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Leveraging green bonds through green innovation for effective CO_2 mitigation: The moderating roles of institutions, market development and business sophistication

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ABSTRACT

The urgent need to improve environmental performance in line with global commitments highlights the critical role of green finance in driving sustainable development. This paper explores the impact of green bonds on greenhouse gas emissions through the mediating role of green innovation. We clarify the effect by collecting and analyzing secondary data from 70 countries from 2012 to 2020 by adopting a country-fixed effects model and a moderated mediation analysis. Empirical results support the hypothesis that green bonds promote environmental quality through the mediating role of green innovation. The findings affirm the significance of sources from green bonds for implementing green innovation. We also validate our findings in different settings with the mediating roles of institutional quality and supporting conditions for innovation at the country level. We found statistical evidence supporting the three proxy variables. Countries with high-quality institutions and strong innovation support can reduce CO2 emissions by utilizing green bonds to conduct green innovation. Our results highlight the importance of green bonds in facilitating green innovation and the role of institutions, markets, and business supporting conditions in reducing CO2 emissions.

Contribution/ Originality: Our study addresses existing research gaps by examining the nuanced interplay between green bonds and environmental performance, underscored by the catalytic role of green innovation, providing more comprehensive insights into the effectiveness and sustainability of green financing, thereby facilitating more holistic strategies to enhance environmental quality.

1. INTRODUCTION

Sustainable Development Goal 13 (SDG 13) emphasizes the urgent need for governments worldwide to take climate action (Filho, Wall, Salvia, Dinis, & Mifsud, 2023). This urgency was emphasized at COP26 and reinforced at COP28, marking a critical turning point in global efforts to combat climate change. After a series of international conferences on climate action plans, 31 countries pledged to contribute $12.8 billion to the Green Climate Fund (Climate Bond Initiative, 2023). The focus of COP29 is to unlock climate finance for developing countries through innovative financial instruments. This objective emphasizes the importance of green bonds and green innovation at the global and national levels in addressing energy transition and greenhouse gas emissions.

Green bonds are innovative and hybrid debt instruments considered practical tools for raising climate finance and funding green projects. Existing literature highlights the critical role of green bonds in reducing CO2 emissions

and accelerating the transition process to a low-emission economy (Chang, Taghizadeh-Hesary, Chen, & Mohsin, 2022; Flammer, 2023; Saha & Maji, 2023). However, the green bond issuance only contributes 7.15 trillion dollars (Climate Bond Initiative, 2020) to the total estimated demand of nearly 53 trillion dollars for energy-related projects of the Paris Agreement (International Energy Agency, 2014). The limited amount of capital from green bonds raises the question of which factors are relevant to promoting green capital flows, especially for developing countries, which will suffer substantial losses and damage from climate change.

The cross-border situation of the green bond market indicates dispersion in volume, objectives, and maturity of green bond issuance worldwide. Green innovation, an umbrella term for any advancements in sustainable technologies, practices, and solutions, is the primary driver of the low-carbon transmission process. It reduces the carbon footprint, enhances energy efficiency, and improves eco-friendly transformation in industries, resulting in improved environmental quality (Singh, Del Giudice, Chierici, & Graziano, 2020). However, green innovation can demonstrate its full potential impact on carbon emissions by supporting other contextual factors such as institutional quality and economic incentives (Del Río, Peñasco, & Romero-Jordán, 2016). Therefore, examining the effect of green bonds and innovation concerning different circumstances on environmental qualities will enrich the literature on green finance and provide comprehensive solutions to facilitate green flows for a low-emission globe. While previous studies considered green bonds and green innovation as two separate environmental quality factors, our study fills the gap by hypothesizing that green innovation moderates the impact of green bonds on environmental quality. We also validate theoretical backgrounds on the impact of green bonds on environmental quality at a global scale, which is more comprehensive than other previous studies on a national level (mainly firms in China). We draw the overall picture of green bonds and how they promote carbon transmission in different countries by conducting an empirical study on 70 countries from 2012 to 2020.

