with the Environmental Kuznets Curve (EKC) hypothesis [19]. This phenomenon is crucial as it affects the economic structure governing green finance, indicating that emerging financial development may not always align with sustainable practices, but established institutions can facilitate greener transitions [20].

Such dynamics highlight that financial systems cannot be evaluated in isolation, as their environmental consequences are often intertwined with broader forces of globalization. Globalization has many impacts; it facilitates technical transfer and resource efficiency in certain contexts while concurrently intensifying resource exploitation and environmental injustice in others [21]. Globalization has exacerbated environmental deterioration through heightened resource consumption, deforestation, and biodiversity loss [22]. The global food system, influenced by trade-oriented intensive agriculture, exacerbates the depletion of natural resources and accelerates climate change. Ecological sustainability emerges from the complicated interaction among finance, energy infrastructure, institutional quality, and global integration, all contingent upon context-specific variables and the robustness of policies, rather than isolated elements [23]. The combination of these elements is vital to achieving a sustainable future that aligns globalized processes with environmental imperatives.

Due to its rapid economic growth and environmental challenges, Vietnam presents an ideal setting for studying green finance, renewable energy, financial development, globalization, and ecological impact. Over the past two decades, energy-intensive sectors and foreign direct investment have pushed Vietnam's industrialization, urbanization, and GDP growth, increasing its ecological footprint and greenhouse gas emissions [24]. Despite the government's Paris Agreement targets to peak emissions by 2030 and reach carbon neutrality by 2050, balancing economic growth and environmental sustainability remains a policy problem [8]. Vietnam's financial industry has grown, allowing green finance initiatives to invest in renewable energy and sustainable technologies. Green financing has environmental benefits, but legislative loopholes, greenwashing hazards, institutional capacity restrictions, and insufficient enforcement mechanisms limit it [25]. The globalization of resource use and industry has raised ecological pressures, affecting sustainability initiatives [26]. Advanced methods like quantile-on-quantile regression and wavelet coherence analysis can capture these elements' nonlinear, dynamic connections in Vietnam across temporal and ecological contexts. This comprehensive understanding is essential to devising policies that support Vietnam's socio-economic conditions and global climate goals through a low-carbon transition. Figure 1 illustrates Vietnam's ecological footprint and biocapacity from 2000 to 2021, showing an ecological deficit occurring together with a significant transformation. Implementing evidence-based policy remains very challenging [27]. The absence of long-term, high-frequency environmental data in Vietnam has hindered a comprehensive empirical analysis of the correlation between green financing, sustainable energy usage, and environmental impacts. Wavelet coherence and quantile-on-quantile regression are advanced methodologies that offer an in-depth examination of interactions affected by temporal and frequency variables [28].

The present study examines three significant issues. Initially, it addresses the current research gap in emerging economies, with a specific focus on Vietnam, where empirical studies frequently depend on conventional mean-based models that are inadequate for capturing the complex, nonlinear, and heterogeneous effects of financial and energy variables across various levels (quantiles) of environmental stress. Second, it addresses the issue of restricted analytical scope by incorporating the ecological footprint - a comprehensive, multidimensional indicator of environmental impact—rather than the more limited focus on carbon emissions commonly found in local studies. Third, it addresses the limitations of time-domain analysis by employing Wavelet Coherence to reveal the dynamic temporal and frequency relationships among these variables, which is essential for formulating both long-term and short-term policies. The significance of this study

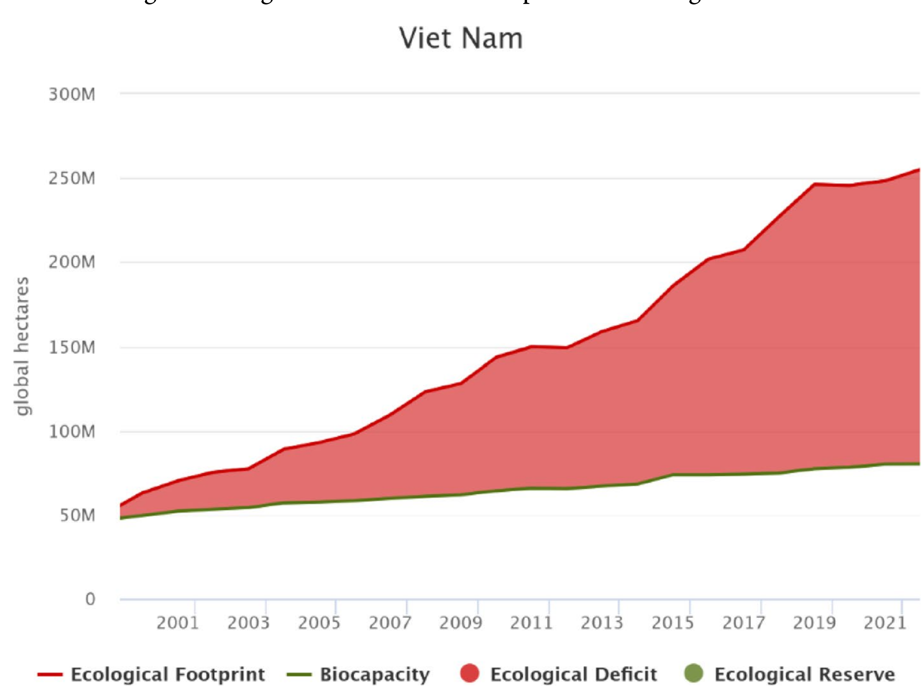

Fig. 1 Ecological deficit in Vietnam

is thus twofold: it presents the inaugural comprehensive, time-frequency, and quantile-aware empirical analysis of the green finance - ecological footprint relationship in Vietnam, delivering nuanced insights that are unattainable through traditional approaches. Furthermore, while emphasizing Vietnam's distinctive economic and environmental circumstances, the findings provide valuable insights that are broadly applicable to other swiftly industrializing countries within the ASEAN region and worldwide. These transferable insights are essential for policymakers dedicated to harmonizing rapid economic development with international climate objectives.

The current research enhances the existing literature by employing the ecological footprint, which offers notable advantages over carbon emissions in evaluating sustainable environmental performance. Unlike carbon emissions, the ecological footprint reflects how societies utilize resources such as land and water and assesses their capacity for regeneration, thereby providing a more comprehensive perspective on environmental stress and resource use [29]. While previous studies in Vietnam have largely concentrated on carbon emissions, often overlooking the broader implications of the ecological footprint [30], this paper extends the literature by adopting a multidimensional approach. Methodologically, it diverges from conventional time-domain and mean-based models such as Vector Autoregression (VAR), Vector Error Correction Model (VECM), Autoregressive Distributed Lag (ARDL), Dynamic Ordinary Least Squares (DOLS), Fully Modified Ordinary Least Squares (FMOLS), Ordinary Least Squares (OLS), and Generalized Method of Moments (GMM), and instead applies an integrated framework combining quantile-on-quantile regression and wavelet coherence analysis. This approach allows us to capture the nonlinear and dynamic interactions between green finance, renewable energy, financial development, globalization, and ecological footprint across quantiles, time, and frequency [31]. This is the first study to explore these relationships in Vietnam, thereby filling a critical gap in understanding sustainability challenges in emerging economies. By focusing on Vietnam's unique economic–environmental context, findings generate nuanced insights into how these factors interact under varying ecological pressures and provide robust evidence to inform targeted, evidence-based policy measures. Ultimately, the study contributes new empirical knowledge that not only strengthens the discourse on environmental sustainability in rising economies but also supports global agendas.

The following portions of this document are structured as outlined below. Section 2 provides a synopsis of relevant theoretical and empirical studies. Section 3 outlines the econometric framework and details the data included in the analysis. Section 4 delineates and analyzes the empirical findings and primary issues addressed in the study. Section 5 summarizes the key observations and outlines the related policy consequences.

2 Literature review

2.1 Theoretical framework

The theoretical framework supporting this study is thoroughly grounded in established environmental economics, chiefly the Environmental Kuznets Curve (EKC) hypothesis and Sustainable Development Theory (SDT). The notable EKC suggests that while economic growth initially results in environmental degradation, beyond a certain income threshold, societies begin to invest in green technologies and sustainability, thereby reducing their ecological footprint [32, 33]. The EKC suggests a non-linear relationship whereby economic growth, typically driven by financial development and globalization, initially intensifies environmental degradation but ultimately results in improvement once a specific income level is attained, owing to institutional maturity and technological advancement. The study's model employs the ecological footprint as a comprehensive, multidimensional indicator of environmental impact to empirically evaluate this dynamic. Crucially, the shift to the mitigating phase proposed by the EKC relies on particular policy mechanisms, thereby incorporating SDT [34]. Green finance is conceptualized as the essential financial mechanism necessary to effectively direct capital toward sustainability initiatives, with a particular emphasis on expediting the adoption of renewable energy consumption [35, 36]. In addition, labour market participation and innovation competencies are important enablers of sustainable transitions, as they strengthen the ability of economies to adopt and diffuse green technologies effectively [37, 38]. Therefore, the incorporation of GF and REC enables us to evaluate the effectiveness of the proposed financial and technological solutions, going beyond solely depending on passive economic growth. Finally, globalization is integrated to reflect its dual role - both as a facilitator of clean technology diffusion and as a potential source of environmental dumping - thus establishing a comprehensive framework essential for deriving policy-relevant insights into how these factors collectively influence ecological outcomes in an emerging economy.

Green finance has emerged as a unique paradigm from conventional financial methods, emphasizing not just profitability but also the environmental risks and advantages inherent in investments. It is essential in promoting investments in renewable energy initiatives, thereby aiding the shift towards a sustainable economy [39, 40]. Green finance plays a direct role in mitigating carbon emissions and improving air quality. This is achieved through the allocation of resources to sustainable initiatives such as solar, wind, and other renewable energy sources. These initiatives are essential for reducing and controlling ecological footprints [41, 42]. Furthermore, research demonstrates that green finance improves the environmental performance of banks, showing a direct correlation between financial development and enhanced ecological results [43].

Globalization exacerbates this link. Globalization has resulted in heightened trade, international investment, and the swift spread of technology, which can either enhance or compromise local environmental regulations. As countries grow increasingly interconnected, the interaction between national financial systems and international capital flows facilitates the expansion of renewable energy investments and the promotion of environmentally sustainable practices globally [44]. The proliferation of green technologies via global supply chains exemplifies how collaborative initiatives can reduce costs and enhance the accessibility of renewable energy sources, thus facilitating a decrease in ecological footprints on a larger scale [45].

Nevertheless, the capacities of financial institutions are frequently impeded by legal frameworks and external funding limitations, which affect their capacity to incorporate green money into their operations efficiently. Stringent environmental restrictions can stimulate breakthroughs in green technology that further diminish ecological footprints [46, 47]. Conversely, in markets devoid of legislative support, green finance initiatives may not realize their promise for environmental enhancement [33]. This underscores the imperative for synergistic policies that fully leverage the potential of financial development in advancing green transition routes.

In summary, the theoretical framework that integrates green finance, renewable energy, financial development, and globalization illustrates their collective ability to diminish ecological imprints. This connection is consistent with the goals of sustainable development and represents a comprehensive strategy for comprehending and influencing environmental performance on a variety of dimensions. The efficacy of initiatives intended to mitigate the ecological consequences of human activity will be determined by the influence of policy, global collaboration, and the intricacies of financial ecosystems; these factors will continue to shape these linkages.

