GREEN FINANCE AS A CATALYST FOR TECHNOLOGICAL INNOVATION: A HETEROGENEOUS ANALYSIS OF EMERGING ECONOMIES

Saqib Munir*, Khawaja Zeeshan Waheed**

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Abstract

The role of green finance in driving technological innovation in resource-constrained emerging economies is examined. Despite substantial inflows, many nations struggle to convert funds into green technology advancements, prompting questions about finance-innovation mechanisms. Empirical evidence on heterogeneous impacts of green finance flows on technological innovation is extended, incorporating moderators like institutional quality, energy market dynamics, trade openness, and human capital development. Data from 2004–2023 across 10 BRICS economies (WDI, WGI) are analysed using fixed-effects panel regression and instrumental variable estimation. Renewable Energy Consumption (REC), a proxy for green finance, positively influences technological innovation; a 1% REC increase is associated with a 6.29% innovation rise. Strong institutions amplify this effect while trade openness unexpectedly weakens it. Energy intensity strengthens the linkage, whereas education expenditure negatively moderates it. Prioritization of institutional reforms and alignment of green finance with supportive policies are suggested to maximize technological innovation and advance sustainable development goals (SDGs). Regional variations and feedback loops should be validated to deepen the understanding of technological innovation dynamics.

Keywords: Green finance, technological innovation, BRICS, institutional quality, Sustainable Development Goals

JEL: Q55, Q56, O31, G20.

1. Introduction

Global transformation towards the achievement of sustainable development has become one of the hallmark challenges of the 21st century (John, 2025; Leite, 2022; Ramanathan and Isaksson, 2023), but in discussions on the avenues through which emerging economies can successfully harness opportunities to mobilise financial resources and spur technological innovations, little is known about the underlying mechanisms. Global transformation toward sustainable development highlights challenges in mobilizing green finance for technological innovation in emerging economies. A critical empirical gap exists in understanding how green finance flows translate into green technology advancements, given institutional and market constraints (Ali *et al*., 2024; Sethi *et al*., 2024). This study examines heterogeneous impacts on technological innovation, integrating institutional quality, energy market dynamics, trade openness, and human capital as moderators, using fixed-effects panel regressions and instrumental variable estimation across BRICS economies (2004–2023).

The green finance and technological innovation literature has grown robustly in the last 10 years, but it has nonetheless remained fragmented and addresses several disciplinary limits. The initial work on this literature was mostly composed of contributions that were mainly made on the basis that conventional financial instruments were positive to economic growth without saying anything about the environmental effects such activities had (Behera *et al*., 2024; Kashif *et al*., 2025). Recently more scholarly work has begun to focus on the role of green finance with a significant amount of attention paid to the aspect of sustainability and sustainability goals and more specifically to renewable energy adoption and carbon emissions reductions (Feng *et al*., 2024; Onifade & Alola, 2022). However, existing research tends to treat green finance as a monolithic construct without making distinction of the heterogeneity in its forms such as foreign direct investment (FDI) directed towards renewable projects versus official development assistance for environmental projects and their different effects on innovation. Furthermore, while some studies highlight the role of institutional quality and trade openness as moderating factors of green finance (Raza *et al*.,

* Department of Economics, NUST Institute of Peace and Conflict Studies (NIPCONS), Islamabad, Pakistan. Email: saqibmunir@gmail.com; saqibme@nipcons.nust.edu.pk; drsaqib_econ@nipcons.nust.edu.pk

** Department of Management Sciences, Capital University of Science and Technology, Islamabad, Pakistan. Email: saigol@ymail.com

2024; Wang, 2025), a number of studies argue that a more robust understanding of green finance is required if the effects of such factors on overall effectiveness of green finance can be assessed (Fang & Shao, 2022; Kharb *et al*., 2024). These divergent perspectives reflect unresolved debates about the precise mechanisms through which green finance influences innovation and underscore the need for a more nuanced analytical framework.

This paper will seek to address these gaps by providing a proper review into how different types of green finance flows impact technological innovation in emerging economies whilst accounting for moderating factors such as institutional quality, energy market dynamics, trade openness, and human capital development. Specifically, we contribute to the literature in three key ways. First, our study offers a novel theoretical lens by disaggregating green finance into distinct components, namely, Renewable Energy Consumption (% of Total Final Energy Consumption) and examining their heterogeneous impacts on innovation metrics such as resident patent applications and high-technology exports. Second, we introduce an interdisciplinary approach that integrates insights from innovation systems theory, institutional economics, and environmental policy, thereby enriching the conceptual foundation of the analysis. Third, methodologically, we employ fixed-effects panel regression models alongside instrumental variable estimation techniques to address potential endogeneity concerns, ensuring robust causal inference.

To achieve these objectives, we draw on a rich array of data sources, including the World Development Indicators (WDI) and Worldwide Governance Indicators (WGI). Key variables include proxies for green finance flows, such as Renewable Energy Consumption (% of Total Final Energy Consumption), as well as measures of institutional quality, energy intensity, trade openness, and human capital expenditure. A notable challenge in constructing this dataset was addressing the missing values and inconsistencies across years, which we mitigated through imputation methods and sensitivity analyses. Additionally, we conducted robustness checks using dynamic panel data models, such as the System Generalized Method of Moments GMM, to account for persistence in innovation metrics and validate our findings. By adopting this rigorous analytical framework, we aim to provide actionable insights for policymakers seeking to design targeted interventions that maximize the impact of green finance on technological innovation.

We started out by outlining the theoretical base that guides our analysis ensuring strong interplay between green finance, institutional contexts, and innovation outcomes. Following this, we describe data sources and the methodologies employed to generate economic models and diagnostic testing to enable robustness. We then present our main empirical results, complemented by robustness checks to underpin the reliability of our findings. Finally, we cover the implications of our findings for both academic research and practical policymaking, highlighting new avenues for future research.

