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DO GREEN FINANCE, GREEN TRADE, ECONOMIC DEVELOPMENT, AND ENVIRONMENTAL TAXES ENHANCE ENVIRONMENTAL SUSTAINABILITY? EVIDENCE ON THE MEDIATING ROLE OF TECHNOLOGICAL INNOVATION IN DEVELOPED AND DEVELOPING COUNTRIES

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ABSTRACT

This study examines the dynamic effects of green finance, environmental taxation, economic development, and green trade on environmental sustainability, with technological innovation serving as a mediating mechanism. Grounded in Sustainable Development Theory, Innovation and Technology Theory, and the Environmental Kuznets Curve (EKC) hypothesis, the research adopts a comparative empirical framework using balanced panel data covering 20 developed and 20 developing countries from 2000 to 2023.Methodologically, the study employs Dynamic Fixed Effects (DFE) estimation, Generalized Estimating Equations (GEE), and panel cointegration techniques, complemented by robustness checks including the Sargan test and cross-sectional dependence diagnostics. The empirical findings reveal that green finance significantly enhances environmental sustainability in developed countries, where institutional quality and regulatory effectiveness are relatively strong. In contrast, green finance exerts a negative impact in developing economies, largely due to misallocation of financial resources and weak implementation frameworks. Environmental taxation contributes positively to environmental sustainability in developing countries by discouraging environmentally harmful activities, whereas its effect in developed economies is mixed, potentially reflecting diminishing marginal environmental gains and policy saturation. Economic development intensifies environmental degradation in developing countries, consistent with the upward phase of the EKC, while its adverse effects are mitigated in developed economies due to advanced technologies and stricter environmental regulations. Furthermore, green trade exhibits a limited or negative influence on environmental sustainability in both country groups, particularly in developing nations, where trade-driven industrial expansion often occurs at the expense of environmental protection. The mediating analysis indicates that technological innovation significantly strengthens the effectiveness of green finance, environmental taxation, and green trade in promoting environmental sustainability in developed countries. However, its mediating role remains weak in developing countries, reflecting persistent structural, technological, and institutional constraints.

Keywords: Green finance; environmental taxation; economic development; green trade; environmental sustainability; technological innovation

1. Introduction

Environmental sustainability has rapidly shifted from a peripheral policy aspiration to a binding macroeconomic constraint, because ecological pressure is still strongly linked to how economies grow, trade, and industrialize. Recent studies to show that economic growth and trade openness can intensify ecological pressure (e.g., via higher ecological footprint or emissions), even in advanced economies, unless policy and technological upgrading actively decouple production from environmental damage (Javed et al., 2024; Dahmani, 2024). At the same time, the literature increasingly treats "environmental sustainability" (the dependent variable in this study) as a high-stakes development outcome because weak environmental sustainability translates into higher climate-risk exposure, higher abatement costs later, competitiveness risks from environmental standards, and widening welfare losses (health/productivity) associated with pollution-intensive growth (Dahmani, 2024; Umar & Safi, 2023).Importantly, the drivers of environmental sustainability are not "one-size-fits-all" across income groups. Evidence from developed-country settings shows that well-designed environmental taxes and environment-related technologies can reduce greenhouse gas pressure and support an EKC-type pattern (where environmental damage eventually moderates as economies mature and policy/technology improve) (Dahmani, 2024). Likewise, for advanced economies, green finance tends to perform better when markets, institutions, and policy coherence allow financial resources to convert into real technological upgrading and cleaner production (Umar & Safi, 2023; Deng et al., 2024). In contrast, emerging/developing contexts often exhibit stronger "implementation frictions" (limited innovation capacity, weaker enforcement, financing constraints), which can reduce the sustainability return of finance and trade reforms unless innovation channels are strengthened (Ayaz et al., 2025; Ghouse et al., 2025). To foreground both the crisis dimension and the policy technology solution space, Table 1 summarizes a small set of recent findings showing (i) why environmental sustainability remains under pressure, and (ii) why policy instruments (green finance, green trade, and environmental taxes) increasingly matter *through* technological innovation.

Table 1. Illustrative evidence on environmental sustainability pressures and policy/innovation channels

Study (SSCI)	Sample/context	Environmental sustainability proxy (illustrative)	Key takeaway relevant to this study
Javed et al. (2024)	G7 economies	Ecological footprint / ecological sustainability	Trade openness and growth can increase ecological pressure; green technology innovation and environmental policy strengthen ecological sustainability.
Dahmani (2024)	G7 economies	GHG emissions / environmental sustainability	Environmental taxes and environment-related technologies help reduce environmental degradation; EKC-type dynamics supported in developed economies.
Umar & Safi (2023)	OECD economies	Trade-adjusted CO_2 emissions	Green finance and green innovation reduce emissions; growth and imports can raise emissions without strong policy/innovation offsets.
Omri et al. (2024)	G7 economies	CO_2 emissions + ecological footprints	Green finance improves sustainability outcomes; environmental innovation mediates the finance–sustainability linkage; policy and

Study (SSCI)	Sample/context	Environmental sustainability proxy (illustrative)	Key takeaway relevant to this study
			digital/FinTech factors can strengthen channels.
Matterne et al. (2024)	British Columbia (carbon tax)	Carbon intensity / innovation outcomes	Environmental taxation can induce process innovation; innovation mediates part of the tax-to-emissions-intensity effect.
Yu et al. (2024)	Global environmental goods trade network	Green innovation / trade patterns	"Green trade" (environmental goods trade dynamics) is closely connected to green innovation diffusion and structural change.
Ayaz et al. (2025)	Emerging economies	Sustainable development / environmental management	Green trade openness and green technological innovation support sustainability/net-zero progress in developing contexts.

Sources: Javed et al. (2024), Dahmani (2024), Umar & Safi (2023), Omri et al. (2024), Matterne et al. (2024), Yu et al. (2024), Ayaz et al. (2025).

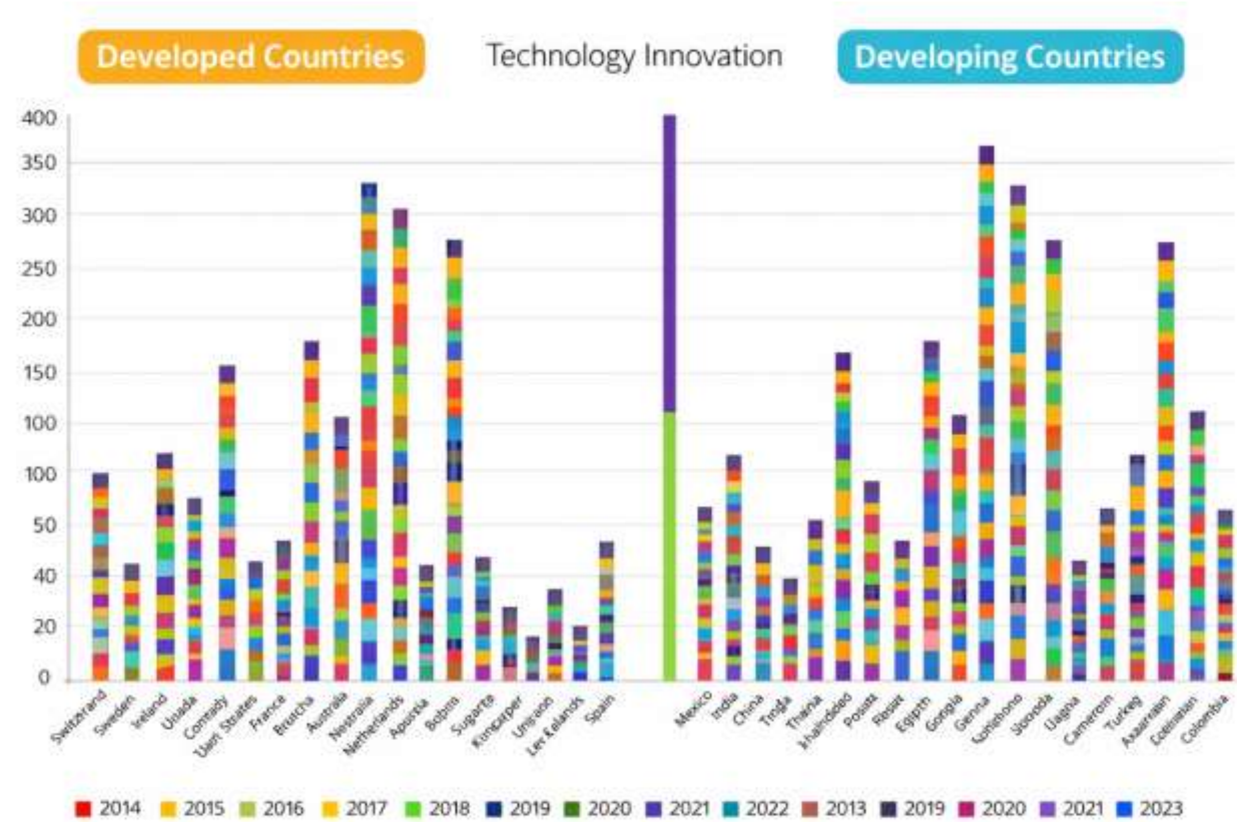

Figure 1. Percentage of technological innovation in developed versus developing countries from 2014 to 2023.
Source: Developed by the researchers