2.2 Green finance and ecological footprint

The connection between green finance and lowering ecological footprints has received increased attention from researchers, especially since the world is facing environmental problems and needs economic systems that are more sustainable. Green finance usually means financial actions that help initiatives that are good for the environment, like putting money into renewable energy, low-carbon technologies, and managing resources in a way that is good for the environment. A lot of real-world research shows that green finance can help the environment by making it easier to invest in renewable energy and cutting down on greenhouse gas emissions. Nonetheless, recent research highlights apprehensions about the practical difficulties associated with green finance. These include the dangers of greenwashing, inconsistent policy enforcement, and different levels of efficacy because of different institutional frameworks and regulatory capacity. So, green finance should be seen as a promising but complicated tool that needs strict rules, clear standards, and strong monitoring to make sure it really helps protect the environment [10, 48].

Empirical studies consistently underscore the impact of green financing on environmental sustainability. Green investments are acknowledged for enhancing energy efficiency, reducing greenhouse gas emissions, and strengthening the viability of renewable energy initiatives [49, 50]. Bibliometric reviews, including those by Tan, et al. [51], validate this story by demonstrating how green finance fosters innovation in sustainable energy systems and environmental technologies. Javed, et al. [52] report findings from G7 countries indicating a robust positive link between green investments and improvements in environmental quality. Moreover, research focused on the Chinese context indicates that green finance initiatives are closely linked to reductions in carbon emissions and enhancements in industrial sustainability [53, 54]. Research corroborates these findings by demonstrating the mediating role of corporate social responsibility, revealing that green financing improves environmental outcomes while aligning with broader business sustainability goals [55]. Empirical studies from Europe confirm that well-designed green finance initiatives improve ESG compliance and long-term sustainability [56, 57].

Although green finance is often portrayed as a powerful driver of sustainable transformation, emerging evidence suggests that its environmental benefits are more complex and conditional than typically assumed. Critics caution that the implementation of green finance remains vulnerable to systemic inefficiencies, unintended consequences, and the persistent risk of greenwashing. For instance, Jäger and Schmidt [58] argue that prevailing financial systems may inadvertently perpetuate environmental injustices and economic inequalities, thereby undermining the intended benefits of green initiatives.

Similarly, Sinha, et al. [59] highlight that green bonds may serve more as symbolic instruments than effective tools for genuine ecological change when market incentives emphasize visibility over impact. Li, et al. [60] further contend that the spillover effects of green finance can lead to resource misallocation or even heightened ecological strain in certain regions, masking unsustainable practices rather than addressing them. These concerns underscore the need for robust governance frameworks, explicit classification standards, and stringent monitoring mechanisms to safeguard the credibility of green finance. Moreover, the effectiveness of such financing is contingent upon contextual conditions—including regulatory quality, market maturity, and technological readiness—without which outcomes may be superficial or counterproductive. As noted by Tian and Hou [61], green finance can enhance industrial land-use efficiency and regional growth, but such gains are not universal and cannot be guaranteed across weak institutional environments.

Despite the optimistic narrative around green finance, growing research suggests caution. The question of whether green financing benefits the environment is more complicated than typically thought. Green finance has great potential, but critics say systemic inefficiencies and unforeseen consequences make it risky. Jäger and Schmidt [58] argue that current financial institutions may perpetuate environmental and economic injustices, harming green finance projects. Sinha, et al. [59] worry that green bonds may be symbolic rather than effective tools for environmental change, especially when market incentives promote visibility above tangible benefits. A major drawback is greenwashing, where corporations exaggerate their environmental efforts to get financing or boost their image without making real changes. Li, et al. [60] also worry that green finance spillovers may misallocate resources or strain ecosystems in certain places. Green financing may hide unsustainable activity under these conditions. These findings caution against naive optimism and emphasize the need for strong governance frameworks, defined criteria, and rigorous monitoring to guarantee green finance satisfies environmental requirements. The efficiency of green financing depends on legal frameworks, market maturity, and technology readiness. Green finance can increase industrial land-use efficiency and regional growth, but not in all institutional contexts, according to Tian and Hou [61]. Policy capture, superficial adherence, and poor environmental consequences are more likely in regions with little regulatory monitoring or unclear “green” investment standards.

When used to support renewable energy, clean technologies, and ethical business practices, green money helps promote ecological sustainability. A lot of empirical and theoretical research shows that it reduces ecological footprints. Transparent governance, clear criteria, and ongoing review are essential to this initiative’s success. Green money may become a token rather than an instrument for change without these controls. Thus, while green finance has great potential, its implementation requires careful oversight to ensure that financial resources support environmental concerns and long-term sustainability goals.

2.3 Renewable energy consumption and ecological footprint

The relationship between renewable energy utilization and the ecological footprint is complex, exhibiting both positive and negative impacts. This complexity arises from several dynamics influencing energy-producing systems and their environmental effects.

Multiple studies indicate that increased renewable energy usage correlates with a reduction in ecological impact. Anser et al. [62] have shown that a 1% increase in renewable energy usage might lead to an approximate 0.32% decrease in the ecological footprint. This reduction is attributed to renewable energy's ability to diminish ecological demands, hence mitigating environmental degradation associated with fossil fuels. Sahoo et al. [10] observed a significant negative impact of renewable energy on ecological footprints, noting a decrease of 2.91% in the ecological footprint for every 1% increase in renewable energy utilization. Nan et al. [63] also promote the long-term benefits of renewable energy use in reducing the ecological footprint, aligning with this observation.

Subsequent assessments of certain national contexts, including Turkey and many MINT countries (Mexico, Indonesia, Nigeria, and Turkey), reveal an inverse association between renewable energy utilization and ecological footprint [64, 65]. Recent work further links trade market behavior to renewable energy adoption [66, 67]. Research in Turkey indicates that the utilization of renewable energy might significantly reduce ecological strain over the long run. Increased utilization of renewable energy might substantially diminish the ecological footprint in India [68]. However, the impact of renewable energy on the ecological footprint is not exclusively advantageous. Particular literature delineates challenges associated with renewable energy generation. While renewable energy might diminish ecological footprints by replacing fossil fuels, its production may need additional land and water resources, thus leading to ecological degradation [69]. Infrastructure developments associated with renewable energy may disrupt local ecosystems and generate waste, complicating the sustainability dialogue.

Moreover, evidence suggests that renewable energy can increase ecological footprints in certain situations due to the resource extraction necessary for energy technology, like solar panels and wind turbines. Cui, et al. [70] investigate the considerable ecological expenses linked to the establishment and upkeep of renewable infrastructure, which necessitates extensive natural resources and energy throughout its existence. This highlights that, while the operational phase of renewable energy is generally more environmentally benign than fossil fuels, the ecological costs during the production phase can be substantial. The relationship between economic structure and renewable energy consumption is crucial; financial development and institutional quality can affect the effectiveness of renewable energy in reducing ecological footprints. Economic factors and institutional quality may influence the extent to which renewable energy mitigates ecological pressures, suggesting a complex relationship among these variables [71]. Economic growth significantly affects the impact of renewable energy on ecological footprints, either enhancing or diminishing the benefits of renewable energy, based on the economic context [72].

In conclusion, while renewable energy consumption generally provides a method to mitigate environmental limitations by reducing reliance on fossil fuels, many complexities remain. These relate specifically to the environmental costs linked to the development of renewable infrastructures and the broader economic systems in which these energy sources operate. Future policy initiatives must tackle this complexity to maximize the benefits of renewable energy while alleviating any negative repercussions associated with its adoption and integration into economic systems.

2.4 Financial development and ecological footprint

Financial development exhibits paradoxical effects on the ecological footprint, being intricately linked to economic growth, technological advancement, and institutional practices that may either adversely affect or promote environmental sustainability. Empirical studies have revealed various patterns that illustrate both beneficial and harmful consequences.

Financial development is associated with increased economic activity, often leading to higher energy use and greater environmental degradation. Studies demonstrate that augmented financial resources facilitate investments in energy-intensive initiatives, leading to increased carbon dioxide emissions and a larger ecological footprint [73, 74]. Ağan [75] asserts that financial institutions are crucial for providing capital for energy investments, including non-renewable projects, which may lead to adverse environmental consequences. Moreover, financial progress in developing nations has been associated with a notable increase in greenhouse gas emissions, as improved access to financial services promotes the growth of pollution-intensive industries [76]. Conversely, financial development presents opportunities for enhancing environmental sustainability. Certain studies indicate that a properly regulated financial sector can enhance the financing of green technologies and the implementation of sustainable practices [77, 78]. Ruza and Carretero [79] identify a non-linear relationship between financial development and environmental degradation, suggesting that initial phases of financial progress may lead to negative environmental consequences, which later transition towards sustainability as financial systems mature and adopt green financing strategies. This aligns with the EKC hypothesis, which posits that economic growth and financial development initially lead to environmental degradation, subsequently resulting in improved environmental standards as resources for sustainable practices become more available [80].

Financial development outcomes depend on the quality of the financial system regulators. Effective institutional frameworks can reduce environmental consequences by investing in sustainable initiatives, fostering a cycle of ecological improvement and economic growth [77, 81]. By investing in outmoded and dangerous technology without considering environmental costs, inadequate regulatory frameworks may increase the ecological footprint [82]. Financial inclusion affects environmental consequences, according to recent studies. Financial inclusion can improve equal financial access and green investments, but if not sustainable, it may support environmentally detrimental initiatives [76]. In developing nations, financial inclusion increases per capita emissions, showing a complex relationship that could accelerate environmental deterioration if not regulated [83]. According to G7 research, financial development and environmental quality may vary depending on regional circumstances and economic maturity. Economic growth does not significantly affect these industrialized nations' ecological footprints [79]. This means that technical advances and regulatory frameworks may have a greater impact on environmental results in these scenarios.

Financial development can catalyze economic growth and foster technology advancements that may improve environmental quality. Nonetheless, it may also exacerbate ecological damage via increased pollution and resource depletion. The quality of institutions, the technological landscape, and the distinct economic conditions of each nation significantly influence the outcomes. Thus, the pathway to reconciling financial progress with environmental sustainability necessitates the establishment of robust institutions, the encouragement of green investments, and the alignment of financial systems with sustainable development goals.

2.5 Globalization and ecological footprint

Globalization, a multifaceted phenomenon encompassing economic, social, and political transformations across borders, has ignited significant discourse over its effects on the ecological footprint. The ecological footprint, which quantifies human demand on nature, suggests that globalization can provide both beneficial and detrimental impacts on environmental sustainability. From a positive perspective, globalization can enhance resource efficiency and stimulate innovation, resulting in a reduction in ecological effects. Research indicates that globalization fosters technological advancement and the spread of knowledge, enabling countries to adopt more sustainable practices [84]. Adeleye, et al. [85] discovered an inverse relationship between globalization and carbon dioxide emissions in South Asian countries, suggesting that global integration may promote better environmental circumstances by strengthening institutional capacity and reducing greenhouse gas emissions. Bi, et al. [86] observed that both favorable and unfavorable changes in economic globalization complicate the association with ecological footprints, indicating that not all aspects of economic globalization uniformly harm ecological outcomes.

Conversely, numerous academics assert that globalization exacerbates environmental degradation. Figge et al. highlighted that increased economic globalization correlates with a larger ecological footprint due to intensive natural resource extraction and subsequent environmental pressures [87]. Globalization intensifies income inequality within countries, consequently aggravating environmental deterioration, since wealthy individuals frequently utilize resources at an excessively high rate [88]. Moreover, Ahmed et al. [89] illustrated that while globalization may enhance economic growth, it simultaneously intensifies ecological footprints due to increased trade and fossil fuel consumption in G7 nations, leading to rising carbon emissions. The impact of globalization on the ecological footprint varies across regional contexts and specific sectors. Tourism research indicates that globalization promotes visitor growth, which, while economically beneficial, often results in a significant rise in ecological footprints associated with energy consumption and pollution [90]. Furthermore, globalization positively correlates with ecological footprints in Indonesia, suggesting that the influx of wealth and corporate operations has not uniformly yielded environmental benefits [91]. The connection between globalization and the ecological footprint can be complex and nonlinear. Globalization, at certain levels, may adversely affect well-being due to its association with increased ecological footprints, leading to a deterioration in environmental quality [92]. The interplay between globalization and environmental concerns requires advanced policy frameworks that can mitigate negative ecological impacts while capitalizing on advantageous results from international collaboration.

