

Article

RETRACTED: Smart Growth or Footprint Trap? A Quantile Approach to FinTech, Natural Resources, and Governance in Emerging Markets

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Abstract

Amid rapid industrialization and the growing integration of financial technologies, emerging economies face increasing pressure from rising ecological footprints (ECOF). This study examines the environmental impacts of natural resource rents (NRES) and digital financial technology (DFIN), emphasizing the moderating role of governance (INST), using data from the top 10 emerging economies between 1995 and 2023. The Method of Moments Quantile Regression (MMQR) approach is employed to capture heterogeneous effects across different levels of environmental stress. The results reveal that both NRES and DFIN exacerbate ECOF, particularly in economies facing higher ecological pressures. However, strong governance significantly reduces these adverse effects, especially at higher ECOF quantiles, highlighting its pivotal role in aligning resource management and digital innovation with environmental sustainability goals. Interaction terms further confirm that effective institutional quality can buffer the ecological risks associated with resource exploitation and FinTech expansion. Additionally, Dumitrescu–Hurlin panel causality tests reveal a unidirectional causality from NRES and economic growth (EGRO) to ECOF, while bidirectional relationships are observed between DFIN, INST, education, urbanization, renewable energy, and ECOF. These findings underscore the complex interlinkages between economic growth, technological advancement, and institutional frameworks. In the context of post-COP28 climate commitments and Sustainable Development Goals, this study provides timely policy recommendations to promote sustainable growth through robust governance, responsible resource utilization, and balanced FinTech integration.

Keywords: environmental degradation; fintech; governance; natural resources; emerging economies



Academic Editor: Bruce Morley

Received: 3 August 2025

Revised: 22 September 2025

Accepted: 23 September 2025

Published: 26 September 2025

Retracted: 26 August 2026

Citation: Yin, J.; Edward, D. RETRACTED: Smart Growth or Footprint Trap? A Quantile Approach to FinTech, Natural Resources, and Governance in Emerging Markets. *Sustainability* **2025**, *17*, 8673.

<https://doi.org/10.3390/su17198673>

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1. Introduction

Climate change stands as one of the defining global challenges of the 21st century, posing serious threats to environmental stability, economic resilience, and human well-being [1]. Despite international agreements and successive climate summits emphasizing low-carbon pathways, many emerging economies continue to pursue aggressive growth strategies that conflict with environmental sustainability goals [2]. In these economies, rapid industrial expansion has been largely driven by intensive reliance on natural resource rents (NRES), which has increased ecological pressures through ecosystem degradation, biodiversity loss, and heightened ecological footprints (ECOF). This extractive growth

model, while boosting short-term GDP, undermines the long-term prospects for sustainable development by eroding natural capital and destabilizing environmental systems. The simultaneous rise in financial technology (DFIN) introduces new dynamics to this environmental dilemma [3]. On one hand, digital financial technologies—such as mobile banking and online investment platforms—can facilitate sustainable financing by promoting green innovation and supporting renewable energy projects. On the other hand, they can also stimulate unsustainable consumption and energy-intensive industries, thereby escalating environmental pressures [4]. This dual role makes DFIN a crucial factor for emerging economies as they attempt to balance modernization with environmental protection.

Similarly, institutional quality (INST) plays a decisive role in shaping how these economic and technological forces impact the environment [5]. Strong institutions can guide resource management, regulate financial markets, and enforce environmental policies effectively. Conversely, weak governance structures foster corruption, regulatory loopholes, and poor enforcement, which amplify the ecological damage caused by both resource exploitation and uncontrolled financial technology expansion [6]. Given these challenges, understanding the interactions between NRES, DFIN, and ECOF is critical for advancing the post-COP28 agenda. This study addresses this need by examining how NRES and DFIN affect ECOF across different levels of environmental stress in the world's leading emerging economies, while highlighting the moderating role of INST. By employing a Moment Quantile Regression (MMQR) approach, the research uncovers heterogeneous effects and provides actionable insights for policymakers. The findings are expected to inform strategies that promote responsible resource use, align technological progress with sustainability, and strengthen institutional capacity to achieve balanced and inclusive green growth.

Meanwhile, the ecological footprint (ECOF) serves as a comprehensive indicator of environmental pressure, revealing whether a population's resource use aligns with the Earth's regenerative capacity [7]. According to the Global Footprint Network (GFN), ECOF quantifies the biologically productive land and water required to meet human consumption needs and absorb generated waste. It is measured in global hectares (gha) and incorporates several components, including carbon emissions, agricultural output, and land used for infrastructure and commodity production. By comparing a country's ECOF with its biocapacity, policymakers can identify whether development practices are within sustainable limits or pushing ecosystems toward degradation [8]. This makes ECOF a vital tool for identifying sectors that require improved environmental management and sustainable resource practices. Historically, natural resource rents (NRES) have been a cornerstone of economic growth in emerging economies. However, the extraction and use of these resources, especially fossil fuels, are major drivers of ecological damage and environmental stress [9]. The environmental impact of NRES is complex. Excessive resource extraction accelerates deforestation, pollution, and carbon emissions, worsening ecological degradation [10]. Conversely, when revenues from natural resources are strategically reinvested into renewable energy, green infrastructure, and eco-friendly technologies, they can help mitigate environmental damage and promote sustainable growth [11]. Thus, the ultimate effect of NRES on environmental quality depends on how effectively these rents are managed and allocated. Emerging economies, in particular, stand to benefit from redirecting resource rents toward renewable energy transitions and low-carbon innovation to balance economic expansion with sustainability goals.

Meanwhile, financial technology (DFIN) is reshaping the financial services landscape through mobile banking, internet-based platforms, and innovative technologies such as blockchain. DFIN holds the potential to accelerate green transitions by mobilizing green finance and supporting investments in renewable energy and sustainable projects [12].

However, its rapid growth comes with environmental risks. Blockchain mining, data centers, and extensive digital infrastructure demand significant energy, leading to increased emissions and electronic waste [13,14]. Without appropriate regulatory oversight, DFIN could unintentionally exacerbate environmental degradation instead of alleviating it. The role of institutional quality (INST) is central to determining whether NRES and DFIN promote sustainability or intensify ecological harm. Effective governance systems regulate resource extraction, enforce environmental policies and guide financial innovation toward eco-friendly outcomes [15]. In contrast, weak governance fosters corruption, policy inefficiencies, and unmonitored technological expansion, which together amplify environmental pressures. In this context, strong INST mechanisms are essential to ensure that NRES revenues are invested in sustainable development projects and that DFIN growth aligns with climate objectives rather than threatening them [16].

This study emerges from the critical position that both NRES and DFIN shape the environmental and economic trajectories of emerging markets. Expanding higher education levels fosters green skills, research, and policy innovation, helping economies decouple growth from resource-intensive practices [17]. However, disparities in educational access across emerging markets create uneven capacities for sustainable transitions. Similarly, the swift expansion of digital financial services, while boosting economic inclusivity and innovation, can also increase energy demand and generate new sources of environmental pressure [18]. Despite their importance, the combined effects of NRES and DFIN remain underexplored, especially within economies that exhibit varying levels of institutional capacity. Understanding how INST moderates the relationship between these factors and ECOF is vital for designing strategies that simultaneously achieve economic growth and environmental sustainability, as envisioned under post-COP28 climate frameworks.

To strengthen the theoretical foundation, this study introduces a conceptual mechanism that explains how governance interacts with financial technology and natural resource rents to shape environmental outcomes. Strong governance structures act as an institutional filter, directing financial and technological growth toward sustainable investments and efficient resource allocation [19,20]. When institutional quality is high, regulatory oversight and environmental enforcement ensure that FinTech-driven capital flows are used to promote green innovation, renewable energy adoption, and cleaner industrial practices [21]. Conversely, weak governance amplifies ecological risks by enabling unchecked digital expansion and rent-seeking behaviors, which lead to excessive resource extraction and unsustainable growth [22,23]. This theoretical lens positions governance not only as a moderating variable but also as a pivotal force that determines whether emerging markets transition toward sustainable pathways or remain trapped in resource-dependent ecological degradation.

To ground this study within established theoretical foundations, we draw on Ecological Modernization Theory (EMT) and Innovation Diffusion Theory (IDT). EMT posits that technological advancements, when supported by strong institutional frameworks, can decouple economic growth from environmental degradation by promoting cleaner production, green financing, and sustainable resource use [24]. In this context, FinTech serves as a transformative tool that can mobilize capital for green investments, enhance transparency in resource management, and incentivize low-carbon economic transitions. Meanwhile, IDT explains how emerging digital financial technologies are adopted and diffused across economies, influencing patterns of consumption and investment. By linking these theories, our study provides a conceptual basis for understanding how FinTech interacts with natural resource rents and governance to shape environmental outcomes in emerging markets [25]. This integration moves beyond descriptive analysis to offer a

mechanistic explanation of how financial digitalization can either exacerbate ecological footprints or serve as a catalyst for sustainability.

This study seeks to answer whether the rapid development of FinTech in emerging economies represents a pathway to smart, sustainable growth or whether it risks becoming a footprint trap that intensifies ecological degradation. By integrating ecological modernization theory and innovation diffusion theory, the research positions governance as a central mechanism that determines whether FinTech expansion drives environmental benefits or harms. This framing ensures a direct connection between the research question, theoretical foundations, and empirical testing.

Current research has identified several macroeconomic and socio-political drivers of environmental sustainability, but many studies focus narrowly on either economic growth or energy consumption [26,27]. The key contribution of this research lies in its integrated analysis of NRES and DFIN impacts on ECOF across the top 10 emerging economies between 1995 and 2023, explicitly considering the moderating influence of INST. By employing the Moment Quantile Regression (MMQR) method, the study captures heterogeneous effects across different environmental stress levels—relationships that conventional mean regression models often overlook. This approach provides deeper insights into how institutional strength shapes the complex dynamics between resource dependency, financial innovation, and ecological sustainability [28,29]. This research makes several contributions to the existing literature. First, it advances empirical understanding of how natural resource dependency and financial technology expansion jointly affect ecological outcomes, moving beyond the traditional focus on GDP growth and energy consumption. Second, it highlights the moderating role of institutional quality, which has been largely neglected in prior studies, offering a more nuanced view of how governance structures can balance technological innovation with environmental safeguards. Third, this study is among the few to investigate these relationships in the context of leading emerging economies, offering practical insights for policymakers. The results are expected to guide strategies for redirecting NRES revenues toward green projects such as renewable energy development, eco-friendly technologies, and resilient infrastructure, while ensuring that DFIN innovations are governed by strict environmental regulations.

The paper is structured as follows: Section 2 provides a comprehensive review of the relevant literature, Section 3 describes the methodology and data, Section 4 presents the empirical results and discussion, and Section 5 concludes with policy implications and future research directions.

2. Literature Review

2.1. Natural Resource Rents and Ecological Footprint

Natural resource rents (NRES) represent the economic returns generated from extracting natural assets such as oil, gas, minerals, and forests [30]. In contrast, the ecological footprint (ECOF) reflects the extent of human demand placed on the planet's ecosystems [31]. Examining these two variables together is vital, as the extraction of resources can stimulate economic growth but often at the expense of increased environmental stress and ecological degradation. Several empirical studies have explored this relationship, but the findings remain mixed. For instance, ref. [32] analyzed the disaggregated effects of various resource rents on ECOF across 24 countries using a Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) framework. Their results revealed that oil, natural gas, and mineral rents all heightened ECOF, with oil rents exerting the strongest negative environmental impact. Moreover, they found a bidirectional relationship between oil and mineral rents and ECOF, suggesting that policies aimed at reducing ecological pressure may inadvertently affect resource extraction revenues.

