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Redesigning Sustainability: How Renewable Energy and Eco-Innovation Shape Ecological Footprints in Leading Tourist Destinations

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ABSTRACT

This study investigates the environmental determinants of ecological footprint in the top 25 tourist destination countries. The primary objective is to assess how renewable energy consumption, green growth, environmental innovation, and financial development influence ecological sustainability. Using annual data from 2002 to 2022, the study applies second-generation econometric techniques, including DSUR, CUP-FM, CUP-BC estimators, and Dumitrescu-Hurlin panel causality tests to account for cross-sectional dependence and heterogeneity. Results confirm that renewable energy consumption, green growth, and environmental innovation significantly reduce the ecological footprint, while financial development has a detrimental effect. Bidirectional causality exists between the ecological footprint and key predictors, except financial development, which shows a unidirectional link. The findings validate the Environmental Kuznets Curve (EKC) hypothesis. The study's novelty lies in its focus on tourism-intensive economies and the integration of innovation and green policy variables into an ecological footprint framework, which remains limited in prior research. It contributes methodologically by applying robust second-generation estimators. Policy recommendations include enhancing investment in clean energy, promoting green innovation, and integrating sustainability into financial decision-making to align tourism growth with ecological resilience.

Keywords: Ecological Footprint, Renewable Energy, Green Growth, Environmental Innovation, Financial Development
JEL Classifications: Q56, O44, Q01, C33

1. INTRODUCTION

Tourism worldwide accounts for approximately 8–11% of CO_2 emissions, with the aviation sector alone responsible for more than 40% of this total (Sun et al., 2023; Scott et al., 2023). Small island economies, especially those in the Caribbean, face significant vulnerabilities. In this context, the growth of tourism demonstrates a significant relationship with emissions, where a 10% increase in tourism activity correlates with an increase in emissions of up to 3.2% (Cevik, 2022; Nosheen et al., 2021). The present trends highlight the potential risk of "carbon leakage" in nations that focus on swift tourism growth while lacking corresponding environmental protections. Innovations in the supply chain, such as digital demand forecasting, have the potential to decrease emissions by 9–15% by optimizing routing and resource allocation. Hotels that have implemented heat-pump solar water systems have achieved a 27% reduction in energy consumption (Li et al., 2019). Integrating tourism with rural sectors like agriculture fosters the development of circular economies. In China, the transformation of agricultural residues into textiles has resulted in a 12% reduction in emissions intensity (Zhou et al., 2024a). By integrating renewable energy and sustainable farming practices, tourism has the potential to transition from a competitive model for resources to one that fosters collaboration.

There is a noticeable shift in consumer attitudes. Tourists in Italy demonstrate a readiness to invest an additional 15–25% for accommodations that prioritize low-carbon options (Raffaelli et al., 2021) However, industries such as aviation necessitate significant policy assistance to lower emissions, as the costs associated with abatement exceed \$200 per ton of CO_2 (Scott et al., 2023). Although OECD countries have progressed in the adoption of renewable energy (Dogru et al., 2020), emerging economies frequently encounter rebound effects. For example, even with investments in renewable energy, the elasticity of emissions related to tourism in Pakistan is recorded at 0.48 (Khan et al., 2020). The IPCC warns that, in the absence of specific sectoral reforms, the tourism industry may fail to meet its net-zero commitments by a significant margin of 75–90%.

The transition toward low-carbon tourism economies is significantly accelerated by digital innovation, circular economic models, and synergistic cross-sectoral policies. The digital economy reduces emissions through data-driven resource optimization—smart energy grids in hotels cut energy use by up to 25%, while AI-powered demand forecasting minimizes transportation-related emissions (Jiang and Lv, 2024; Wu et al., 2024). Digital platforms also enable virtual tourism experiences, directly substituting carbon-intensive travel. Agro-tourism integration exemplifies sectoral synergy, where rural tourism promotes low-carbon agricultural practices; for instance, in China, agro-tourism clusters lowered agricultural carbon intensity by 17% through efficient resource recycling and local supply chains (Zhou et al., 2024b). Policy frameworks like emissions trading schemes (ETS) incentivize decarbonization, though their efficacy depends on complementary measures such as green subsidies (Meng et al., 2020). Circular economy principles further reinforce this: hotels adopting waste-to-energy systems and reusable amenities reduce landfill contributions by 30–50% while enhancing brand loyalty among eco-conscious travelers (Axhami et al., 2023; Rodríguez et al., 2020). International commitments, like the Glasgow Declaration, provide unified targets, with countries such as Bali demonstrating regenerative tourism models that preserve natural capital while cutting emissions (Law et al., 2016; Scott and Gössling, 2022).

This study investigates the role of renewable energy, green growth, environmental innovation, and financial development in facilitating the decarbonization process among the leading 25 tourism nations. The choice of these variables is driven by their diverse ability to facilitate a shift towards low-carbon economies, focusing on both the supply and demand aspects of energy consumption and technological progress within the tourism industry. Renewable energy plays a crucial role in the decarbonization agenda, as its incorporation into tourism infrastructure effectively lowers carbon intensity by offering an alternative to reliance on fossil fuels (Jiménez-Islas et al., 2024). Delineate the intersection of scientific knowledge pertaining to renewable energy and tourism, highlighting that the implementation of renewable energy technologies not only reduces carbon emissions but also bolsters the resilience of tourism operations in the face of fluctuating fossil fuel markets. Additionally, Mehmood and Kaewsaeng-on (2024) illustrate that investing in renewable energy leads to significant decreases in carbon footprints within high-impact tourism areas, especially in the upper quantiles. The empirical evidence underscores the importance of renewable energy as a crucial mechanism for achieving decarbonization in economies reliant on tourism.

Strategies for green growth act as an additional approach within the framework of decarbonization. The concept of green growth, characterized by economic expansion that is independent of environmental harm, has been shown to enhance the sustainability of tourism sectors as well as contribute to wider socioeconomic progress. Research indicates that implementing policy measures that promote green credit and encourage renewable energy can create an environment where environmental sustainability and economic performance enhance each other (Mehmood and Kaewsaeng-on, 2024). The significance of this issue is heightened in leading tourism countries, where swift economic development frequently clashes with objectives aimed at environmental conservation. In addition to this, Sethi et al. (2023) present evidence indicating that green finance initiatives play a crucial role in enhancing renewable energy projects and fostering eco-innovation, which in turn drives green growth.

Environmental innovation serves as a vital catalyst for decarbonization, encompassing the creation and dissemination of advanced technologies and sustainable methodologies. Ma et al. (2021) demonstrate that the advancement of green technology innovation, as indicated by the increase in green patents, plays a crucial role in reducing costs associated with renewable energy production and enhancing environmental performance. This occurrence is especially relevant in the tourism industry, where innovative eco-friendly practices and sustainable amenities are being sought after by consumers who are mindful of environmental issues.

The advancement of financial systems serves a twofold purpose in promoting the acceleration of decarbonization efforts. Advanced financial markets play a crucial role in facilitating the mobilization of significant capital investment needed for large-scale renewable energy initiatives and green infrastructure development. Zoaka et al. (2022), Strong financial development plays a crucial role in improving environmental quality through the facilitation of green investments. Conversely, research conducted by Zheng et al. (2023) demonstrates that green finance mechanisms significantly reduce the capital costs associated with renewable energy technology projects, thereby facilitating their widespread adoption across various sectors, including tourism. The relationship between financial development and investments in renewable energy facilitates the creation and large-scale implementation of innovative environmental solutions.