The complex effects of globalization on ecological footprints require a thorough review of the law. International trade agreements and environmental regulations are crucial to analyzing globalization's sustainability impact. Integrating environmental rules into globalization to mitigate its negative consequences and boost its sustainable development potential [93]. This approach supports academics' call for global initiatives to establish trade regulations that consider environmental impacts [94]. Globalization's dual influence on ecological footprints requires governments, industry, and civil society to work together to create laws that balance economic goals with environmental protection. Sustainable growth in a globalized world depends on governments regulating environmental deterioration while harnessing international cooperation and innovation. Finally, globalization provides ecological footprint difficulties and opportunities. Policymakers must comprehend this complexity to promote sustainability and reduce the environmental impacts of global integration. Empirical studies on localized impacts and regulatory frameworks that balance economic growth and environmental sustainability will enhance the debate.

2.6 Research gaps

Table 1 summarizes the numerous significant deficiencies that persist in spite of the expanding body of literature that underscores the potential contributions of green finance, renewable energy, financial development, and globalization to environmental sustainability. The majority of current research employs linear modeling methods and concentrates exclusively on CO_2 emissions, thereby neglecting nonlinear dynamics and broader metrics, such as the ecological footprint, that encompass more comprehensive aspects of sustainability. Additionally, the majority of previous research has focused on developed economies or global-level analyses, which has resulted in limited empirical insights into emerging economies such as Vietnam, where institutional structures, market maturation, and policy enforcement differ significantly. The neglect of temporal dynamics and frequency-dependent patterns in these relationships, particularly their evolution across different time horizons or under varying ecological stress levels, is another notable limitation. Furthermore, the dual function of green finance - as both a potential enabler of sustainability and a potential source of ecological strain when screening mechanisms are weak - has not been adequately examined using advanced non-linear or time-frequency methodologies. The current study also explicitly highlights the failure of traditional mean-based models to capture dynamic and quantile-dependent effects, as well as the lack of high-frequency data analysis in the environmental literature. Specifically, the present study utilizes wavelet coherence analysis and quantile-on-quantile regression to address these voids, providing new evidence on the impact of green finance, renewable energy, financial development, and globalization on Vietnam's ecological footprint across various quantiles and time frames. This research offers context-specific insights and actionable policy implications that are consistent with the country's sustainability objectives and institutional conditions.

To situate the methodological contribution within the broader academic discourse, the structure of existing research is analyzed through a keyword co-occurrence network. The keyword co-occurrence network in Fig. 2 illustrates the ecological footprint as the central node, representing interconnected research themes in environmental economics. Notable clusters concentrate on energy dynamics, including renewable and nonrenewable energy consumption, carbon emissions, and total energy use. These clusters highlight the effects of resource exploitation on environmental pressures. Socio-economic drivers constitute a core theme, including trade openness, economic globalization, population growth, urbanization, foreign direct investment, and economic expansion as catalysts of ecological degradation. Sustainability serves as a unifying factor, integrating environmental sustainability, sustainable development, and innovation

Table 1 Summary of existing empirical studies

Authors	Period	Region/ Country	Methods	Findings
Zhang et al. [28]	1994–2021	China	Quantile-on-Quantile Regression (QQR), Granger causality in quantiles, Wavelet coherence, PCA	Green investment and digital financial inclusion improve environmental sustainability asymmetrically
Nosheen, et al. [67]	1990–2021	Top 20 renewable energy-consuming countries globally	Panel econometrics: CIPS unit root, Pedroni cointegration, DOLS, FMOLS, Dumitrescu-Hurlin causality	Renewable energy positively impacts long-run GDP growth. Non-renewable energy impact varies.
He, et al. [9]	1996–2021	France	Wavelet Quantile Regression, Wavelet Quantile Correlation, Quantile-on-Quantile Granger Causality	Nuclear energy effects vary term-wise. Renewable energy supports green growth in the short/medium term. Economic globalization and financial development positively affect green growth consistently.
Adeshola, et al. [2]	2000–2017	23 European Union countries	Pooled Mean Group (PMG) estimator, Dynamic Panel Threshold Regression	ICT and environmental taxes reduce GHG emissions; R&D and income per capita increase emissions; Joint promotion of digitalization and environmental taxes recommended for sustainability.
Mu, et al. [95]	1988–2022	United States	Wavelet correlation, coherence, cohesion, time-frequency causality	Natural gas promotes CO2 short/medium term; Renewable energy reduces CO2 medium/long term; Monetary policy and trade impact vary. Causal feedback at multiple time scales noted.
Sun, et al. [96]	1984–2018	Malaysia	ARDL, Bootstrap Time-Varying Causality, FMOLS, DOLS, CCR	Economic globalization harms ecological sustainability in the long term. Economic complexity, political stability, and energy transition promote sustainability. Bidirectional causalities and policy implications are discussed.
Awosusi, et al. [97]	1990–2021	Top 9 energy transition economies	Method of Moments Quantile Regression (MMQR), DOLS, FE-OLS, FM-OLS, Granger causality	Coal and natural gas efficiency reduce CO2; Resource efficiency, globalization, and economic growth increase CO2; Bidirectional causality is mostly found; policy promotes energy efficiency alongside fossil fuels.
Behera, et al. [98]	1990–2021	14 Emerging Economies	Cross-Sectional Autoregressive Distributed Lag (CS-ARDL), MMQR, Dumitrescu–Hurlin panel causality test	Coal efficiency and natural gas efficiency reduce CO2 emissions, while resource efficiency, globalization (economic, social, political), and economic growth increase CO2 emissions. Bidirectional causality exists between CO2 and most variables except coal efficiency and economic globalization (unidirectional causality observed).
Behera, et al. [99]	1993–2022	BRICS	Dynamic Fixed Effect (DFE), CS-ARDL	Hydro and nuclear energy increase the ecological footprint. Green technology innovation significantly reduces it. Political stability decreases ecological footprint in the long term, but results vary in robustness checks. Natural resource rents and economic growth increase ecological footprint.

Table 1 (continued)

Authors	Period	Region/ Country	Methods	Findings
Awosusi, et al. [100]	1970–2018	Malaysia	ARDL, Bootstrapped Time-Varying Causality (TVC)	Biomass energy and resource efficiency enhance the load capacity factor (LF), while trade globalization reduces it. The load capacity curve hypothesis is confirmed, with feedback causality between LF and factors like biomass energy, economic growth, resource efficiency, and globalization.
Ibrahim, et al. [101]	1992–2019	BRICS	Second-generation panel methods, including cross-sectional dependency tests, bootstrap Westerlund cointegration, MMQR, FMOLS, DOLS, and Dumitrescu-Hurlin causality test	Nonrenewable energy, urbanization, and technological innovation increase CO2 emissions; Renewable energy, nuclear energy, and service value-added reduce CO2 emissions. Bidirectional causality between CO2 and technological innovation.
Awosusi, et al. [97]	1990–2021	Top energy transition economies (Netherlands, UK, Finland, Norway, Switzerland, France, Australia, Denmark, Sweden)	MMQR, DOLS, FE-OLS, FMOLS, Panel Granger causality test	Coal and natural gas effectively reduce CO2 emissions due to lower carbon content and higher conversion efficiency compared to other fossil fuels. Resource efficiency, various dimensions of globalization (economic, social, political), and economic growth tend to increase CO2 emissions. Bidirectional causality between CO2 emissions and most explanatory variables, except coal efficiency and economic globalization, exhibits unidirectional causal relationships.
Zeng, et al. [1]	1990–2020	MINT Countries	DOLS, FMOLS, Canonical Cointegration Regression, Feasible GLS, MMQR, GMM	Renewable energy consumption and technological innovation reduce CO2 emissions in the long term. Environmental policy stringency initially increases emissions but reduces them over time. Geopolitical risk lowers emissions, possibly due to economic slowdowns. Bidirectional causality between CO2 and variables
Ayobamiji and Somoye [102]	1989–2018	Colombia	Nonlinear Autoregressive Distributed Lag (NARDL), Frequency domain causality	Positive shocks in technological innovation and hydroelectric usage diminish CO2 emissions in the long term. Negative shocks in hydroelectricity exacerbate environmental degradation. GDP growth and financial instability elevate CO2 emissions. Bidirectional causality between technological innovation and CO2 emissions. Unidirectional causality from hydroelectricity to CO2 emissions.

for damage mitigation, alongside methodological indicators like panel cointegration for empirical rigor. Contextual considerations, like a focus on China, can reveal biases in specific geographical research. This network situates contemporary research within the environment-socioeconomic nexus, highlighting underexamined phenomena particular to Vietnam. It distinctly demonstrates nonlinear, quantile-specific impacts. These include the counterintuitive rise in ecological stress attributable to green finance at low-to-medium levels and the enhanced mitigation potential of renewable energy under

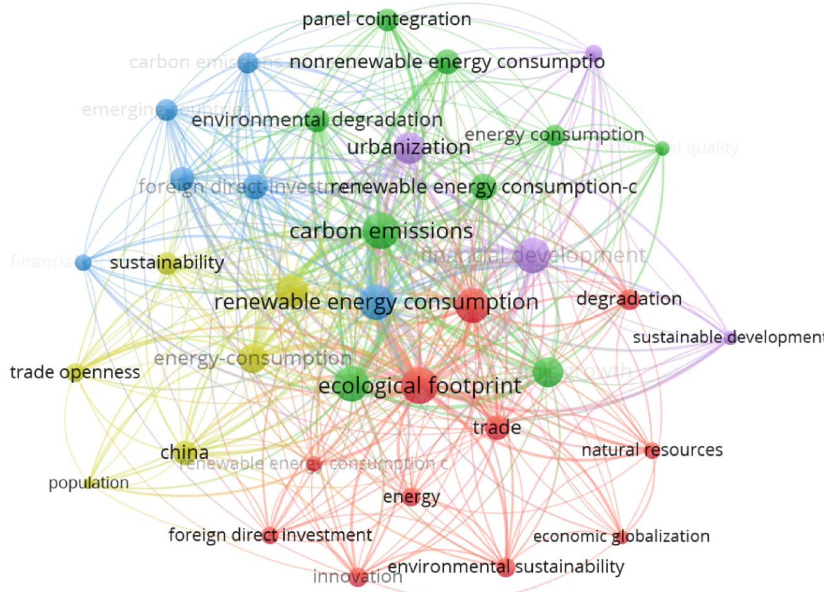

Fig. 2 Co-occurrence of keywords between ecological footprints and related economic factors

high-pressure circumstances. Moreover, wavelet coherence discerns time-varying interactions, encompassing the transition of financial development from detrimental to beneficial effects, thereby offering tailored policy recommendations for particular contexts and rectifying deficiencies in temporal and distributional analyses present in the existing literature.