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Despite this fast-expanding literature, several research gaps remain that motivate a comparative (developed vs. developing) panel investigation of green finance, green trade, economic development, and environmental taxes as joint drivers of environmental sustainability through technological innovation. First, the variable-system gap is still prominent: many studies examine (a) green finance and environmental outcomes, (b) environmental taxation and emissions/footprint, or (c) green trade and environmental pressure as relatively separate strands yet recent evidence shows these instruments interact and often operate through innovation mechanisms (Umar & Safi, 2023; Dahmani, 2024; Yu et al., 2024). In particular, "green trade" (e.g., environmental goods trade, cleaner value chains, and trade openness oriented toward low-carbon goods/technologies) is increasingly discussed as a channel for technology diffusion and structural upgrading, but it is still rarely integrated *together with* green finance and environmental taxes in a single empirically tested sustainability framework (Yu et al., 2024; Ayaz et al., 2025). Second, the mechanism gap persists: while innovation is repeatedly emphasized as pivotal, fewer studies explicitly model technological innovation as a mediating pathway through which finance, fiscal signals (taxation), and trade composition convert into sustainability outcomes (Deng et al., 2024; Omri et al., 2024; Matterne et al., 2024).

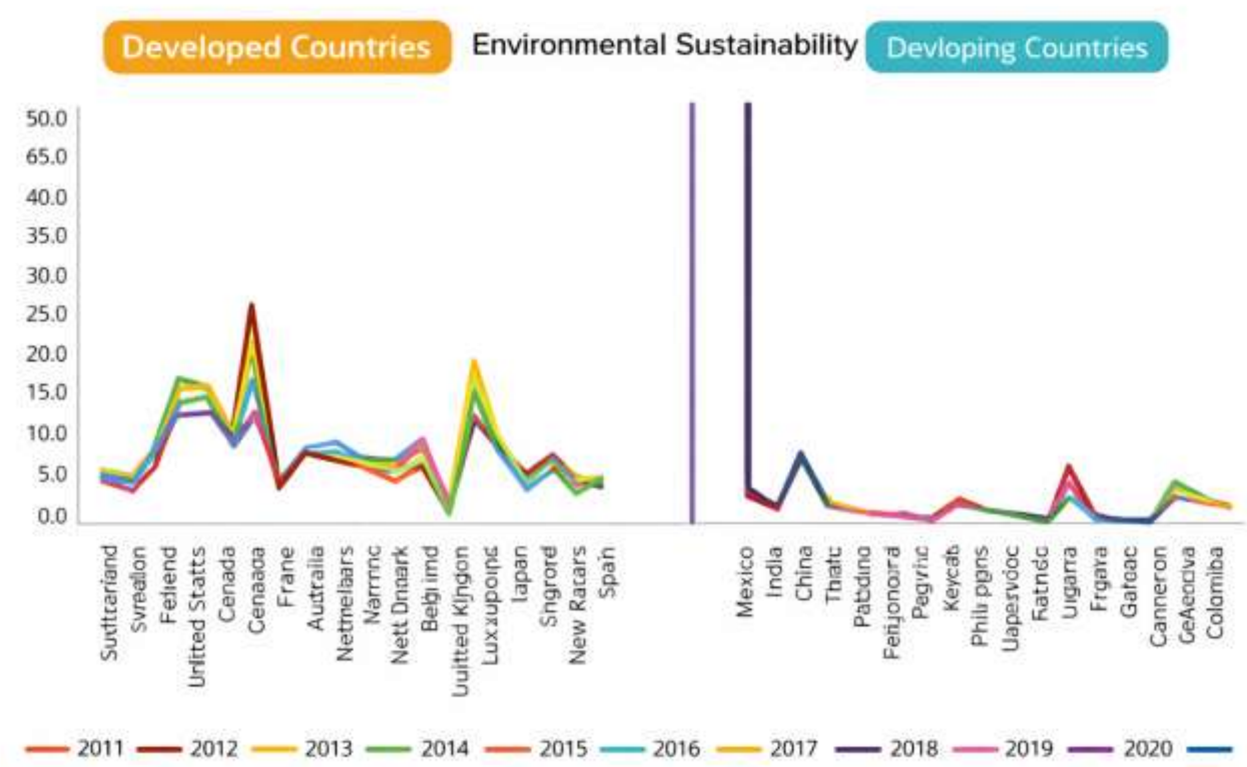

Figure 2. Environmental sustainability trends in developed and developing countries (2011–2020).
Source: Developed by the researchers.

Third, the methodology gap remains non-trivial. Sustainability panels are typically dynamic (environmental outcomes persist), exposed to common shocks, and potentially subject to correlated error structures; however, much empirical work remains concentrated around standard FE/GMM variants or single-estimator approaches, which can leave results sensitive to specification and dependence structures (Umar & Safi, 2023; Dahmani, 2024).This motivates an estimator design that treats dynamics and correlation as first-order features—hence the value of combining dynamic panel approaches with correlation-robust estimation strategies in a comparative setting. Finally, the population and time-dimension gaps are clear in recent work: many influential studies focus on OECD/G7-only samples (developed focus) or on selected emerging blocs (E7/emerging focus), rather than a balanced dual-economy design; similarly, many panels end around 2018–2022, leaving the most recent policy/finance/innovation period underexplored (Umar & Safi, 2023; Omri et al., 2024; Ghouse et al., 2025; Ayaz et al., 2025).

Building directly on these gaps, this study develops research questions and objectives that explicitly connect policy instruments (green finance, green trade, and environmental taxes) and growth dynamics to environmental sustainability via the innovation mechanism, while allowing the relationships to differ between developed and developing economies. The study therefore asks:

- Do green finance, green trade, economic development, and environmental taxes exert statistically and economically meaningful effects on environmental sustainability in developed and developing countries?
- Does technological innovation mediate these relationships, and does the magnitude/direction of mediation differ systematically across development levels?
- Are these effects robust when modeled dynamically and comparatively over a long panel window (2000–2023), given the persistence and interdependence of macro-environmental indicators?

These questions are operationalized through four objectives: (1) to estimate the dynamic effects of green finance, green trade, economic development, and environmental taxes on environmental sustainability separately for developed and developing panels; (2) to test a mediation structure in which technological innovation transmits (or weakens) policy effects into environmental sustainability outcomes, consistent with recent findings that innovation is a key transmission mechanism linking finance and policy to environmental performance (Deng et al., 2024; Omri et al., 2024; Matterne et al., 2024);(3) to validate long-run relationships and address panel complexities through complementary estimation/diagnostic strategies appropriate for macro-panels; and (4) to translate comparative results into development-sensitive policy implications, recognizing that the same instrument (taxation, finance, or trade openness) can have different environmental outcomes depending on institutional capacity and innovation readiness (Dahmani, 2024; Ayaz et al., 2025).

The contribution (novelty) of this research is fourfold and directly fills the stated gaps. First, it offers an integrated sustainability policy model that treats green finance, green trade, environmental taxes, and economic development as a joint system rather than isolated determinants consistent with the recent scientific studies that finance effects strengthen when paired with innovation capacity and coherent policy signals, and that trade patterns can either worsen ecological pressure or facilitate green diffusion depending on composition and technology (Umar & Safi, 2023; Yu et al., 2024). Second, it advances explanation beyond "does X reduce emissions?" by explicitly testing technological innovation as a mediating channel, aligning with recent mechanism-oriented findings: clean technology innovation mediates the green finance → green growth relationship in developed contexts (Deng et al., 2024), environmental innovation mediates green finance → sustainability in G7 settings (Omri et al., 2024), and process innovation mediates part of environmental taxation's effect on carbon intensity (Matterne et al., 2024). Third, it contributes a dual-economy comparative design (developed vs. developing countries) that responds to the clear segmentation in current empirical evidence (OECD/G7 vs. emerging-only studies) and directly tests whether policy tools behave differently under distinct institutional and innovation regimes (Umar & Safi, 2023; Ghouse et al., 2025; Ayaz et al., 2025). Fourth, it extends the time horizon to 2000–2023, improving inference across multiple transition phases and allowing more credible long-run and dynamic interpretation than shorter-window studies. In sum, the paper provides a mechanism-based, development-sensitive, and empirically robust assessment of whether green finance, green trade, economic development, and environmental taxation enhance environmental sustainability through technological innovation—offering clearer guidance on why certain tools work better in developed economies and what institutional/innovation investments are necessary for similar effectiveness in developing economies.