This research constituents of several reasons. First, it seeks to uncover how renewable energy can offset environmental damage in tourism economies. Second, it examines whether green growth and innovation in these countries can decouple economic activity from resource depletion. Third, it considers if financial development helps or hinders ecological outcomes, recognizing that capital can drive both sustainable and unsustainable growth. Fourth, the study

delivers practical implications for governments aiming to manage the trade-off between economic gain and ecological stability. The research addresses the following questions:
- What is the impact of renewable energy consumption on the ecological footprint of top tourism countries?
- How does green growth affect the ecological footprint in these nations?
- What is the role of environmental innovation in reducing ecological footprints where tourism is prevalent?
- Does financial development support or undermine ecological sustainability in these contexts?

The study tests these hypotheses:
- H_1: Higher renewable energy consumption reduces the ecological footprint in tourism-intensive countries.
- H_2: Green growth initiatives are linked with a smaller ecological footprint.
- H_3: Environmental innovation leads to measurable reductions in the ecological footprint.
- H_4: The effect of financial development on ecological footprint is indeterminate and may vary by context and policy.

The study contributes to the existing literature as follows: First, this study contributes to the literature by offering a comprehensive assessment of how renewable energy, green growth, environmental innovation, and financial development jointly shape the ecological footprint in tourism-driven economies. Prior research has often focused on isolated variables or limited regions, leaving a gap in understanding the systemic effects across high-tourism nations. By employing panel data from the top 25 tourist destinations over two decades, the study integrates cross-sectional and temporal dimensions. This approach enables more robust generalizations and deepens insight into the unique environmental pressures associated with tourism-led development. Second, the research advances empirical analysis by applying second-generation panel estimators that account for cross-sectional dependence and slope heterogeneity. Earlier works frequently overlooked these issues, risking biased results in highly globalized and interconnected economies. The methodology adopted here ensures that the findings reflect the interconnected nature of environmental, economic, and financial dynamics within tourism-intensive countries. Third, the study addresses the ambiguity in the relationship between financial development and environmental outcomes. While financial growth can promote sustainability by supporting green investments, it can also drive unsustainable expansion if not properly regulated. This duality has been recognized but not thoroughly examined in tourism economies. By revealing a significant positive association between financial development and ecological footprint in these contexts, the study highlights the need for regulatory reforms and targeted green finance mechanisms. Fourth, the research underscores the mutual causality between environmental outcomes and policy drivers. The findings show bidirectional causality between ecological footprint and key determinants such as renewable energy use, green growth, and innovation. This feedback loop signals that environmental policy cannot be static. Instead, dynamic and adaptive strategies are needed to address the evolving relationship between economic activity, technological progress, and environmental impact in rapidly changing tourism sectors.

2. LITERATURE REVIEW

2.1. Environmental Innovation and Ecological Footprint

Environmental innovations include a continuum of technological innovations that seek to reduce environmental harm whilst advancing sustainability. Sahoo et al. (2024) state that a transformative innovation, such as clean technology, greatly contributes to sustainable goals. The study empirically confirms that technological innovation means contributing to the reduction of ecological footprints as it helps to achieve efficiency levels and reduce wastages in various industries. More so, Chien et al. (2022) confirm that within the context of ASEAN countries, ecological innovations have played an integral part in minimizing the ecological footprints and reaching the Sustainable Development Goals. The cleaner source of energy and industrial operations has been identified to reduce the emissions and consumption of resources significantly. One of the key studies which was performed by Ke et al. (2020), examines the relationship between innovation efficiency and the ecological footprints in Chinese cities. The authors describe a situation whereby the innovations' efficiency could at first help to decrease the ecological footprints, and then complex relations between the other economic and environmental aspects could appear. This complex. More analysis on the relationship between green innovations and sustainability is done by Koseoglu et al. (2022). Their research shows that when there is an increase of 1% in the consumption of renewable energy, this brings a definite reduction of the ecological footprint. This finding will also provide the need to incorporate renewable energy technology alongside the traditional practices to minimize the impact on the environment.

Such policies of green growth are so critical in the development of environmental innovations. Khalid et al. (2023) claim that governments and regulatory frameworks affect the ways in which the required technology for the sustainability of the environment is developed. The businesses are likely to exercise minimisation of the ecological footprint in places that encourage innovation. Hassan et al. (2023) investigates the interrelation of green growth, natural resources, and ecological footprints, showing how those innovations, which are resource-efficient, can help in economic growth without contributing to environmental degradation. Such policies will contribute to switching to sustainable practices, that is, not only reducing ecological footprints but also catalyse economic development. A similar observation was made by Alhassan et al. (2020) established that the existence of strong trade relationships and the integrity of the government bring about positive environmental performance. Such policies will play a pivotal role in promoting technological breakthroughs to tone down Ecological footprints and economic activity.

Environmental innovation does not necessarily mean that it is wrapped in high-tech fixes. Instead, it would be more about good practices in different sectors.

Although there is promising potential for environmental innovations, some challenges present themselves. The connection between economic development and ecological degradation is complicated because greater economic growth can, in fact, result in greater consumption of natural resources and waste production. Usman et al. (2021) observe that knowledge of investment dynamics of renewable energy research and innovation can equip policymakers to formulate strategic decision-making that will optimally respond to ecological footprints. Besides, external pressures may influence the efficiency of innovation activities, for example, international market swings and environmental rules (Li, 2022). In order to strike a middle ground rather than an extreme, on the subject of economic growth, innovation, and environmental stewardship, there has to be a harmonious approach that considers the manifold things that affect ecological footprints.

From the literature available, there is a high interrelation between environmental innovation and the reduction of ecological footprints in various ways, such as technology, policy, funding support, and industrial activities. Environmental innovations have been proven to be the solution to sustainability, with significant reduction of consumption and emissions. However, it should be said that some complexities and difficulties come with these innovations. There is a need for an all-around effort strategy that involves supportive policies, robust financial setups, and involvement of the public to guarantee that the maximum effect of environmental innovations is felt on the ecological footprint. As global environmental challenges continue to be intensified, there will be a need to develop an innovative culture to provide a sustainable future for everyone.

2.2. Financial Development and Ecological Footprint

The changing debate of the idea of sustainable development has gradually sculpted the focus in the direction of intricate formulation of the nexus between financial growth and ecological footprints. Financial development that can be assessed via the width and depth of financial instruments, institutions, and markets has had a complex relationship with environmental outcomes. This review is an integration of prior studies to give an account of how the financial systems influence ecological sustainability and the positive and negative influence in different contexts.

New evidence indicates that the environmental impacts of financial development are mixed. Yasin et al. (2025), however, observe that although sophisticated financial systems may help to enhance access to capital on the part of environmentally sustainable technologies, they may at the same time enable further consumption and industrialization, thus deepening the extent of environmental degradation. This contrast shows that financial services have a conditional element, in which ecological outcomes depend on the way resources are used and when they are used, throughout economic development. The emergent strength in this regard is the application of green finance. According to Aslam et al. (2024), green finance emerges as an essential mechanism to integrate economic growth with environmental protection schemes. They speculate that green finance may have an important role to play in financing infrastructure and technologies related to ecology, particularly in places such as East Asia, where environmental aspects are becoming more closely incorporated into developmental policies. They promote the development of green financial mechanisms to fill the gap between growth interests and ecological protection.

However, not all the research publications give a positive outlook. Destek and Sarkodie (2019) highlight their fear of the adverse effects of a mix of financial globalization and industrial production on environmental deterioration in emerging market economies. The authors recommend that, in response to these concerns, sustainability can and should be a core aspect of international financial policies. Regional data disclosed by Topaloğlu et al. (2025), indicate that the significance of financial development for ecological footprints varies significantly from country to country in the BRICS bloc. Such outcomes result from differences in institutional efficacy, policy preferences, and natural resource uses, indicating the need for context-specific financial-environmental policies.