Our study covers 70 countries from 2012 to 2020 to provide insights into the impact of green bonds on environmental quality at the global level. The evolution of the global green bond market began with the idea of Swedish investors in 2006. In 2008, the World Bank issued the first green bond. Soon after this milestone, the green bond market expanded rapidly (Reichelt, 2018). The growing phase was from 2010. However, we chose the time range for our study starting from 2012 for two main reasons. The first is to maintain the continuity of data for observed countries. The second is to ensure that the bond market in general and the green bond market in particular have fully recovered after the global financial crisis. Seventy countries in our sample cover almost the entire global green bond market and ensure the variance and diversification of observed variables. Although the authorities of many countries emphasize the rapid expansion of the global green bond value, the green bond markets of some countries, especially developing countries, are at an early introduction stage. Therefore, the green bond issuance volume and value show high volatility. Because of that, we adopt the fixed country effect model to examine the impact of green bonds on environmental quality and the mediating role of green innovation.

A country fixed effects model alongside a mediation framework is built to address existing research gaps by examining the nuanced interplay between green bonds and environmental performance, underscored by the catalytic role of green innovation. By highlighting these interconnected relationships, the research aims to provide more comprehensive insights into the effectiveness and sustainability of green financing, thereby facilitating more holistic strategies to enhance environmental quality. Furthermore, our research significantly contributes to the field by shifting the emphasis from firm-level analyses to macro-level insights, which encompass the dynamics among green bonds, green innovation, and environmental quality across varying institutional frameworks, levels of market sophistication, and degrees of business acumen through the incorporation of moderated mediation analysis. The findings offer a thorough understanding of how green finance can facilitate CO_2 mitigation, emphasizing the critical roles of financial mobilization, regulatory environments, and innovation capacity while delivering actionable insights for policymakers, financial institutions, corporations, and global sustainability initiatives.

The study is structured into five main sections: Introduction, Literature Review and Hypotheses Development, Data and Methodology, Results and Discussion, Conclusion and Implications.

2. LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

2.1. Green Bonds and Environmental Qualities

The significance of the green bonds in promoting environmental quality can be explained by two theories, the sustainable resource and the resource dependency theory (Saha & Maji, 2023). The first theory indicates that an organization will optimize resource utilization for long-term viability. A green bond is critical for raising green capital, which will be used for future investment in green projects or environmental initiatives. The second theory suggests that a firm can maintain its competitive advantages with sustainable business strategies by optimally using a bundle of resources. Finance is the primary driving force for dual goal achievement. Sustainable practices at the firm level can mitigate environmental problems at the global scale (Saha & Maji, 2023).

Previous studies on the impact of green finance (GF) on environmental quality (EQ) provided mixed results (Chang et al., 2022). Positive effects have been indicated in some studies when GF reduces carbon intensity, promotes ecological innovation, enhances EQ through spatial spillover effects, or funds renewable energy and environmental protection initiatives (Guo & Hu, 2019). However, adverse or insignificant effects exist concerning regional or temporal factors. Green finance does not always mean environmental sustainability, particularly in cases where it hinders green innovation or fails to reduce carbon emissions in certain regions (Zhang, Zhang, & Liu, 2024). The mixture underscores the complexity of the relationship between green finance and environmental quality. It also calls for consideration of contextual factors when examining the impact of green finance on environmental quality. At the global level, we propose that green bonds facilitate environmental quality. The hypothesis is:

H_1: Green bonds positively impact environmental quality.

2.2. Green Bonds and Green Innovation

According to Lee, Wang, and Chang (2023), the theoretical consideration focuses on the direct, indirect, and spatial effects of green bonds on green innovation, respectively in terms of (i) the long-term financial support for green technology R&D, (ii) the broader economic growth and rising income levels that indirectly facilitate green innovation, and (iii) the spatial spillover effect of green bonds on green innovation adoption. For the direct effect of capital injection, green bonds offer essential long-term financial backing for green technology research and development, alleviating short-term financial burdens and capital risks.