Similarly, ref. [33] examined 90 Belt and Road Initiative economies from 1991 to 2018, focusing on the interplay between NRES, financial development, and technological innovation. Their results indicated that NRES consistently contributed to environmental degradation across all income groups. Interestingly, when technological innovation interacted with NRES, the negative environmental effects were partially mitigated, implying that innovation can play a pivotal role in decoupling economic growth from ecological harm. In highly industrialized economies, heavy dependence on fossil fuels and extractive industries exacerbates environmental challenges. For example, ref. [34] investigated the G7 nations and reported that the expansion of resource extraction was directly linked to higher ECOF, emphasizing how overexploitation of fossil fuels accelerates environmental degradation in advanced economies.

Conversely, other studies have reported contrasting outcomes. For example, ref. [35] explored the relationship among renewable energy (RENEW), income, NRES, urbanization (URBG), and ECOF in BRICS countries between 1992 and 2016. Their findings demonstrated a negative effect of NRES on ECOF, suggesting that resource rents, when effectively managed, could be directed toward activities that reduce ecological damage. In a related study, ref. [36] used a modified ecological footprint model to investigate the joint effects of renewable energy use and NRES on environmental outcomes in ASEAN-5 countries. Their Moment Quantile Regression (MMQR) results confirmed the Environmental Kuznets Curve (EKC) hypothesis, indicating that while early stages of economic development increase ECOF, higher levels of income and renewable energy adoption eventually lead to environmental improvements. Importantly, their results showed that both NRES and RENEW reduced ECOF across all quantiles, highlighting the potential for sustainable resource management. Another dimension of this debate involves the diversity of resource types. Furthermore, ref. [37] studied 31 OECD countries between 2009 and 2019, emphasizing how diverse natural resource portfolios affect ECOF. They found that environmental harm was more severe in countries with weak environmental policies and lower ecological standards. Likewise, ref. [38] examined resource-rich MENA nations from 2000 to 2021 using a pooled mean group estimator, reporting that a 1% increase in NRES raised environmental degradation by 0.053%, indicating a direct link between resource dependency and rising ECOF.

2.2. FinTech and Ecological Footprint

FinTech can shape environmental outcomes by expanding green capital, diffusing low-carbon technologies, and tightening information flows that discipline polluters [39,40]. Empirically, studies increasingly link digital finance and FinTech ecosystems to smaller environmental footprints or improved eco-efficiency [41]. City-level evidence for China shows that digital finance lowers urban carbon-footprint pressure, with effects operating through green innovation and green-finance intermediation, and varying by region, which signals heterogeneous capacity to translate FinTech into mitigation gains [42,43]. Furthermore, the work by ref. [44] finds that FinTech development raises carbon-emission efficiency directly and via green technological innovation, with spatial spillovers across cities. Moreover, in cross-country and sectoral contexts, FinTech complements green finance to support decarbonization, reduce ecological degradation, and improve composite sustainability measures such as the load capacity factor, although magnitudes depend on institutional and resource structures [45]. Another study shows that there is also growing evidence that green-finance instruments mobilized within increasingly digital financial systems, like green bonds, are associated with subsequent reductions in firm-level emissions [46].

Interestingly, the ecological footprint implications are not uniformly positive, which underscores the role of governance and financial design [47]. Some studies show FinTech's

environmental benefits are strongest where institutions steer digital finance toward climate goals or where FinTech interacts with climate finance and disclosure policies [48]. Moreover, in resource-intensive economies, FinTech can still help correct ecological imbalances when paired with targeted green-finance channels, but outcomes hinge on complementary policies that prevent rebound effects from easier credit and faster diffusion of brown technologies [49,50]. Even within payments, where digitalization is often assumed to be greener, assessments differ by country, electricity mix, and lifecycle boundaries: some analyses find point-of-sale cash has a higher warming potential than digital payments, while others report small average differences across systems, which cautions against blanket claims [51,52]. As a final outcome, the literature suggests FinTech can reduce ecological footprints when it expands green capital, strengthens disclosure and screening, and aligns with credible policy frameworks, but its sustainability dividend is contingent on governance quality and the orientation of financial flows.

2.3. The Role of Governance and Ecological Footprint

Institutional quality (INST), encompassing governance structures, regulatory frameworks, and policymaking systems, plays a fundamental role in shaping the trajectory of ECOF [53]. Effective governance directly influences environmental outcomes by setting, enforcing, and monitoring policies aimed at reducing ecological degradation. Strong institutions ensure that environmental regulations are implemented effectively, promoting sustainable practices that help limit the ECOF [54]. For instance, ref. [55] highlighted China's experience, where comprehensive governance mechanisms—such as robust anti-corruption measures, regulatory quality improvements, and strict environmental legislation—have helped mitigate environmental damage despite rapid industrialization. Similarly, ref. [56] combined Analytical Hierarchy Process (AHP) modeling with ECOF analysis to evaluate sustainability planning, demonstrating that governance quality serves as a foundational element for achieving environmental balance. Furthermore, ref. [57] also found that European Union countries with higher institutional capacity and transparent governance systems achieved lower ECOF levels and improved sustainability outcomes, emphasizing the benefits of coherent environmental governance.

However, the influence of governance is far from uniform across regions. Local political, social, and economic conditions often shape how governance mechanisms operate. For example, ref. [58] examined Sub-Saharan African nations and observed that improvements in INST were associated with reductions in ECOF, though the magnitude of the effect varied considerably among countries. These findings underscore the importance of context-specific approaches when evaluating governance–environment linkages. Beyond direct environmental regulation, INST plays a broader role in mediating political interests and coordinating diverse stakeholders to create long-term climate strategies [59]. Moreover, refs. [60,61] emphasized that strong institutions are necessary to facilitate consensus-building and the development of cohesive policies addressing climate change. Additionally, ref. [62] further argued that political stability and institutional strength are prerequisites for implementing effective climate adaptation policies, which indirectly shape ECOF by influencing both mitigation and adaptation measures.

Further continuing, expanding the geographic scope, ref. [63] revealed that in BRICS countries, investments in green technology coupled with improvements in INST significantly reduced ECOF, demonstrating a synergistic relationship between governance, technological advancement, and ecological sustainability. Similarly, ref. [64] studied G7 nations and found a clear negative association between ECOF and green governance structures, particularly when paired with financing mechanisms aimed at promoting renewable energy. These results suggest that governance is not only a regulatory tool but also a catalyst for

low-carbon economic transitions. Evidence from developing regions also supports the critical role of governance. Moreover, another study by ref. [65] documented how governance effectiveness exerted a dampening effect on environmental degradation across Sub-Saharan Africa, while refs. [66,67] highlighted the roles of political stability, corruption control, and bureaucratic efficiency in reducing ECOF levels. Collectively, these studies demonstrate that INST operates as both a direct and indirect determinant of ecological sustainability. Strong governance structures enhance policy effectiveness, foster green innovation, and align economic growth with environmental objectives. Conversely, weak institutions exacerbate resource mismanagement and policy failures, leading to higher ecological pressures.

2.4. Research Gap

Despite growing research on environmental sustainability, the joint role of natural resource rents (NRES), digital financial technology (DFIN), and institutional quality (INST) in shaping the ecological footprint (ECOF) remain underexplored. Existing studies provide mixed evidence: some argue that resource rents can finance renewable energy and green technologies, while others link resource dependency to ecological degradation through fossil fuel reliance and overexploitation. Similarly, the environmental impact of DFIN is ambiguous, although it facilitates green financing and eco-innovation, its rapid expansion raises concerns about energy use and electronic waste. Moreover, the moderating role of governance in aligning resource wealth and financial digitalization with environmental goals has received little attention. Prior research often examines NRES or financial development in isolation, neglecting potential interaction effects with institutional quality. The mechanisms through which governance moderates these relationships, especially in emerging economies with uneven institutional capacity, remain unclear. Finally, conventional mean regression methods fail to capture heterogeneous impacts across different environmental stress levels, leaving a methodological gap in understanding how these factors jointly influence ECOF.

3. Methodology

3.1. Variable and Sample Selection

This study investigates how institutional quality (INST) moderates the relationship between natural resource rents (NRES) and financial technology (DFIN) in shaping the ecological footprint (ECOF) across the top 10 emerging economies over the period 1995–2023. The analysis incorporates a balanced set of economic, environmental, and socio-economic indicators to capture the multidimensional factors influencing sustainability. These include economic growth (EGRO), higher education (HEDU), urbanization (URBG), renewable energy consumption (RENEW), and governance quality (INST) alongside the primary variables of interest—NRES, DFIN, and ECOF. Table 1 provides detailed information on each variable, its measurement, and data source. The selected variables are designed to provide a comprehensive view of how resource dependency and financial digitalization interact within different governance contexts to impact environmental sustainability. Understanding these dynamics is essential for identifying policies that balance economic modernization with environmental preservation. The results of this research are expected to guide policymakers and stakeholders in designing strategies for emission reduction and green transition initiatives aligned with post-COP28 climate objectives.

Table 1. Description of the variables.

Acronym	Variable	Measurement	Source
ECOF	Ecological Footprint	Total ecological footprint of consumption per person (gha per person)	GFN
NRES	Natural Resource Rents	Total natural resource rents (% of GDP)	WDI
DFIN	Financial technology	Index via PCA (financial development index, mobile subscriptions per 100 people, internet users %)	IMF and WDI
INST	Institutional Quality	Index via PCA (government effectiveness, regulatory quality, control of corruption, political stability, rule of law, voice and accountability)	WGI
EGRO	Economic Growth	GDP growth (annual %)	WDI
HEDU	Higher Education	Gross tertiary enrollment (% of population aged 18–22)	WDI
RENEW	Renewable Energy	% of total final energy consumption	WDI
URBG	Urbanization	Urban population (% of total population)	WDI

Note: GFN = Global Footprint Network, IMF = International Monetary Fund, WDI = World Development Indicators, WGI = World Governance Indicators, ECOF = Ecological Footprint, NRES = Natural Resource Rents, DFIN = Financial Technology, INST = Institutional Quality, EGRO = Economic Growth, HEDU = Higher Education, RENEW = Renewable Energy, URBG = Urbanization.

The Financial Technology (DFIN) index was constructed using Principal Component Analysis (PCA) to combine multiple indicators, including financial development, mobile subscriptions per 100 people, and internet user penetration rates. PCA was selected to reduce dimensionality while retaining maximum variance from the underlying variables. The DFIN in this study integrates three core components: mobile subscriptions, internet penetration, and the financial development index. While these variables capture the overall level of digital financial activity, they represent diverse processes with potentially different environmental impacts. For instance, mobile banking and e-payments can promote financial inclusion and support green financing initiatives, while data-intensive technologies such as blockchain and large-scale digital infrastructure may increase energy demand and

emissions. Similarly, e-government platforms and online public services have the potential to reduce ecological pressure by improving governance and transparency. By combining these dimensions into a single index, the study captures the overall digital financial ecosystem but acknowledges that it cannot fully isolate the specific environmental effects of individual FinTech components. Future research could use more disaggregated measures to better identify which technological drivers are most closely linked to environmental gains or losses.