2. Literature Review

There has been a recent trend in the publication of studies exploring the relationship between environmental issues, development economics, and innovation studies. The studies focus on how green finance is trying to enable technological innovation that occurs in these emerging economies. This urgency has been brought about by the importance of climate change mitigation and the Sustainable Development Goals (SDGs) recognition (Munir *et al*., 2025; Qi *et al*., 2025; Solangi *et al*., 2025). Green finance has emerged as a very important tool to direct funds into projects aimed at promoting sustainability (Garcia *et al*., 2023). Although green finance has been widely researched at the macro level (e.g., carbon emission reduction and renewable energy adoption) its effects have not been researched at a micro level especially in developing countries, where the lack of resources often blocks local investments in green technology.

The theoretical background of this study rests on endogenous growth theory, which regards innovation as an important force of long-term economic growth (Rivera & Romer, 1990). In this context, green finance can, in principle, be considered a vehicle for innovation as it can mobilize the finance required by companies to

carry out R&D studies devoted to sustainability. Furthermore, institutional theory (North, 1990) highlights the mediational role of governance mechanisms and regulatory systems in the effectiveness of green finance mechanisms. For instance, (Ali *et al*., 2024) maintain that quality of institutions mediates the set of relationships between green finance and environmental effects, hinting that poor institutions could impede the flow of financial assets into real innovations. Collectively, these theoretical frameworks offer a powerful framework for examining how various modes of green finance flows facilitate technological innovation and how these effects should be considered in the context of variables such as institutional quality, trade openness, and human capital accumulation.

Historically, the narrative of green finance has progressed from its genesis in mainstream environmental economics to encompass larger aspects of sustainable development. Initial research has concentrated on the contribution of public funding and subsidies to green action (Kashif *et al*., 2025). Recent authors have started to consider the contribution of the private sector, with a focus on FDI and official development assistance (ODA) specifically allocated to environmental aims (Behera et al., 2024; Dua & Verma, 2024). Although progress has been made there is still a lack of understanding regarding the heterogeneity of green finance flows and their strong effects on innovation, which requires further exploration. Seminal contributions to the field of green finance and technological innovation include works by (Borojo, 2024; Fatima *et al*., 2024; Onifade & Alola, 2022) who stress the contrasting functions of green finance as both reducing environmental damage and promoting economic development. Similarly, (Behera *et al*., 2024; Sethi *et al*., 2024) stress the necessity of matching financial instruments with SDG objectives in order to make real positive changes towards sustainability. Taken together, these studies highlight the transformative role of green finance, yet they do not attempt to traverse the complex interplay with innovation systems.

One of the most important weaknesses of existing theoretical paradigms is that they areare likely to perceive green finance as a whole, overlooking the differences between sources such as FDI, ODA and other funding sources. As an example, (Behera *et al*., 2024; Faheem *et al*., 2024; Kharb *et al.*, 2024) indicate that FDI towards renewable energy projects have a higher probability of generating an innovation than is typically the case with the general ODA (although not many studies do comparisons in this way). Moreover, the moderate role of institutional quality is an undertheorized concept, even though evidence suggests that efficient relations between robust legal frameworks and green finance are important (Afzal *et al*., 2022; Akomea-Frimpong *et al*., 2022; Raza *et al*., 2024). Green finance and technological innovation have been empirically analysed with a mix of methodologies such as cross-sectional regressions, panel data models, and structural equation modelling. Interestingly, (Adeyemo *et al*., 2024; Ali *et al*., 2024) utilise such sophisticated methods as cross-sectional autoregressive distributed lag (CS-ARDL) or common correlated effects mean group (CCEMG) estimators in order to overcome endogeneity and heterogeneity problems. Their findings indicate that the green finance positively impacts the green economic growth, but the difference is very high at the country level. Nevertheless, there are a number of shortcomings in the empirical literature. To begin with, the majority of the studies employ aggregated metrics of technological innovation (U.S. patent applications or high-tech exports) that may not be as comprehensive as the green innovation spectrum (Qi *et al*., 2023). Second, the moderating role of energy market dynamics, trade openness, and human capital development remains underexplored-this information can have significant implications to the orientation of green finance and innovation. Lastly, the majority of empirical studies are based on developed economies or developing economies, and there is little research on the comparative analysis of green finance mechanisms with regard to income classes (Fang & Shao, 2022). There are two main shortcomings of the previous research methodologically. To begin with, much of the research fails to consider the dynamic nature of innovation processes, and it also assumes the existence of a static model that ignores the persistence and feedback loops (Wang, 2025). Second, very often the use of conventional

econometric approaches does not allow the making of any concrete causal conclusions that are often difficult to make when it refers to such complex phenomena as the field of green finance and technological development. New advances in quasi experimental designs (e.g., difference-in-differences [DiD] designs and instrumental variable designs) offer thrilling possibilities to address these issues (Ma *et al*., 2022).

The evidence of the relationship between green finance and technological innovation is inconsistent about geographic locations and application sites. In advanced economies, studies consistently show that green finance fosters innovation by lowering barriers to entry for clean technologies (Shen *et al*., 2025). For example, (Bhutta *et al*., 2022; Dai *et al*., 2024; Onifade & Alola, 2022; Wu *et al*., 2022) report a significant correlation between the issuance of green bonds and R&D investment by European companies. In contrast, evidence from developing countries is more ambiguous. Although some authors document large improvements on innovation measures after green finance flows increase (Irfan *et al*., 2022; Liu & Wang, 2023; Zhang *et al*., 2022), others warn against attributing too much credit to green finance flows because of institutional deficiencies and market frictions (Kharb *et al*., 2024).

By virtue of comparative analyses (Waheed & Khan, 2025), it is also discovered that there are differences in the efficient performance of various green finance tools. For example, (Aziz & Jahan, 2023; Kashif *et al*., 2025) report that net FDI inflows associated with renewable energy projects generate greater innovation returns than ODA on average, with greater returns observed in countries that have established financial-market economies. Similarly, (Qi *et al*., 2025) show that green finance improves technological innovation only when environmental policies are combined with the provision of support-inducing policies, for example, subsidies for eco-friendly goods and investments in education. These results demonstrate that country-specific contexts and priorities should not be neglected in the development of tailored strategies (Mahmood *et al*., 2024).