3 Methodology

3.1 Data

The dataset comprises five principal variables: ecological footprint (LNECOFOOT) from the Global Footprint Network (GFN), green finance (LNGREEN_FIN) from Our World in Data, renewable energy consumption (LNRENEW) from the World Development Indicators (WDI), financial development index (FD) from the International Monetary Fund (IMF), and globalization (LNGLOBAL) from the KOF Globalisation Index. The variety and reliability of these sources guarantee that the study encompasses a wide and trustworthy range of criteria. The research period of 2000–2021 was deliberately selected to ensure both data consistency and reliability. Specifically, the year 2000 marks the point at which green finance data first became systematically available through Our World in Data, providing a valid starting benchmark for analysis. The year 2021 was chosen as the endpoint because the financial development index from the IMF database is currently updated only up to this year. Consequently, the selected timespan represents the maximum range with complete and comparable data, thereby ensuring a robust foundation for empirical investigation. To mitigate the constraints of low-frequency data, annual values were transformed into quarterly frequency utilizing the quadratic match-sum interpolation approach [26]. All series, with the exception of the financial development index, underwent a log transformation to rectify heteroscedasticity and enhance the robustness of statistical inference based on previous studies, such as Kayani, et al. [103], Sethi, et al. [104], and Behera, et al. [99]. Table 2 contains all these variables.

Table 2 Descriptives of examined variables

Variable	Symbol	Unit of Measurement	Data source
Ecological footprint	LNECOFOOT	Global hectares (gha) per person	GFN
Green Finance	LNGREEN_FIN	International finance received for clean energy (US dollars)	Our World in Data
Renewable energy consumption	LNRENEW	Renewable energy consumption (% of total final energy consumption	WDI
Financial development index	FD	Financial institutions and markets' depth and efficiency index Composite index (Composite index 0–1 scale)	IMF
Globalization	LNGLOBAL	The Globalization Index measures the economic, social, and political dimensions of globalization (Composite index (0–100 scale)	KOF

Our World in Data (see https://ourworldindata.org/grapher/international-finance-clean-energy?time=earliest&mapSelect=~VNM#explore-the-data), WDI (see https://databank.worldbank.org/source/world-development-indicators), IMF (see https://legacydata.imf.org/?sk=f8032e80-b36c-43b1-ac26-493c5b1cd33b&sid=1481126573525), KOF (see https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html), and GFN (see https://data.footprintnetwork.org/#/countryTrends?cn=5001&type=BCtot,EFCtot)

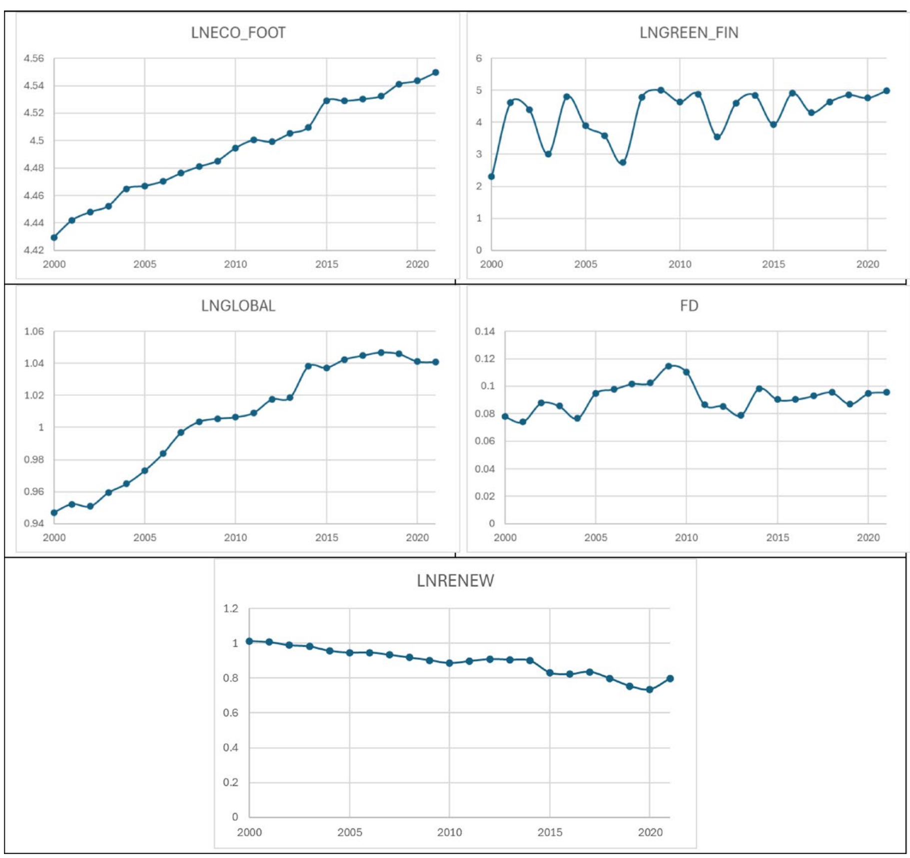

Fig. 3 Trend graph of selected variables in Vietnam, 2000–2021

Figure 3 depicts the temporal trends of essential factors from 2000 to 2021. The ecological footprint, green finance, globalization, and financial development exhibit upward trajectories, whereas renewable energy consumption consistently diminishes, suggesting potential sustainability challenges despite enhanced financial and global integration.

Notes: Globalisation rose steadily from 2000 to 2021, demonstrating global interconnectedness. Green financing fluctuated but rose, signifying sustainable finance investment. The ecological footprint increased over time, indicating economic growth-related environmental stresses. In these years, financial development was stable with a minor upward trend, indicating a moderate increase in financial sector capacity.

3.2 Methods

The analysis flowchart in Fig. 4. delineates a methodical approach to the research technique, commencing with data collection and transformation, and advancing via diverse statistical and economic tests to reveal significant insights from the data. Each phase is structured to build upon the preceding one to guarantee thorough and comprehensive results.

Step 1 Data Collection & Transformation involves aggregating data from several credible sources, including GFN, Our World in Data, WDI, IMF, and the KOF Globalization Index. The annual data collected is subsequently transformed into a quarterly frequency, facilitating a more nuanced temporal analysis appropriate for the ensuing methodologies employed.

Step 2 Descriptive Statistics and the Correlation Matrix offer a preliminary assessment of the chosen variables. This initial analysis examines the attributes of each variable and analyzes their pairwise relationships at a specific moment. This stage is essential for comprehending the fundamental data structure prior to using more intricate approaches.

Step 3 Quantile Unit Root Tests are used to examine the stationarity of the whole conditional distributions of the research variables. This method evaluates stationarity across many quantiles, in contrast to conventional tests that concentrate on mean effects, hence confirming the data's appropriateness for sophisticated quantile-based analysis.

Step 4 The methodology thereafter includes Quantile-Quantile plots and Brock-Dechert-Scheinkman (BDS) Tests. These tests assess the data for normalcy and identify any nonlinear trends. Recognizing nonlinearity guides the selection of suitable econometric models and substantiates the assumptions foundational to regression analysis.

Step 5 Quantile-on-Quantile Regression (QQR) and its comparison with Quantile Regression (QR). This study uses the QQR method, as proposed by Sim and Zhou [105] to examine nonlinear and asymmetric effects that vary across the entire distribution of the variables. The QQR approach is particularly advantageous as it simultaneously captures the dependence structure among different quantiles of both dependent and independent variables, offering a more thorough insight than conventional mean-based or single-quantile models.

Let Y_t signify the ecological footprint and X_t represent an explanatory variable, such as green funding or renewable energy use. The conditional quantile function of Y_t given X_t at the τ-th quantile is articulated as:

$$Q_Y^{\tau}(X_t) = \alpha^{\tau} + \beta^{\tau}(X_t - x) + \epsilon_t^{\tau} \tag{1}$$

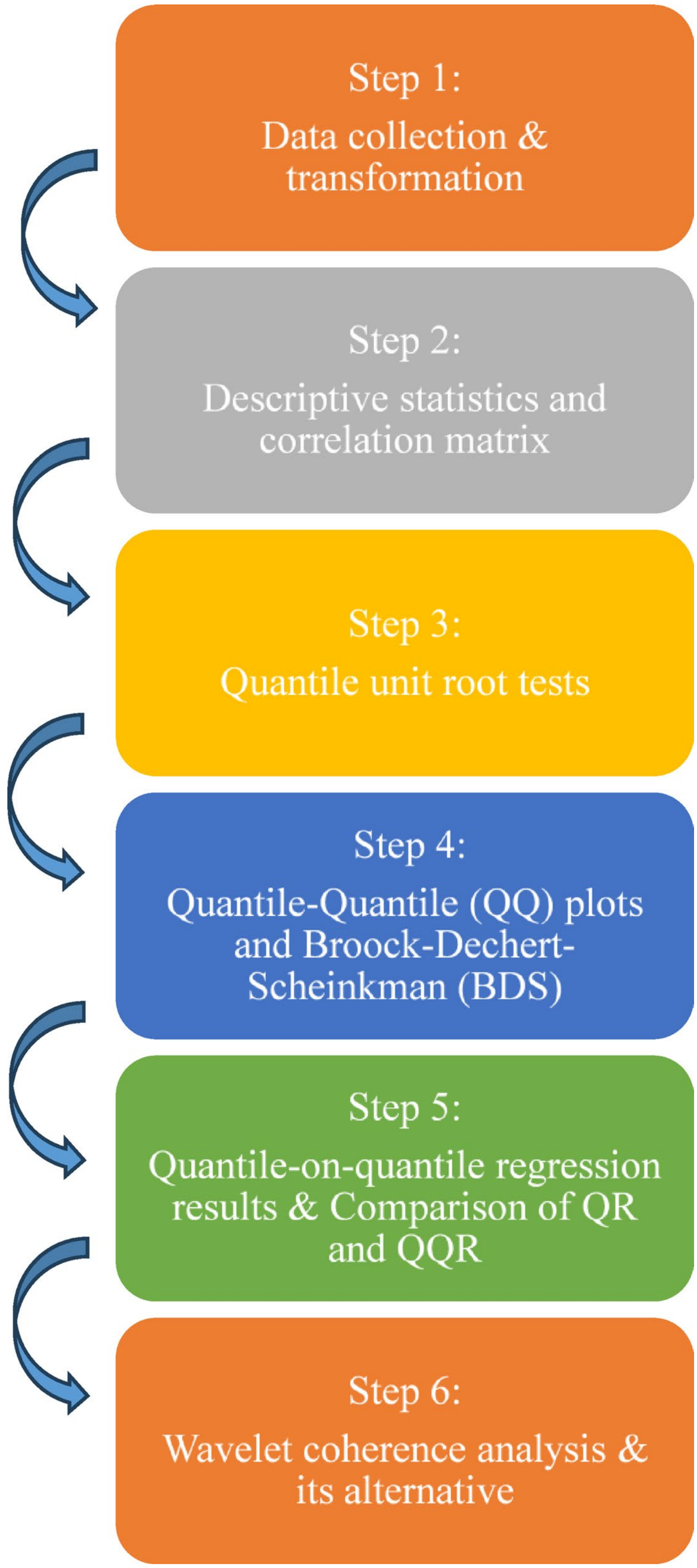

Fig. 4 Analysis flowchart

In this context, α^{τ} represents the intercept, β^{τ} denotes the localized impact of X_t on $T = Y_t$ at the designated quantile, and x serves as the reference point for the local approximation. The error term ϵ_t^{τ} is presumed to meet the conventional quantile regression criterion $Q_Y^{\tau}(\epsilon_{t\ t}^{\tau}) = 0$. A kernel weighting methodology is employed to ascertain the local linear association at each quantile, facilitating an in-depth analysis of tail behaviors and nonlinearities. Furthermore, the preceding QQR technique is validated through a comparison with standard QR results, thus reinforcing the robustness of the findings.