The sample focuses on the top 10 emerging economies, which include major industrialized nations from international economic blocs, with the exception of Vietnam. These countries are also members of the E-7 economies and the EAGLEs group, representing the most dynamic and influential emerging markets globally. Their inclusion is critical due to their pivotal roles in global production networks, rapid industrial growth, and increasing contributions to climate change mitigation and adaptation efforts. By studying these economies, this research offers valuable insights into the trade-offs and synergies between economic expansion and environmental sustainability in some of the most environmentally and economically significant regions of the world. The final sample of countries included in this study consists of Brazil, Russia, India, China, South Africa, Mexico, Indonesia, Turkey, Nigeria, and Argentina. These countries were selected because they are recognized as the most influential emerging markets globally and are collectively part of international blocs such as the BRICS and MINT groups. They also represent the E-7 economies and members of the EAGLEs framework, which identify nations expected to drive future global economic growth. Vietnam was excluded because of its comparatively smaller economic size and lack of consistent long-term data coverage for key variables such as renewable energy consumption, financial technology indicators, and governance measures. Including it would have introduced missing data issues and compromised the robustness of the panel analysis. This deliberate selection ensures that the study focuses on economies with both global influence and complete, reliable data, thereby enhancing the validity and representativeness of the results. Moreover, Figure 1 displays the ECOF trends in the countries under discussion in the current study. As shown in Figure 1, the ecological footprint per capita varies widely among the selected emerging economies between 1995 and 2023. Russia exhibits persistently high environmental pressures, while India and Nigeria remain at lower levels. These contrasting trends underscore the need to investigate how natural resources, financial technology, and governance shape ecological outcomes across diverse contexts.

To ensure transparency and robustness, missing values in the panel dataset were addressed using a two-step procedure. First, when data gaps were small and occurred within a continuous series, linear interpolation was applied to maintain temporal consistency. Second, in cases of extensive or persistent missing data for a variable or country, listwise deletion was used to prevent introducing bias, which also guided the final selection of the ten countries in our sample. This approach allowed for a balanced panel covering the 1995–2023 period while preserving the integrity of the dataset. Regarding variable construction, the Financial Technology (DFIN) index was synthesized using Principal Component Analysis (PCA) to combine three indicators: (1) financial development index, (2) mobile subscriptions per 100 people, and (3) internet user penetration rates. Prior to PCA, all indicators were standardized to remove scale differences. The first principal component was selected because it explained 74.6% of the total variance, indicating a strong underlying factor. Sensitivity checks were performed by removing one indicator at a time, and the index remained stable, confirming its reliability and robustness. These details ensure that the methodology is replicable for future research.

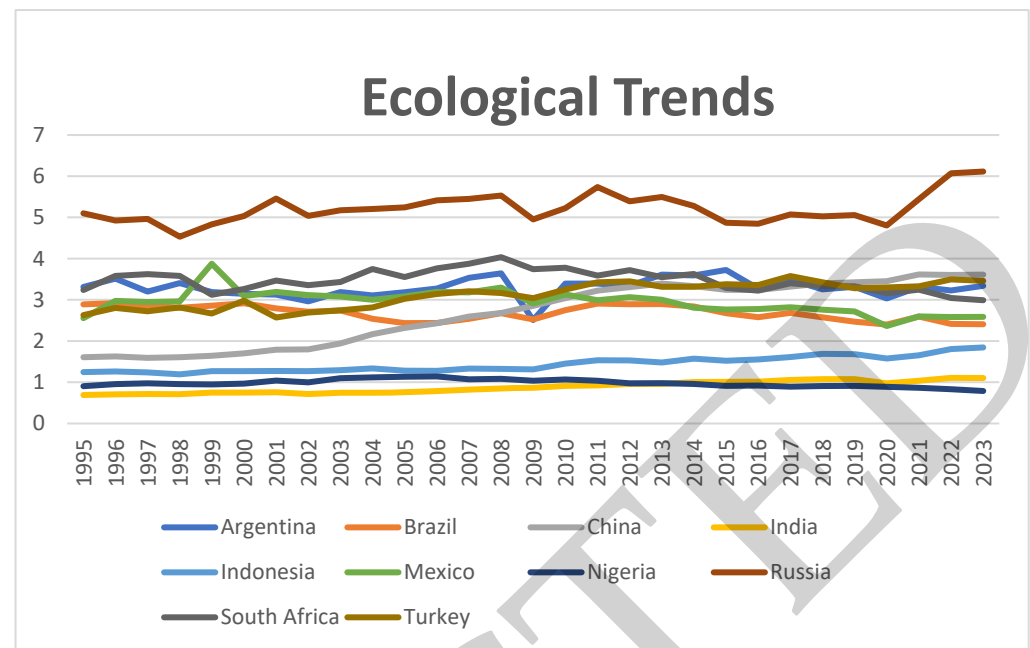


Figure 1. Ecological footprint trends (1995–2023) for ten emerging economies, showing cross-country differences in environmental pressures.

The present study examines the influence of Natural Resource Rents (NRES) and Financial technology (DFIN) on Ecological Footprint (ECOF) for the Top 10 emerging economies. Further, the role of Institutional Quality (INST) is taken as a moderator. The aforementioned variables serve as the principal indicators affecting environmental sustainability. Based on the theoretical framework, the following hypotheses are developed:

- H1.** *Natural resource rents (NRES) increase the ecological footprint (ECOF) by encouraging resource-intensive growth.*
- H2.** *FinTech development (DFIN) has a dual potential, but in the absence of strong governance, it increases the ecological footprint.*
- H3.** *Institutional quality (INST) directly reduces the ecological footprint by promoting environmental regulation and sustainable practices.*
- H4.** *Institutional quality moderates the relationship between NRES and ECOF, mitigating the adverse environmental effects of resource dependency.*
- H5.** *Institutional quality moderates the relationship between DFIN and ECOF, ensuring that FinTech-driven growth supports environmental sustainability rather than degradation.*

These hypotheses derive directly from ecological modernization and innovation diffusion theories, which emphasize the role of institutions in guiding technological and economic transitions. This study's model is built on the theoretical framework presented earlier, with the functional and econometric forms shown in Equations (1)–(8).

$$\text{ECOF} = f(\text{NRES}, \text{INST}, \text{EGRO}, \text{HEDU}, \text{RENW}, \text{URBG}) \quad (1)$$

$$\text{ECOF} = f(\text{NRES}, \text{INST}, \text{INST} \times \text{NRES}, \text{EGRO}, \text{HEDU}, \text{RENW}, \text{URBG}) \quad (2)$$

$$\text{ECOF} = f(\text{DFIN}, \text{INST}, \text{EGRO}, \text{HEDU}, \text{RENW}, \text{URBG}) \quad (3)$$

$$ECOF = f(DFIN, INST, INST \times DFIN, EGRO, HEDU, RENW, URBG) \quad (4)$$

$$ECOF_{it} = \alpha_0 + \alpha_1 NRES_{it} + \alpha_2 INST_{it} + \alpha_3 EGRO_{it} + \alpha_4 HEDU_{it} + \alpha_5 RENW_{it} + \alpha_6 URBG_{it} + \varepsilon_{it} \quad (5)$$

$$ECOF_{it} = \alpha_0 + \alpha_1 NRES_{it} + \alpha_2 INST_{it} + \alpha_3 (INST \times NRES)_{it} + \alpha_4 EGRO_{it} + \alpha_5 HEDU_{it} + \alpha_6 RENW_{it} + \alpha_7 URBG_{it} + \varepsilon_{it} \quad (6)$$

$$ECOF_{it} = \alpha_0 + \alpha_1 DFIN_{it} + \alpha_2 INST_{it} + \alpha_3 EGRO_{it} + \alpha_4 HEDU_{it} + \alpha_5 RENW_{it} + \alpha_6 URBG_{it} + \varepsilon_{it} \quad (7)$$

$$ECOF_{it} = \alpha_0 + \alpha_1 DFIN_{it} + \alpha_2 INST_{it} + \alpha_3 (INST \times DFIN)_{it} + \alpha_4 EGRO_{it} + \alpha_5 HEDU_{it} + \alpha_6 RENW_{it} + \alpha_7 URBG_{it} + \varepsilon_{it} \quad (8)$$

where i denotes the cross-sectional units (countries), t represents time, α indicates the coefficients of the variables, and ε is the error term. Panel data estimation techniques are employed to examine the effects of NRES and DFIN on ECOF, while assessing the moderating role of INST.

3.2. Econometric Methodology

The econometric analysis in this study follows a systematic approach, incorporating unit root tests, cross-sectional dependency (CD), slope heterogeneity (SH) evaluation, cointegration testing, and long-run estimation techniques. These steps ensure the reliability and accuracy of the panel data results by addressing potential statistical issues commonly observed in multi-country datasets [68]. A correlation analysis was conducted to examine the relationships among variables and assess the smoothness of the data distribution. Standard statistical techniques were applied to determine whether the data follow a normal distribution. If the normal probability plot exhibits a nearly linear pattern, it suggests that the data are normally distributed. Conversely, noticeable deviations from linearity imply non-normality. The correlation coefficient provides further insight into this relationship, where higher values indicate stronger associations.

3.2.1. Variance Inflation Factor and Cross-Sectional Dependence

In addition to correlation analysis, we employed the Variance Inflation Factor (VIF) technique to assess multicollinearity among the explanatory variables. VIF values are a more rigorous diagnostic tool, with values greater than 10 generally indicating serious multicollinearity problems [69]. This additional step ensures that the estimated coefficients are not biased by overlapping information among the regressors. While the correlation matrix provides an initial overview of pairwise relationships, VIF analysis captures multicollinearity in a multivariate context, offering a more comprehensive assessment of the dataset's reliability [70].

Cross-sectional dependence (CD) evaluates the correlation among panel units, such as countries in this study. When a shock in one country affects others, CD exists and must be addressed to avoid biased and inconsistent estimates. Accounting for CD is crucial because conventional unit root tests that ignore this dependency often produce unreliable results. The CD test, developed by ref. [71], measures the degree of interconnection among residuals across cross-sections. The test is based on the methodology proposed by Breusch and Pagan (1980) and is expressed in Equations (9) and (10) [72].

$$CD = T \sum_{i=1}^{n-1} \sum_{j=i+1}^n \hat{\rho}_{ij}^t \quad (9)$$

The CD test statistic is computed in Equation (10).

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{n-1} \sum_{j=i+1}^n \hat{\rho}_{ij} \right) \quad (10)$$

Here, $\hat{\rho}_{ij}$ represents the correlation coefficient between the residuals of cross-sectional units i and j , while T and N denote the time dimension and the number of cross-sections, respectively.