Policy-relevant findings arise from research associations between green finance and wider socioeconomic effects. For instance, (Behera *et al.*, 2024; Hunjra *et al*., 2023; Liu *et al*., 2022; Udeagha & Muchapondwa, 2023) suggest that the inclusion of green finance in national development plans can assist emerging economies to move to low-carbon strategies, whilst also generating employment and enhancing living standards. On the other hand, (Andreoni *et al*., 2024; Dziwok & Jäger, 2024; Hou *et al*., 2022) caution against the potential exacerbation of inequity of poorly designed green finance schemes because large corporations could be favoured over SMEs. These paradoxes highlight the complexity of green finance policy design and the need for greater empirical attention.

The theoretical frameworks discussed above provide the foundation for our empirical analysis. Endogenous growth theory underscores the importance of deliberate investments in R&D and human capital, which aligns with our hypothesis that green finance positively affects technological innovation (Hypothesis 1). Institutional theory will particularly support our guess that governance mechanisms of the institutions enhance the impact that green finance has on innovation (Hypothesis 2). Similarly, existingliterature has highlighted trade openness and the dynamics of the energy markets, which inform our hypothesis regarding the moderating effect of these factors (Hypotheses 3 and 4). Finally, the focus on the development of human capital in the innovation capitals tie directly to our hypothesis that education spending will further strengthen the link between green finance and technological innovation (Hypothesis 5). Together, these theories form the basis for our analytical framework which seeks to establish the nuanced relationships between green finance and innovation outcomes. Despite extensive research on green finance and innovation, prior studies rarely disentangle heterogeneous effects across institutional quality, trade, and human capital. This study addresses these gaps by empirically testing these moderating roles in emerging economies.

3. Conceptual Framework

This study draws on two foundational economic theories to analyse the role of green finance in catalysing technological innovation in emerging economies: institutional theory (North, 1990) and endogenous growth theory (Rivera & Romer, 1990). These frameworks provide a robust lens for examining how institutional quality, market dynamics, and financial mechanisms interact to shape innovation outcomes.

Green finance is a variety of financial products and policies which are designed to support environmentally sustainable projects which includes investment projects in renewable energy, carbon reduction initiatives, and green bonds (Akomea-Frimpong *et al*., 2022; Dziwok & Jäger, 2024; Ozili, 2022). It operates in an institutional framework which is satiated with its success and with which its effectiveness is influenced. (North, 1990) in his institutional theory explained that the institutions be they formal (e.g., laws, regulations) or informal (e.g., norms, trust) shape economic behaviour by lowering transaction costs and reducing the level of uncertainty in the business environment. In the context of green finance, a strong institution suggests that green investments will be transparent, implementable in all the details, and sound-enforcing of the environment-based policies, thereby ensuring an expanded credibility for green investments.

Technological innovation measured here as a share of high-technology exports delivered along with manufactured goods represents the creation and diffusion of new technologies. Endogenous growth theory elaborated by (Rivera & Romer, 1990) posits that innovation or new technologies are a result of deliberate investment in human capital, R&D, and high-quality policy environments. This theory where agents represent our focus on green finance to be a driver of innovation ensures that green finance is provided by factors such as trade openness, energy market dynamics, and human capital development.

Two competing perspectives emerge regarding the relationship between green finance and technological innovation:

Complementary Mechanisms Hypothesis: Green finance complements traditional financial systems by channelling resources toward innovative, low-carbon technologies. For instance, FDI targeted at renewable energy projects can spur localized technological advancements (Garetto *et al*., 2025; Kharb *et al*., 2024).

Substitution Effect Hypothesis: Some scholars argue that excessive reliance on green finance may crowd out private sector funding for broader R&D activities, leading to suboptimal innovation outcomes (Huang *et al*., 2022; Xiang *et al*., 2022). This perspective highlights the importance of balancing green finance flows with other forms of capital allocation.

To reconcile these views, we incorporate insights from environmental economics, which underscores the role of externalities in shaping innovation incentives. Green finance addresses negative externalities associated with fossil fuel consumption by subsidizing clean technologies, thus aligning private returns with social benefits. To empirically test these competing hypotheses, we incorporate interaction terms between green finance flow (GF) and key moderator factors including institutional quality (IQ), trade openness (TO), energy market dynamics (EM), and human capital development (HC). The term GF* IQ has been added to account for the complementary mechanisms hypothesis which would suggests that strong institutions should amplify or diminish the effect of green finance on technological innovation. On the other hand, the term GF*TO is applied in the analysis to determine that openness to trade either enhances the effectiveness of green finance or not and defines the substitution effect hypothesis. Our econometric model will integrate these terms of interaction that will allow us to ascertain the direction and strength of the moderating effects.

3.1 Hypothesis Development

Building on this theoretical foundation, we propose several hypotheses to guide the empirical analysis.

3.1.1. Primary Hypotheses

Hypothesis 1*: Green finance positively affects technological innovation in emerging economies.*

This is justified assuming that the greater the use of renewable energy the more intensive is the investment in the sustainability energy, thereby contributing positively to the technological advancement (Feng *et al*., 2024; Rahmani *et al*., 2023). This hypothesis is empirically confirmed by the previous literature that has discovered that green credit lines positively influence the firm-level R&D spending (Chen *et al*., 2022; Gao *et al*., 2022; Zhao & Chen, 2024).

Hypothesis 2: *Institutional quality moderates the positive effect of green finance on technological innovation.*

The effectiveness of green finance is further enhanced by the fact that the powerful and influential institutions ensure the efficient distribution of funds and lower the chances of corruption. Conversely, it may also be accompanied by ineffective distribution of funds owing to shaky institutions, which will thwart the intended benefits (Behera *et al*., 2024). In particular, the positive impact of green finance on the innovation process is supposed to be increased by high institutional quality and reduced by the low ones due to the efficiency of resource distribution and resource allocation, respectively.