Step 6 Wavelet Coherence Analysis and its alternative are conducted to examine how the relationships between variables evolve over both time and frequency domains. This work employs Wavelet Coherence (WTC) analysis to investigate the time-varying and frequency-specific connections between the ecological footprint and its potential drivers. This technique is advantageous as it enables the decomposition of time series data into time-frequency space, thereby simplifying the identification of co-movement patterns that emerge across various time horizons [106]. The WTC is particularly significant in environmental research, as the strength and direction of correlations may fluctuate over time due to structural changes or regulatory interventions.
The squared wavelet coherence coefficient for two time series Y_t and X_t is defined as:

$$R_{YX}^2(s,\ \tau) = \frac{|S(W_{YX}(s,\tau))|^2}{S\left(|W_Y(s,\ \tau)|^2\right) * S\left(|W_X(s,\ \tau)|^2\right)} \tag{2}$$

In this expression, $W_Y(s,\ \tau)$ and $W_X(s,\ \tau)$ represent the continuous wavelet transforms of Y_t and X_t, respectively, assessed at scale s (associated with frequency) and time τ; $W_{YX}(s,\tau)$ signifies their cross-wavelet transform, and $S\left(|\bullet|^2\right)$ implies a smoothing operator used in both the time and scale dimensions. The coherence measure varies from 0 to 1, reflecting the localized intensity of correlation - numbers approaching 1 denote remarkable coherence, while values nearing 0 suggest weak or nonexistent linkage. This tool additionally discloses the phase difference, enabling the identification of lead-lag interactions and the direction of causality across time.

4 Findings and discussion

4.1 Descriptive statistics and correlation matrix

Table 3 demonstrates considerable heterogeneity among the primary factors. LNECO_FOOT demonstrates a stable mean of 4.495 with negligible variability (SD = 0.035), signifying persistent ecological pressure throughout time. In contrast, LNGREEN_FIN demonstrates considerable variability (SD = 0.810), indicating fluctuations in green finance inflows. LNRENEW demonstrates significant variability (mean = 0.894), whereas

Table 3 Descriptive statistics

Variable	Observation	Mean	Std. dev.	Min	Max	VIF
LNECO_FOOT	88	4.495	0.035	4.423	4.553	-
LNGREEN_FIN	88	4.273	0.810	0.886	5.155	1.30
LNRENEW	88	0.894	0.078	0.729	1.014	5.71
FD	88	0.092	0.010	0.073	0.115	1.14
LNGLOBAL	88	1.006	0.034	0.944	1.047	5.86

FD remains persistently low (mean = 0.092), signifying constrained financial development. LNGLOBAL exhibits a narrow range, with a mean of 1.006, signifying a stable level of globalization. The data indicate significant heterogeneity among the independent elements, requiring advanced modeling to appropriately evaluate their influence on the ecological footprint. The results from the variance inflation factor (VIF) indicate no serious issue of multicollinearity, as all VIF values are below the threshold of 10 [107].

Figure 5 displays the correlation matrix, offering a first look at the linear relationships among the principal variables in the study. The ecological footprint has a significant negative connection with renewable energy consumption (r = -0.96), indicating that heightened reliance on renewable energy is associated with a major reduction in environmental degradation. Ecological footprint exhibits a strong positive correlation with globalization ($r = 0.97$), suggesting that further global integration may intensify environmental challenges in Vietnam. A slight positive association exists between green finance (LNGREEN_FIN) and ecological footprint ($r = 0.51$), indicating that green finance has not substantially mitigated ecological stress. The correlations among the remaining variables are diminished, particularly those associated with the Financial Development Index, suggesting a negligible direct association with ecological outcomes in the current context. These correlations provide essential background information but require additional investigation via quantitative analysis, including nonlinear or asymmetric estimates.

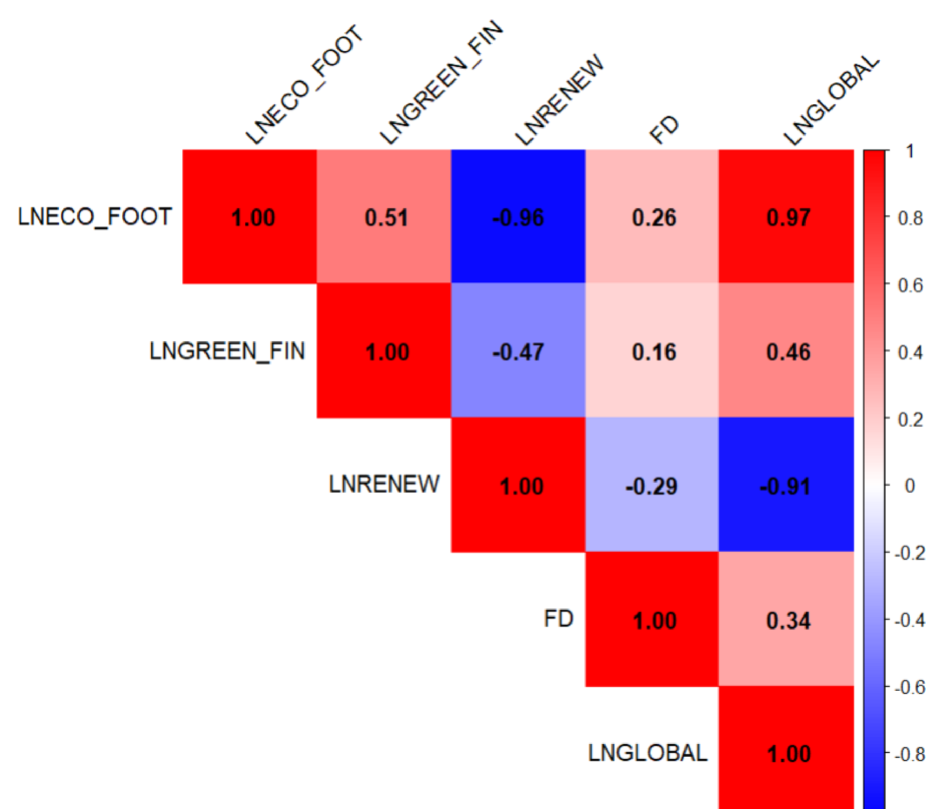

Fig. 5 Correlation matrix of all variables

4.2 Quantile unit root tests

In this section, a set of preliminary analyses is presented to see the basic characteristics of the obtained series, such as stationarity and nonlinearity.

The Quantile Augmented Dickey-Fuller (QADF) tests depicted in Fig. 6 indicate asymmetric stationarity in LNECO_FOOT, LNGREEN_FIN, LNRENEW, and FD, exhibiting non-stationarity in lower-to-middle quantiles while demonstrating enhanced stationarity in upper quantiles, as evidenced by first differences attaining I(1) integration. This quantile-dependent behavior validates Quantile-on-Quantile regression, which captures heterogeneous effects across distributions, thereby addressing nonlinearities overlooked by mean tests. Wavelet coherence further analyzes time-frequency co-movements in differing series, uncovering dynamic trends and providing a robust examination of emerging relationships in the context of non-stationarity.

4.3 Quantile-quantile (QQ) graphs and Broock-Dechert-Scheinkman (BDS) nonlinearity test

The QQ graphs in Fig. 7 also reveal that the variables under examination, such as ecological footprint, renewable energy, financial development, and globalization, have a non-normal distribution with heavier tails.

Table 4 presents the BDS (Brock-Dechert-Scheinkman) test statistics utilized to assess the nonlinear attributes of the examined series [108]. The null hypothesis asserts that each variable is independently and identically distributed (i.i.d.). The table demonstrates that all variables - ecological footprint, green finance, renewable energy consumption, financial development, and globalization - reject the null hypothesis at the 1% significance level across all embedding dimensions (from 2 to 6). The significant BDS statistics indicate the presence of strong nonlinear dynamics in the data. Thus, these findings validate the appropriateness of employing nonlinear analytical techniques, such as QQR and WTC, in this study, since they are superior in capturing complex interdependencies across distributions and time-frequency domains.

4.4 Quantile-on-quantile regression results

This study used the QQR approach to analyze the effects of green financing, globalization, and renewable energy consumption on Vietnam's ecological footprint at various distributional levels of each variable. Unlike traditional models, QQR encompasses the interactions among several quantiles of both dependent and independent variables, enabling a comprehensive examination of asymmetric and nonlinear relationships. In this context, the ecological footprint serves as a comprehensive metric of environmental impact, encompassing land use (e.g., agricultural land, pasture, forest, aquatic resources, and urban areas) and carbon emissions, with higher values signifying greater ecological pressure. This analytical paradigm enhances the comprehension of differences in environmental and financial dynamics across different scenarios, offering insights that traditional regression models may neglect.

Figure 8a depicts the QQR estimation outcomes about the asymmetric impact of green finance on the ecological footprint. In the lower quantile range (0.05–0.25) of ecological footprint, the influence of green finance is relatively modest yet beneficial, suggesting that even in less environmentally taxing conditions, green finance has not led to significant ecological improvement, possibly due to ineffective allocation or early-stage