2. Literature review

Theoretical framework

The frameworks that have been applied in this study are SDT and Technology and Innovation Theory. SDT is concerned with the balance between economic growth, social equality and conservation of the environment. This balance is particularly applicable in the light of the growing global challenges to climate change and resource depletion (Winnipeg, 1999). SDT application in this research enables one to investigate the relationship of emerging problems like GF, GT and economic development in relation to ES in both developed and developing nations. SDT suggests that these components should be perfectly synchronized, which implies that integrative policies should be adopted to facilitate economic development and environmental conservation.

Technology and Innovation Theory is a complement to SDT and introduces a perspective according to which technological innovations can be regarded as the most important facilitators of sustainable development. TINN plays the leading role in creating green technologies and facilitating the transition to the low-carbon economy Siregar I, Ma'rifataini LD, An-Nahidl NA, et al. This theory describes the specific underlying reasoning in the mediating effect of technological progress in the association among GF, GT, and ES, particularly in the developed countries with good infrastructure and financial frameworks.

In addition to these theories, the EKC theory is applicable to this work. EKC writes that economic devel- opment pollutes the environment at the beginning of its development, but at higher incomes, countries can implement cleaner technology and more effective environmental policies, which enhances the quality of the ecology. This theory provides a clue on how economic development, GF and TINN can work together to bring about sustainability, particularly in the transitional phases of developed and developing nations.

1) Green finance and environmental sustainability

Green finance is widely theorized as a *capital-reallocation channel* that shifts funding away from pollution-intensive activity and toward low-carbon production, clean infrastructure, and environmentally responsible innovation. Recent evidence shows the environmental payoff is strongest when green finance *changes real investment decisions*—for example, by relaxing firms' financing constraints and accelerating green capital expenditure and cleaner technology adoption (Zhang et al., 2024). Green finance has emerged as a critical mechanism for supporting environmental sustainability by directing financial resources towards environmentally friendly and sustainable projects.Empirical studies generally suggest that green finance supports environmental sustainability (e.g., lower environmental degradation / improved sustainability indicators), though its effectiveness can be shaped by energy use, urbanization, and policy design (Khan et al., 2022; Zakari & Khan, 2022), and strengthened when aligned with environmental regulation and development dynamics (Tariq & Hassan, 2023) as well as national ESG-oriented strategies and spillover effects (Kwilinski et al., 2025). At the same time, the evidence base is rapidly expanding and increasingly synthesized through systematic/bibliometric reviews that map dominant themes, methods, and research gaps in the green finance–sustainability nexus (Khan et al., 2024; Kumar et al., 2024). Parallel work on green trade/green openness shows that trading environmental goods and the structure/complexity of trade can influence sustainability outcomes, including via new indices of "green trade openness," and that effects may depend on macro-policy settings and urbanization thresholds (Can et al., 2021; Can et al., 2022; Lee et al., 2023; Hu et al., 2024; Ramizo et al., 2025). At the same time, recent studies also stress that "more green finance" is not automatically "more sustainability." Firm-level evidence indicates that larger green bond volumes are associated with lower future carbon intensity, but a non-trivial share of green-bond financing does not translate into measurable environmental gains—consistent with concerns about weak additionality and greenwashing risk (ElBannan & Löffler, 2024). Macro-level work similarly finds that sustainable finance instruments (e.g., green bonds and ESG investment) can reduce emissions, and that stronger regulatory oversight and transparency amplify these benefits (Wang & Wang, 2025).

H1: Green finance plays a significant role towards environmental sustainability.

2) Green trade and environmental sustainability

Green trade is typically framed as trade patterns, rules, and product composition that support environmental objectives—especially via diffusion of cleaner technologies, expansion of environmental goods markets, and upgrading toward cleaner production. Recent cross-country evidence suggests that trade openness can mitigate emissions in advanced economies when it is aligned with green innovation and technology diffusion rather than pure scale expansion (Mehmood & Kaewsaeng-on, 2026). Green trade is increasingly seen as a policy lever for environmental sustainability: greater trade in environment-friendly goods ("green openness") is linked with improved environmental outcomes—especially in OECD countries—and has inspired metrics such as the Green (Trade) Openness Index to capture trade–environment linkages more precisely (Can et al., 2021; Can et al., 2022). Evidence also suggests these benefits depend on context, with macroeconomic policy settings and economic complexity shaping how green trade translates into ecological performance (Hu et al., 2024; Lee et al., 2023). Moreover, the environmental effects of green and circular trade vary with development conditions, as urbanization can amplify or dampen net gains (Ramizo et al., 2025).

Figure 4. Green trade facilitation mechanisms and their impact on environmental sustainability.
Source: Developed by the researchers.

However, the trade–environment relationship remains heterogeneous, because openness can also expand production and transport emissions if environmental standards and upgrading are weak. Recent panel evidence connecting "green trade openness" with net-zero orientation indicates that the environmental benefits of greener trade integration are stronger when countries simultaneously build green technological innovation capacity and supportive transition policies (Ayaz et al., 2025). Complementary evidence focusing on environmental-goods trade also supports the idea that trade can improve sustainability when it accelerates innovation and clean-technology diffusion rather than reinforcing pollution haven dynamics (Yu et al., 2024).

H2: Green Trade has a significant impact on environmental sustainability.

3) Economic development and environmental sustainability

Economic development influences environmental sustainability through scale, composition, and technique effects, making the net impact theoretically ambiguous and empirically nonlinear. Recent multi-country evidence continues to support the Environmental Kuznets Curve (EKC) intuition in many settings—environmental pressure tends to rise at earlier stages of development and can decline after structural upgrading and stronger institutions take hold (Bildirici et al., 2023).

Even so, newer distributional (quantile) evidence shows that growth can remain environmentally costly at medium-to-high emission levels, especially where energy systems and industrial structures are carbon-intensive(Furtado et al., 2000) .For OECD economies, recent results show economic growth significantly increases CO_2 emissions in the middle and upper parts of the emissions distribution, even when other "green transition" factors improve (Mehmood & Kaewsaeng-on, 2026). (For developing economies, recent panel evidence highlights that the growth–environment tradeoff is shaped by governance and structural conditions, reinforcing the need to model heterogeneity rather than assuming one universal growth–sustainability path (Hunjra et al., 2024).

H3: Economic development has a significant impact on environmental sustainability.

4) Environmental taxes and environmental sustainability

Environmental taxes are classically justified as a Pigouvian instrument that internalizes environmental externalities by increasing the relative cost of pollution-intensive activity, thereby incentivizing cleaner production, substitution toward low-carbon inputs, and energy efficiency. Recent evidence continues to show that the environmental effectiveness of taxation depends on credibility, coverage, and the broader policy mix: well-designed carbon/eco taxes can shift incentives and reduce emissions, but weak enforcement or narrow tax bases can limit impacts (Dahmani, 2024). Environmental taxes are increasingly viewed as effective instruments for environmental sustainability, especially when reinforced by environmental innovation, cleaner energy use, and strong governance (Ali et al., 2023; Liu et al., 2023). Evidence from OECD, G-20, and leading green economies suggests such taxes can reduce pollution and ecological pressures and may yield "double dividend" benefits, though impacts vary across contexts and distributions (Murad et al., 2025; Soufiene et al., 2025; Ullah et al., 2023). Policy-oriented work further stresses that green tax reforms should align with SDGs while balancing environmental goals with equity considerations (Sapiri, 2025; Sing et al., 2025)

A key modern insight is that taxes also work through *innovation responses*. Evidence from a major carbon tax setting finds that environmental taxation can stimulate innovation, reinforcing the Porter-type mechanism where price signals induce technological upgrading (Carraro et al., 2024). (Related cross-country work shows that environmental taxes can complement green finance and clean technology pathways, including threshold-type dynamics where taxes strengthen environmental outcomes once policy intensity surpasses a minimum level (Kharuddin et al., 2024).

H4: Environmental taxes play a significant role towards environmental sustainability

5) Mediating effect of technological innovations

Technological innovation is increasingly modeled as the *transmission mechanism* that converts policy instruments (green finance, green trade orientation, and environmental taxation) into measurable sustainability outcomes. Recent mediation-based evidence shows that green finance improves environmental performance more reliably when it stimulates environmental innovation, indicating that finance affects sustainability partly by accelerating eco-innovation adoption rather than only reallocating capital on paper (Omri et al., 2024). FinTech is increasingly viewed as a key enabler of green finance by improving transparency, lowering transaction costs, and widening access, which helps allocate and monitor green capital more efficiently (Zaid et al., 2025; Thomas et al., 2025). Its integration into financial systems also supports new sustainable financial products and stimulates green innovation, helping curb environmental deterioration linked to resource-intensive production and high energy use (Al-Kasasbeh et al., 2024; Sohail et al., 2024). By channeling funds into environmental finance and reinforcing financial innovation—especially within banking—FinTech can accelerate progress toward SDGs and carbon-neutral pathways aligned with global commitments such as the Paris Agreement (Zaid et al., 2024; Miled, 2025; Thomas et al., 2025).