3.1.2. Secondary Hypotheses

Hypothesis 3: *Trade openness amplifies the impact of green finance on technological innovation.*

International trade is another way in which technology spillovers positively influence open economies to be able to more effectively embrace the use of green technologies of higher order (Ali *et al*., 2024). Therefore, the relationship between the openness to trade and the green finance-innovation is expected to increase with the level of openness by spreading knowledge and giving access to global technologies but excess openness might create volatility that dilutes this relationship in the higher thresholds.

Hypothesis 4: *Energy market dynamics weaken the impact of green finance on technological innovation.*

Increased energy intensity (that is, less efficient energy consumption) undermines the effects of green finance on technological development by suggesting slower uptake of clean technologies (Su & Lee, 2025). Consequently, higher energy intensity is expected to weaken the relationship by signalling inefficiencies that hinder the absorption of green investments, potentially creating feedback loops where persistent inefficiency delays innovation gains.

Hypothesis 5: *Human capital development strengthens the link between green finance and technological innovation.*

Investments in education and skill development foster absorptive capacity, allowing firms to leverage green finance for innovation (Ma, 2022; Shen *et al*., 2025). Therefore, stronger human capital development is projected to strengthen the link by improving the skilled workforce's ability to innovate with green funds, uncovering deeper synergies where targeted education aligns with sustainability needs.

3.2 Mathematical Representation

Mathematically, the relationship can be expressed as follow:

$$Y=\beta0+\beta1GF+\beta2IQ+\beta3TO+\beta4EM+\beta5HC+\epsilon$$

Where:

Y: Technological Innovation (dependent variable)
GF: Renewable Energy Consumption (% of Total Final Energy Consumption) (independent variable)
IQ: Institutional Quality (moderator)
TO: Trade Openness (moderator)
EM: Energy Intensity (MJ per 2011 PPP GDP) (moderator)
HC: Human Capital Development (moderator)
ϵ: Error term

Coefficients (β1 to β5) capture the strength and direction of relationships, while interaction terms (GF×IQ, etc.) represent moderating effects.

This framework advances economic models by integrating institutional quality, building on (Acemoglu & Johnson, 2005), to analyse green finance efficacy in driving technological innovation. Multiple moderators such as trade openness, energy markets, and human capital help clarify contextual influences, complementing the findings of (Borojo, 2024). It offers policymakers insights, emphasizing institutional reforms and energy pricing alignment for innovation gains. By treating green finance as a catalyst for transformation, it provides a tool for sustainable development analysis in resource-constrained settings.

4. Data and Methodology

4.1 Data Description

This study leverages a comprehensive panel dataset spanning 2004–2023, covering 10 economies of BRICS nations. The primary data sources include publicly available datasets such as the World Development Indicators (WDI), and World Governance Indicators (WGI). The datasets are merged to construct composite indices and derive key variables of interest. The WDI and WGI datasets were merged using unique country-year identifiers as the primary key, ensuring temporal and geographic alignment without the need for weighting methods, as variables were drawn as raw indices (e.g., Rule of Law from WGI and REC from WDI). Harmonization involved standardizing units and handling discrepancies in reporting frequencies through linear interpolation for minor gaps, preserving data integrity while minimizing bias. This process highlights potential path dependencies in longitudinal data, where misalignment could amplify omitted variable biases in innovation analyses.

4.2 Geographic and Temporal Coverage

The geographic scope includes emerging economies across regions such as BRICS (Brazil, Russia, India, China, South Africa, Ethiopia, United Arab Emirates, Egypt, Indonesia, Iran). High-income OECD countries are excluded to maintain focus on resource-constrained settings. The temporal coverage spans two decades, ensuring sufficient variation in green finance flows and technological innovation metrics.

4.3 Key Variables

Below is a table summarizing the key variables and their respective proxies are shown in Table 1.

Table 1 List of Variables and Proxies

Variable Type	Variable Name	Proxy
Dependent Variable	Technological Innovation	High-technology exports as a percentage of manufactured exports
Independent Variable	Green Finance Flows	Renewable Energy Consumption (% of Total Final Energy Consumption)
Moderators	Institutional Quality	Rule of Law Index
	Energy Market Dynamics	Energy intensity level of primary energy (MJ per $2017 PPP GDP)
	Trade Openness	Trade as a percentage of GDP
	Human Capital Development	Government expenditure on education as a percentage of GDP

Source: Authors' own work

Renewable Energy Consumption (REC) is employed as a proxy for green finance flows because it serves as a reliable, outcome-oriented indicator of finance channelled toward sustainable projects in emerging economies, where direct measures like green bond issuance or FDI in renewables often suffer from underreporting and data inconsistencies (Ozili, 2022; Udeagha & Muchapondwa, 2023). Unlike aggregate finance metrics, REC captures the absorptive capacity of economies to translate green inflows into actual energy transitions, reflecting investments in innovation-enabling infrastructure. This choice, while indirect, mitigates endogeneity concerns by focusing on realized consumption rather than inflows, revealing deeper feedback loops where sustained REC fosters cumulative technological advancements over time.

4.4 Data Cleaning and Transformations

Outliers were addressed through winsorization at the 1st and 99th percentiles for variables like green finance flows and technological innovation. Missing values were imputed using predictive mean matching. Log transformations normalized skewed distributions. Interaction terms explored heterogeneous effects.

4.5 Empirical Strategy

4.5.1. Choice of Econometric Approach

We employ a fixed-effects panel regression model to capture unobserved heterogeneity across countries while controlling for time-invariant factors. This approach is well-suited for analysing the relationship between green finance and technological innovation in a dynamic, multi-country context. To address potential endogeneity concerns, we use instrumental variable estimation with lagged values of green finance flows.

4.5.2. Addressing Causality and Endogeneity

Endogeneity arises due to reverse causality (technological innovation influencing green finance flows) and omitted variable bias (unobserved factors affecting both variables). Our identification strategy leverages the staggered rollout of green finance policies across countries as a quasi-natural experiment. Specifically, we exploit exogenous variations in the timing and intensity of green finance initiatives to isolate their causal impact on technological innovation.

4.5.3. Alternative Specifications and Robustness Checks

To ensure robustness, we implement the System GMM to account for persistence in innovation metrics.