3.2.2. Slope Homogeneity and Unit Root Test

Following the CD test, we assess the uniformity of slope coefficients across countries. Due to differences in economic structures and demographic patterns, slope parameters may vary, which can affect the reliability of panel estimators. To account for this, the slope heterogeneity (SH) test proposed by [73] is applied. The test is based on the following equations:

$$\tilde{\Delta}_{SH} = (N)^{\frac{1}{2}} (2N)^{-\frac{1}{2}} \left(\frac{1}{N} \tilde{S} - K \right) \quad (11)$$

$$\tilde{\Delta}_{adjSH} = (N)^{\frac{1}{2}} \left(\frac{2k(T-k-1)}{T+1} \right)^{-\frac{1}{2}} \left(\frac{1}{N} \tilde{S} - K \right) \quad (12)$$

where $\tilde{S}$ represents the standardized sum of squared residuals, K denotes the number of explanatory variables, T is the time dimension, and N is the number of cross-sectional units. This test helps identify whether the panel data exhibit homogeneity or heterogeneity in slope coefficients. Spurious regression issues can arise when working with non-stationary panel data. Therefore, it is essential to examine the stationarity of each variable before model estimation. When the time span for each cross-sectional unit increases, checking for unit roots becomes crucial to ensure valid results. After evaluating cross-sectional dependence (CD), appropriate unit root tests are applied. First-generation panel unit root tests assume independence across units, whereas second-generation tests allow for interdependencies. Ref. [74] introduced the cross-sectionally augmented Dickey–Fuller (CADF) test, which accounts for such dependencies and evaluates stationarity at the individual series level. The CADF test is represented in Equations (13)–(15), with the t -statistic given in Equation (16).

$$Y_{it} = (1 - \phi_i)\mu_i + \phi_i Y_{it-1} + v_{it} \quad (13)$$

$$\text{Here } v_{it} = \gamma_i f_t + \varepsilon_{it}$$

$$\Delta Y_{it} = \alpha_i + \rho_i Y_{it-1} + \gamma_i f_t + \varepsilon_{it} \quad (14)$$

$$\text{Here } \alpha_i = (1 - \phi_i)\mu_i \text{ and } \rho_i = -(1 - \phi_i)$$

$$\Delta Y_{it} = \alpha_i + \rho_i^* Y_{it-1} + d_0 \bar{Y}_{t-1} + d_1 \bar{Y}_t + \varepsilon_{it} \quad (15)$$

$$\text{Here } \Delta Y_{it} = Y_{it} - Y_{it-1}$$

$$t_i(N, T) = \frac{\Delta Y_{it} \bar{M}_w Y_{i-1}}{\hat{\sigma}_i \sqrt{(Y'_{i-1} \bar{M}_w Y_{i-1})}} \quad (16)$$

Here, $\bar{Y}_t$ and its lagged values serve as instrumental variables for the unobserved common factor f_t . The null hypothesis (H_0) assumes the presence of a unit root, while the alternative hypothesis (H_1) suggests stationarity. The panel-level cross-sectional augmented

Im-Pesaran-Shin (CIPS) test statistic is obtained by averaging individual CADF statistics, as shown in Equation (17).

$$\text{CIPS} = N^{-1} \sum_{i=1}^N \text{CADF}_i \quad (17)$$

H0 is rejected if the computed CIPS value exceeds critical thresholds, indicating that the series is stationary.

3.2.3. Westerlund Co-Integration Test

To examine long-run equilibrium relationships among the variables, ref. [75] second-generation cointegration test is applied. Unlike earlier approaches such as those by Kao and Pedroni, Westerlund's method accounts for cross-sectional dependence and heterogeneity, providing more robust results. This test consists of four statistics: two group-mean tests (G_t , G_a) and two panel tests (P_t , P_a). The panel statistics assume homogeneity, while the group statistics allow for heterogeneity. The model is represented in Equation (18).

$$\Delta Y_{it} = \delta_i d_t + \mu_i \Delta x_{it} + \gamma_i Y_{it-1} + \varphi_i x_{it-1} + \varepsilon_{it} \quad (18)$$

The numerical metrics for the investigation are as follows:

$$G_t = \frac{1}{N} \sum_{i=1}^N \frac{\hat{\alpha}_i}{\text{SE}(\hat{\alpha}_i)} \quad (19)$$

$$G_a = \frac{1}{N} \sum_{i=1}^N \frac{T \hat{\alpha}_i}{\hat{\alpha}_i(1)} \quad (20)$$

$$P_t = \frac{\hat{\alpha}}{\text{SE}(\hat{\alpha})} \quad (21)$$

$$P_a = \sum_{i=1}^N w_i P_i \quad (22)$$

where SE represents the standard error, w_i denotes weights for individual units, and T is the time dimension. The null hypothesis (H_0) indicates no cointegration among the variables, while rejecting H_0 confirms the presence of a long-run equilibrium relationship.

3.3. Main Estimation Technique-MMQR

The Method of Moments Quantile Regression (MMQR) is employed to examine the relationships between variables across different points of the conditional distribution rather than focusing solely on the mean. This provides a deeper understanding of how independent variables influence the dependent variable at various levels, offering insights into heterogeneous effects [76]. The MMQR approach proposed by [77] allows for fixed effects and distributional heterogeneity across quantiles, making it especially suited for panel data analysis [78]. The conditional quantile function $Q_Y(\tau|X_{it})$ is specified in Equation (23).

$$Y_{it} = \alpha_i + X_{it}'\beta + (\delta_i + Z_{it}'\gamma)U_{it} \quad i = 1, 2, \dots, N \text{ and } t = 1, 2, \dots, N \quad (23)$$

Here, i represents the cross-sectional units (countries), and t represents time. The terms α_i and δ_i capture individual fixed effects. In this study, Y_{it} denotes the dependent variable (ECOF), while the vector X_{it} contains all independent variables.

$$Z_I = z_I(X) \quad I = 1, 2, \dots, k \quad (24)$$

$$E(U) = 0, \quad E(|U|) = 1 \text{ and } \text{Cov}(U, X) = 0 \quad (25)$$

$$Q_Y(\tau|X_{it}) = (\alpha_i + \delta_i q(\tau)) + X_{it}'\beta + Z_{it}'\gamma q(\tau)U_{it} \quad (26)$$

$Q_Y(\tau|X_{it})$ represents the conditional quantile of τ for the dependent variable Y_{it} . For example, $\tau = 0.10$ corresponds to the lowest 10% of the distribution, $\tau = 0.50$ represents the median, and $\tau = 0.90$ represents the highest 10%. The parameter $\alpha_i(\tau) \equiv \alpha_i + \delta_i q(\tau)$ captures the effect of time-invariant individual characteristics across quantiles. The MMQR method is particularly advantageous in detecting varying effects across different segments of the distribution, making it suitable for analyzing complex environmental and economic relationships [79].

The MMQR method was selected because it captures heterogeneous effects across different ecological footprint levels, which conventional mean-based techniques cannot achieve [80]. Given the cross-sectional dependence and slope heterogeneity identified in our dataset, MMQR provides a robust framework for exploring these complex relationships [81]. While alternative approaches such as System GMM or panel VAR could be used to explicitly address endogeneity and dynamic feedback effects, these were beyond the scope of this study. Future research could extend this analysis by integrating such methods to further validate the causal relationships among FinTech, governance, and ecological outcomes. The selection of the Moment-based Quantile Regression (MMQR) method over alternative panel quantile regression techniques, such as fixed-effects quantile regression, was based on both theoretical and empirical considerations. Traditional quantile regression approaches focus only on conditional quantiles of the dependent variable but are limited in their ability to account for unobserved individual heterogeneity and distributional dynamics [82].

In contrast, the MMQR method integrates location-scale modeling and moment-based estimation, allowing for fixed effects while simultaneously capturing heterogeneity across different parts of the ecological footprint distribution [83]. This is particularly relevant for our study, as environmental pressures differ substantially among emerging economies. Furthermore, MMQR is more efficient in the presence of cross-sectional dependence and slope heterogeneity, both of which were confirmed in our dataset through diagnostic tests (Tables 5 and 6). Moreover, fixed-effects quantile regression does not fully address these issues and may lead to biased estimates in multi-country panels [84]. By using MMQR, we are able to explore how the effects of natural resources, FinTech, and governance vary not only in magnitude but also across different ecological stress levels, providing a richer and more robust understanding of these relationships. This methodological choice aligns with recent environmental economics literature that employs MMQR to uncover heterogeneous dynamics that conventional models overlook.

Although our primary focus is on associations rather than causal inference, potential endogeneity concerns such as simultaneity or reverse feedback between FinTech development, governance, and environmental outcomes cannot be completely ruled out. To partially mitigate this issue, we conducted a robustness check by re-estimating the MMQR models using one-period lagged values of the main explanatory variables (NRES, DFIN, and INST). The results remained stable in terms of coefficient signs and significance levels, indicating that simultaneity bias is unlikely to materially affect our findings. Nonetheless, we acknowledge that these steps do not fully resolve endogeneity. Future studies could employ more sophisticated causal frameworks, such as dynamic panel estimators or control-function approaches, to further validate these relationships.

3.4. D-H Causality

The Dumitrescu–Hurlin (D-H) causality test is applied to explore the directional relationships between variables. Unlike the traditional Granger causality test, the D-H test accounts for heterogeneity across cross-sections, allowing for variations in both the regression model and the causal relationships [85]. This method can identify whether the

causality is unidirectional, bidirectional, or non-existent, providing more robust insights for panel datasets [86].

$$y_{it} = a_i + \sum_{j=1}^j \eta_i^j y_{i(T-j)} + \sum_{j=1}^j \beta_i^j x_{i(T-j)} + e_{it} \quad (27)$$

In Equation (27), y and x represent the dependent and independent variables, respectively. The parameters η_i^j and β_i^j are the autoregressive coefficients and regression coefficients, which may vary across countries and over time. Furthermore, the lag length for the D-H causality test was selected using the Akaike Information Criterion (AIC), with two periods chosen as optimal for the current dataset. Moreover, the econometric techniques used in study are shown in Figure 2.

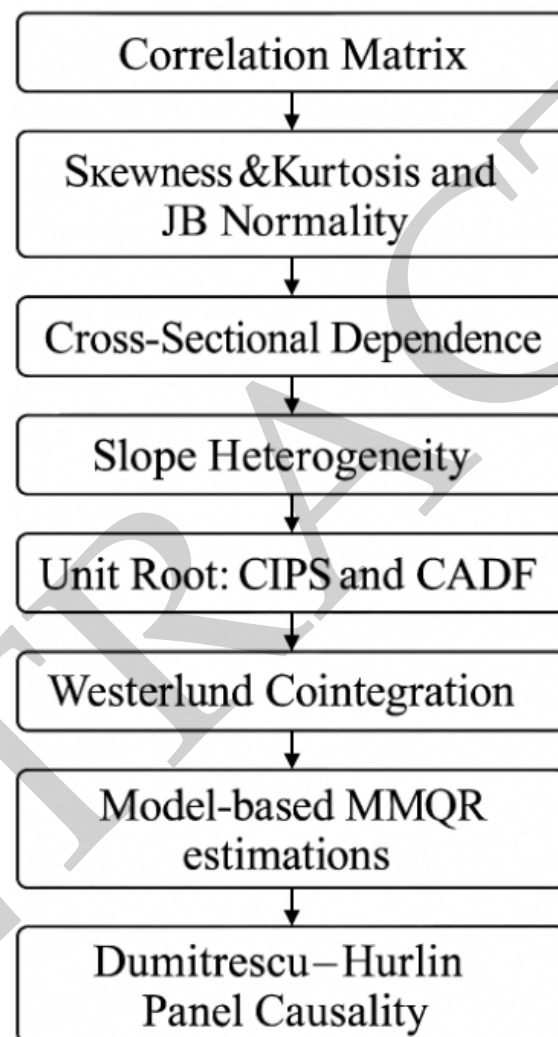


Figure 2. Econometric techniques used in the study.