Recent studies also show that this mediation logic extends beyond finance. Clean/green innovation can strengthen the environmental returns to policy mixes that include taxes and broader sustainability instruments, and it helps explain why results differ across institutional settings. For example, evidence using structural modeling highlights green innovation as a key mediator linking green finance to sustainability outcomes in emerging-economy contexts (Ghouse et al., 2025). Similarly, recent cross-country analysis finds that clean technology innovation mediates the green-finance → green-performance pathway and that environmental tax intensity can shape (amplify) this mechanism through threshold effects (Kharuddin et al., 2024).

H5: Technological innovation has a mediating effect on the relationship between green finance, eco- nomic development, green trade, Environmental Tax and environmental sustainability.

3. Data and methods

Data source and variables description

The sources of information employed in this study are the World Development Indicators (WDI) database, OECD, and the World Bank. These sources represent a whole of international data on environmental, social and financial issues and national and regional estimates. The years of the studies were 2000-2023, and specific focus on GF environmental taxes, economic development, Green and TINNs. ES is dependent variable and TINN is the mediator of the independent variables. The paper relies on the data of 20 developed and 20 developing nations to make a comparative analysis. Developing countries to be selected are Mexico, India, China, Brazil, Pakistan, Nigeria, Bangladesh, Kenya, Egypt, the Philippines, Sri Lanka, Uganda, Ukraine, Ghana, Cameroon, Rwanda, Turkey, Azerbaijan, Jamaica and Colombia. Switzerland, Sweden, Ireland, the United States, Canada, Germany, the United Kingdom, France, Australia, the Netherlands, Norway, Denmark, Finland, Belgium, Luxembourg, Japan, Iceland, Singapore, New Zealand and Spain are the developed countries.

Table 1. Variables description.

Variables	Abbreviation	Unit of measurements	Data sources
Green finance	GF	Green tax incentives as a % of GDP	OECD
Economic development	GDP	Growth domestic product (% annual growth)	OECD
Environmental taxes	ET	Environmental tax revenues (% of GDP)	OECD
Green trade	GT	Green trade openness (% of GDP)	WDI
Technology innovation	TINN	ICT capital as a % of GDP	OECD

Variables	Abbreviation	Unit of measurements	Data sources
Environmental sustainability	ES	CO_2 emissions (metric tons per capita)	WDI

Source: Developed by the researchers.
Abbreviations: WDI: World Development Indicators.

Table 1 presents the variables and measurements that were used in the study. These variables are chosen due to the available literature, which gives a good ground of their applicability in the study of ES. Considering the extent of the data, the comprehensive analysis of the causal pathways of these factors that vary over time and ecological results in developed and developing nations can be made.

Data methodology

The paper relies on the panel data method, where annual data of the years 2000 to 2023 is used in the development and developed countries. Based on panel data, one would be able to examine the effects of alterations in GF, economic development, green trade, environmental tax and TINN on ES in the long run. The analysis of the data of various countries and different years captures both within country and cross-country changes providing a detailed account of the dynamics behind this. In order to ensure that the dataset is reliable, the missing values are dealt with either through interpolation or omission depending on their significance. This makes the dataset as healthy and suitable to be analyzed by economic methods. The empirical study is based on the use of STATA software that estimates the dynamic panel data models and robustness checks.

The choice and justification of models

The analysis of panel data is done using the RE (random effects) model. This study is quite appropriate to the RE model because it is effective in explaining individual-specific heterogeneity, which may explain the dependent variable (ES) that is not reflected in the model. The model is capable of analyzing both within and between-entity variation and it is particularly applicable to the dataset, which is composed of countries at various levels of development and varying number of observations over time.

Robustness is also checked by the use of the fixed effects (FE) model. The FE model enables time-invariant country differences to be controlled which will make the factors country unique that are not evolving to be captured in this model. Comparison of the results obtained using both models will enable us to substantiate the strength of the results. Lag structures are also incorporated in the study in order to examine the long- term effects of GF, GT, ET and ES. This will ensure that the analysis may be comprised of the short-term and long-term effect of the independent variables.

Flow chart of econometric method.

Figure 5 provides the econometric method flowchart.

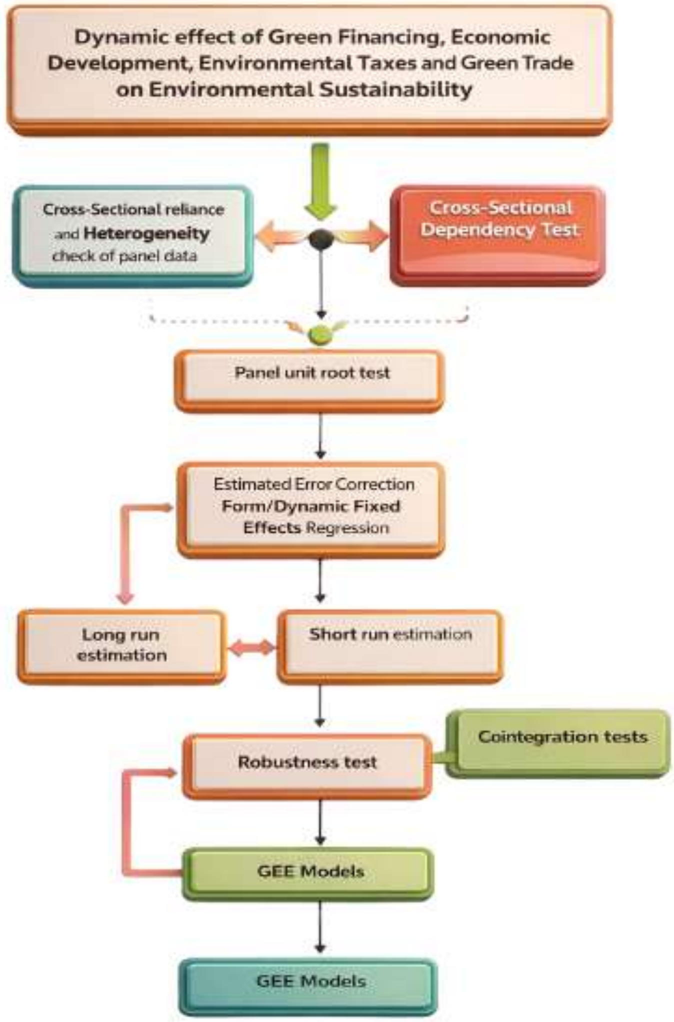

Figure 5. Econometric method flowchart.

Source: Developed by the researchers.

The conceptual framework of this research examines the relationships among four independent variables—green finance (GF), economic development, environmental taxes, and green trade—and their influence on environmental sustainability (ES), the dependent variable, through technological innovation (TINN) as a mediating variable. Green finance and environmental taxes contribute to environmental sustainability by encouraging investment in clean production, discouraging pollution-intensive activities, and promoting the adoption of sustainable technologies. Technological innovation, particularly advancements in artificial intelligence and energy-efficient technologies, serves as a critical mechanism that optimizes resource use, enhances production efficiency, and supports the effective implementation of environmentally oriented financial and fiscal policies, thereby facilitating the transition toward sustainable economies.