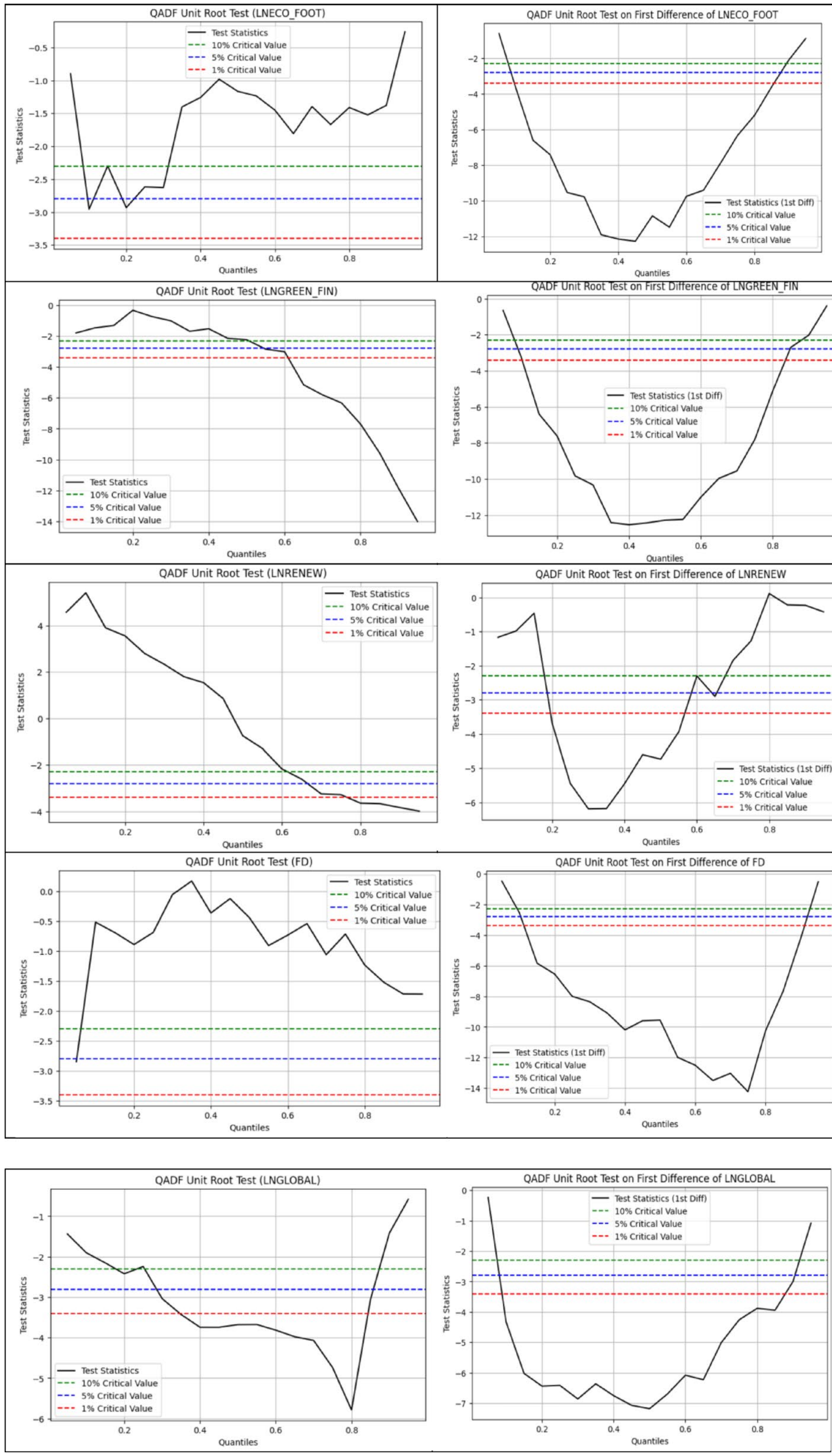

Fig. 6 Estimates of the Quantile ADF Unit Root Test

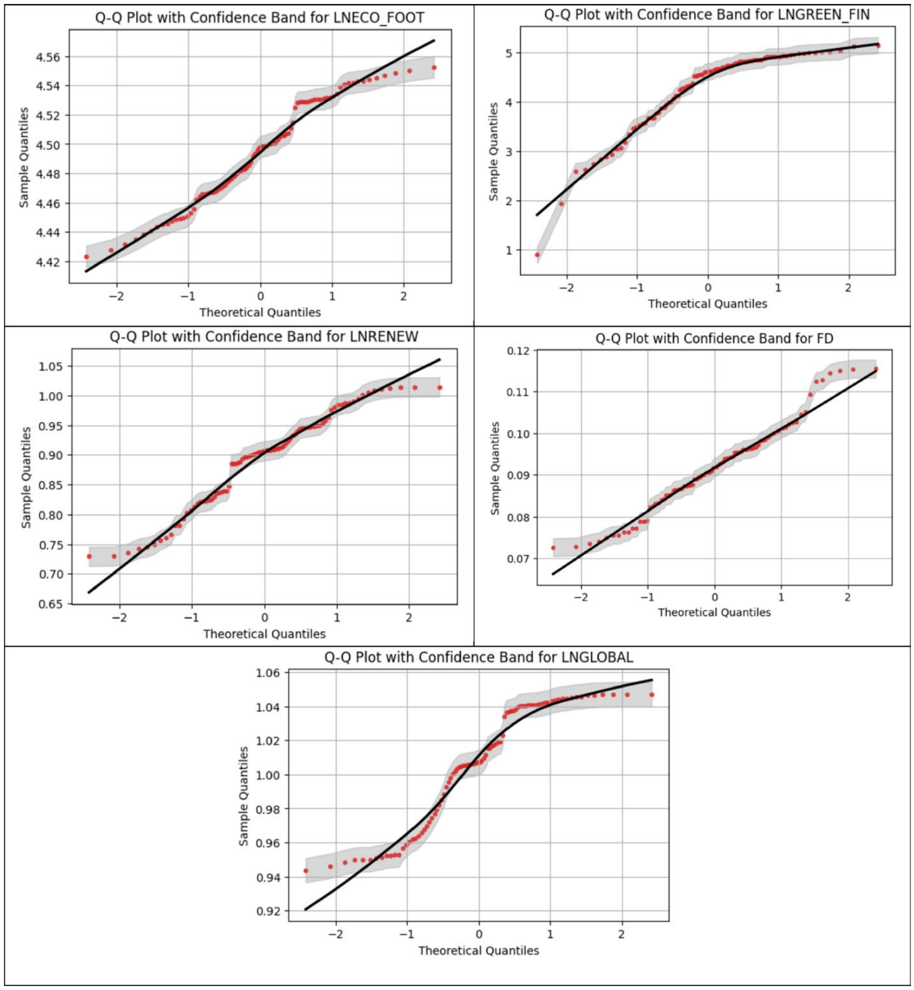

Fig. 7 Q-Q Graphs of the quarterly selected variables

Table 4 BDS nonlinearity test

Dimension	LNECO_FOOT	LNGREEN_FIN	LNRENEW	FD	LNGLOBAL
	BDS Statistic	**BDS Statistic**	**BDS Statistic**	**BDS Statistic**	**BDS Statistic**
2	0.202***	0.139***	0.193***	0.152***	0.205***
3	0.341***	0.219***	0.321***	0.248***	0.347***
4	0.438***	0.262***	0.404***	0.303***	0.444***
5	0.507***	0.285***	0.457***	0.330***	0.512***
6	0.557***	0.289***	0.494***	0.340***	0.560***

*** indicates the rejection of the null hypothesis that the series are independent and identically distributed at the 1% significance level

implementation, as demonstrated in Vietnam before 2010. In the medium quantiles (0.35–0.65), the positive effect amplifies and stabilizes, possibly signifying periods of green financing expansion that are misaligned with environmental goals—an issue highlighted by Nguyen, et al. [109] and Hoang, et al. [110] about greenwashing in Southeast Asia. At high quantiles (0.75–0.95), indicative of substantial environmental degradation, the QQR coefficients reach their peak, implying that mismanaged green financing may be contributing to or intensifying ecological decline. The QQR coefficients are predominantly positive, suggesting that increases in green finance are paradoxically

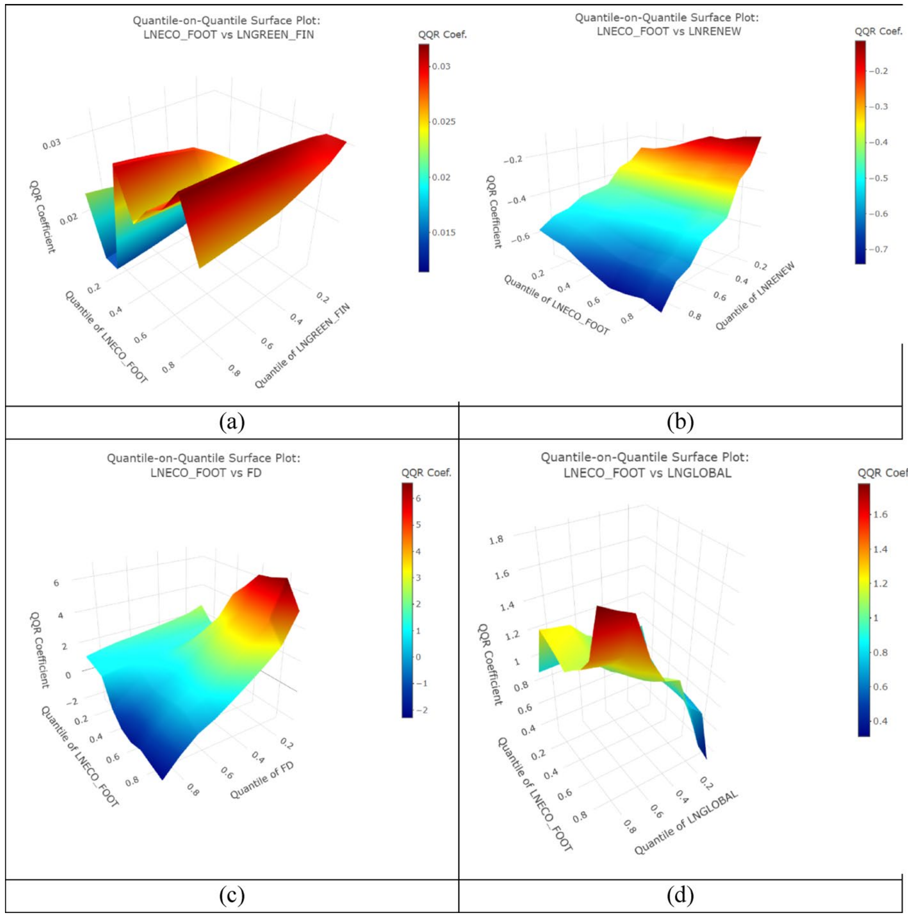

Fig. 8 **a** Effects of energy consumption on ecological footprint, **b** Effects of financial development on ecological footprint, **c** Effects of FD on ecological footprint, **d** Effects of globalization on ecological footprint. The x-axis represents the quantiles of the ecological footprint, whereas the y-axis indicates the quantiles of the variable of interest. The z-axis and color spectrum denote QQR coefficients. Warmer hues (red/yellow) signify a more pronounced positive impact of green finance on ecological footprint across the respective quantile combinations, whilst cooler hues (blue/green) imply weaker correlations.

associated with heightened ecological burdens across the majority of quantile combinations. This nonlinear and imbalanced pattern suggests that green financing may not be a reliable environmental mitigation tool, especially when it lacks strategic guidance or targets unproductive industries. Vietnam's green finance sector still faces considerable drawbacks that limit its effectiveness. Regulatory weaknesses, such as the absence of comprehensive ESG standards, weak enforcement, and unclear policy mandates, undermine credibility and consistency [111]. Financial and capacity constraints also persist, with green projects struggling to access long-term funding, a shortage of skilled professionals, underdeveloped ESG data systems, and limited capacity among smaller issuers [112]. In addition, market and behavioral challenges—including low awareness, skepticism about project credibility, lack of fiscal incentives, and fears of greenwashing - further reduce investor confidence and slow adoption [113]. This suggests that, in reality, green finance may not be substantially alleviating environmental burdens, potentially indicating issues such as greenwashing or inadequate regulatory compliance [114]. These findings resonate with prior apprehensions expressed by Zakari and Khan [115], who contend that green money may sustain cosmetic environmental assertions without providing significant ecological advantages. Xia, et al. [116] assert that inconsistent regulatory frameworks may impede the efficacy of green financing projects in emerging economies. These results may not be in line with the work of Rasoulinezhad and Taghizadeh-Hesary [117], showing that green bonds represent an appropriate mechanism for advancing green energy initiatives and substantially decreasing CO2 emissions. Consequently, despite its theoretical potential [118], green finance may not achieve its desired impact unless transparency, accountability, and institutional governance are substantially improved.

Figure 8b demonstrates a persistent downward trend in the QQR coefficients of the relationship between renewable energy consumption and ecological footprint, indicating that higher renewable energy consumption is associated with reduced ecological burden over most quantile ranges. This result confirms the ecological benefits of implementing renewable energy, particularly when implemented effectively. In the lower quantiles (0.05–0.25) of the ecological footprint, the QQR coefficients demonstrate moderate negativity and relative consistency. This suggests that even in relatively less polluted settings, renewable energy contributes to environmental improvement, albeit modestly, presumably reflecting the early stage of Vietnam's renewable energy sector. In the intermediate quantiles (0.35–0.65), the detrimental effect exacerbates, particularly with increased renewable energy consumption. This trend corresponds with Vietnam's expansion in solar and wind energy from 2016 to 2020, which coincided with escalating environmental challenges. Substantial negative coefficients are observed in the upper quantiles (0.75–0.95) of the ecological footprint, particularly when LNRENEW surpasses the median. This indicates that renewable energy is most efficacious in mitigating environmental degradation during times of considerable ecological strain, supporting the findings of Wang, et al. [119] and Doğan, et al. [65], which emphasized the advantageous impacts of renewables in high-emission contexts. Saboori, et al. [120] indicate that renewable energy is a vital instrument for safeguarding the security of energy supply, promoting technological innovation, supporting regional development, and generating employment opportunities. The results of this study align partially with those of Mu, et al. [95], which indicated that renewable energy positively influences CO_2 emissions in the short term but exhibits a negative and moderating correlation with CO_2 emissions over medium and long terms. Thus, the QQR analysis highlights the considerable and uneven environmental benefits of renewable energy, especially in cases of severe ecological damage. These findings highlight the imperative to accelerate investments in renewable energy in Vietnam's most environmentally vulnerable sectors and regions.