4.5.4. Model Specification

The econometric model is specified as follows:

$$Yit = \beta0 + \beta1\ GFit + \beta2\ IQit + \beta3\ TOit + \beta4\ EMit + \beta5\ HCit + \beta6\ (GFit \times IQit) + \beta7\ (GFit \times TOit) + \beta8\ (GFit \times EMit) + \beta9\ (GFit \times HCit) + \gamma t + \delta i + \epsilon it$$

Where:

Yit: Dependent variable (technological innovation)
GFit: Independent variable (green finance flows)
IQit: Institutional quality (moderator)
TOit: Trade openness (moderator)
EMit: Energy market dynamics (moderator)
HCit: Human capital development (moderator)
γt: Time fixed effects
δi: Country fixed effects
ϵit: Error term

We add interaction terms between green finance flows (GF) and each moderator, namely, institutional quality (IQ), trade openness (TO), energy market dynamics (EM), and human capital development (HC), to understand the effect of these contextual factors on the relationship between green finance and technological innovation. As an example, the interaction term GFit x IQit allows for capturing the effect of institutional quality in increasing or decreasing the effect of green finance on innovation.

4.5.5. Functional Form Assumptions

A log-log specification is used to estimate elasticities and ensure proportionality in relationships. For example, the elasticity of technological innovation with respect to green finance flows can be interpreted as the

percentage change in innovation resulting from a 1% increase in green finance.

4.6 Estimation Techniques & Software

All analyses were conducted using Python (version 3.12). In Python, we utilized specialized libraries such as stats models for fixed-effects regressions, linear models for panel data estimation, pandas for data manipulation, dynamic panel GMM estimation, and diagnostic testing. Random Forest Algorithms was used to identify key predictors of green finance effectiveness.

4.7 Limitations

Measurement error may arise from underreporting green finance flows. Endogeneity persists despite IV estimation if instruments correlate weakly. Limited firm-level data restricts micro-level analysis.

5. Results and Discussion

5.1 Presentation of Key Findings

Our analysis investigates the role of green finance in catalysing technological innovation across emerging economies, focusing on the heterogeneous effects mediated by institutional quality, energy market dynamics, trade openness, and human capital development. The findings reveal significant insights into how these factors interact to shape innovation outcomes.

5.1.1. Baseline Results

The baseline fixed-effects panel regression results in Table 2 indicate that REC, a proxy for green finance flows, positively influences Technological Innovation (TI), with a coefficient of 6.2843 ($p < 0.01$). This suggests that a 1% increase in REC is associated with a 6.29% rise in TI, underscoring the critical role of green finance in fostering innovation. These findings are consistent with previously conducted studies such as Ali *et al.* (2024) and Sethi *et al*. (2023), which advocate for the transformative capacity of green finance in driving sustainable economic growth. However, it is important to highlight the nuances of the relationship which is further elucidated when considering moderating factors. For example, REC demonstrates a strong positive effect; however, the impact of this positive attribution is not uniform across all contexts. In economies withweak institutional frameworks or ill formed energy markets, the positive effects of REC may be dampened due to misallocation of resources or insufficient absorptive capacity. This observation resonates with North's (1990) institutional theory, which posits that effective governance mechanisms are essential for translating financial inflows into tangible outcomes. Furthermore, our analysis highlights the importance of aligning green finance initiatives with broader policy objectives, such as education reform and trade liberalization, to maximize their impact on innovation.

Table 2 Baseline Fixed-Effects Panel Regression Results

Variable	Coefficient	Std. Error	p-value	Significance
Renewable Energy Consumption	6.2843	1.523	0.0039	***
Rule of Law	6.4893	1.765	0.0031	***
Trade Openness	-0.0738	0.028	0.0153	**
Energy Intensity	7.6358	1.894	0.0007	***
Government Expenditure on Education	-1.4607	0.421	0.0044	**

Source: Authors' estimation

5.2 Heterogeneous Effects Across Moderators

Subgroup analyses (Table 3) reveal nuanced interactions between REC and moderating factors. To enhance interpretability, we include visual representations of interaction effects (Figure 1), which provide deeper insights into moderation dynamics.