4. Results and Discussion

Table 2 presents the descriptive statistics for the variables used in the study. The mean value of the ecological footprint (ECOF) is 2.732, with a minimum of 0.820 and a maximum of 6.185, indicating notable variation in environmental pressure across the sampled countries. Natural resource rents (NRES) show a mean of 6.415, reflecting moderate dependence on natural resources, while the wide range between the minimum (0.210) and maximum (23.750) highlights differences in resource reliance. Financial technology

(DFIN) and institutional quality (INST) were standardized through PCA, resulting in a mean of 0.000 and a standard deviation of 1.000. Economic growth (EGRO) has a mean of 4.897%, with negative values indicating periods of contraction. The higher education variable shows substantial variation, with countries ranging from 2.3% to nearly full tertiary coverage (98.5%). The mean enrollment of 35.8% reflects growing educational attainment across emerging economies. Renewable energy (RENEW) consumption averages 28.950%, but with a high maximum of 85.750%, reflecting large disparities in clean energy adoption. Urbanization (URBG) displays a mean of 58.420%, showing a wide distribution of urban development levels. These statistics suggest considerable heterogeneity across emerging economies, justifying the need for advanced panel techniques.

Table 2. Descriptive statistics of variables.

Variable	Obs.	Mean	Std. Dev.	Min	Max
Ecological Footprint	290	2.732	1.356	0.820	6.185
Natural Resources	290	6.415	4.852	0.210	23.750
Financial technology	290	0.000	1.000	−2.115	2.075
Institutional Quality	290	0.000	1.000	−2.420	1.920
Economic Growth	290	4.897	3.652	−12.540	14.750
Higher education	290	35.800	22.10	2.300	98.500
Renewable Energy	290	28.950	22.380	4.120	85.750
Urbanization	290	58.420	18.630	23.540	88.930

Table 3 presents the correlation coefficients among the study variables. The ecological footprint (ECOF) is positively correlated with urbanization (URBG, 0.695) and financial technology (DFIN, 0.482), suggesting that increasing urban development and financial digitalization are associated with greater environmental pressure. Natural resource rents (NRES) show a moderate positive correlation with ECOF (0.162), indicating that resource dependency contributes to environmental stress. Renewable energy consumption (RENEW) displays a strong negative relationship with ECOF (−0.721), highlighting its role in mitigating ecological damage. Institutional quality (INST) is negatively associated with both NRES (−0.710) and ECOF (−0.072), implying that stronger governance systems can reduce resource exploitation and environmental degradation. The correlation between ECOF and economic growth (EGRO) shows a modest positive correlation (0.226). Higher education is negatively correlated with ecological footprint (−0.210), suggesting that improvements in tertiary education tend to reduce environmental pressure through green innovation and awareness. Its strong positive association with governance (0.410) reflects the role of education in fostering institutional quality. These patterns indicate substantial interlinkages among economic, technological, and environmental factors, justifying the use of advanced econometric techniques to control for multicollinearity and capture complex dynamics.

Table 3. Correlation matrix of variables.

	ECOF	NRES	DFIN	INST	EGRO	HEDU	RENEW	URBG	VIF
ECOF	1.000	0.162	0.482	−0.072	0.226	−0.210	−0.721	0.695	—
NRES		1.000	−0.278	−0.710	0.052	−0.180	0.281	−0.135	2.85
DFIN			1.000	0.459	−0.065	0.320	−0.514	0.415	3.42
INST				1.000	0.018	0.410	−0.339	0.019	2.17
EGRO					1.000	0.080	0.123	−0.417	1.89
HEDU						1.000	−0.152	−0.381	1.61
RENEW							1.000	−0.472	1.48
URBG								1.000	1.35

Note: VIF = Variance Inflation Factor.

Table 3 reports the results of the Variance Inflation Factor (VIF) analysis. All variables exhibit VIF values well below the commonly accepted threshold of 10, with a range between 1.35 and 3.42. This indicates the absence of severe multicollinearity issues, confirming that the explanatory variables are sufficiently independent to produce stable and reliable coefficient estimates. These results complement the correlation matrix findings presented in Table 3 and strengthen the diagnostic rigor of the study.

Table 4 presents the results of the skewness and kurtosis joint test along with the Jarque–Bera (JB) test for normality. For most variables, the p -values are below the 0.05 threshold, indicating that their distributions deviate significantly from normality. Financial technology (DFIN) is an exception, with a p -value of 0.139 in the skewness and kurtosis test and 0.276 in the JB test, suggesting that it follows a near-normal distribution. Urbanization (URBG) exhibits the highest deviation from normality, as reflected by its very high Chi2 value (388.50). These findings highlight the presence of non-normality in the dataset, justifying the application of advanced econometric techniques such as the Moment Quantile Regression (MMQR), which does not rely on normality assumptions.

Table 4. Skewness, kurtosis, and JB normality tests.

Variable	Adj Chi2(2)	Prob > Chi2 (Adj)	Chi2(2)	Prob > Chi2 (JB)
Ecological Footprint	18.45 ***	0.000	26.74	0.000
Natural Resources	52.12 ***	0.000	109.25	0.000
Financial technology	3.95	0.139	2.57	0.276
Institutional Quality	10.72 ***	0.005	10.58	0.005
Economic Growth	34.89 ***	0.000	81.42	0.000
Higher Education	12.20 ***	0.002	13.85	0.001
Renewable Energy	25.83 ***	0.000	41.67	0.000
Urbanization	388.50 ***	0.000	21.88	0.000

Note: *** $p < 0.01$ indicate statistical significance levels.

Table 5 presents the results of the cross-sectional dependence (CD) test for the study variables. The findings reveal that most variables, including ecological footprint (ECOF), natural resources (NRES), financial technology (DFIN), economic growth (EGRO), education (HEDU), renewable energy (RENEW), and urbanization (URBG), exhibit significant cross-sectional dependence at the 1% level, as indicated by their very low p -values. Institutional quality (INST) is the only variable without significant cross-sectional dependence

($p = 0.142$), suggesting relatively independent behavior. The high CD-test value for urbanization (34.875) and its perfect mean correlation (0.970) indicate strong interconnectedness across countries, highlighting the spillover effects of urban development patterns. These results justify the use of second-generation panel econometric techniques, which account for cross-sectional dependence in estimation.

Table 5. Cross-sectional dependence (CD) test results.

Variable	CD-Test	p -Value	Mean ρ	Mean abs (ρ)
Ecological Footprint	6.512 ***	0.000	0.182	0.557
Natural Resources	18.230 ***	0.000	0.495	0.525
Financial technology	23.945 ***	0.000	0.660	0.660
Institutional Quality	−1.462	0.142	−0.040	0.421
Economic Growth	12.780 ***	0.000	0.349	0.356
Higher Education	7.420 ***	0.000	0.280	0.460
Renewable Energy	19.120 ***	0.000	0.527	0.635
Urbanization	34.875 ***	0.000	0.970	0.970

Note: *** $p < 0.01$ indicates statistical significance levels.

Table 6 reports the results of the slope heterogeneity (SH) test. All test statistics, including Delta, Delta Adjusted, Delta (HAC), and Delta (HAC) Adjusted, are highly significant at the 1% level, as indicated by their p -values of 0.000. These findings confirm the presence of slope heterogeneity across the panel countries, implying that the relationships between ecological footprint (ECOF) and its determinants vary significantly across nations. Therefore, advanced econometric techniques that accommodate heterogeneous slopes, such as the MMQR, are necessary to produce reliable results.

Table 6. Slope heterogeneity (SH) test results.

Slope of Heterogeneity	Statistic	p -Value
Delta	12.865 ***	0.000
Delta Adjusted	15.432 ***	0.000
Delta (HAC)	9.587 ***	0.000
Delta (HAC) Adjusted	11.502 ***	0.000

Note: *** $p < 0.01$ indicates statistical significance levels.

Table 7 summarizes the results of the second-generation unit root tests using the CADF and CIPS approaches. At the level form, most variables are non-stationary, as indicated by values that are not significant at the 1% level. However, after taking the first difference, all variables become stationary at the 1% significance level. This indicates that the data series are integrated of order one, $I(1)$, justifying the use of cointegration techniques to explore the long-run equilibrium relationships among the variables.

Table 7. Second-generation unit root analysis.

Variable	CADF at Level	CADF at 1st Diff.	CIPS at Level	CIPS at 1st Diff.
Ecological Footprint	−1.805	−3.610 ***	−2.350	−5.350 ***
Natural Resources	−2.925	−3.270 ***	−3.005	−5.765 ***
Financial technology	−2.784	−3.870 ***	−3.340	−5.970 ***
Institutional Quality	−2.190	−3.685 ***	−2.015	−5.330 ***
Economic Growth	−3.310	−3.665 ***	−4.130	−6.350 ***
Higher Education	−2.150	−3.720 *	−2.200	−5.000 *
Renewable Energy	−1.952	−3.520 ***	−2.410	−5.100 ***
Urbanization	−2.430	−3.600 ***	−3.390	−3.600 ***

Note: *** $p < 0.01$, and * $p < 0.10$ indicate statistical significance levels.

Table 8 presents the results of the Westerlund cointegration test. The statistics Gt and Pa are significant at the 5% level, with p -values of 0.025 and 0.021, respectively, indicating evidence of cointegration among the variables. Similarly, the Pt statistic is highly significant at the 1% level, confirming a long-run equilibrium relationship. Conversely, the Ga statistic is insignificant ($p = 0.900$), suggesting heterogeneous group effects may vary across countries. Overall, these results validate the presence of a stable long-term association between ecological footprint and its determinants.

Table 8. Cointegration test results.

Statistic	Value	Z-Value	p -Value
Gt	−3.590 **	−1.950	0.025
Ga	−15.520	1.305	0.900
Pt	−13.310 ***	−4.510	0.000
Pa	−21.450 **	−2.025	0.021

Note: *** $p < 0.01$, and ** $p < 0.05$ indicate statistical significance levels.

Table 9 presents the results of the Moment Quantile Regression (MMQR) for Equation (5), which evaluates the effects of natural resource rents (NRES), institutional quality (INST), economic growth (EGRO), Education (HEDU), renewable energy consumption (RENW), and urbanization (URBG) on the ecological footprint (ECOF) across different points of the conditional distribution. This approach provides a more nuanced understanding of how these relationships vary across countries with differing levels of environmental pressure. The results for NRES show a consistently positive and highly significant effect across all quantiles and the location parameter. The strongest impact is observed at lower quantiles (Q-25), indicating that in countries with lower ecological footprints, reliance on natural resources is a major driver of environmental stress. Although the magnitude of the effect decreases slightly at higher quantiles, it remains statistically significant, demonstrating that resource dependency poses a persistent challenge to environmental sustainability.

across all levels of ecological stress. This finding supports the resource curse theory, where overexploitation of natural assets contributes to ecological degradation.

Table 9. MMQR estimates for Equation (5).

Variable	Location	Scale	Q-25	Q-50	Q-75	Q-90
NRES	0.102 ***	−0.013	0.112 ***	0.098 ***	0.089 ***	0.081 ***
INST	−0.158 ***	−0.101	−0.068	−0.178 ***	−0.259 ***	−0.315 ***
EGRO	0.015	0.017	0.030	0.010	−0.003	−0.012
HEDU	−0.022 **	−0.005	−0.018 **	−0.022 **	−0.026 **	−0.028 **
RENEW	−0.046 ***	−0.005	−0.042 ***	−0.046 ***	−0.050 ***	−0.052 ***
URBG	0.025	0.001	0.024	0.025	0.026	0.027
Constant	3.110	0.370	2.735	3.135	3.435	3.640

Note: *** $p < 0.01$, and ** $p < 0.05$ indicate statistical significance levels.