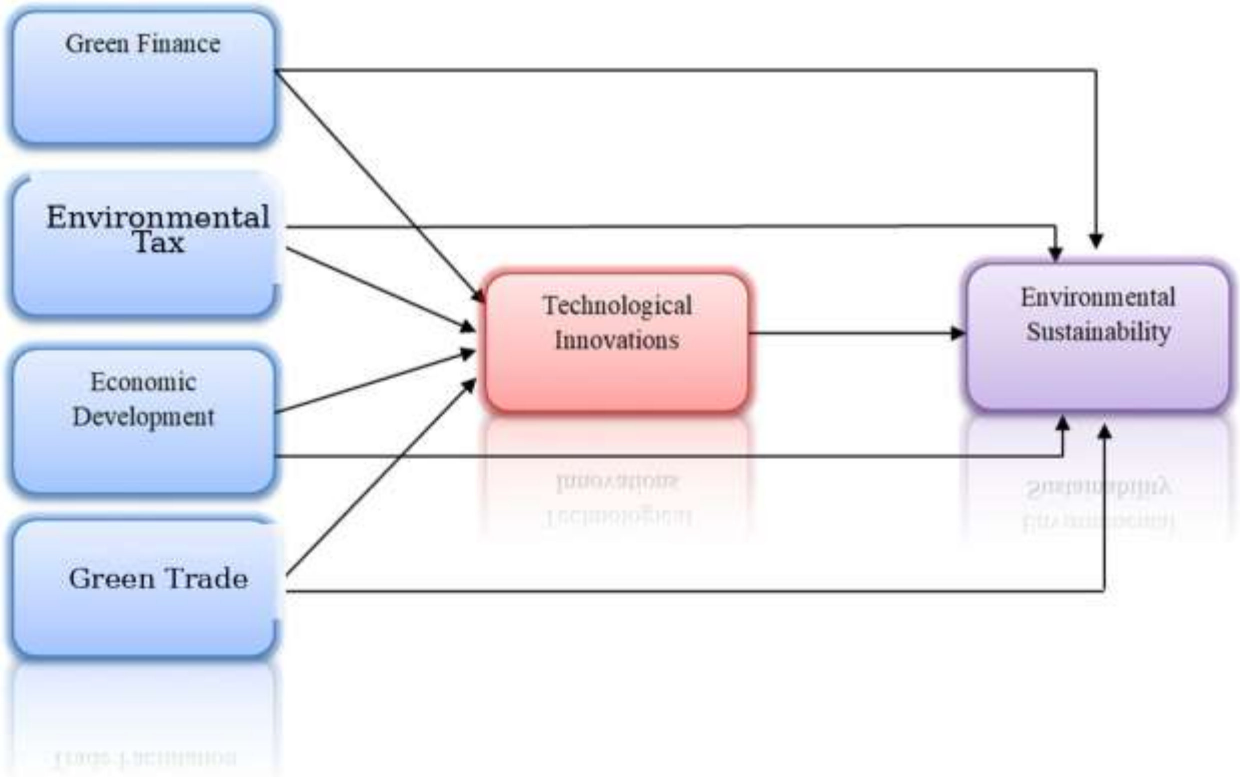

Figure 6. Conceptual framework of the study.

Source: Developed by the researchers.

These relationships are more complex in developing countries due to financial constraints, infrastructural limitations, and policy inefficiencies that may reduce the effectiveness of green finance and environmental taxes. According to the Environmental Kuznets Curve (EKC) hypothesis, the early stages of economic development are often associated with environmental degradation; however, progress in technological innovation, green finance, and environmental taxation can help decouple economic growth from environmental harm, ultimately promoting sustainability. Furthermore, green trade facilitates the diffusion of environmentally friendly technologies and sustainable production practices across countries, strengthening environmental performance, particularly in developed economies. In contrast, in developing countries, the impact of green trade may be less evident, as trade liberalization can sometimes stimulate industrial expansion without adequate environmental regulations. The conceptual framework of the study is presented in Figure 6.

Results and discussion

Descriptive statistics

Table 2 presents the descriptive statistics of the variables employed in the study. The table summarizes the central tendency and dispersion of the variables, highlighting cross-country variations over the study period.

In the context of the present research, green finance (GF) records a mean value of 1.703 with a standard deviation of 1.046, indicating moderate variability across countries. The values range from −1.53, reflecting negative incentives or limited support for green projects, to 5.10, representing strong positive incentives toward green financing initiatives. Economic development, measured by GDP growth, shows an average growth rate of 2.259 with a relatively high standard deviation of 3.133, suggesting substantial fluctuations. The minimum value of −11.167 reflects periods of economic contraction, while the maximum value of 24.616 indicates episodes of rapid economic expansion.

Table 2. Descriptive statistics.

Variable	Obs	Mean	Standard deviation	Minimum	Maximum
GF	725	1.703	1.046	−1.53	5.1
GDP	528	2.259	3.133	−11.167	24.616
ET	640	922,091.58	1,732,512.9	770.693	8,084,482
GT	960	58.185	45.322	13.712	344.488
ES	840	5.807	5.216	0.053	25.61
TINN	959	472.369	280.428	1	956

Source: Authors' calculations using STATA.
Abbreviations: GDP: gross domestic product; ES: environmental sustainability; GF: green finance; ET: environmental taxes; GT: green trade; TINN: technological innovation.

Environmental taxes (ET) exhibit considerable variation across countries, with a mean value of 922,091.58 and a high standard deviation of 1,732,512.9. The values range from a minimum of 770.693 to a maximum of 8,084,482, highlighting substantial disparities in the scale and implementation of environmental tax policies among countries over time. These variations reflect differences in fiscal capacity, environmental policy stringency, and institutional frameworks. Green trade (GT), measured as an indicator of environmentally oriented trade openness, has an average value of 58.185 and a standard deviation of 45.322, indicating wide differences in the degree of integration into green trade activities. The minimum value of 13.712 suggests limited engagement in green trade, while the maximum value of 344.488 reflects highly trade-integrated economies with a strong focus on environmentally sustainable goods and services. Environmental sustainability (ES), proxied by CO_2 emissions per capita, has an average value of 5.807, with values ranging from 0.053 to 25.61. This wide range demonstrates significant disparities in emission levels across countries, underscoring differences in energy structures, industrialization levels, and environmental regulations. Finally, technological innovation (TINN), measured through ICT investment as a percentage of GDP, has a mean value of 472.369 and a standard deviation of 280.428, indicating substantial heterogeneity in technological advancement across countries, with values ranging from 1 to 956.

Overall, the descriptive statistics reveal pronounced disparities in economic performance, environmental policies, trade orientation, and technological capacity between developed and developing countries. These differences provide a strong empirical foundation for further analysis of how green finance, environmental taxes, green trade, and technological innovation influence environmental sustainability.

Table 3. Pairwise correlations.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) GF	1.000					
(2) GDP	0.071	1.000				
(3) ET	−0.248	−0.051	1.000			
(4) GT	0.107	0.003	−0.220	1.000		

(5) ES	0.288	0.048	−0.056	0.255	1.000	
(6) TINN	0.222	−0.021	−0.201	0.037	−0.047	1.000

Source: Authors' calculations using STATA.
Abbreviations: GDP: gross domestic product; ES: environmental sustainability; GF: green finance; ET: environmental taxes; GT: green trade; TINN: technological innovation.

Table 4. Cross-sectional dependence test

Friedman's test of cross-sectional independence reports a test statistic of 59.043 with a corresponding p-value of 0.0000, indicating strong evidence against the null hypothesis of cross-sectional independence. These results confirm the presence of cross-sectional dependence among the model variables across countries over time.

The Friedman cross-sectional dependence test statistic is computed as:

$$Q = 12 / [N\,T\,(T + 1)] \times \Sigma_{i=1}{}^{N} R_j{}^2 - 3N(T + 1))$$

where N denotes the number of cross-sectional units, T represents the number of time periods, and R_j is the average rank of the jth cross-sectional unit across periods

Source: Authors' calculations using STATA.

The pairwise correlation analysis presented in Table 3 provides important insights into the relationships among the study variables. The correlation between green finance (GF) and economic development (GDP) is positive but very small (0.071), indicating that GF has only a marginal association with economic performance. GF exhibits a moderate negative correlation with environmental taxes (ET) (−0.248), suggesting that higher levels of green finance are associated with lower environmental tax intensity. In addition, GF shows a moderately positive correlation with green trade (GT) (0.107) and a stronger positive correlation with environmental sustainability (ES) (0.288), implying that higher green finance is associated with increased CO_2 emissions per capita. Furthermore, GF is moderately positively correlated with technological innovation (TINN) (0.222), indicating that increased green finance is linked to greater investment in ICT and technological development.

Economic development (GDP) displays a weak positive relationship with environmental sustainability (0.048) and no meaningful correlation with environmental taxes (−0.051) or green trade (0.003), suggesting that GDP growth alone exerts a negligible influence on these variables. As hypothesized, environmental taxes are negatively and significantly correlated with green trade (−0.220) and technological innovation (−0.201), indicating that higher environmental tax levels may be associated with lower green trade activity and reduced ICT investment. The correlation results further reveal that green trade is positively associated with environmental sustainability, with a coefficient of 0.255, suggesting that greater green trade intensity is linked to higher CO_2 emissions per capita. Although the correlation between green trade and technological innovation is weak (0.037), it remains positive. Overall, the findings demonstrate varying degrees of association among the variables, with green finance and green trade exhibiting relatively stronger links with environmental sustainability and technological innovation. These preliminary correlations provide a foundation for the subsequent econometric analysis examining causal and dynamic relationships.

Cross-sectional dependence test

The results of the cross-sectional dependence test are reported in Table 4. The Friedman test statistic equals 59.043, with an associated p-value of 0.0000, leading to the rejection of the null hypothesis of cross-sectional independence. This finding provides strong evidence of significant cross-sectional dependence among the panel units. The presence of cross-sectional dependence indicates that shocks affecting one country are likely to spill over to others, implying that the variables are interrelated across cross-sections over time. Ignoring such interdependence may result in biased and inconsistent parameter estimates, ultimately leading to misleading inferences. Therefore, the detection of cross-sectional dependence justifies the use of estimation techniques that explicitly account for this feature of the data, such as second-generation panel unit root, cointegration, and regression methods. Incorporating these approaches ensures more reliable and robust empirical results.