Figure 8c notably illustrates the relationship between FD and LNECO_FOOT in Vietnam. In the lower quantiles (0.05–0.25) of the ecological footprint, the QQR coefficients are predominantly positive, mainly when FD is also situated within the lower quantile range. This suggests that during the early stages of financial development, economic expansion may lead to increased resource use and environmental degradation, a finding consistent with the scale effect emphasized in the EKC studies. The connection becomes less reliable at the middle quantiles (0.35–0.65). While specific advantageous impacts persist, some sectors have neutral or slightly negative coefficients, possibly signifying transitional stages where financial resources are partially directed towards more sustainable enterprises but are impeded by insufficient regulatory enforcement. In the upper quantiles (0.75–0.95) of the ecological footprint, particularly with significant financial development, the coefficients demonstrate a marked negative correlation, indicating that sophisticated financial systems may start to promote cleaner technologies, green credit, and sustainable investments. This aligns with the findings of He, et al. [121], which demonstrated that advanced financial development can foster environmental improvements when supported by appropriate institutional frameworks. The QQR analysis reveals that financial development in Vietnam exerts a dual impact on the ecological footprint: it may initially exacerbate environmental degradation, but at higher levels, it can mitigate ecological costs.

Figure 8d depicts the correlation between globalization and ecological footprint in Vietnam. In the lowest quantiles (0.05–0.25) of ecological footprint, the QQR coefficients are modest yet positive, suggesting that even in relatively "clean" or emerging contexts, globalization intensifies environmental costs. This may stem from the influx of foreign direct investment and manufacturing activities lacking sufficient environmental safeguards during Vietnam's early phases of globalization. In the central quantiles (0.35–0.65), particularly when LNGLOBAL is high, the coefficients attain greater significance, suggesting an increased environmental impact as trade and industrial activities intensify. This conclusion aligns with the "pollution haven hypothesis", which asserts that developing economies attract ecologically harmful manufacturing due to more permissive regulations. At higher quantiles (0.75–0.95) of ecological footprint, the relationship stabilizes or undergoes slight attenuation; still, it remains positive. This suggests that above a certain threshold, globalization continues to exert environmental pressure, perhaps due to broad liberalization through global value chain mechanisms [122]. The findings of this study are consistent with the study of Awosusi, et al. [100], who demonstrated that economic and trade globalization exhibits signs of potentially diminishing the load capacity factor in Malaysia. Additionally, the increase in ecological footprint is directly linked to production expansion propelled by globalization, as companies expand operations to satisfy worldwide market demands. This trend is especially pronounced among multinational firms, which frequently integrate industrial processes to enhance efficiency and productivity. As manufacturing intensifies, energy requirements escalate, predominantly met by fossil fuels, which significantly contribute to the growth of the ecological footprint [97]. The QQR findings indicate that globalization, despite its economic benefits, substantially contributes to environmental degradation in Vietnam.

To evaluate the robustness of the results, the mean slope coefficients from the QQR analysis are compared with those from traditional QR. As illustrated in Figs. 9 **(a)-(d)**, the mean QQR coefficients exhibit a pattern that closely aligns with the QR estimations in both direction and magnitude. This agreement asserts that the QQR model delivers reliable and consistent information regarding the environmental impacts of green financing, globalization, and renewable energy in Vietnam.

4.5 Wavelet coherence results

Figure 10a demonstrates that wavelet coherence analysis uncovers a dynamic correlation, both temporally and spectrally, between green financing and ecological footprint from 2000 to 2020, highlighting significant short-term coherence clusters (2–4 periods) in the intervals of 2000–2003, 2010–2012, 2014–2016, and 2018–2020. Between 2000 and 2003, 2010 and 2012, and 2018 and 2020, arrows were predominantly oriented rightward and marginally downward, indicating a positive, synchronous association

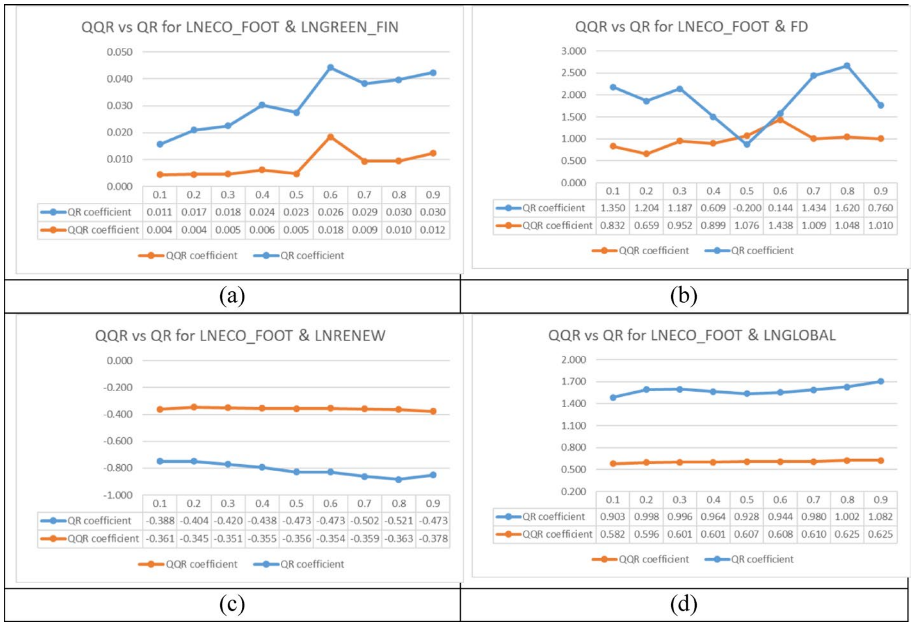

Fig. 9 Comparison of QR and QQR estimates of the impact of green finance (**a**), financial development (**b**), renewable energy (**c**), and globalization (**d**) on ecological footprint

with green finance as the primary catalyst. This synchronization aligns with an increased ecological footprint, suggesting that activities financed under the 'green' label may have inadvertently caused environmental damage. This may signify the ecological costs linked to the first green investment initiatives, insufficient screening criteria, or the concurrent presence of green finance with high-footprint commercial activities, perhaps including greenwashing. In contrast, the 2014–2016 period exhibits arrows oriented leftward and slightly upward, signifying an out-of-phase and negative connection, in which green financing lags behind environmental degradation. This pattern suggests that declining ecological conditions necessitated corrective financial measures, with green investments enabling environmental improvements. It illustrates a responsive and environmentally advantageous role of green finance in the context of increased global environmental consciousness and legislative modifications. The effectiveness of green finance in Vietnam has varied significantly over time due to differences in timing, policy context, and execution quality. Prior to 2012, green financing lacked institutional frameworks and often focused on economic recovery, hence intensifying the ecological footprint. Between 2014 and 2016, improved policy alignment enabled green finance to adopt a corrective and environmentally beneficial role. Between 2018 and 2020, despite an increase in green financial activities, the absence of a unified taxonomy and insufficient monitoring allowed resource-intensive projects to persist, undermining sustainability objectives.

Figure 10b displays the WTC plot, which analyzes the dynamic time-frequency relationship between ecological footprint and renewable energy use from 2000 to 2021. The intensity of color represents coherence strength, while the direction of arrows denotes phase differences and lead-lag interactions across short-term (1–4 periods), medium-term (4–8 periods), and long-term (8 + periods) frequencies. From 2000 to 2004, notable coherence is evident at both medium- and long-term frequencies. At medium-term intervals (4–8 periods), arrows denote a leftward and slightly upward trajectory, indicating an out-of-phase relationship wherein the ecological footprint leads. Over prolonged

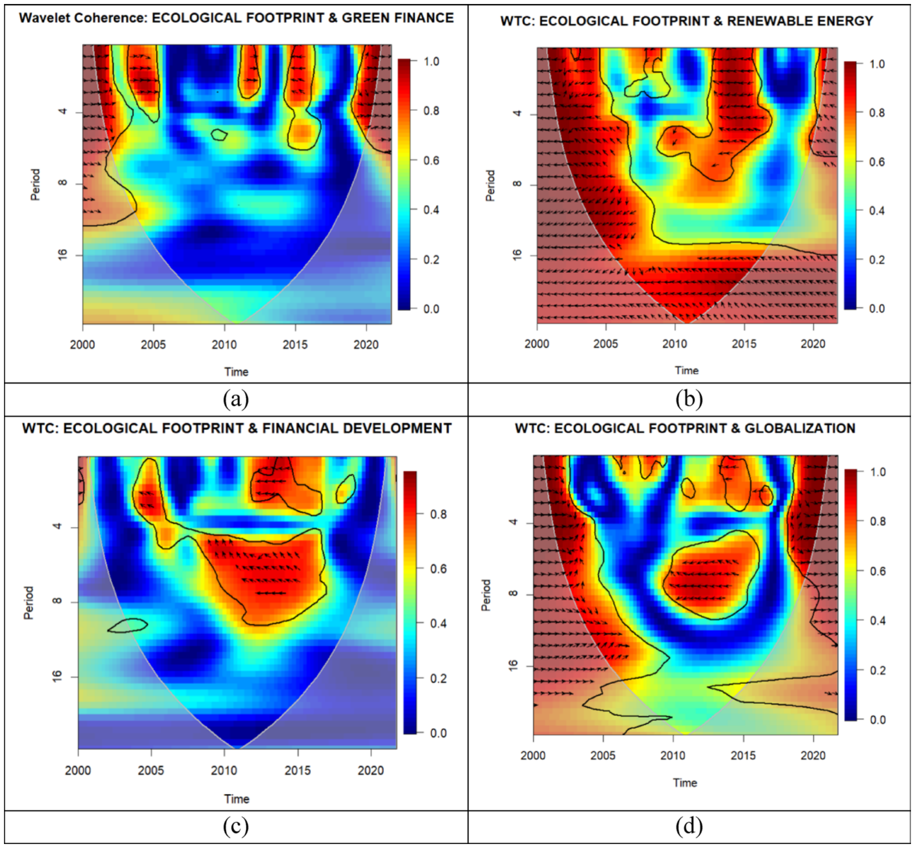

Fig. 10 Wavelet coherence analysis examining the linkage between the ecological footprint and four factors: green finance (**a**), renewable energy (**b**), financial development (**c**), and globalization (**d**). Each plot displays time on the x-axis and frequency/period on the y-axis, with the color gradient from blue to red indicating the degree of coherence between the ecological footprint and the explanatory variable. Warmer colors signify enhanced co-movement, whereas arrows illustrate the phase direction: rightward arrows represent positive correlations in phase, leftward arrows identify negative or out-of-phase interactions, and angled arrows indicate lead–lag dynamics. The cone of influence delineates the area impervious to edge effects, hence guaranteeing the integrity of results.

intervals (8–16 periods), the arrows shift leftward and marginally downward, remaining out of phase, while renewable energy starts to respond incrementally. This suggests that environmental degradation in the early 2000s delayed the transition to renewable energy sources. Between 2008 and 2012, significant coherence remains at medium- to long-term frequencies, with arrows showing a leftward and slightly downward trajectory, implying a continuous out-of-phase connection primarily influenced by ecological stress. This period likely signifies increased climate consciousness and the swift enactment of renewable energy policies following the global financial crisis. Between 2012 and 2015, the arrows indicate a precise leftward direction, illustrating an out-of-phase dynamic devoid of a recognizable lead-lag pattern. This signifies a synchronous but inverse association, where ecological pressure and renewable energy deployment vary in opposite directions at the same time, perhaps demonstrating both reactive and proactive energy planning. Subsequent to 2016, coherence declines across all dimensions, and directional consistency drops, indicating a more diffuse and complex relationship. The WTC results reveal a persistent out-of-phase correlation, especially at medium- and long-term intervals, where the growth of renewable energy generally lags behind or aligns with prior ecological degradation, rather than swiftly alleviating environmental damage.