Other analyses depict the expansion of the financial sector in a more positive way than the more critical ones do. In the view of Li et al. (2023a), financial infrastructure improvements can lead to wide-ranging investment in protective technologies that may mitigate the environmental effects. Such flexible and ecologically supportive funding mechanisms can produce significant ecological benefits, notably in technology-advanced regions. Adebayo et al. (2022) only strengthen this view by calling for more financial inclusion to promote participation in green investments, particularly when it comes to renewable energies. Their analysis serves as a robust support for the idea that enhancing financial access for environmental purposes will probably result in a significant reduction in ecological footprint.

2.3. Green Growth and Ecological Footprint

The ability for green growth depends on the continuous advancement of green technology and techniques that strive to reduce environmental degradation. Nabi et al. (2025) also, from the example of the case in Pakistan, communicate that massive investments in green finance are important in furthering ecological innovations, hence contributing to sustainable development. Their research indicates that an intense focus on finance may reduce the ecological footprint by 1-7%, reflecting the supportive nature of financial strategies towards achieving sustainable technological advances. The evidence from East Asia and the Pacific region, as cited by Aslam et al. (2024), substantiates the core function of green finance in facilitating sustainable transitions. The research reports that the targeted investment in green technologies and infrastructure is linked to significant shrinkage of the ecological footprint, thus confirming the indispensability of financial policies in promoting green growth.

The process of technological innovation development is an important aspect of sustainable growth. Koseoglu et al. (2022), based on empirical information, indicate that the increase in environment-oriented technological innovation by 1% results in approximately a. The findings reveal the need to invest in significant environmental benefits that contribute to the growth of the economy when promoting green technology innovation. The same effects are achieved through the governance measures when green growth is included in the sustainable development plans. Employment of practices supporting the growth of renewable energy, sustainable agriculture, and circular economy savings enhances the economy without causing much impact on the environment (Agarwal, 2025). The study of Tariq et al. (2024) determined that adequate green finance and governance are important in curbing ecological damages. It is indicated by the study that specific policy initiatives supported through financial incentives initiate green investment, hence, achieving benefits that meet the economic and environmental objectives. Habib et al. (2024) describe the interplays between green finance, governance standards, and ecological sustainability in detail. Their analysis of the situation reveals the fact that good institutional governance and efficient anti-corruption regulation contribute a lot to amplifying the impact of green finance, thus assisting in stabilizing the ecosystems and enhancing the effectiveness of green finance.

Hassan et al. (2023) found that green electricity, regulation policies, and institutional strength promote environmental sustainability. From their findings, the uprising from the challenges of inefficiency and corruption can have a massive multiplier expansion on the capacity of green growth to reduce the ecological footprint. Green finance can be effectively used in promoting environmental sustainability. As reported by Jóźwik et al. (2025), an increase in green investments is associated with a significant decrease in ecological footprints in many countries. Such an outcome accentuates the role of financial instruments in a successful transformation of the Sustainable Development Goals into reality. The use of the fiscal policy, i.e., environmental taxes, is very important. As reported by Saqib et al. (2025), the simultaneous use of environmental taxes and green energy alternatives leads to profound shrinkage of ecological footprints; an overwhelming proportion of the footprints' reduction is caused by the individual's and businesses' preferences. Such findings bring out the need for complementary financial approaches in achieving the green growth objectives.

2.4. Renewable Energy and Ecological Footprint

The transition to renewable energy (RE) is widely regarded as an important step towards environmental sustainability. Gkalonaki and Karatzas (2022), Winardi and Zm (2023), and Lamhamedi and Vries (2022). Renewable energy sources, which include solar, wind, hydro, geothermal, and bioenergy, have enormous potential to reduce greenhouse gas emissions, combat climate change, and ensure a stable energy supply. The investigation of the land-energy nexus by Lamhamedi and Vries (2022) even discovers the complex responses of ecosystems to different renewable energy adaptations and highlights the concerned interactions between land consumption and energy production. These analyses help to reveal that even though renewables may come with some localized environmental costs, the benefits they provide in advancing our sustainability objectives often exceed those costs.

According to the reviews of Tira et al. (2023) and Liu et al. (2024), wind and solar technologies are more environmentally friendly. Also, the economic elements of the shift towards renewable energy in national electricity networks must be considered. From the findings of Jafri and Liu (2023) and Byaro et al. (2023), it is evident that the expansion of renewable energy adoption is positively correlated with sustainable development indices, thus making progress towards the United Nations Sustainable Development Goals (SDGs). According to Koval et al. (2023), more and more countries are recognizing that renewable energy investments strengthen the integrity of the environment and the economy, and create jobs, prompting conversations on the transition, prioritizing clean energy resources. Case studies and empirical research Bashir et al. (2021), and Rakhmatov et al. (2024) highlight the uniqueness of these challenges across countries, reinforcing the argument for greater financial incentives and compliance measures to promote renewable solutions across global society.

Although renewable and non-renewable energy systems have different impacts, renewable energy systems typically have a smaller environmental footprint. This is especially in assessing life cycle assessments (LCA) of alternative energy technologies. Studies of Neumüller et al. (2023), Jiaduo et al. (2023), and Basit et al. (2022) show that renewable energy projects, such as solar and wind farms, produce less carbon emissions and resource demand than fossil fuel systems. Nevertheless, Liu et al. (2022) and Amk and Ms (2021) state that to achieve broader environmental assessments, it is essential to comprehend the overall environmental effects of renewable energy technologies from the emissions deriving from material extraction and the construction stages of projects. Ekechukwu and Simpa (2024), and Bozkaya et al. (2023) showcase that Renewable energy technologies are clearly preferable to fossil fuels in terms of pollutants and ecological degradation, as they provide substantial reductions in CO_2 emissions and improved air quality.

The socio-economic aspects of renewable energy adoption also deserve acknowledgment. There is a growing awareness in the literature of Uzondu and Joseph (2024) and Rakhmatov et al. (2024) that RE projects can contribute to community and local economy development, and potentially enhance societal resilience with the implementation of equitable distribution practices. Consequently, it is important to work towards guaranteeing that the advantages gained from renewable energy drive greater livelihood, and not just energy access. Moreover, according to Balžekienė and Budžytė (2021) and Tira et al. (2023) this dimension indicates the need for a more inclusive energy transition that is based not just on the technological dimension but also equitable and socially just in the environmental approach. However, substantial barriers remain. Adebayo et al. (2021) and Odunaiya et al. (2024) emphasize that, especially in developing economies, the adoption of renewable energy technologies has been hampered by high upfront costs, low capacity infrastructure, and institutional weaknesses. Furthermore, Achuo and Ojöng (2023) and Mukhtarov (2023) state that the risk of leaning too much on renewables can only be mitigated through a mix of energy. The report of Winardi and Zm (2023) state that the transitional phase offers opportunities for technology advancement, efficiency gains, and circular economy promotion that can aid environmental sustainability without threatening overall economic stability.

3. DATA AND METHODOLOGY OF THE STUDY

3.1. Model Specification

The motivation of the study is to gauge the role of renewable energy in subduing the environmental degradation in 25 top tourism nations in terms of total international tourist arrivals are: France, Spain, United States, China, Italy, Turkey, Mexico, Thailand, Germany, United Kingdom, Japan, Greece, Austria, Portugal, Malaysia, Russia, Netherlands, Canada, Saudi Arabia, Hong Kong, South Korea, Singapore, Croatia, Indonesia, and Vietnam for the period 2002-2022. The choice of panel data is strategic, allowing us to capture both cross-sectional (between-country) and temporal (over-time) variations, enhancing the robustness and generalizability of our findings. Ecological footprint (EF) is the dependent variable, and renewable energy consumption (REC), green growth (GG), environmental innovation (EI), and financial development (FD) are the explanatory variables. After applying the natural logarithmic transformation to reduce heteroscedasticity and facilitate elasticity interpretation, the base empirical model is specified as:

Equation (1):

$$EF_{it} = f\,(REC_{it}, GG_{it}, EI_{it}, FD_{it}) \quad (1)$$

Where, i represents the country (i = 1..., 25), t denotes the year (2002 ≤ t ≤ 2022). All variables are expressed in their natural logarithmic form. Translating the functional form into a linear panel regression model with fixed or random effects, the model becomes:

Equation (2):

$$\ln EF_{it} = \alpha_i + \beta_1 \ln REC_{it} + \beta_2 \ln GG_{it} + \beta_3 \ln EI_{it} + \beta_4 \ln FD_{it} + \varepsilon_{it} \quad (2)$$

Where, α_i captures country-specific fixed effects, β_1, β_2, β_3, β_4 are coefficients representing the elasticity of EF with respect to the explanatory variables, εit is the idiosyncratic error term.