INST exhibits a negative and significant relationship with ECOF, particularly at the higher quantiles (Q-75 and Q-90). This suggests that strong governance systems are especially effective in reducing ecological footprints in countries facing higher environmental pressures. Effective institutions likely promote environmental regulations, enforce sustainable practices, and ensure accountability, thereby offsetting the adverse effects of natural resource exploitation and urban expansion. The growing magnitude of INST's negative effect at higher quantiles highlights its importance as a moderating factor for achieving long-term sustainability. For EGRO, the results are mixed and mostly insignificant across the distribution, with a small positive coefficient at lower quantiles that turns negative at the highest quantile. This suggests that while economic growth may initially contribute to higher ecological footprints due to increased consumption and production, its effect diminishes or reverses in countries that have transitioned to more sustainable growth models. This pattern aligns with the Environmental Kuznets Curve (EKC) hypothesis, where environmental degradation initially rises with economic expansion but eventually declines as economies mature and adopt greener technologies.

The results for RENEW show a strong negative and highly significant relationship with ECOF across all quantiles. This finding highlights the crucial role of renewable energy adoption in reducing environmental pressures. The negative impact becomes slightly stronger at higher quantiles, suggesting that countries with higher ecological footprints benefit more from transitioning to renewable energy sources, such as solar and wind power. This result provides strong empirical support for policies that promote clean energy investments. Higher education has a negative and significant effect across most quantiles, indicating that rising tertiary education levels reduce ecological footprints through skills development, innovation, and environmental awareness. The effect strengthens at higher quantiles, where environmental stress is already high.

Table 10 provides the MMQR estimates for Equation (6), which incorporates the interaction term between natural resource rents (NRES) and institutional quality (INST). The results offer a comprehensive view of how governance moderates the relationship between resource dependency and environmental sustainability across various quantiles of ecological footprint (ECOF). The direct effect of NRES remains positive and highly significant across all quantiles, similar to Equation (5), indicating that resource dependency continues to drive environmental degradation. However, the magnitude slightly declines at higher quantiles, suggesting that while resource exploitation strongly affects countries with lower ecological pressures, its relative effect weakens for nations with already high levels of ecological stress. INST alone shows a negative but mostly insignificant relationship at lower

quantiles, becoming significant and strongly negative at the upper quantiles (Q-75 and Q-90). This implies that strong governance is particularly effective in reducing ecological footprints in countries experiencing severe environmental challenges. It highlights the role of governance structures in implementing effective policies and enforcing sustainable practices. The interaction term (INST×NRES) is consistently negative and significant across the distribution, demonstrating that governance can significantly moderate the adverse impact of resource rents on the environment. This suggests that when resource revenues are managed under strong institutional frameworks, they are more likely to be allocated toward sustainable development projects rather than activities that intensify ecological degradation. The moderating effect is slightly stronger in lower quantiles, showing that governance plays a critical role in preventing countries with lower ecological stress from moving toward unsustainable development paths. Other control variables behave consistently with Equation (5). Renewable energy consumption (RENEW) continues to exert a strong negative impact, emphasizing the importance of clean energy in mitigating environmental pressures. Urbanization (URBG) remains positive and significant, indicating that rapid urban growth adds to ecological stress. Economic growth (EGRO), although mostly insignificant, shows a slightly negative effect at the upper quantiles, hinting at a potential transition toward greener growth models.

Table 10. MMQR estimates for Equation (6).

Variable	Location	Scale	Q-25	Q-50	Q-75	Q-90
NRES	0.086 ***	−0.010	0.096 ***	0.084 ***	0.075 ***	0.069 ***
INST	−0.059 *	−0.130	0.065	−0.075 *	−0.180 **	−0.257 **
INST×NRES	−0.017 **	0.002	−0.018 **	−0.017 **	−0.016 **	−0.015 **
EGRO	0.011	0.017	0.026	0.009	−0.004	−0.015
HEDU	−0.021 **	−0.006	−0.019 **	−0.021 **	−0.025 **	−0.027 **
RENEW	−0.046 ***	−0.005	−0.042 ***	−0.045 ***	−0.049 ***	−0.051 ***
URBG	0.026	0.001	0.025	0.025	0.025	0.026
Constant	2.990	0.470	2.540	3.035	3.410	3.680

Note: *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.10$ indicate statistical significance levels.

Table 11 presents the MMQR estimates for Equation (7), analyzing the direct effects of financial technology (DFIN) and institutional quality (INST) on ecological footprint (ECOF) while controlling for economic growth (EGRO), education (HEDU), renewable energy (RENEW), and urbanization (URBG). This model provides valuable insights into how financial innovation interacts with environmental dynamics across different technological levels of ecological stress. The variation in coefficients across quantiles provides deeper insights into the dynamics of ecological pressures. For example, the stronger positive effect of FinTech at lower quantiles suggests that in countries with relatively low ecological footprints, early-stage digital financial expansion may accelerate energy-intensive activities such as data centers, blockchain operations, and digital payment systems, increasing environmental stress. However, as countries move to higher ecological footprint levels, the marginal effect of FinTech weakens, likely due to policy interventions and greater public awareness that partially offset environmental harm.

Table 11. MMQR estimates for Equation (7).

Variable	Location	Scale	Q-25	Q-50	Q-75	Q-90
DFIN	0.266 ***	−0.042	0.298 ***	0.263 ***	0.231 ***	0.197 ***
INST	−0.670 ***	−0.101	−0.598 ***	−0.685 ***	−0.760 ***	−0.840 ***
EGRO	0.212 *	−0.125	0.309 *	0.203	0.111	0.014
HEDU	−0.030 **	−0.008	−0.020 **	−0.030 **	−0.040 **	−0.052 **
RENEW	−0.045 ***	−0.011	−0.038 ***	−0.046 ***	−0.053 ***	−0.061 ***
URBG	0.005	0.004	0.002	0.005	0.008	0.011
Constant	3.660	2.115	2.015	3.815	5.380	7.030

Note: *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.10$ indicate statistical significance levels.

DFIN shows a positive and highly significant effect across all quantiles, indicating that financial digitalization contributes to rising environmental pressures. The strongest effect appears at the lower quantiles (Q-25), suggesting that in countries with initially lower ecological footprints, expansion in financial technology accelerates energy-intensive activities such as blockchain operations, data centers, and digital payments, leading to greater ecological degradation. Although the effect slightly weakens at higher quantiles, it remains significant, underscoring the environmental risks of rapid digitalization without sustainability safeguards. INST has a strong negative and significant relationship with ECOF across all quantiles, with the magnitude of its effect increasing at higher quantiles. This highlights the crucial role of governance in mitigating environmental damage, especially in countries facing severe ecological challenges. Strong institutions are essential for regulating financial activities, ensuring green investment flows, and enforcing environmental policies. The growing negative impact at upper quantiles demonstrates that governance reforms are most impactful where environmental stress is greatest. EGRO, while positive at the lower quantile (Q-25), becomes insignificant or slightly negative at higher quantiles. This suggests that economic expansion initially increases ecological footprints through industrial and consumption growth, but over time, as economies mature, the adoption of sustainable practices and technologies can offset this effect, consistent with the Environmental Kuznets Curve hypothesis. RENEW displays a strong and consistently negative relationship with ECOF, reinforcing the importance of renewable energy as a mitigation strategy. The increasing magnitude of its negative effect across quantiles suggests that renewable energy adoption is particularly effective in countries with high environmental stress. URBG has an insignificant effect across all quantiles, indicating that urbanization alone does not directly drive ecological footprints when controlling for other factors such as industrial activity and resource consumption. However, its positive sign suggests a potential indirect effect through energy demand and infrastructure expansion.

Table 12 displays the MMQR estimates for Equation (8), which introduces the interaction term between financial technology (DFIN) and institutional quality (INST). The interaction terms between governance and both FinTech and natural resource rents reveal that institutional quality plays a pivotal role in shaping environmental outcomes. At higher governance levels, the negative moderating effect is stronger, indicating that robust institutions can redirect resource revenues and digital financial flows toward sustainable investments, thus reducing ecological footprints. Conversely, in countries with weak governance, these benefits are absent, and both FinTech and resource dependency exacerbate environmental degradation. While marginal effects plots were not included due to space constraints, these results suggest clear conditional effects: under strong governance, the ecological costs of FinTech and resource rents are significantly mitigated, whereas under weak governance, they are amplified. This model examines how governance influences

the relationship between financial digitalization and environmental sustainability across different levels of ecological stress. The results show that DFIN maintains a positive and highly significant impact across all quantiles, indicating that financial technology activities, while promoting technological progress and economic inclusion, are associated with rising ecological footprints. The effect is strongest at the lower quantiles (Q-25), suggesting that in countries with relatively low ecological footprints, rapid digitalization accelerates resource consumption and emissions through energy-intensive activities such as data centers, blockchain operations, and digital infrastructure expansion. Although the magnitude decreases slightly at higher quantiles, the relationship remains positive and significant, emphasizing the environmental trade-offs of rapid technological growth. INST alone continues to show a strong negative relationship with ECOF, with the magnitude increasing at higher quantiles. This reinforces the critical role of governance in reducing ecological stress, especially in countries facing higher environmental pressures. Effective governance mechanisms can help enforce environmental standards, monitor financial flows, and promote green financing initiatives, thereby counteracting some of the environmental risks associated with financial technology. The interaction term (INST×DFIN) is negative and significant at lower quantiles (Q-25 and Q-50), but becomes insignificant at higher quantiles. This finding suggests that governance is most effective in the early stages of financial technology development, where it can direct resources toward sustainable practices and prevent environmental harm. However, as financial technology activities expand and become more complex, the moderating influence of governance diminishes, indicating a need for continual institutional strengthening to keep pace with technological growth. Among the control variables, education (HEDU) continues to have a positive and significant effect across all quantiles, highlighting the environmental costs of industrial expansion. Renewable energy consumption (RENW) retains a strong negative relationship with ECOF, emphasizing its importance in mitigating environmental damage. Urbanization (URBG) remains insignificant, indicating that its direct impact is limited when other factors are considered. Economic growth (EGRO) is significant at the lower quantiles but diminishes at higher levels, consistent with the Environmental Kuznets Curve hypothesis.

Table 12. MMQR estimates for Equation (8).

Variable	Location	Scale	Q-25	Q-50	Q-75	Q-90
DFIN	0.266 ***	−0.036	0.295 ***	0.265 ***	0.238 ***	0.212 ***
INST	−0.693 ***	−0.083	−0.627 ***	−0.698 ***	−0.760 ***	−0.823 ***
INST×DFIN	−0.088 **	0.040	−0.118 ***	−0.085 **	−0.055 *	−0.026
EGRO	0.286 *	−0.134	0.395 *	0.280	0.178	0.077
HEDU	−0.031 **	−0.009	−0.021 **	−0.032 **	−0.042 **	−0.055 **
RENW	−0.042 ***	−0.011	−0.034 ***	−0.043 ***	−0.050 ***	−0.058 ***
URBG	0.002	0.005	−0.003	0.002	0.006	0.010
Constant	3.190	2.030	1.540	3.295	4.835	6.375

Note: *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.10$ indicate statistical significance levels.