Between 2006 and 2014, the WTC plot in Fig. 10c illustrates a concentrated region of substantial coherence between ecological footprint and financial development during short- to medium-term intervals (1–8 periods). During this period, arrows predominantly indicate a leftward and slightly upward direction, denoting an out-of-phase relationship in which the ecological imprint precedes. This suggests that increases in environmental degradation frequently preceded or triggered alterations in financial development, either through regulatory changes, capital reallocation, or increased demands to integrate environmental risks into financial systems. The upward orientation of the arrows signifies that the environmental signal precedes financial responses, illustrating a reactive tendency in which financial institutions may have adjusted to ecological concerns with a lag. This pattern may suggest a discord between financial growth and sustainability goals during that period, since economic advancement was often detached from environmental responsibility. The period from 2006 to 2014 highlights a short-to-medium-term negative connection, in which financial systems respond to prior environmental stress instead of alleviating it.

The WTC plot in Fig. 10d depicts the dynamic time-frequency connection between ecological footprint and globalization from 2000 to 2021. Two intervals of significant coherence emerge at long and medium frequencies, each distinguished by distinct directional patterns and implications. From 2000 to 2005, strong consistency is apparent at long-term intervals (8–16 periods), with arrows oriented to the right and slightly upward. This indicates a synchronous connection, with globalization slightly before the ecological footprint. The results demonstrate that the rapid expansion of globalization in the early 2000s, driven by trade liberalization, foreign direct investment, and transnational production, intensified ecological strain. The ecological effects seem to be closely related to the speed of globalization, showing the environmental costs of greater economic integration. From 2008 to 2016, on the other hand, there is a considerable area of coherence at medium- to long-term scales (4–16 periods), with vectors pointing slightly up and to the left. This indicates a continuing out-of-phase dynamic wherein the ecological impact drives globalization. The discovery suggests that increasing environmental stress during this period may have initiated constraints or alterations to globalization tendencies. This fits with talks that have taken place since the crisis about sustainable development, carbon footprints in global supply chains, and how to include environmental concerns in trade and investment rules. These findings collectively indicate a temporal shift in the globalization-environment interaction. Globalization seemed to make environmental degradation happen faster in the past. In subsequent years, ecological degradation started to impact globalization, underscoring a shift towards sustainability in global systems.

The wavelet quantile regression developed by Adebayo and Özkan [123] is used to assess the robustness of the results. Figure 11 demonstrates the heterogeneous and scale-dependent effects of diverse predictors on the ecological footprint. The effect on LNGREEN_FIN is negligible in the short and medium run. Nonetheless, it grows progressively important over time, especially across all quantiles, signifying a delayed environmental degradation linked to green funding. Conversely, LNGLOBAL demonstrates a substantial positive influence on ecological footprint at higher quantiles and across all

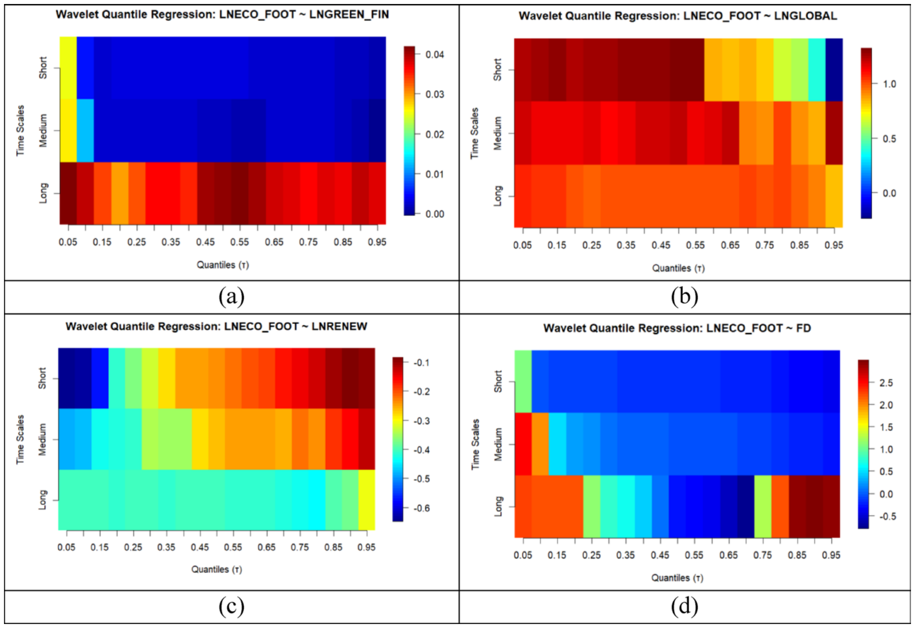

Fig. 11 Wavelet quantile regression for the interrelationship between ecological footprint and green finance (**a**), globalization (**b**), renewable energy (**c**), and financial development (**d**)

temporal scales, especially in the near and medium terms, indicating that globalization may intensify environmental degradation, particularly in high-impact scenarios. Regarding LNRENEW, its coefficients are consistently negative, especially at short and medium scales, indicating that increased renewable energy consumption substantially reduces environmental stress across most quantiles. Ultimately, FD demonstrates a heterogeneous pattern: its advantageous impact is apparent only at lower quantiles in the short and medium term, while its effect becomes negligible or adverse at higher quantiles and longer time frames. These findings underscore the nonlinear and dynamic relationships between sustainability drivers and environmental outcomes, suggesting the importance of tailored policy responses across different timeframes.

5 Conclusion

5.1 Summary of main findings

This research employs quantile-on-quantile and wavelet coherence techniques to elucidate the dynamic and nonlinear interrelations among green finance, renewable energy, financial development, globalization, and environmental results in Vietnam. The results indicate multiple significant trends. Initially, green financing does not inherently diminish environmental strain; instead, it exhibits a positive correlation with the ecological footprint at lower to medium quantiles of environmental effect. This indicates insufficient screening criteria, the simultaneous presence of environmentally sustainable and high-impact activities, and the concealed expenses associated with early green expenditures. Secondly, renewable energy exhibits significant potential to alleviate ecological loads, especially in high-impact situations, transitioning from a reactive to a proactive approach in reducing environmental stress. Initially, financial development intensifies environmental deterioration; nevertheless, it subsequently aids in mitigation, indicating a delayed yet beneficial reaction to ecological difficulties. Ultimately, globalization is persistently associated with increased environmental deterioration, with its adverse repercussions becoming increasingly evident in recent years. The research indicates that economic and financial mechanisms do not produce consistent environmental advantages. Their impacts are contingent upon contextual factors, quantile distributions, and the caliber of institutional control. These results underscore the necessity for meticulously crafted policies that enhance green finance frameworks, promote renewable energy adoption, match financial advancement with sustainability objectives, and incorporate environmental protections into globalization initiatives. Vietnam's shift towards sustainable development necessitates a sophisticated, evidence-driven strategy that harmonizes economic advancement with environmental conservation.

This study contributes to the empirical literature by combining quantile-on-quantile regression with wavelet coherence analysis to capture the nonlinear, dynamic relationships between green finance, renewable energy, financial development, globalization, and ecological footprint at various temporal scales and distributional quantiles. This study fills crucial gaps in understanding the sustainability issues of rising economies by concentrating on Vietnam's unique economic and environmental circumstances. The study's specific goal is to determine how these elements interact over time and across varied levels of ecological pressure, resulting in nuanced insights that will inspire targeted, evidence-based policy actions. These objectives reflect the need for comprehensive, temporal, and frequency-aware analyses that go beyond traditional mean-based approaches, providing new empirical evidence to support the sustainable development goals and climate commitments articulated in global frameworks.

5.2 Policy implications

The empirical findings yield several concrete and actionable policy recommendations to advance Vietnam's trajectory towards sustainable development. First, strengthening green finance frameworks is essential. The observed positive correlation between green finance and ecological footprint at lower to medium quantiles suggests that current practices may not fully align with ecological objectives. Authorities should develop a unified green finance taxonomy consistent with international standards, supported by digital verification platforms to minimize greenwashing and increase transparency. Establishing mandatory disclosure requirements and a centralized registry of green projects would ensure accountability and channel capital into initiatives that deliver verifiable environmental benefits.

Second, accelerating renewable energy deployment must be prioritized. Among all variables, renewable energy demonstrates the greatest ability to alleviate environmental stress, especially under high-impact scenarios. Policymakers should integrate renewables more deeply into the national energy framework through long-term power purchase agreements, feed-in tariffs, and targeted subsidies. Establishing green energy investment funds and supporting research hubs for clean technologies can further stimulate innovation and position Vietnam as a regional leader in sustainable energy.

Third, aligning financial development with sustainability is critical. The nonlinear effect of financial progress—initial deterioration followed by eventual improvements—underscores the need for strategic allocation. Regulators should require banks and investors to adopt ESG-based lending criteria, expand green credit lines for SMEs, and promote sustainability-linked bonds. A mandatory environmental risk assessment framework integrated into all major financial decisions would further safeguard resilience and long-term ecological benefits.

Fourth, embedding environmental safeguards in globalization is imperative. The consistent association between globalization and environmental degradation calls for stricter oversight. Trade and investment agreements should include legally binding environmental clauses and require corporate sustainability reporting from multinational enterprises. Moreover, integrating environmental impact assessments into cross-border cooperation projects and providing incentives for eco-friendly supply chains would mitigate negative externalities while leveraging globalization to attract green technologies and knowledge transfer.

In conclusion, these recommendations emphasize the importance of a comprehensive, context-sensitive approach. By adopting green finance taxonomies with digital monitoring, scalable renewable energy policies, ESG-driven financial instruments, and sustainability-focused globalization strategies, Vietnam can effectively align economic growth with environmental conservation and lay a robust foundation for long-term sustainable development.

5.3 Limitations and future research

Although this work provides useful insights, it is not without limits, which present opportunities for further research. The analysis is confined solely to Vietnam, limiting the generalizability of the results. Expanding the methodology to encompass a cross-country or regional panel dataset would yield comparison evidence and enhance the external validity of the findings. The study utilizes the ecological footprint as the exclusive indicator of environmental degradation. Future research may include alternative dependent variables, such as carbon intensity or load capacity factor, to elucidate various aspects of environmental stress and validate the robustness of findings. Third, although the current model incorporates green finance, renewable energy, financial development, and globalization, it neglects numerous emerging and increasingly significant variables. Integrating variables such as economic complexity, green bonds, and eco-innovation would yield a more thorough comprehension of the factors influencing environmental sustainability. Future work should also explore how HRM, digital finance innovations, green tax innovations, or carbon tax policy can complement renewable energy for a holistic sustainability framework [124–126]. By overcoming these constraints, future research can improve the framework's explanatory capacity and provide more substantial assistance for policymakers aiming to reconcile economic growth with environmental conservation.

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Data availability
Data are readily available at request from the corresponding authors.

Declarations

Competing interests

The authors declare no competing interests.

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