Co-integration tests

Table 5. Pedroni Test for Co-integration

Item	Statistic / Description	p value
H_0	No co-integration	
H_a	All panels are co-integrated	
Co-integrating vector	Panel specific	
Panel means	Included	
Time trend	Not included	
AR parameter	Panel specific	
Number of panels	21	
Average number of periods	14.952	
Kernel	Bartlett	
Lags	2.00 (Newey–West)	
Augmented lags	1	
Modified Phillips–Perron t	5.1941	0.000
Phillips–Perron t	−6.0472	0.000
Augmented Dickey–Fuller t	−5.4316	0.000

Table 5 reports the results of the Pedroni panel co-integration test, which examines the existence of a long-run equilibrium relationship among the variables across 21 cross-sectional units, with an average of approximately 15 time periods per panel. The test specification allows for panel-specific co-integrating vectors and autoregressive parameters, incorporates panel means, and excludes a deterministic time trend. Estimation is conducted using the Bartlett kernel with Newey–West automatic bandwidth selection (lag length = 2) and one augmented lag. The results indicate that all three test statistics—the Modified Phillips–Perron t, the Phillips–Perron t, and the Augmented Dickey–Fuller (ADF) t—are statistically significant at the 1% level, with corresponding p-values of 0.000. Specifically, the Modified Phillips–Perron t-statistic equals 5.1941, while the Phillips–Perron and ADF t-statistics are −6.0472 and −5.4316, respectively. These findings lead to a rejection of the null hypothesis of no co-integration, providing strong evidence that the panel variables share a stable long-run co-integrating relationship across all cross-sectional units.

Table 6. Heterogeneity Test Results

Test statistic	Value	p value
Delta	7.940	0.000
Adjusted Delta	10.598	0.000

Note. The test examines slope heterogeneity following Pesaran and Yamagata (2008). The null hypothesis (H_0) assumes homogeneous slope coefficients. Variables are partialled out with a constant. Source: Developed by the researchers using STATA.

The results of the slope heterogeneity test indicate a Delta statistic of 7.940 and an adjusted Delta statistic of 10.598, both of which are statistically significant at the 1% level, as evidenced by *p*-values of 0.000. These findings lead to a rejection of the null hypothesis of slope homogeneity, implying that the estimated slope coefficients differ across cross-sectional units.

The rejection of slope homogeneity suggests substantial cross-country variation in the relationship between the dependent and independent variables. Consequently, imposing a common slope coefficient across all countries would result in biased and inconsistent estimates, as such an approach fails to account for structural differences among the sample units. The presence of slope heterogeneity implies that the impact of economic development, green finance, environmental taxes , trade efficiency, technological advancement, and environmental degradation is not uniform across countries.

Panel unit root

The following autoregressive specification is considered:

$$y_{it} = \rho_i y_{it-1} + \varepsilon_{it}$$

where y_{it} denotes the variable of interest (either dependent or independent) for cross-sectional unit i at time t. The coefficient ρ_i captures **heterogeneous autoregressive dynamics across entities**, which is a key feature of the Im–Pesaran–Shin (IPS) panel unit root test. The term ε_{it} represents the idiosyncratic error component.

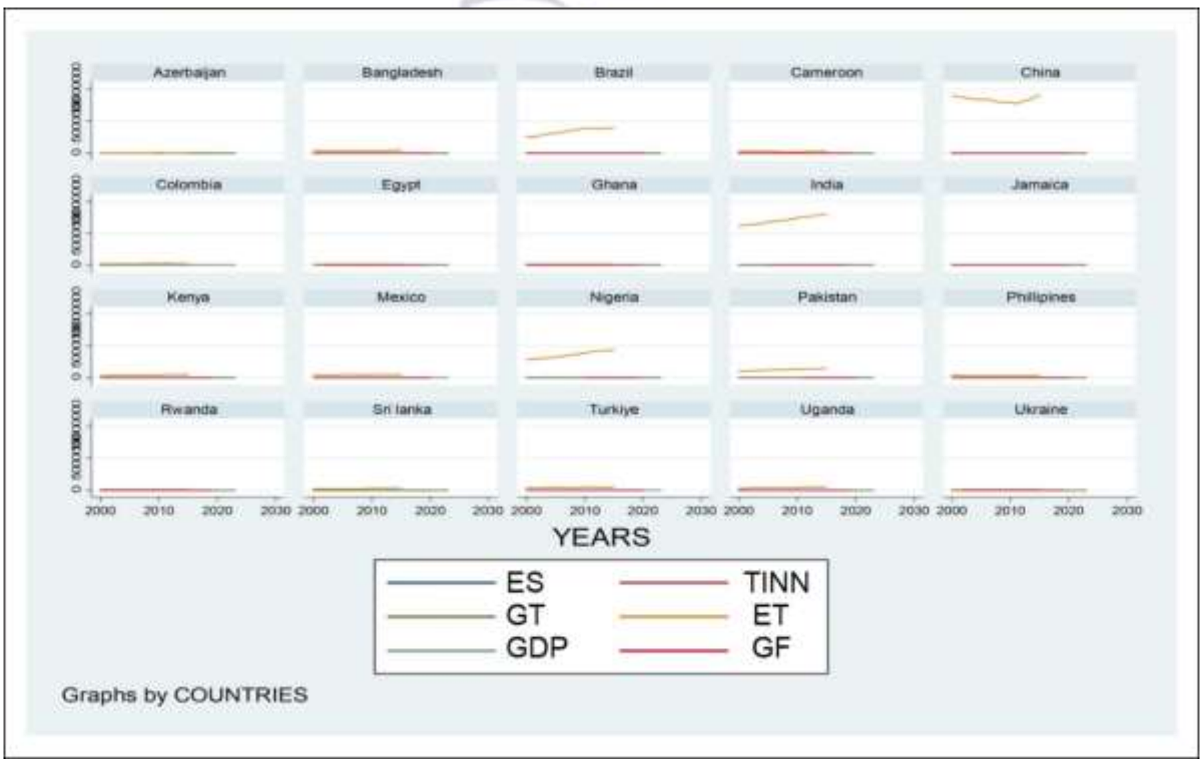

Figure 7. Developing countries.

Source: Authors' calculations using STATA.

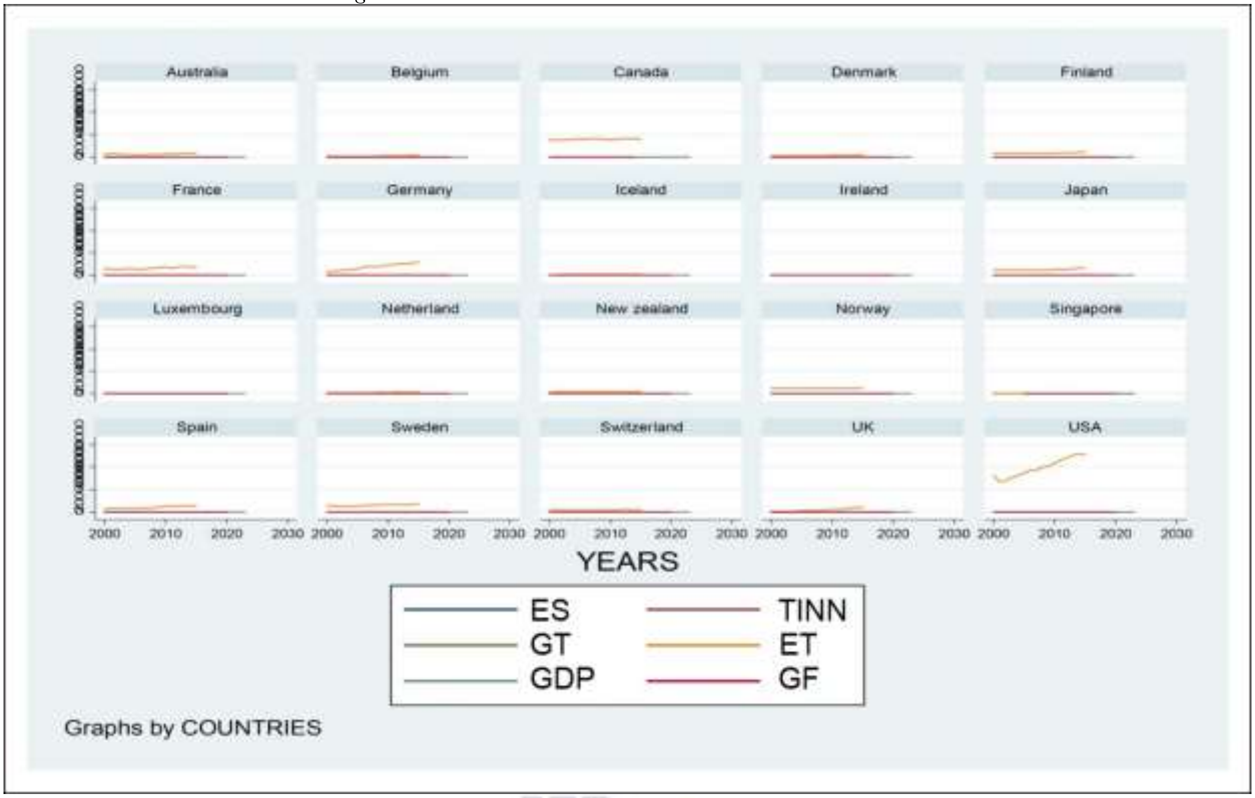

Figure 8. Developed countries.