3.2. Dependent Variable: Ecological Footprint (EF)

Ecological footprint quantifies the biologically productive land and water area required to produce the resources consumed and absorb the wastes generated by a population, under prevailing technology and resource management practices. The study used Global hectares per capita (gha/capita), as compiled by the Global Footprint Network. EF is a multidimensional indicator encompassing carbon emissions, forest land use, fishing grounds, built-up land, and cropland. It is increasingly used as a holistic alternative to CO_2 emissions (Wackernagel and Rees, 1996; Usman et al., 2020). Its comprehensive nature is particularly pertinent in tourism-dependent countries, where the ecological impact spans across sectors

3.3. Independent Variables Definitions, Proxy Measures, and Anticipated Sign of Coefficients

Renewable Energy Consumption (REC), REC reflects the share of energy derived from renewable sources—such as hydro, wind, solar, geothermal, and biomass—in total final energy consumption. The study considered Renewable energy consumption (% of total final energy consumption), sourced from the World Bank's World Development Indicators (WDI). Renewable energy mitigates environmental degradation by reducing reliance on fossil fuels. In the context of ecological modernization theory, it plays a central role in technological and institutional reform that leads to more sustainable outcomes (Qamruzzaman, 2025). Empirical research consistently demonstrates a negative relationship between REC and EF This link is especially relevant in tourism-driven economies where energy demand is high due to infrastructure, transportation, and accommodation services. An increase in renewable energy consumption is expected to reduce EF, justifying a negative sign for β1 significantly. The ecological modernization theory argues that technological advancements and cleaner energy systems decouple environmental harm from economic growth. In the context of tourism-centric countries, high energy demand from transportation, accommodation, and infrastructure amplifies environmental stress. Therefore, transitioning to renewable energy sources—solar, wind, and hydro—can curb fossil fuel reliance and mitigate ecological overshoot (Lee and Min, 2015; Mukhtarov, 2023). This relationship has been validated in several empirical studies, making REC a pivotal variable in sustainable development analyses. Green growth refers to fostering economic growth and development while ensuring that natural assets continue to provide the resources and environmental services necessary for human well-being. Adjusted net savings (% of GNI) as provided by the World Bank. Green growth incorporates environmental considerations into economic development strategies. It aligns with the Environmental Kuznets Curve (EKC) hypothesis, which suggests that environmental degradation increases in early stages of economic growth but decreases after reaching a certain income threshold due to increased environmental awareness, regulations, and clean technologies. Studies have shown that countries prioritizing green investments and sustainability exhibit declining EF over time (Muhammad et al., 2022; Muhammad et al., 2020; Usman et al., 2020). The coefficient β2\beta_2β2 is also expected to be negative, as green growth initiatives are designed to harmonize economic development with environmental preservation. Green growth includes investment in clean technologies, regulatory frameworks for sustainable production, and eco-efficient infrastructure. The theoretical foundation lies in the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation initially rises with income but eventually declines as nations invest in environmental regulation and cleaner technologies (Grossman and Krueger, 1995). Tourism economies that institutionalize green growth policies—such as eco-tourism and energy-efficient transport—can reduce their ecological burdens.

Environmental innovation refers to the introduction and diffusion of new technologies, products, or processes that reduce environmental harm. Study considered R&D expenditures in environment-related sectors (% of GDP), often available from OECD or WIPO databases. Endogenous growth theory underscores the role of innovation in enhancing productivity and sustainability (Romer, 1990). Environmental innovation facilitates energy efficiency, waste minimization, and decarbonization, contributing

Table 1: Variables, proxy, data sources, and anticipated sign

Variable	Notation	Proxy Measure	Data Source	Expected Sign
Ecological Footprint	EF	Global hectares per capita (gha/capita)	Global Footprint Network	Dependent Variable
Renewable Energy Consumption	REC	Renewable energy consumption (% of total final energy consumption)	World Bank (WDI)	Negative (Î²â, < 0)
Green Growth	GG	Adjusted net savings (% of GNI)	World Bank	Negative (Î²â,, < 0)
Environmental Innovation	EI	Environmental-related R&D expenditures (% of GDP)	OECD/WIPO	Negative (Î²â,*f* < 0)
Financial Development	FD	Domestic credit to the private sector (% of GDP)	World Bank	Ambiguous (Î²â,,,)

to a reduced EF (Carfora et al., 2022; Sinha et al., 2023). Given the structural transformation and service intensification in tourism economies, EI can yield substantial environmental dividends through innovations in green infrastructure and sustainable mobility. The sign of β3 is expected to be negative as well. Environmental innovation involves the creation and diffusion of new technologies that improve environmental performance, such as emission-reducing systems, sustainable architecture, and low-impact logistics. In high-tourism nations, environmental innovation is particularly critical in offsetting the pressures of large tourist inflows.

Financial development describes the extent and efficiency of financial markets and institutions in mobilizing capital and allocating it productively. As a measurement of FD, the study utilized Domestic credit to the private sector (% of GDP) as available from the World Bank.

The effect of FD on EF is theoretically indeterminate. On the one hand, well-functioning financial systems can support sustainable investment, green bonds, and low-carbon technologies (Sadorsky, 2011). On the other hand, unregulated financial expansion may incentivize excessive industrialization, overconsumption, and environmental negligence (Tamazian and Rao, 2010). This duality renders the coefficient sign ambiguous. For tourism economies, the quality and orientation of financial flows—towards sustainable tourism or carbon-intensive infrastructure—can critically shape their environmental trajectory (Anthony Osei, 2019). The coefficient β4 is theoretically ambiguous. Financial development can enhance sustainability by mobilizing capital for green investments, supporting eco-entrepreneurship, and facilitating environmental risk management (Sadorsky, 2011). However, in the absence of regulatory oversight, financial liberalization may spur environmentally harmful consumption and industrial expansion. For tourism economies, the environmental outcome of financial development hinges on how effectively financial resources are allocated—toward sustainability or toward unchecked growth. Tabe 1 displayed the details of research variables.

The Variance Inflation Factor (VIF) analysis presented in Table 2 indicates no evidence of multicollinearity among the independent variables. All VIF values are well below the conventional threshold of 10, with the highest being 1.5975 for the dependent variable proxy. The mean VIF of 1.4155 further confirms a low degree of collinearity across the model. These results suggest that the estimated coefficients are reliable and unaffected by redundant information among the regressors, ensuring robustness in the interpretation of the regression outputs. Thus, the model maintains statistical validity for further inference and policy implications in sustainability analysis.