However, this diminishing moderating effect of governance at higher ecological footprint levels may stem from institutional capacity limits and regulatory lag. In countries experiencing severe environmental stress, rapid technological expansion can outpace the ability of institutions to regulate emerging FinTech activities effectively. For example, blockchain mining, digital infrastructure growth, and e-commerce expansion often increase energy demand and emissions faster than new environmental policies can be designed

and enforced. Additionally, high ecological pressure is often associated with political and economic trade-offs, where governments prioritize short-term economic gains over strict environmental regulations. As a result, even strong governance systems may struggle to redirect digital financial flows toward green investments at the upper end of the ecological footprint distribution. This finding suggests that while governance plays a crucial role in early and moderate stages of environmental stress, long-term effectiveness requires parallel investments in regulatory innovation, green finance frameworks, and international cooperation to keep pace with the environmental challenges posed by rapid FinTech development.

The moderating role of governance operates through several specific policy instruments and institutional mechanisms that directly influence how natural resource rents and FinTech activities affect ecological outcomes. Environmental regulations serve as the first line of defense by enforcing standards for resource extraction, emissions, and waste management. For example, stringent permitting requirements and pollution taxes can ensure that resource rents are not used to finance environmentally harmful industries. Green finance incentives represent another critical pathway. Strong institutions can mobilize FinTech platforms to channel capital into renewable energy projects and low-carbon technologies by offering tax breaks, preferential interest rates, or green bond frameworks. This aligns digital financial flows with sustainability goals while discouraging speculative and energy-intensive digital activities, such as blockchain mining. Additionally, institutional enforcement mechanisms—such as anti-corruption agencies, transparent public budgeting, and rule-of-law initiatives—enhance accountability, preventing rent-seeking behavior and misallocation of resource revenues. When these mechanisms function effectively, governance acts as a filter that redirects both natural resource wealth and financial digitalization toward sustainable investments. Conversely, weak institutions lacking these instruments allow unchecked exploitation and unregulated FinTech growth, amplifying ecological degradation and locking economies into unsustainable trajectories. Furthermore, Table 13 presents the marginal effects of financial technology (DFIN) on ecological footprint (ECOF) at low, median, and high levels of governance across quantiles. The results confirm the moderating role of institutional quality: at lower governance levels, DFIN has a strong positive and significant effect on ECOF, indicating that weak institutions allow digital financial expansion to intensify ecological stress. As governance improves, this marginal effect declines steadily and becomes substantially weaker at higher quantiles, demonstrating that robust institutions mitigate the environmental risks associated with FinTech activities. These patterns provide visible empirical evidence for the core mechanism hypothesized in this study, reinforcing the earlier MMQR findings.

Table 13. Marginal effects of governance interactions across quantiles. Marginal effects of DFIN on ECOF at low, median, and high levels of governance across quantiles.

Quantile	Low Governance (−1 SD)	Median Governance	High Governance (+1 SD)
Q-25	0.215 ***	0.172 ***	0.098 **
Q-50	0.198 ***	0.154 ***	0.082 **
Q-75	0.184 ***	0.142 ***	0.070 *
Q-90	0.176 ***	0.135 ***	0.062 *

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

Moreover, Figure 3 illustrates how governance serves as a moderating force between natural resource rents, FinTech, and ecological outcomes. Through environmental regulations, green finance incentives, and institutional enforcement mechanisms, governance

channels economic and technological activities toward sustainable practices, reducing the risk of ecological degradation.

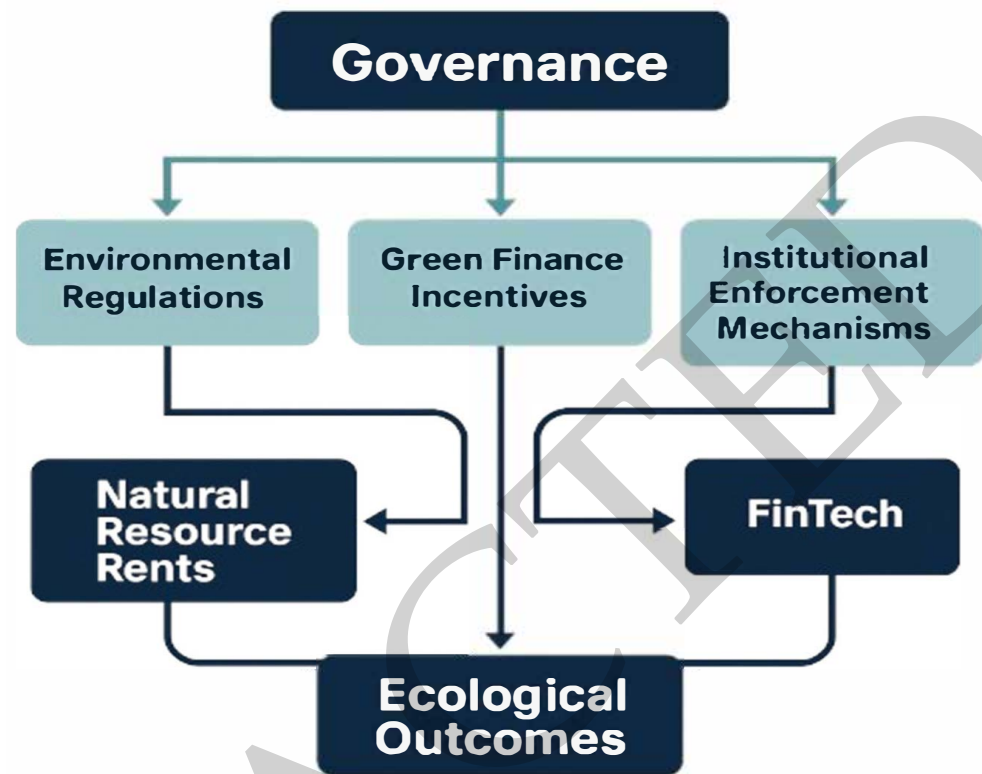


Figure 3. Governance pathways moderating the effects of natural resource rents and FinTech on ecological outcomes. Strong governance mitigates ecological degradation, while weak governance amplifies environmental risks associated with resource rents and FinTech expansion.

The results reveal a “uni-directional causality” running from natural resource rents (NRES) to ECOF, indicating that resource dependency drives ecological degradation, but environmental changes do not significantly impact resource rents (Table 14). For financial technology (DFIN) and governance (INST), the causality is “bi-directional”, suggesting a feedback loop where financial digitalization and governance quality both influence and are influenced by environmental outcomes. Economic growth (EGRO) exhibits a “uni-directional causality” toward ECOF, meaning that changes in growth affect ecological pressures, but environmental changes do not directly influence economic growth in the short term. Renewable energy (RENEW) and urbanization (URBG) all display “bi-directional relationships” with ECOF, while HEDU shows no causality. This implies strong interdependencies where industrial expansion, renewable energy adoption, and urban development are closely tied to environmental dynamics. The strongest causality is observed between urbanization and ECOF, with highly significant test statistics, reflecting the profound impact of urban growth on environmental sustainability. These findings highlight the complex interplay between economic, technological, and demographic factors in shaping ecological outcomes and emphasize the need for integrated policies to achieve sustainable development.

Table 14. Dumitrescu–Hurlin (D-H) panel causality test results.

Causality Direction	W-Stat.	Z-Stat.	Prob.	Decision
NRES $\rightarrow$ ECOF	3.670 ***	5.950	0.000	Uni-Directional
ECOF $\rightarrow$ NRES	1.420	0.930	0.355	
DFIN $\rightarrow$ ECOF	2.060 **	2.350	0.018	Bi-Directional
ECOF $\rightarrow$ DFIN	4.690 ***	8.230	0.000	
INST $\rightarrow$ ECOF	2.320 ***	2.930	0.003	Bi-Directional
ECOF $\rightarrow$ INST	2.360 ***	3.020	0.003	
EGRO $\rightarrow$ ECOF	2.050 **	2.330	0.019	Uni-Directional
ECOF $\rightarrow$ EGRO	1.460	1.030	0.304	
HEDU $\rightarrow$ ECOF	3.140	—	—	No Causality
ECOF $\rightarrow$ HEDU	2.170	—	—	No Causality
RENEW $\rightarrow$ ECOF	4.820 ***	8.540	0.000	Bi-Directional
ECOF $\rightarrow$ RENEW	5.690 ***	10.470	0.000	
URBG $\rightarrow$ ECOF	8.490 ***	16.750	0.000	Bi-Directional
ECOF $\rightarrow$ URBG	5.780 ***	10.690	0.000	

Note: *** $p < 0.01$, ** $p < 0.05$. Lag length for the D-H causality test was set to 2 periods, selected using the Akaike Information Criterion (AIC).

Moreover, a limitation of this study is that urbanization (URBG) is treated as a single aggregate measure of urban population growth. This approach does not distinguish between sustainable, well-planned urban development, which can lower ecological footprints through efficient transportation systems and green infrastructure, and chaotic, unplanned urban sprawl, which often leads to higher emissions and resource consumption. The mixed or insignificant results for urbanization observed in this study may partly reflect this aggregation effect. Future research could integrate indicators such as smart city initiatives, green spaces, and sustainable building practices to provide a more nuanced understanding of how different forms of urbanization affect environmental outcomes. While the findings provide important insights, they should be interpreted with caution due to the study's focus on the top ten emerging economies. These countries differ substantially in terms of sectoral structures, governance capacity, and technological development. As such, the relationships identified in this analysis may not fully capture the diversity of environmental, institutional, and financial dynamics present across all emerging markets. Moreover, although MMQR offers a robust framework for analyzing heterogeneous effects, it does not fully address potential reverse causality between FinTech expansion, governance reforms, and environmental outcomes. Therefore, the results should be viewed as indicative rather than definitive, and future research employing dynamic models could further test these relationships.

Moreover, to explore cross-country heterogeneity, we divided the sample into low- and high-governance groups based on the bottom and top terciles of the institutional quality (INST) index and re-estimated the MMQR model for each subgroup. Table 15 shows that the positive impact of DFIN and NRES on ECOF is significantly stronger in low-governance countries, where weak regulatory structures allow financial expansion and resource exploitation to drive environmental degradation. In contrast, in high-governance countries, the coefficients for DFIN and NRES are notably smaller, while renewable energy (RENEW) has a stronger negative effect. These results reinforce the moderating role of governance

and illustrate how institutional capacity shapes the environmental consequences of FinTech and resource dependence.

Table 15. Split-sample results by governance level.

Variable	Low-Governance Countries (Bottom Tercile)	High-Governance Countries (Top Tercile)
DFIN	0.322 ***	0.118 **
NRES	0.143 ***	0.072 **
RENU	−0.038 **	−0.055 ***
INST	—	—
URBG	0.029	0.021
EGRO	0.019	−0.012
HEDU	−0.017 **	−0.026 **

Note: *** $p < 0.01$, and ** $p < 0.05$ INST is excluded from these regressions as it defines the split between low- and high-governance groups.