Source: Authors' calculations using STATA

Table 7(a) reports the panel unit root test results for each variable. The findings indicate that GDP and trade (GT) are stationary at levels, i.e., integrated of order zero I(0), whereas the remaining variables become stationary after first differencing, indicating integration of order one I(1).

Table 7(b) presents additional unit root test results, showing that GDP is stationary at level I(0), while all other variables are stationary at first difference I(1).

Dynamic fixed effects regression

The general form of the DFE model can be written as:

$$y_{it} = a_{it} + X_{it}\beta + \varepsilon_{it}$$

$$y_{it} = a + \beta X_{it} + \gamma Z_{it} + u_{it} + \varepsilon_{it}$$

$$ES_{it} = aES_{i(t-1)} + \beta 1 GF_{it} + \beta 2 GT_{it} + \beta 3 GDP_{it} + \beta 4 ET_{it} + \gamma TINN_{it} + u_i + \varepsilon_{it}$$

where:

- ES_{it} denotes environmental sustainability for individual i at time t.
- $ES_{i,t-1}$ represents the lagged dependent variable, capturing the previous period's level of environmental sustainability for individual i.
- GF_{it} refers to green finance for individual i at time t.
- GT_{it} denotes green trade for individual i at time t.
- GDP_{it} represents gross domestic product for individual i at time t.
- ET_{it} refers to environmental tax for individual i at time t.
- $TINN_{it}$ denotes the mediating variable (technological innovation) for individual i at time t.
- α is the coefficient associated with the lagged dependent variable, capturing the dynamic adjustment effect.

Table 7. Im–Pesaran–Shin (IPS) Unit Root Test

(a) Developed Countries

Variables	T-statistics	p-value	Order of Integration
GF	−4.1087***	0.0000	I(1)
GDP	−4.8539***	0.0000	I(0)
ET	−4.4089***	0.0000	I(1)
GT	−2.2277***	0.0008	I(0)
TINN	−5.4949***	0.0000	I(1)
ES	−4.7405***	0.0000	I(1)

(b) Developing Countries

Variables	T-statistics	p-value	Order of Integration
GF	−4.3072***	0.0000	I(1)
GDP	−4.8743***	0.0000	I(0)
ET	−3.5925***	0.0000	I(1)
GT	−4.4651***	0.0000	I(1)
TINN	−4.8526***	0.0000	I(1)
ES	−3.4325***	0.0000	I(1)

Notes:
*Critical values at the 1%, 5%, and 10% significance levels are denoted by ***, **, and *, respectively.*
Source: *Developed by the authors using STATA.*
Abbreviations:
ES = environmental sustainability; GDP = gross domestic product;GF = green finance; ET =environmental tax; TINN = technological innovation; GT = green trade.

- $\beta_1, \beta_2, \beta_3$,and $\beta_4$denote the coefficients associated with the independent variables green finance (GF), green trade (GT), gross domestic product (GDP), and environmental tax (ET), respectively.
- γrepresents the coefficient of the mediating variable technological innovation (TINN).
- $\mu_i$captures individual-specific fixed effects, accounting for time-invariant unobserved heterogeneity across cross-sectional units.
- ε_{it}denotes the idiosyncratic error term.

Table 8 reports the results of the Arellano–Bond serial correlation tests, which are used to evaluate the presence of autocorrelation in the residuals of the dynamic panel model. The findings indicate a statistically significant first-order serial correlation (AR(1)), as evidenced by an m-statistic of −8.5757, a rho value of −5.6868, and a p-value of 0.0000. The detection of AR(1) correlation is consistent with expectations in dynamic panel estimations and does not invalidate the model.

In contrast, the second-order serial correlation test (AR(2)) yields an m-statistic of 0.4657, a rho value of 0.2769, and a p-value of 0.4657, indicating the absence of statistically significant second-order autocorrelation. The lack of AR(2) correlation confirms the correct specification of the dynamic model and supports the validity of the instrumental variables employed.

Table 8. Results of the Arellano–Bond Test for Serial Correlation

Test order	m-Statistic	rho	SE(rho)	Prob.
AR(1)	−8.57572	−5.68682	0.76762	0.0000
AR(2)	0.465728	0.276876	0.84651	0.4657

Table 9. Dynamic Fixed Effects (DFE) Error Correction Model Estimates

Table 9. Results of the Dynamic Fixed Effects Error Correction Model

	Developing Countries			*Developed Countries*	
	(1)	*(2)*	*(3)*	*(4)*	*(5)*
Variables	*_ec*	*SR*	*_ec*	*SR*	*TINN*
Lagged_ES		*2.176******		*3.572******	
		(0.013)		*(0.029)*	
_ec		*0.102*		*0.257******	
		(0.0912)		*(0.0358)*	
D.GF		*−0.0624*		*0.248*	
		(0.0738)		*(0.264)*	
D.GDP		*−0.00430*		*0.0482******	
		(0.00855)		*(0.0144)*	
D.ET		*7.74e-07*		*−3.86e-07*	
		(1.50e-06)		*(5.86e-07)*	
D.TR		*−0.00630*		*0.00634*	
		(0.0108)		*(0.00600)*	
D.TINN		*−0.00691*			
		(0.0240)			
GF	*−0.492******		*0.728******		*0.9462******
	(0.003)		*(0.040)*		*(0.0130)*
GDP	*−0.310******		*−0.00551****		*−0.0557****
	(0.022)		*(0.0056)*		*(0.0289)*
RE	*4.00e-05******		*−1.78e-06******		*−0.05676******
	(0.05)		*(6.75e-07)*		*(0.0442)*
GT	*0.0151*		*−0.00289*		*−0.2792*
	(0.113)		*(0.0157)*		*(0.027)*
INN			*0.00111******		*0.573******
			(0.00163)		*(0.0143)*
D.INN				*−5.43e-05*	
				(0.000483)	
Constant		*1.733*		*−2.548*	
		(1.575)		*(0.488)*	
Observations	.	.	.	.	

Notes:
*Critical values at the 1%, 5%, and 10% significance levels are denoted by ***, **, and *, respectively.*
Source: *Developed by the authors using STATA.*
Abbreviations:
ES = environmental sustainability; GDP = gross domestic product;GF = green finance; ET =environmental tax; TINN = technological innovation; GT = green trade

The variation in outcomes across different model specifications points to the presence of structural and policy-related heterogeneity among countries, highlighting the importance of designing sustainability policies that reflect national contexts. The results indicate that uniform policy approaches are unlikely to be effective across diverse economic and institutional settings. Instead, policy frameworks should be tailored to account for differences in institutional capacity, innovation systems, and the level of financial market development in order to effectively promote environmental sustainability. Furthermore, the findings suggest the necessity of conducting additional robustness analyses, including alternative model specifications and controls for potential omitted variables, to confirm the stability of the results and strengthen the credibility of the associated policy implications.

Table 10. Sargan Test Results for Overidentifying Restrictions

Null hypothesis (H_0): The overidentifying restrictions are valid.
$\chi^2(22) = 20.1932$
p-value $= 0.5710$

Source: Authors' calculations based on STATA output.

Robustness Tests

Table 10 reports the results of the Sargan test for overidentifying restrictions, which is used to assess the validity of the instruments employed in the GMM estimation. The test evaluates the null hypothesis that the instruments are exogenous, meaning they are uncorrelated with the error term and appropriately excluded from the estimated equation. The chi-square statistic, calculated with 22 degrees of freedom, is 20.1932, with an associated p-value of 0.5710. Since the p-value exceeds conventional significance thresholds, the null hypothesis cannot be rejected. This outcome confirms that the chosen instruments are valid and do not introduce overidentification bias, thereby supporting the reliability and robustness of the GMM estimation results.