Table 2: Outputs from VIF analysis

Output	REC	GG	EI	FD	Y
VIF	1.1048	1.1368	1.5869	1.2173	1.5975
1/VIF	0.9051	0.8796	0.6301	0.8214	0.6259
Mean VIF	1.4155				

3.4. Estimation Strategies

The cross-sectional dependence (CD) test proposed by Juodis and Reese (2022) provides a robust diagnostic tool for detecting cross-sectional dependence in panel data models, particularly those characterized by unobserved common factors. Traditional CD tests, such as Pesaran's (2004), can suffer from size distortions under strong cross-sectional dependence or in the presence of unbalanced panels. Juodis and Reese address these limitations by introducing a refined CD test that adjusts for potential factor structure in the residuals, thereby increasing reliability and robustness.

$$CD_{JR} = \sqrt{\frac{2T}{N(N-1)}}\sum_{i<j}\hat{\rho}_{ij}^{JR}\ with\ \hat{\rho}_{ij}^{JR} = \frac{\tilde{e}_i'\tilde{e}_j}{\sqrt{(\tilde{e}_i'\tilde{e}_i)(\tilde{e}_j'\tilde{e}_j)}} \qquad (3)$$

where e^i and e^j are residuals from individual regressions. This formulation ensures that the statistic maintains desirable asymptotic properties under various forms of cross-sectional dependence and panel dimensions.

A key benefit of the Juodis and Reese CD test is its robustness to incidental parameter problems and factor structure misspecification. This makes it particularly suitable for macroeconomic panels and large datasets commonly used in empirical research. The test remains valid even when the number of periods is small relative to the cross-sectional dimension. The use of this test is justified when evaluating the validity of independence assumptions in error terms across cross-sectional units. Confirming or rejecting cross-sectional independence is crucial for accurate inference, especially when using estimators that assume independence across units.

The SH test proposed by Bersvendsen and Ditzen (2021) is a diagnostic tool designed to detect slope heterogeneity in panel data models. Traditional panel estimators often assume slope homogeneity across cross-sectional units, which can be restrictive and misleading when heterogeneity exists. The SH test addresses this by examining whether individual slope coefficients differ significantly across units. The basic concept is grounded in testing the null hypothesis of slope homogeneity against the alternative of heterogeneity. Formally, for a panel regression model

$$yit=\alpha i+\beta ixit+\epsilon it ,$$

The test evaluates the hypothesis $H0:\beta i=\beta\ \forall I$ versus $H1:\beta i\neq\beta j$ for some $i\neq j$. The SH test statistic is based on a transformation of pairwise differences of slope estimates, standardized by their variances. One key benefit of the SH test is its robustness to cross-sectional dependence and nonstationarity, making it suitable for macro panels where such issues are prevalent. Moreover, it does not require strong parametric assumptions and can be applied to heterogeneous dynamic panels. The justification for its use lies in the importance of recognizing heterogeneity in empirical models. Misleading inferences may arise if heterogeneity is ignored, potentially biasing coefficient estimates and affecting policy implications. Therefore, the SH test serves as a vital diagnostic prior to applying pooled estimators, ensuring the model specification aligns with the underlying data structure.

Panel unit root tests are essential tools in econometrics for determining the stationarity properties of variables across cross-sectional units over time. Among the advanced methodologies, the Cross-sectionally Augmented Dickey-Fuller (CADF) and Cross-sectionally Im-Pesaran-Shin (CIPS) tests represent significant developments, particularly in accounting for cross-sectional dependence—a common feature in macroeconomic panel datasets.

The CADF test, introduced by Pesaran (2007), augments the standard ADF regression with cross-sectional averages of lagged levels and first differences of the series. This adjustment mitigates the bias from unobserved common factors. The CADF test is applied individually to each cross-sectional unit, and its test statistic is used to evaluate unit-specific non-stationarity. Formally, it estimates:

$$\Delta y_{it} = \alpha_i + \beta_i\, y_{i',t-1} + \gamma_i\, y^{-}t-1 + \delta_i \Delta y^{-}t + \varepsilon_{it} \tag{4}$$

Where $y^{-}t$ is the cross-sectional average. The CIPS test aggregates the CADF statistics by computing their cross-sectional mean. This allows for a panel-level inference on stationarity, enhancing test power while accounting for interdependencies:

$$CIPS = 1N\sum I = 1NtCADF,I \tag{5}$$

Herwartz and Siedenburg (2008) further refined panel unit root testing by proposing a bootstrap approach to enhance inference under cross-sectional dependence. Their methodology employs factor models and recursive bootstrap techniques to construct more reliable critical values, ensuring robustness under Heteroskedasticity and complex dependence structures. Incorporating CADF, CIPS, and the Herwartz-Siedenburg methods enables more accurate detection of unit roots in panels, crucial for dynamic modeling and long-run equilibrium analysis in economic research.

The panel cointegration test developed by Westerlund and Edgerton (2008) offers a robust methodology for assessing long-run equilibrium relationships in panel data, particularly under conditions of cross-sectional dependence and structural breaks. Unlike traditional residual-based tests, this approach is based on structural dynamics and employs error-correction models that directly test for the existence of cointegration by evaluating whether the error-correction term is significantly negative. A key strength of this test is its flexibility in allowing for cross-sectional dependence through bootstrapped critical values and the accommodation of structural breaks at unknown points in the series. This enhances the reliability of inference, especially in macroeconomic panels where policy shifts and external shocks are common. The Westerlund-Edgerton test improves upon earlier methods by maintaining good size and power properties even in small samples, making it especially suitable for empirical research in economics and finance that requires precise long-term relationship validation.

Dynamic Seemingly Unrelated Regression (DSUR), Continuously Updated Bias-Corrected (CUP-BC), and Continuously Updated Fully Modified (CUP-FM) estimators are advanced econometric techniques for panel cointegration analysis that offer robust estimation in the presence of cross-sectional dependence, non-stationarity, and endogeneity. These techniques are particularly suitable for macro-panel data models where variables are often integrated of order one (I(1)) and subject to common shocks.

DSUR accounts for contemporaneous correlation across panel units and allows for heterogeneous coefficients. It extends the Seemingly Unrelated Regression (SUR) model to dynamic panels by incorporating lags and cointegration dynamics.

3.4.1. Transformed DSUR equation

$$\Delta EF_{it} = \alpha_i + \delta_{i\Delta X_{it}} + \lambda_{i\left(EF_i,t-1-\beta_{iX_i},t-1\right)} + \varepsilon_{it} \tag{5}$$

Where X_{it} = [REC_{it}, GG_{it}, EI_{it}, FD_{it}] and λ_i captures the speed of adjustment to the long-run equilibrium. DSUR is ideal when error terms across equations are correlated, and the panel consists of heterogeneous dynamics. It efficiently estimates the long-run relationship while considering cross-equation error correlations.

Proposed by Bai et al. (2009), the CUP-BC estimator handles cross-sectional dependence by incorporating common factors extracted from the data. It corrects for bias arising from endogeneity and serial correlation.

3.4.2. Transformed CUP-BC equation

$$EF_{it} = \alpha_i + \beta_1\, REC_{it} + \beta_2\, GG_{it} + \beta_3\, EI_{it} + \beta_4\, FD_{it} + \gamma i' F_t + \varepsilon_{it}$$

Here, Ft are unobserved common factors affecting all cross-sectional units (e.g., global shocks), and γi\gamma_iγi are factor loadings. The CUP-BC method estimates the parameters and factors simultaneously and then corrects the estimator for asymptotic bias. CUP-BC is effective when global stochastic trends influence the data. It yields consistent estimates even in the presence of non-stationarity and unobserved common factors, making it suitable for global environmental or financial panel studies.

CUP-FM is similar to CUP-BC but uses fully modified procedures to eliminate endogeneity and serial correlation without relying solely on bias correction.

3.4.3. Transformed CUP-FM equation

$$EF_{it} = \alpha_i + \beta_1\, REC_{it} + \beta_2\, GG_{it} + \beta_3\, EI_{it} + \beta_4\, FD_{it} + \gamma i^{\wedge}{}'\, F_t + \eta_{it} \quad (6)$$

It adjusts for endogeneity by non-parametrically correcting the long-run covariance between the regressors and the residuals, providing efficient and unbiased estimates. CUP-FM is particularly useful when there is strong endogeneity among variables. It is more robust than traditional FM-OLS in the presence of cross-sectional dependence and is recommended when estimating long-run equilibrium relationships.