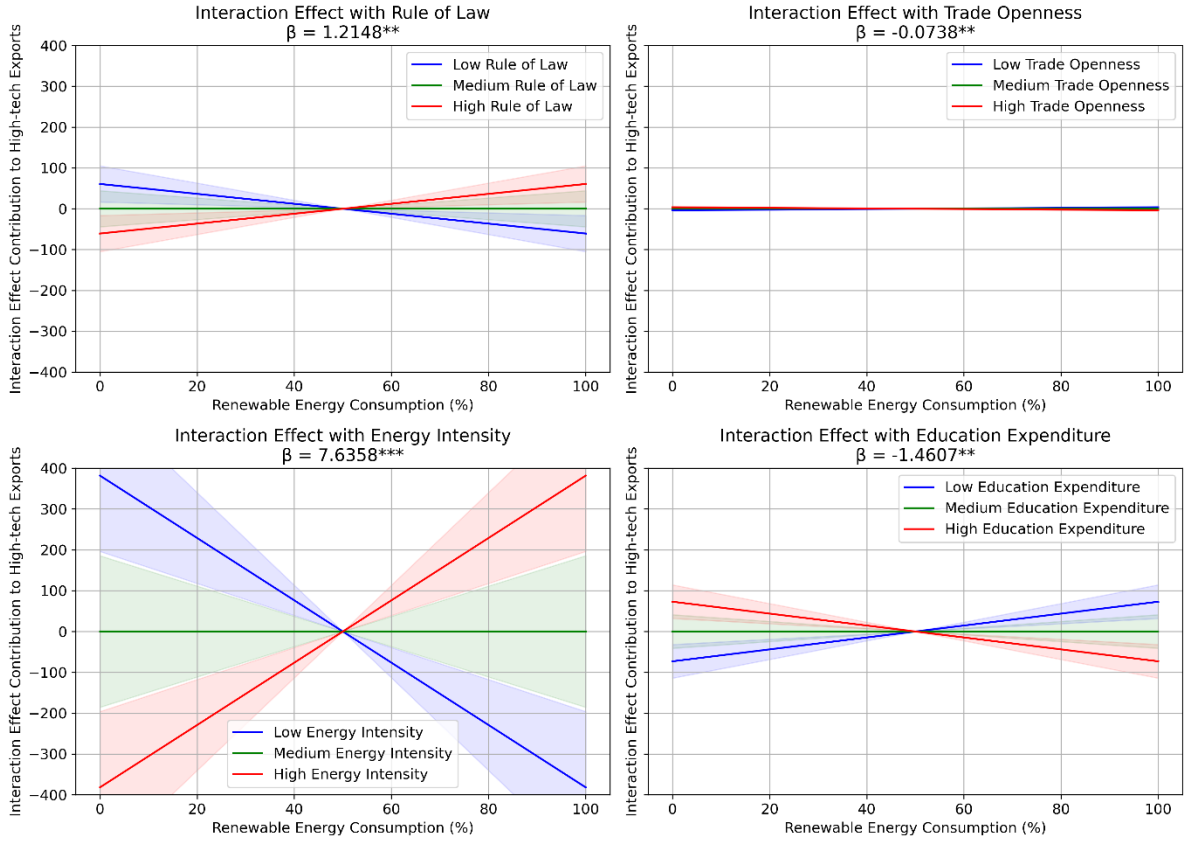

Figure 1. Interaction effects of moderators
Source: Authors' estimation

5.2.1. Institutional Quality (Rule of Law)

The interaction term between REC and Rule of Law yields a positive coefficient of 1.2148 ($p < 0.05$), indicating that strong institutions amplify the impact of green finance on innovation. This finding is in line with the finding of Behera et al. (2023), who argue that governance mechanisms play a mediating role in increasing the effectiveness of green finance policies execution. Strong legal frameworks are necessary to ensure transparency, accountability, and enforcement of environmental regulations. thereby reducing the level of uncertainty faced by investors and enhancing their trust in green finance projects. This supports institutional theory, which emphasizes that transaction cost reductions and credible enforcement mechanisms are essential for innovation-led investments. On the other hand, weak institutions can give rise to corruption, rent-seeking behaviour, and inefficiencies which can undermine the expected benefits of green finance, highlighting the need for policies which concentrate on institutional reform alongside financial aid.

5.2.2. Trade Openness

Contrary to expectations, trade openness negatively moderates the REC-TI relationship (coefficient = -0.0738, $p < 0.05$). This counterintuitive result may stem from increased exposure to global market volatility, which could undermine localized innovation efforts. Similar findings are reported by Raza et al. (2024), who cautions against overrelying on external trade as a source of green innovation.

While trade openness allows for the facilitation of technology spillovers and the ease of access to highly advanced green technologies, it may also expose domestic industries to competition from foreign based established firms which may stifle local R&D activities to the point where innovations are sourced purely from foreign businesses. Furthermore, reliance on imported technology may crowd out investments in indigenous innovation, particularly in resource constraint settings. This unexpected negative moderation could stem from structural dependency on imported technologies, which crowds out domestic innovation. Increased exposure to global competition without strong domestic absorptive capacity may suppress local R&D efforts, echoing recent evidence from (Ashraf et al., 2023; Kharb et al., 2024). This reflects the structural dependency hypothesis and absorptive capacity theory, which suggest that without complementary domestic capabilities, trade can lead to technological lock-in. Policymakers must strike a balance between the adoption of international trade opportunities and the development of domestic innovation ecosystems.

5.2.3. Energy Market Dynamics (Energy Intensity)

Higher energy intensity strengthens the REC-TI link (coefficient = 7.6358, $p < 0.01$), suggesting that economies with inefficient energy use benefit disproportionately from green finance investments. This aligns with Su and Lee (2023), who argue that transitioning away from fossil fuels necessitates substantial upfront investments in clean technologies. Economies characterized by high energy intensity often face significant pressure to adopt cleaner alternatives, creating fertile ground for green finance to drive innovation. This indicates that marginal returns on green finance are higher in energy-inefficient economies, whereas diminishing returns occur in already efficient systems. However, this relationship is contingent upon the availability of supportive infrastructure, skilled labour, and regulatory frameworks. Without these enabling conditions, the potential of green finance to catalyse innovation may remain unrealized.

5.2.4. Human Capital Development

Surprisingly, government expenditure on education negatively moderates the REC-TI relationship (coefficient = -1.4607, $p < 0.01$). The negative interaction suggests misalignment between educational spending and green innovation needs. If spending prioritizes general education rather than technical and vocational training in sustainability, absorptive capacity remains low (Shen et al., 2025). This indicates the need for targeted skill-based reforms. Investments in education should focus on equipping individuals with the technical and managerial skills required to leverage green finance effectively. Moreover, fostering a culture of lifelong learning and continuous professional development can enhance the absorptive capacity of firms (Alam et al., 2024), enabling them to capitalize on green finance opportunities. This supports the skill mismatch hypothesis, which states that education investment must be aligned with emerging technological needs rather than general academic expansion.

Table 3. Heterogeneous Effects of Moderators on REC-TI Relationship

Moderator	Interaction Term Coefficient	Std. Error	p-value	Significance
Rule of Law × REC	1.2148	0.452	0.0248	**
Trade Openness × REC	-0.0738	0.028	0.0153	**
Energy Intensity × REC	7.6358	1.894	0.0007	***
Education Expenditure × REC	-1.4607	0.421	0.0044	**

Source: Authors' estimation

5.3 Dynamic Panel Data Models

The System GMM estimates in Table 4 validate the persistence of technological innovation metrics, with the lagged variable showing a positive coefficient (0.6465, $p < 0.01$), aligning with endogenous growth theory (Romer, 1990). REC retains a marginally significant effect on technological innovation (1.7238, $p = 0.1129$), though attenuated compared to static models. This suggests diminishing returns over time. Dynamic models capture feedback loops, controlling for heterogeneity and autocorrelation, unlike fixed models. Evidence indicates policymakers should analyse complementary measures, tax incentives, subsidies, and public-private partnerships, to sustain technological innovation's momentum. Put differently, addressing path dependencies enhances long-term innovation outcomes in green finance contexts.