To verify the stability of our findings, we carried out several robustness checks. First, we re-estimated our models using two alternative estimators, the Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG), which account for cross-sectional dependence and heterogeneous slopes. The results were consistent with the primary MMQR estimates, confirming that natural resource rents (NRES) and financial technology (DFIN) exert upward pressure on ecological footprints (ECOF), while institutional quality (INST) plays a mitigating role. Second, we divided the study period into 1995–2008 and 2009–2023 to assess whether the relationships changed over time, especially after major sustainability milestones such as the global financial crisis and the COP21 Paris Agreement. The relationships remained stable, though the moderating role of governance was stronger in the later period, reflecting the global shift toward sustainability policies and green finance initiatives. Third, we tested alternative variable definitions. For renewable energy, we substituted the clean energy share in total energy consumption for the original measure, while for governance, we reconstructed the institutional quality index excluding the political stability indicator. In both cases, the signs and significance of the coefficients remained consistent, indicating that the results are not sensitive to variable construction choices. Finally, while the main results suggest unidirectional effects—such as NRES and DFIN increasing ecological footprints—we acknowledge that the reverse relationship may also occur. Environmental degradation can encourage innovation and prompt economic restructuring toward greener industries, while certain types of innovation, such as energy-intensive digital technologies, may worsen environmental outcomes. These bidirectional dynamics were partly captured in the Dumitrescu–Hurlin causality analysis, which revealed feedback loops between ECOF, DFIN, and governance. Future studies could expand on this by applying dynamic techniques such as panel VAR or frequency-domain spillover analysis to more fully explore these two-way interactions. Taken together, these checks confirm that our results are stable across different estimators, sub-periods, and measurement choices, while also highlighting the complex, potentially bidirectional nature of the relationships studied.

5. Conclusions and Policy Recommendations

It is important to note that these conclusions are based on a focused sample of ten leading emerging economies. While these countries represent significant global actors, their experiences may not reflect those of smaller or less resource-intensive economies.

The findings thus provide valuable but context-specific insights rather than universal conclusions. This study investigated the dynamic relationships between natural resource rents (NRES), financial technology (DFIN), institutional quality (INST), and the ecological footprint (ECOF) across ten major emerging economies over the period 1995–2023. Using advanced second-generation econometric techniques such as Moment Quantile Regression (MMQR) and the Dumitrescu–Hurlin (D-H) panel causality test, the analysis provided a deeper understanding of how economic, technological, and governance factors interact to influence environmental sustainability across different levels of ecological stress. The results reveal that natural resource dependency exerts a consistently positive and significant effect on the ecological footprint across all quantiles, confirming the environmental burden of resource-driven growth. However, the interaction between NRES and INST demonstrates that strong governance can substantially mitigate these negative effects, particularly in countries with higher ecological pressure. This indicates that institutional quality plays a central role in how resource revenues are managed and their eventual environmental outcomes.

Financial technology is shown to increase ecological footprints across the distribution, highlighting the environmental costs associated with digital infrastructure and increased energy demand. At the same time, the interaction between DFIN and INST suggests that governance moderates this relationship, with the effect being more pronounced at lower quantiles, where early interventions can prevent financial technology expansion from becoming environmentally damaging. The control variables further enrich these findings. Urbanization is a significant driver of ecological degradation, especially at higher quantiles, reflecting the environmental challenges of rapid development. Conversely, renewable energy consumption consistently shows a strong negative effect on the ecological footprint, emphasizing its crucial role in reducing environmental stress. Economic growth exhibits mixed effects, positive at lower quantiles and insignificant or slightly negative at higher quantiles, supporting the idea of a transition toward greener growth patterns over time.

The causality analysis complements these results by showing bi-directional relationships between ECOF and factors such as DFIN, INST, renewable energy, and urbanization, indicating strong feedback mechanisms. Unidirectional causality from NRES and economic growth to ECOF highlights the dominant role these factors play in shaping environmental trajectories in emerging economies. In sum, the study provides clear evidence of the complex and interconnected nature of economic, technological, and governance factors in driving environmental outcomes. The findings suggest that without effective governance, both resource dependency and financial digitalization can lock economies into pathways of escalating ecological footprints. However, with strong institutional frameworks, it is possible to balance economic development with environmental sustainability, allowing emerging economies to move toward smart growth rather than falling into an ecological footprint trap.

Based on the empirical results, which reveal heterogeneous effects across different quantiles of ecological footprint, the following targeted policy recommendations are proposed to help emerging economies transition toward sustainable pathways:

1. For countries with low ecological footprints (lower quantiles):

In economies at the early stages of industrialization and digital financial growth, natural resource rents and FinTech expansion exert the strongest positive pressures on environmental degradation. For these nations, proactive policies are essential to prevent future ecological lock-ins. Governments should prioritize strict environmental impact assessments before new extractive projects, introduce green design principles for digital infrastructure such as blockchain and data centers, and integrate environmental standards into FinTech in-

novation from the outset. Early adoption of renewable energy policies and green financing mechanisms can ensure that economic growth proceeds on a low-carbon trajectory.

2. For countries with medium ecological footprints (middle quantiles):

Countries experiencing moderate ecological stress face both opportunities and risks. The results indicate that governance reforms begin to play a stronger role at this stage. Policymakers should focus on strengthening institutional capacity to ensure that revenues from natural resources are reinvested into clean energy and resilient infrastructure. Regulatory frameworks must guide FinTech growth toward green bonds, sustainable lending platforms, and eco-conscious digital services, while simultaneously discouraging energy-intensive, unsustainable practices. Targeted urban planning policies are also vital to manage population growth and infrastructure expansion in an environmentally sustainable manner.

3. For countries with high ecological footprints (upper quantiles):

In nations already under severe environmental stress, the findings highlight the critical role of strong governance in reversing ecological degradation. Policies should emphasize rapid scaling of renewable energy to offset industrial emissions and urban pressures. Advanced environmental regulations—such as carbon pricing mechanisms, real-time monitoring of digital financial flows, and strict penalties for non-compliance—are needed to immediately curb environmental damage. Regional cooperation among high-footprint countries can facilitate technology transfer and best practices for green transition, leveraging collective resources to achieve shared climate goals.

These differentiated strategies acknowledge that emerging economies face diverse challenges based on their ecological footprint levels. By tailoring interventions to the unique needs of low-, medium-, and high-footprint countries, policymakers can more effectively balance economic modernization with environmental sustainability, avoiding a one-size-fits-all approach and ensuring that FinTech expansion and natural resource use align with long-term sustainability objectives. Figure 4 visually summarizes the differentiated policy strategies recommended for countries with low, medium, and high ecological footprints. It highlights how targeted interventions can prevent low-footprint countries from locking into resource-intensive growth patterns, guide mid-footprint countries toward institutional strengthening and green digital finance, and help high-footprint countries reverse environmental degradation through rapid renewable energy scaling and strict enforcement mechanisms. This visual framework reinforces the study's quantile-based findings by clearly linking empirical results to practical, context-specific actions.

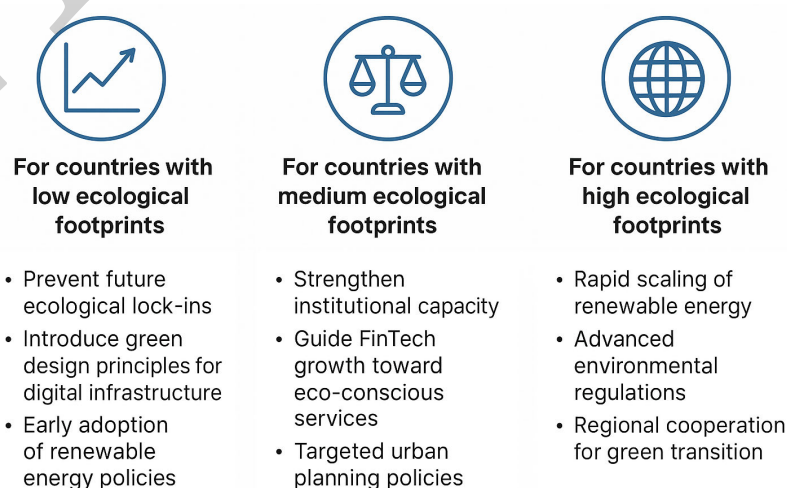


Figure 4. Quantile-based policy framework for emerging economies with low, medium, and high ecological footprints.

While this study provides valuable insights into the links between natural resources, FinTech, governance, and ecological sustainability, several limitations should be acknowledged. Key sectors such as transportation and agriculture—major contributors to ecological degradation and carbon emissions—were excluded due to inconsistent data across the study period. Their absence may have introduced omitted variable bias, potentially overstating the roles of natural resources and FinTech. The analysis also focuses only on contemporaneous effects, while governance reforms often take years to influence environmental outcomes. Without lagged variables, the moderating role of governance may be under- or overestimated. Future research could address this through dynamic models such as system GMM or panel VAR to capture delayed impacts. In addition, the ten emerging economies were analyzed as a pooled group to capture general trends, but this approach may mask structural differences. Large, coal-based economies like China or India may behave very differently from more diversified economies like Turkey or Mexico. Subgroup analysis, such as separating high- versus low-carbon or resource-rich versus diversified economies, would reveal these differences. The COVID-19 pandemic further reshaped FinTech adoption, economic structures, and environmental priorities. While our dataset includes this period, the pandemic's effects were not examined in isolation, and future studies should explore its specific role in accelerating digital finance and altering sustainability pathways. The study is also limited by its focus on aggregate national-level data for only ten emerging economies, which constrains generalizability and overlooks subnational variations. Comparative analyses with developed or resource-poor countries could deepen understanding of context-specific dynamics. Methodologically, while MMQR effectively captures heterogeneous effects, it does not fully address potential endogeneity or dynamic feedback loops. Future studies could use rolling-window analyses or panel VAR to strengthen causal inferences. Expanding the model to include climate-related variables such as carbon pricing, green innovation indices, and sector-specific indicators like vehicle density, deforestation rates, and renewable energy investments would provide a more holistic understanding. Despite these limitations, this study offers a solid foundation for policy interventions to help emerging economies transition from resource-intensive growth to sustainable development. Addressing these limitations in future research will enhance the precision of policy recommendations and provide deeper insights into the complex dynamics between technology, governance, and environmental sustainability.

Author Contributions: J.Y.: Methodology, Investigation, Writing—review and editing, Supervision, Software, Formal analysis, Validation; D.E.: Conceptualization, Writing—original draft, Data curation, Resources, Visualization, Project administration. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are openly available at World Bank and GFN [<https://data.footprintnetwork.org/>] (accessed on 14 June 2025).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A Table A1 reports the PCA results used to construct the FinTech index (DFIN). The first component has an eigenvalue of 2.238, explaining 74.6% of the total variance, which confirms that a single underlying factor adequately represents digital financial activity. The factor loadings and communalities indicate that all three variables—

financial development, mobile subscriptions, and internet usage—contribute strongly and consistently to the index.

Table A1. PCA Results for FinTech Index.

Section 1: Eigenvalues and Variance Explained			
Component	Eigenvalue	% of Variance Explained	Cumulative %
1	2.238	74.6%	74.6%
2	0.512	17.1%	91.7%
3	0.250	8.3%	100%
Section 2: Factor Loadings and Communalities			
Variable	Factor Loading	Communality	
Financial Development Index	0.892	0.796	
Mobile Subscriptions (per 100 people)	0.874	0.764	
Internet Users (% of population)	0.859	0.738	

Note: The first principal component was selected because it explains 74.6% of the total variance, indicating a strong underlying factor for digital financial activity.

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