Each technique—DSUR, CUP-BC, and CUP-FM—offers distinct advantages depending on the data characteristics. DSUR is optimal for heterogeneity and correlated errors, CUP-BC for correcting biases under common global shocks, and CUP-FM for addressing endogeneity robustly. Applying these methods to the model $EF_{\{it\}} = f(REC_{\{it\}}, GG_{\{it\}}, EI_{\{it\}}, FD_{\{it\}}$ Ensures credible and consistent estimation of the long-run environmental impacts of renewable energy, governance, and financial indicators.

3.4.4. Transformed equation

$$EF_{i,t} = \alpha_i + \sum_{k=1}^{K}\phi_k\, EF_{i,t-k} + \sum_{k=1}^{K}\beta_{1k}\, REC_{i,t-k} + \sum_{k=1}^{K}\beta_{2k}\, GG_{i,t-k} + \sum_{k=1}^{K}\beta_{3k}\, EI_{i,t-k} + \sum_{k=1}^{K}\beta_{4k}\, FD_{i,t-k} + \varepsilon_{i,t} \quad (7)$$

This lagged structure enables testing for causal influence from each predictor to EFit. The D-H test is ideal for dynamic environmental models as it accounts for individual country behaviors and identifies causal direction, aiding in targeted policy design for renewable energy, governance, and financial development.

Table 3: Results of the SH and CD test

Panel A: CD test of Juodis and Reese (2022)			
Variables →	**EF**	**REC**	**GG**
Test stat value	10.3598***	10.7401***	12.4754***
Probability	***	***	***
CD exist	Yes	Yes	Yes
Variables →	**EI**	**FD**	**Y**
Test stat value	9.9312***	9.2852***	12.8565***
Probability	***	***	***
CD exist	***	***	***
Panel B: SH test of Bersvendsen and Ditzen (2021)			
	Delta Statistic	**Adjusted Delta Statistic**	**SH exits**
Model	3.5899***	5.0756***	Yes

4. ESTIMATION AND INTERPRETATIONS

The results, see Table 3, of the Cross-Sectional Dependence (CD) and Slope Homogeneity (SH) tests provide critical insights into the structure of the panel dataset. In Panel A, the Juodis and Reese (2022) CD test reports statistically significant test statistics for all variables (EF, REC, GG, EI, FD, and Y), confirming the presence of cross-sectional dependence (CD) at the 1% level. This indicates that shocks or policy changes in one country are likely to affect others, a common phenomenon among highly globalized and tourism-intensive nations. Ignoring CD could lead to biased and inefficient estimates. In Panel B, the Slope Homogeneity (SH) test by Bersvendsen and Ditzen (2021) yields a Delta statistic of 3.5899 and an adjusted Delta of 5.0756, both highly significant. This confirms heterogeneity in slope coefficients, implying that the impact of regressors on ecological footprint varies across countries. These findings justify the use of second-generation panel estimators that account for both CD and heterogeneity in empirical analysis.

The panel unit root test results presented in Table 4 confirm the non-stationarity of all variables at their levels and their stationarity at first differences. Across three complementary tests—CADF, CIPS, and Herwartz & Siedenburg (2008)—none of the variables reject the null hypothesis of a unit root at level, indicating that they are integrated of order one, I(1). However, at the first difference, all variables are statistically significant at the 1% level, confirming stationarity. This is a crucial diagnostic step, as it validates the preconditions for applying panel cointegration techniques, such as the Pedroni or Westerlund tests. Ensuring that variables are I(1) protects the model from spurious regression outcomes and supports the integrity of long-run relationship estimations. As expected in macro-panel analyses, especially across countries with heterogeneous structures, these results underscore the importance of differencing for consistent and unbiased estimations.

The results from Table 5, based on the Westerlund and Edgerton (2008) panel cointegration test, strongly reject the null hypothesis of no cointegration under all three model specifications—no shift, mean shift, and regime shift. All LMτ and LMΦ statistics are significantly negative at the 1% level, indicating robust long-run equilibrium relationships among the variables. The consistency of results across structural shifts enhances the reliability of the cointegration evidence, suggesting that renewable energy, green growth, environmental innovation, and financial development maintain stable long-run associations with ecological footprint in the top tourism economies.

4.1. Model Estimation with DSUR, CUP-BC, and CUP-FM

For renewable energy consumption, see output in Table 6, the estimation outcomes reveal a consistently negative relationship between renewable energy consumption and ecological footprint across all models (DSUR = −0.1187; CUP-FM = −0.1318; CUP-BC = −0.0846). This inverse association underscores the mitigating effect of clean energy sources on environmental degradation in the context of the top tourism-intensive nations. More precisely, a 10% change in REC will result in an improvement in ecological stability with a range of 0.846% to 1.318% in the study nations.

Table 4: Results of the panel unit root test

Variables	CADF test statistic		CIPS test statistic		Herwartz and Siedenburg -2008	
	Level	First difference	Level	First difference	Level	First difference
EF	−1.743	−4.648***	−2.56	−4.19***	−0.1212	8.6188***
REC	−2.506	−2.174***	−1.832	−2.593***	0.5722	8.1233***
GG	−1.68	−6.278***	−2.688	−7.559***	0.1119	6.7477***
EI	−1.019	−5.559***	−2.654	−5.175***	0.3301	4.7727***
FD	−2.33	−6.657***	−1.378	−7.28***	−0.9239	6.4084***
Y	−1.764	−5.718***	−1.346	−5.963***	1.7025	5.6902***

Table 5: Results of the panel Cointegration test of Westerlund and Edgerton (2008)

Output	No shift		Mean shift		Regime shift	
	LMr	LMΦ	LMr	LMΦ	LMr	LMΦ
Model 1	−2.7973***	−4.1863***	−4.208***	−3.7951***	−3.6726***	−4.674***

Table 6: Results of DSUR, CUP-FM, and CUP-BC estimation

Variables	Coefficient	Standard error	t-statistic	Coefficient	Standard error	t-statistic	Coefficient	Standard error	t-statistic
	DSUR			CUM-FM			CUP-BC		
REC	−0.1187	0.0388	−3.0592	−0.1318	0.0428	−3.0794	−0.0846	0.0369	−2.2926
GG	−0.124	0.035	−3.5428	−0.0859	0.0441	−1.9478	−0.0415	0.0453	−0.9161
EI	−0.1141	0.0276	−4.134	−0.056	0.034	−1.647	−0.0829	0.0293	−2.8293
FD	0.112	0.037	3.027	0.1169	0.0403	2.9007	0.0856	0.025	3.424
Y	0.1066	0.0442	2.4117	0.1415	0.0438	3.2305	0.0959	0.0453	2.1169
Y2	−0.0772	0.0327	−2.3608	−0.1097	0.0372	−2.9489	−0.0593	0.0343	−1.7288
C	0.1226	0.24013	0.5105	0.1344	0.24013	0.5596	0.0935	0.24013	0.3893
EKC hypothesis		Exist			Exist			Exist	
Anderson canon. Corr. LM statistics		14.969			14.969			14.969	
Cragg-Donald Wald F statistics		1757.004			1757.004			1757.004	
Stock-Yogo weak ID test critical values		18.5247			18.5247			18.5247	

DIV: Ecological footprint (EF) INV: REC for renewable energy consumption; GG stands for green growth; EI for environmental innovation; FD denotes financial development; Y for economic growth; and Y2 for the square of GDP

Our study is in line with the existing literature, see for instance (Addai et al., 2024; Li et al., 2023b), (Nan et al., 2022), (Oprea et al., 2024). These findings reaffirm the theoretical premise of ecological modernization, which argues that environmentally benign technologies—such as solar, wind, and hydro—can decouple economic activities from ecological harm. By displacing carbon-intensive energy sources, renewable energy directly reduces carbon emissions, lowers ecological overshoot, and fosters energy security (Murshed, 2024). Furthermore, tourism-related sectors that are traditionally energy-intensive (e.g., transport and hospitality) stand to benefit substantially from a transition to renewables, enhancing the environmental performance of these economies(Moon et al., 2020).