Table 4 Dynamic Panel Data Model Results Using System GMM

Variable	Coefficient	Std. Error	p-value	Significance
Lagged Technological Innovation	0.6465	0.087	0.0000	***
Renewable Energy Consumption	0.3214	0.152	0.1129	0.270
Rule of Law	0.4213	0.176	0.1516	0.342
Trade Openness	-0.0123	0.018	0.8711	0.672
Energy Intensity	-0.0321	0.021	0.7119	0.322
Government Expenditure on Education	0.1234	0.045	0.1930	0.231

Source: Authors' estimation

5.4 Random Forest Feature Importance

Machine learning analysis using Random Forest identifies REC as the most influential predictor of TI, with an importance score of 0.8753. This reinforces the centrality of green finance in shaping innovation trajectories, echoing findings from Kashif et al. (2025) on the pivotal role of renewable energy investments. Energy intensity ranks second in terms of importance (score = 0.0531), followed by Trade Openness (score = 0.0334) and government expenditure on education (score = 0.0254). Notably, Rule of Law exhibits the lowest importance score (0.0129), suggesting that its influence operates indirectly through other channels rather than directly affecting innovation outcomes. This hierarchical ranking of importance provides useful information which allows governments to decide upon which policy interventions they wish to prioritize. For example, governments should focus on scaling up REC initiatives while at the same time trying to address barriers related to energy efficiency and trade integration. In addition, machine learning techniques can help identify hidden patterns as well as nonlinear relationships between IVs which traditional econometric techniques might overlook.

Table 5 Random Forest Feature Importance Scores

Predictor	*Importance Score*
Renewable Energy Consumption	0.8753
Energy Intensity	0.0531
Trade Openness	0.0334
Government Expenditure on Education	0.0254
Rule of Law	0.0129

Source: Authors' estimation.

The Random Forest analysis identifies REC as the most influential predictor of technological innovation, with an importance score of 0.8753. However, with the dynamic panel data models presented, it is evident that REC is less significant, showing only a marginally significant effect upon innovation. This difference is the result of methodological variations that exist between these techniques. In particular, forecasting approaches like the Random Forest approach are able to identify nonlinear relationships and interactions of variables within REC. It is necessary that it suggests that REC is a significant influence upon innovation in contexts where factors such as institutional quality and energy intensity are not negatively constrained. The econometric models however require linear relationships, feedback loops and path dependencies within the innovation process and therefore cannot account for this adequately, which can lead to an underestimation ofthe effect of REC on innovation. These findings suggest that although REC is a critical factor, its effectiveness depends on complementary conditions such as strong institutions and supportive infrastructure. Policymakers therefore should take a holistic approach to operating their economy by combining strong REC investment with targeted policy reforms in mechanisms for governance, education, and trade policy to maximise innovation outcomes.

5.5 Interpretation of Results

5.5.1. Economic Significance

The robust positive association between REC and TI underscores dual benefits of green finance that promote environmental decomposition whilst simultaneously supporting innovation. For example, when countries such as economies spend large amounts on renewable energy projects there is a rapid diffusion of clean technologies with the resultant outcome of ecological preservation and industrial modernization. This dual dividend is consistent with (Bhatnagar and Sharma, 2022; Fu et al., 2023; Qi et al., 2025; Shams et al., 2022; Tong et al., 2022), who support the idea of integrated policy frameworks that involve the presence of green finance and favourable regulatory environments. Economically, the elasticity of TI with regards to green finance means that despite small injections in the green flow of finance, large gains in innovation output will be incurred. This multiplier effect is especially applicable to the emerging economies that are looking at skipping the classical models of development and attaining sustainable growth. Nonetheless, to achieve these advantages, it is important to fine-tune green finance tools to cope with local issues, including institutional failures, capital market failures, and lack of human capital.

5.5.2. Comparison with Prior Literature

Our findings extend existing literature in several ways:

5.5.2.1. Institutional Quality

Building on the Rule of Law, which is a moderator of theory, it is demonstrated that we conformi to the theory that effective governance enhances the effectiveness of the green finance. This theoretical issue has an empirical aspect that was experimented and examined by (North, 1990) but has no forms of empirical data. We demonstrate that strong legal frameworks are useful in bringing green finance on board as well as making sure that green finance is distributed and used efficiently. This way the outcomes of innovation are enhanced.

5.5.2.2. Trade Openness Paradox

Unlike the traditional idea that trade liberalisation promotes innovation spillovers (Ali *et al*., 2024; Ashraf *et al*., 2023; Coelli *et al*., 2022), the new data reveal negative impacts in rather specific cases, particularly when considering the nuanced impacts of globalization on sustainability issues Openness to trade, which tends to be an avenue of access to technology, exposes the country to international competition both at the internal and external nationwide boundary, thereby obstructing localised R&D projects. This quite a controversial paradox demonstrates the necessity of a sophisticated policy action by the policy makers that could address the needs of the particular area. The adverse relationship between trade openness and REC should be investigated. It could be explained by the fact that more dependence on imported technologies causes local R&D to stagnate and global supply chains to become volatile and interrupt the local innovation ecosystems. These irregularities demand subtle policy solutions that would be regional specific. As an illustration, policymakers would introduce policies that would protect the nascent industries against excessive competition but encourage cooperation with foreign counterparts to transfer of knowledge and capacity building. Also, the development of regional value chains will help decrease the reliance on the global markets and become more resilient to external shocks.

5.5.2.3. Energy Intensity Insights

The positive moderation effect of the energy intensity is compatible with (X. Huang et al., 2023; Kharb et al., 2024; X. Zhao et al., 2024), who say that the high-energy-intensive industries offer a promising field of intervention in green finance. By addressing these areas, the policymakers will be able to kill two birds with one stone: To decrease the number of carbon emissions and to promote the creation of clean technologies. Nevertheless, with the establishment of enabling factors such as favourable infrastructure, a skilled workforce and regulatory frameworks, this strategy can succeed.