GEE Models

Table 11 reports the results of the generalized estimating equations (GEE) models examining the effects of economic and environmental factors on environmental sustainability (ES) in developing and developed countries. The coefficient of green finance (GF) in developing countries is positive but statistically insignificant (0.0999), suggesting that its contribution to ES is not yet robust in these economies. In contrast, GF has a positive and statistically significant effect on ES in developed countries, with an estimated coefficient of 2.129 ($p < 0.01$). This outcome likely reflects stronger institutional capacity, more effective regulatory enforcement, and the greater maturity of green financial markets in advanced economies. Gross domestic product (GDP) shows a positive but statistically insignificant association with ES in both country groups, indicating that economic growth alone does not necessarily lead to environmental improvements in the absence of targeted sustainability policies. Environmental tax (ET) exhibits heterogeneous effects across samples. In developing countries, ET is positively and significantly associated with ES (2.35e−06, $p < 0.01$), implying that environmental taxation can enhance sustainability outcomes by encouraging cleaner production and consumption practices. Conversely, ET shows a negative and statistically significant relationship with ES in developed countries (−1.86e−06, $p < 0.01$). This counterintuitive result may reflect adjustment costs, transitional inefficiencies, or the interaction between environmental taxes and pre-existing energy and production structures.

Green trade (GT) does not display a statistically significant effect on ES in either developing or developed countries, suggesting that trade-related policies alone are insufficient to improve environmental outcomes. However, their effectiveness may increase when complemented by strong environmental regulations and well-designed green trade frameworks. Regarding taxation and innovation (TINN), the results indicate a negative and statistically significant effect on ES in developing countries (−0.0555, $p < 0.05$), possibly reflecting fiscal inefficiencies, limited institutional capacity, or misallocation of public resources. In developed countries, the effect of TINN remains small and statistically insignificant, highlighting differences in policy effectiveness and institutional quality across income groups.

Although the GEE estimates provide valuable insights into cross-country heterogeneity in the determinants of environmental sustainability, the analysis is subject to limitations. The absence of extensive robustness checks, alternative specifications, and subsample analyses constrains the generalizability of the findings. Future research should strengthen policy relevance by incorporating additional robustness tests and by explicitly linking empirical results to existing literature and policy frameworks, particularly with respect to enhancing green finance mechanisms and institutional effectiveness in developing economies.

Table 11. GEE Models

Variables	(Developing) ES	(Developed) ES
GF	0.0999	2.129***
	(0.185)	(0.584)
GDP	0.00483	0.0291
	(0.0131)	(0.0210)
ET	2.35e−06***	−1.86e−06***
	(1.11e−07)	(3.05e−07)
GT	0.00220	0.0227
	(0.0248)	(0.0200)
TINN	−0.0555**	
	(0.0279)	
TINN01		0.00155
		(0.00127)
Constant	4.435***	4.595*
	(0.576)	(2.365)
Observations	32	303
Number of countries	2	19

Conclusion, implications, and discussion

Discussion

This study examines how green finance (GF), environmental tax (ET), green trade (GT), technological innovation (TINN), and economic development shape environmental sustainability (ES) across developed and developing economies. The results demonstrate marked cross-country heterogeneity, indicating that the effects of these drivers depend strongly on national institutional capacity, market maturity, and technological readiness.

H1 proposed that GF would significantly affect ES, with differential effects across country groups due to disparities in financial development and infrastructure. The empirical results reveal that GF contributes positively to ES in developed countries, but its influence is weaker—or potentially adverse—in developing countries. This pattern challenges the assumption that green finance uniformly improves environmental outcomes. In advanced economies, GF appears to operate effectively through stronger governance, credible regulation, and deeper financial markets that support low-carbon investment and environmental performance. In contrast, in developing economies, limited regulatory oversight, weak monitoring, and institutional inefficiencies may reduce the effectiveness of GF and increase the risk of misallocation, thereby weakening its sustainability benefits.

H2 anticipated that ET would influence ES and that the magnitude and direction would differ by development level. The findings indicate that ET is positively associated with ES in developing countries, implying that environmental taxation may help reduce environmentally harmful activities and encourage cleaner production practices. However, the relationship is negative in developed countries. A plausible explanation is that, in advanced economies, environmental taxation may initially generate adjustment costs, transitional inefficiencies, or sectoral restructuring effects that temporarily offset sustainability gains. These outcomes suggest that the effectiveness of ET depends on design features such as tax base, enforcement, recycling mechanisms, and policy coordination with innovation and industrial transition strategies.

H3 predicted that economic development would affect ES, with stronger adverse effects in developing countries where industrial expansion is often resource-intensive. Consistent with this expectation, the results suggest that growth in developing economies is associated with environmental pressures, reflecting early-stage industrialization dynamics typically highlighted in the Environmental Kuznets Curve (EKC) framework. In developed countries, the negative growth–environment linkage appears weaker, which may reflect stronger regulation, cleaner technologies, and greater capacity to internalize environmental externalities.

H4 proposed that GT would significantly influence ES, with more unfavorable effects in developing countries. The results indicate that GT has a limited direct effect on ES in both groups, suggesting that trade-related mechanisms alone are insufficient to improve sustainability outcomes. Nonetheless, GT can become environmentally beneficial when embedded within supportive institutional settings, including strong environmental standards, enforcement capacity, and incentives that shift trade toward cleaner technologies and green-compliant production.

H5 stated that TINN mediates the relationship between GF, ET, economic development, GT, and ES. The findings support a strong mediating role for TINN in developed economies, indicating that innovation capacity is central to converting financial and regulatory inputs into sustainability gains. In developing countries, the mediating effect is weaker, likely due to constraints in infrastructure, skills, and institutional support. However, the results also imply that strengthening innovation ecosystems could enable developing countries to better translate GF and ET frameworks into improved environmental outcomes.

Conclusion and Implications

This study provides empirical evidence on the dynamic interactions among green finance (GF), environmental tax (ET), economic development, green trade (GT), and technological innovation (TINN) in shaping environmental sustainability (ES) across developed and developing economies over the period 2000–2023. The results underscore that sustainability drivers do not operate uniformly across countries; instead, outcomes are strongly conditioned by institutional quality, policy capacity, and technological readiness.

The findings indicate that GF and TINN strengthen ES in developed countries, reflecting the role of mature financial markets, credible regulation, and innovation systems that channel green capital toward effective environmental improvements. In developing countries, the contribution of GF is less consistent, highlighting the importance of governance, regulatory enforcement, and accountability mechanisms in ensuring that green financial resources are efficiently allocated and linked to measurable environmental gains. Strengthening institutional capacity is therefore essential for improving the sustainability returns of GF in these economies.

The relationship between economic development and ES differs across groups. In developing countries, growth remains closely associated with environmental strain, consistent with development-stage industrialization patterns. In developed economies, this relationship is weaker, suggesting partial decoupling enabled by technological progress and stronger regulatory frameworks. These results imply that developing countries require development strategies that integrate environmental objectives early—through cleaner industrial policy, enforcement of environmental standards, and investment in innovation capacity.

The results for ET are also informative. Environmental taxation appears to support ES in developing economies, indicating its potential as a policy lever for discouraging pollution-intensive activities and promoting cleaner production. However, the negative association observed in developed economies suggests that tax policy alone may not deliver immediate sustainability benefits unless paired with complementary measures such as innovation support, infrastructure upgrades, and well-designed revenue recycling that accelerates green transition and reduces adjustment frictions.

With respect to GT, the results suggest that trade-related mechanisms have limited direct effects on ES in both groups. This implies that trade policies should not be expected to yield sustainability gains without accompanying environmental standards. Countries should therefore adopt green trade frameworks that integrate environmental compliance, encourage clean technology diffusion, and prevent environmentally harmful production relocation.

Limitations

This study offers useful evidence on the relationships among green finance (GF), environmental tax (ET), economic development, green trade (GT), and technological innovation (TINN), but several limitations should be acknowledged. First, data quality and comparability remain uneven across developing countries, particularly for GT- and ET-related indicators, which may affect the stability and robustness of the estimates. Second, although the dynamic fixed-effects approach captures temporal dynamics, it does not establish strict causal relationships. Third, the analysis does not explicitly account for key institutional and policy factors—such as governance quality, regulatory enforcement, and environmental policy stringency—that can materially shape both sustainability outcomes and the effectiveness of GF, ET, and TINN. Finally, using ICT investment as a proxy for TINN may not fully reflect sustainability-oriented innovation, since it does not directly capture green technological progress.

Future Research Agenda

Future research can address these issues by improving data coverage and harmonization for developing economies, especially for GF, GT, ET, and environmental outcome indicators. Stronger causal inference can be pursued using methods such as Granger causality testing, structural equation modeling (SEM), or policy-shock-based identification strategies where feasible. Further studies should also incorporate institutional and governance measures to explain cross-country heterogeneity more explicitly, and adopt richer innovation proxies such as R&D spending, clean-tech patents, or adoption indices for low-carbon technologies. In addition, emerging work could investigate how AI-enabled systems enhance green finance allocation, regulatory monitoring, and sustainability performance, while sector-specific analyses (e.g., energy, transport, agriculture, manufacturing) would help generate more actionable policy guidance tailored to high-impact industries.

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