The policy implications are clear: governments must intensify the deployment of renewable infrastructure, incentivize private investment in green energy technologies, and reform regulatory frameworks to support energy transitions. Key actions include expanding feed-in tariffs, eliminating fossil fuel subsidies, and facilitating grid integration for decentralized renewable sources. Additionally, environmental education campaigns and international partnerships for technology transfer can catalyze long-term sustainability outcomes. These results suggest that increasing the share of renewable energy in the total energy mix is not merely an environmental imperative but also a strategic pathway to achieving lower ecological footprints in service-dominated economies. Hence, consistent and long-term support for renewable deployment is essential to capitalize on its ecological dividends.

Referring to results of green growth, the coefficients for green growth also exhibit a negative sign across estimations (DSUR = −0.124; CUP-FM = −0.0859; CUP-BC = −0.0415), indicating its protective role in reducing the ecological footprint. This finding is consistent with the green economy and EKC hypotheses, which assert that environmentally focused economic growth strategies can curb environmental harm once nations surpass certain developmental thresholds (Hoang et al., 2024; Usman et al., 2023). Green growth encapsulates policies that integrate environmental sustainability into economic planning, such as green budgeting, low-carbon investments, and eco-efficiency standards. The adverse association with EF suggests that such strategies are effective in reducing natural resource depletion and enhancing sustainable production patterns, particularly relevant for the tourism sector, which often exerts stress on water, land, and biodiversity resources (Manisha and Singh, 2025). The findings of (Aydin et al., 2023) advocated that to enhance the role of green growth, states should focus on mainstreaming sustainability into macroeconomic planning, including embedding climate resilience into national development strategies, supporting green SMEs, and mandating environmental impact assessments for major tourism and infrastructure projects. Furthermore, (Al-mulali et al., 2015) and (To et al., 2019) advocated that green procurement policies and public-private partnerships in sustainable infrastructure can operationalize environmental sustainability. Given the increasingly recognized link between economic policy and environmental outcomes, the evidence supports prioritizing green growth strategies as a core pathway to sustainable tourism economies(Dogru et al., 2020). Facilitating green investment flows, ensuring policy coherence, and engaging local communities in ecological stewardship are pivotal actions for maximizing this effect (Yilanci and Pata, 2020; Mahmoodi and Dahmardeh, 2022).

Environmental innovation displays a negative association with ecological footprint across models (DSUR = −0.1141; CUP-FM = −0.056; CUP-BC = −0.0829), reinforcing the critical role of technological advancement in addressing environmental degradation. These findings align with endogenous growth theory, which recognizes innovation as a driver of both economic and ecological transformation (Na et al., 2023; Camino et al., 2023; Giner et al., 2023). Environmental innovation reduces EF by promoting cleaner production techniques, resource-efficient systems, and carbon-minimizing technologies(Fachini et al., 2022). Within tourism-heavy economies, innovation can manifest through green building designs, electric public transit, and intelligent waste management systems. Importantly, innovations also enable the decarbonization of supply chains and improve the lifecycle sustainability of tourism services (Bootz et al., 2022).

To make sure that development driven by tourism does not exceed ecological boundaries, investing in environmental innovation boosts national competitiveness (Na et al., 2023). To promote environmental sustainability while sustaining long-term economic potential, robust innovation ecosystems are important. According to Camino et al. (2023), areas where land tenure is guaranteed help mitigate deforestation in particularly problematic areas. Furthermore, waterborne illnesses may be influenced by urban infrastructure, including wastewater management systems. Industry 4.0's changes are closely related to digitization, which causes manufacturing organizations to change their operations and connect with digital actors in new ways (Fachini et al., 2022). Novel K-enriched sewage sludge biochar fertilizers may release potassium into natural silica sand, allowing for the production of slow-release fertilizers that cause minimum environmental losses. Human fecal biomarkers allow for the monitoring of human disease transmission in communities and may be used to standardize concentrations of target human pathogens.

In contrast to the previous variables, financial development shows a statistically significant and positive relationship with ecological footprint (DSUR = 0.112; CUP-FM = 0.1169; CUP-BC = 0.0856), indicating that expanding financial systems may exacerbate environmental pressures in the current institutional context. This finding reveals a dual-edged reality: while financial development theoretically facilitates capital mobilization for green investments, in practice, it may also fuel carbon-intensive expansion when sustainability mandates are weak (Haykel, 2025). Increased access to credit can support unsustainable tourism infrastructure, foster mass consumption, and promote urban sprawl, all of which intensify ecological degradation. Addressing this requires targeted financial governance reforms. First, regulatory bodies must enforce environmental disclosure standards and integrate ESG criteria into lending practices. Strong ESG disclosure not only guides investment but also lowers corporate financing costs by aligning capital flows with sustainable practices (Hongxuan, 2023; Yi et al., 2024). Second, green financial instruments—such as sustainability-linked loans, green bonds, and climate-aligned portfolios—should be promoted to align capital allocation with environmental goals (Isha and Geeti, 2024; Sapozhnikov et al., 2024). Evidence suggests these tools can mitigate greenwashing risks and improve firm innovation and ESG performance (Dongyang, 2023; Yi et al., 2024). Finally, capacity-building for financial institutions in evaluating ecological risk is essential, especially where ESG integration is still nascent. Without such mechanisms, financial growth may inadvertently reinforce environmental decline. Therefore, reorienting financial development toward green outcomes is vital to transforming it from a risk factor into a driver of sustainability.

Across all models, the coefficient for economic growth (Y) is positive and statistically significant (DSUR = 0.1066; CUP-FM = 0.1415; CUP-BC = 0.0959), suggesting that increased levels of economic output, as measured by GDP, contribute to the expansion of ecological footprints. This direct relationship confirms the environmental cost associated with the scale and intensity of economic activity in tourism-dominated economies. Numerous studies support this view, showing that economic growth tends to increase ecological degradation through higher energy consumption, infrastructure expansion, and resource exploitation (Kongbuamai et al., 2020; Nathaniel et al., 2021; Tarkang et al., 2022). At its core, economic expansion often results in elevated resource consumption, energy demand, and environmental disruption—particularly in sectors like construction, transportation, and mass tourism (Koyuncu, 2024). For many developing and emerging economies, this stage is characterized by infrastructural expansion and industrial growth that prioritize short-term gains over ecological considerations. Consequently, GDP growth may intensify land use changes, increase carbon emissions, and overburden ecosystems (Jiang et al., 2022). This positive association necessitates policy interventions that temper growth-driven environmental degradation. Governments must adopt growth strategies that internalize environmental externalities. Instruments such as carbon pricing, pollution taxes, and ecosystem service valuations can ensure that environmental costs are accounted for in economic decision-making (Hashemizadeh et al., 2021). Moreover, investing in sustainable tourism—emphasizing local sourcing, biodiversity preservation, and cultural heritage—can decouple growth from environmental stress (Naveed et al., 2023). Crucially, while economic growth remains a vital developmental goal, the findings underscore that unregulated expansion undermines ecological sustainability. To reconcile development and environmental objectives, growth trajectories must pivot towards low-impact, resource-efficient models that support long-term ecological integrity.