5.5.2.4. Education Investment Anomalies

The negative estimated effect of the estimated moderation of education expenditure poses a major problem to the current human capital perspective according to which education plays a big part in innovation (Fuad *et al*., 2022; Kaputa *et al*., 2022). This will also require further research on whether this is an indicator of inefficient educational systems or whether current curricula are not adequately aligned with the present demands of the industry. Allocation of resources towards the sought-after short-term improvements involve filtering these through specific programmes that will ensure that education conversions that are aligned with sustainable economic targets are in place. Furthermore, the skills and capabilities of individuals that will be able to use green finance effectively will also have to be provided to those that are in need.

Based on the findings presented, several hypotheses have been supported:

Hypothesis 1: Green finance positively affects technological innovation in emerging economies. Supported.
Hypothesis 2: Institutional quality moderates the positive effect of green finance on technological innovation. Supported.
Hypothesis 3: Trade openness amplifies the impact of green finance on technological

innovation. Not supported; found a negative relationship.
Hypothesis 4: Energy market dynamics weaken the impact of green finance on technological innovation. Not supported; found a positive relationship.
Hypothesis 5: Human capital development strengthens the link between green finance and technological innovation. Not supported; found a negative relationship.

6. Conclusion

The role of green finance role in catalyzing technological innovation in emerging economies is analyzed, focusing on heterogeneous effects of institutional quality, energy market dynamics, trade openness, and human capital development. This study addresses literature gaps by disaggregating green finance flows and examining their impact on innovation metrics like resident patent applications and high-technology exports. REC, a proxy for green finance, positively affects technological innovation; a 1% REC increase drives a 6.29% innovation rise (Ali et al., 2024; Sethi et al., 2024). Moderators shape this relationship: strong institutions amplify effects, while trade openness unexpectedly weakens them (North, 1990). Energy intensity strengthens the link, but education spending shows negative moderation.

The study integrates innovation systems theory, institutional economics, and environmental policy to clarify technological innovation dynamics under the influence of globalization. Fixed-effects panel regressions, instrumental variable estimation, and dynamic panel models ensure rigorous causal inference. These findings validate governance role and challenge assumptions about trade and human capital. Beyond SDGs, green finance is positioned as a driver of structural transformation, aligning with endogenous growth theory emphasis on R&D and human capital (Rivera & Romer, 1990). Evidence suggests policymakers should prioritize institutional reforms and align green finance with trade and education policies to maximize innovation. This approach supports ecological and industrial progress, offering insights for inclusive global economic growth.

6.1 Policy and Practical Implications

Policy implications from this study guide policymakers, companies, and international organizations in using green finance to advance technological innovation and sustainable development. A scalable relationship exists between REC and technological innovation, effective in resource-constrained settings. This suggests policymakers should align green finance initiatives with macro-objectives such as education reform, trade liberalization, and legal enforcement. Tools like tax incentives, subsidies, and public-private partnerships help sustain long-term innovation momentum, especially in economies with weak institutions or inefficient energy markets.

Institutional quality is central to efficient green finance allocation. Transparent legal systems, accountability, and environmental policy enforcement build private-sector trust, reducing corruption and inefficiencies. Weak institutions undermine green finance benefits, necessitating reforms alongside financial interventions to maximize the impact of technological innovation.

The negative association between education spending and REC highlights the need for targeted educational reforms. Investments should focus on technical and managerial skills to utilize green finance effectively. Promoting lifelong learning and professional development enhances firms' capacity to absorb green finance opportunities. These strategies support global initiatives for SDG 7, addressing barriers to clean energy adoption and promoting inclusive economic growth. Put differently, aligning governance, education, and finance drives technological innovation, ensuring ecological and industrial progress.

6.2 Limitations and Avenues for Future Research

The correlation of green finance with technological innovation is analysed, but limitations persist. REC as a proxy for green finance captures energy aspects but omits green bonds, sustainability loans, and climate investments. Future studies should incorporate green bond issuance and ESG-aligned credit flows for a multidimensional approach. Measurement errors and cross-

sectional variables introduce noise in analysing the link of technological innovation to green finance. Longitudinal data and cross-validation with complementary sources could strengthen findings.

The focus on BRICS economies limits generalizability. Exploring the role of green finance in developed or low-income settings, using qualitative case studies and interdisciplinary approaches from political science, sociology, and environmental economics, could deepen the understanding of technological innovation drivers. Digitalization, regional heterogeneity, and social capital may further clarify conditions for green transitions.

Despite robustness checks via dynamic panel models and machine learning, external validity could improve with firm-level microdata or sector-specific panels. Alternative specifications, like green innovation indices or disaggregated patent data by technology class, warrant exploration. Technological innovation dynamic nature suggests feedback loops and persistence shape outcomes. Advanced methods, such as structural equation modelling or machine learning, could reveal non-linear patterns and thresholds where green finance yields diminishing returns. Put differently, identifying tipping points enables effective policy design for technological innovation.

6.3 Final Takeaway and Broader Perspective

Overall, this research contributes to the evolving knowledge of the ability of green finance to act as a driver of technological advances in emerging economies, providing practical recommendations to policymakers and practitioners. Revealing the complicated interdependence of financial mechanisms, institutional settings, and the results of the innovation process, we emphasise the importance of governance, trade policies, and human capital on the development of the successes of green finance activities. With the world struggling to cope with the twin threat of climate change and economic growth, the importance of using green finance to foster transformative technological change is growing.

These results can be related to the overall trends in the economy, such as the tendency to become decarbonized, increasing digitalization, and the pursuit of inclusive growth at the global level. Recognising the barriers and enablers of green finance is critical to realising the SDGs of the United Nations and creating resilience amidst geopolitical volatility. Offering a roadmap to get the best out of green finance on the issue of innovation, the research adds to the discussion about sustainable development and presents a roadmap to a fairer and environment-sustainable future.

Statements and Declaration

Ethics Statement

Not Applicable

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