The coefficient for squared economic growth (Y^2) is consistently negative (DSUR = −0.0772; CUP-FM = −0.1097;

CUP-BC = −0.0593), affirming the existence of an inverted U-shaped Environmental Kuznets Curve (EKC). This result implies that after surpassing a certain income threshold, further economic growth contributes to environmental improvement, as societies shift toward cleaner technologies and sustainable practices. Empirical evidence from tourism-intensive and developing regions, including Turkey and the BRICS countries, confirms the EKC pattern—showing that while early stages of economic and tourism growth are associated with increased emissions, further income growth leads to emission reductions (Noshaba et al., 2020). This transition is typically driven by increased public awareness, stronger environmental regulations, and the availability of capital to invest in eco-friendly infrastructure. Studies confirm that effective environmental policies, institutional strength, and investment in renewable energy are key to sustaining this shift (Raimondas, 2004; Sami and Elif, 2020). In higher-income economies, policy frameworks often evolve to prioritize sustainability through regulatory standards, green certification programs, and fiscal incentives for low-carbon innovation. As such, economic maturity fosters institutional and technological conditions conducive to reducing ecological footprints. For tourism-intensive nations, this turning point is critical. Policymakers must leverage economic gains to enhance environmental governance, enforce tourism zoning regulations, and promote sustainable infrastructure. Public investment should favor green urbanism, smart transport systems, and renewable energy integration in the tourism supply chain. The existence of the EKC suggests that economic development does not inherently conflict with environmental sustainability, but the transition requires deliberate planning and strategic resource allocation. Countries approaching or surpassing the EKC turning point should consolidate progress through robust institutions, green fiscal policies, and ecosystem protection initiatives to ensure lasting environmental gains.

4.2. D.H. Causality Test

The Dumitrescu-Hurlin (D-H) panel causality analysis, see Table 7, reveals significant directional interdependencies among the variables. Specifically, bidirectional causality (↔) is observed between ecological footprint (EF) and renewable energy consumption (REC), green growth (GG), environmental innovation (EI), and economic growth (Y). These results imply mutual influence: not only do these factors affect ecological sustainability, but environmental outcomes also feed back into shaping energy policy, innovation strategies, and growth trajectories. For example, as EF worsens, it may drive stronger renewable adoption or innovation responses, while increased REC or EI further reduces EF. Unidirectional causality (→) is found from financial development (FD) to EF, indicating that changes in FD significantly impact ecological outcomes, but not vice versa. This suggests financial systems may act as a driver of environmental degradation or sustainability, depending on how capital is directed, but EF trends do not significantly alter financial structures in return. These findings underscore the need for integrated policies: improvements in REC, GG, and EI can enhance sustainability, while EF trends should inform their strategic design. Conversely, regulatory oversight is crucial in financial sectors to mitigate their potential ecological impacts. Understanding these feedback loops is vital for creating adaptive and resilient environmental policy systems.

Table 7: Output of DH causality analysis

Null hypothesis	W-Stat.	Zbar-Stat.	Remarks	
EF<==/==>REC	4.4303	4.6695	<---->	Bidirectional
REC<==/==>EF	7.0446	7.425		causality
EF<==/==>GG	10.1349	10.6821	<---->	Bidirectional
GG<==/==>EF	8.4325	8.8878		causality
EF<==/==>EI	6.7183	7.081	<---->	Bidirectional
EI<==/==>EF	5.882	6.1996		causality
EF<==/==>FD	3.8724	4.0815	-->	Unidirectional
FD<==/==>EF	3.3251	3.5046		causality
EF<==/==>Y	7.2019	7.5908	<---->	Bidirectional
Y<==/==>EF	7.3039	7.6983		causality

DIV: ecological footprint (EF) INV: REC for renewable energy consumption; GG stands for green growth; EI for environmental innovation; FD denotes financial development; Y for economic growth; and Y2 for the square of GDP

5. CONCLUSION, POLICY SUGGESTIONS, AND FUTURE RESEARCH DIRECTION

5.1. Conclusion

This study provides robust empirical evidence on the interplay between environmental innovation, financial development, green growth, and renewable energy in reducing ecological footprints across the world's top 25 tourism-dependent nations. The results consistently highlight that increased renewable energy consumption, green growth policies, and environmental innovation all exert significant negative effects on ecological footprints, indicating their collective effectiveness in mitigating environmental degradation. Notably, renewable energy deployment emerges as a central pillar, providing a direct pathway to decouple economic growth from environmental harm, especially in energy-intensive tourism sectors. Green growth, supported by effective macroeconomic and sustainability-driven policies, further reduces ecological pressure by fostering resource-efficient infrastructure and eco-friendly business practices. Similarly, the advancement and diffusion of environmental innovations—such as cleaner technologies and sustainable urban systems—contribute to long-term ecological stability. However, the analysis also uncovers a nuanced reality regarding financial development. While theoretically it can support green transitions through capital mobilization, the findings reveal a positive association between financial development and ecological footprint in the current context, suggesting that financial flows may often be directed toward unsustainable growth unless robust regulatory frameworks are in place.

5.2. Policy Suggestions

Based on the findings of this paper, a multi-faceted policy approach is needed to ensure that the ecological impacts embodied in the tourism-intensive economies and beyond are effectively mitigated. First, Governments will want to begin right away by accelerating the rapid deployment of renewable energy using a mix of regulatory reform, targeted subsidies, and public-private partnerships. Feed-in tariffs, renewable portfolio standards, and tax incentives, among other policy tools, can promote the development of solar, wind, and other CLEAN energy sources. Equally important is the withdrawal of fossil fuel subsidies and a strong carbon price that internalizes environmental costs and lets the market select low-carbon options. The support for international technology transfer, specifically to developing countries dependent on tourism, can also facilitate advanced renewable technology acceptance and economics.

Second, for green growth to derive optimal benefits, economic development strategies need to embed environmental sustainability at every phase of their development. Governments should mainstream green budget practices, Environmental impact assessments (EIAs) for all large infrastructure and tourism projects, and the promotion of green small and medium enterprises (SMEs) should be supported by governments. Eco-friendly products and services should receive preference in public purchasing policies, and support for sustainable tourism, from ecocertification schemes to backing for local, low-impact industries, scaled up. Public sector: national and local authorities should also promote public participation and environmental education, and inform/create awareness among the public, the relevant stakeholders about the importance of green initiatives and ways through which their sustainability can be ensured.

Third, Filled investment in research and development at all levels is necessary to stimulate environmental innovation investment by the public sector and emerging innovation ecosystems formed by collaboration among academia, industry, and government. Green R&D grants, innovation incubators, and public contests are some of the ways to spur the development and dissemination of frontier technologies in energy, transportation, and waste management. "Policies should encourage digitalization and intelligent management of urban and tourism infrastructure to improve the utilization of resources and reduce environmental impact," it says. IP regimes should also incorporate a mixture of protection and openness to make sure crucial environmental solutions are largely accessible, including in low-income settings.

Fourth, Policymakers should impose strict ESG criteria on the financial sector, requiring ESG disclosure and a standard for green lending by all banks and lending institutions. Greater issuance of green bonds, sustainability-linked loans, and climate funds will help guide investments towards jobs that generate a measurable environmental benefit. Meanwhile, financial regulators must supervise against the risks of greenwashing, ensuring that only truly sustainable projects are given preferential treatment. Efforts to build the capacity of financial professionals and institutions to understand better and address ecological risks are needed.

5.3. Limitations and Future Research Direction

The study's considered robust methods, such as cross-sectional dependency, panel cointegration, and causality analysis, make sure that the results are strong and may be used in other situations. Still, certain problems need to be addressed. First, using national statistics as a whole may hide differences between regions and changes in individual sectors within nations. Second, the research does not clearly show how geopolitical threats, institutional quality, or international collaboration might change the consequences of the major factors. Third, although focusing on economies that depend on tourism is useful for making policies, it may not completely show how the environment works in areas with few tourists or those that are still growing. Furthermore, the Environmental Kuznets Curve (EKC) pattern is validated, but we still do not know when and how well policies will work at various phases of economic growth.

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