This support encourages companies, particularly smaller enterprises, to actively pursue green innovation (Nie & Lee, 2023). Green bond policies signal a commitment to sustainable economic development, guiding financial institutions to support green industries, lowering barriers to green innovation, and fostering economies of scale, ultimately boosting confidence and competitiveness in green sectors (Lin & Hong, 2022). Turning to the indirect effects, green bond policies can stimulate economic growth and increase disposable income, thereby promoting green innovation, as abundant capital ensures the quality and quantity of green technology supply, while rising incomes drive demand for green living and clean products that stimulate green innovation (Zhang, Liang, Feng, Yuan, & Jiang, 2020). Also, the spatial spillover effect considers both the potential negative effects of resource outflow from low-return regions and the positive influence of regions that drive neighboring areas to adopt green innovation as supporting measures for green development (Lee et al., 2023).

Furthermore, the empirical evidence also shows that green bonds promote green innovation by addressing financial constraints (Dong, Zhang, & Zheng, 2024; Lee et al., 2023). Moreover, green bonds demonstrate a firm's genuine dedication to sustainable initiatives, thereby enhancing firms' green reputations and competitiveness (Huang & Li, 2017). The empirical finding aligns with signal theory, demonstrating how green bonds can diminish information asymmetries and attract more environmentally conscious investors (Flammer, 2021). Green bonds, by

offering sustained low-cost financial support and drawing public and institutional attention, enhance green innovation through increased R&D investment, particularly in the context of overcoming challenges related to resource limitations, risk, and uncertainty in the innovation process (Chang, Chen, Wang, Zhang, & Zhang, 2019; Dong et al., 2024; Flammer, 2021). Based on those above theoretical and empirical rationales, the study proposes the hypothesis.

H_2: Green bonds promote green innovation.

2.3. Green Innovation and Environmental Qualities

Green innovation refers to any advancement in all aspects of an organization's operations, leading to a reduced environmental impact compared to conventional practices (Tolliver, Keeley, & Managi, 2020). The impact of green innovation on environmental quality is based on the resource-based view theory (RBV) (Barney, 1991). The combination of natural resources with internal capacity enables a firm to achieve profitability and reduce pollution, leading to sustainable performance in the long run. Green innovation in process and product is a key organizational asset that firms utilize to boost environmental performance and build goodwill with key stakeholders, driving sustainable success (Kraus, Rehman, & García, 2020).

Green innovation aligning with environmental management agendas reduces waste and costs and strengthens competitive advantages (Weng, Chen, & Chen, 2015). Previous studies, such as Chen and Lee (2020), Kraus et al. (2020), and Singh et al. (2020) emphasized that environmentally friendly technologies are critical to environmental performance. However, unintended adverse effects were found in some studies. According to Weng et al. (2015), environmental goals were undermined by industries with high sensitivity to environmental issues since such innovation accidentally increased emissions. Hao et al. (2020) identified that the costs and operational inefficiencies in industries with strict environmental regulations could reduce productivity, further complicating their environmental impact. Guo and Hu (2019) identified resource misallocation when a firm places more emphasis on green projects. In such cases, critical environmental and business functions are neglected, leading to a decline in environmental performance.

In summary, the impact of green finance on environmental quality depends on the nature and efficiency of green innovation. Green bonds promote investment in green innovation, including the development and implementation of environmentally friendly technologies and processes (Flammer, 2021; Lee et al., 2023). Environment-oriented practices facilitate environmental quality and sustainability (Wen et al., 2022; Weng et al., 2015). Therefore, green innovation plays a mediating role in the impact of green bonds on environmental quality. The hypothesis can be interpreted as follows:

H_3: The impact of green bonds on environmental quality is mediated by green innovation.

2.4. The Influence of Institutional Quality, Market Sophistication, and Business Sophistication on the Green Bond–Green Innovation–Environmental Performance Nexus

Based on Institutional Theory North (1990) and Scott (1995) Resource-Based View (Barney, 1991) and Financial Development Theory Levine (1997), this study hypothesizes that institutional quality, market sophistication, and business sophistication are essential in order to determine the effectiveness of green bonds in fostering green innovation and improving environmental quality. Institutional Theory contends that economic performance is a function of formal regulations, governance institutions, and mechanisms of enforcement, which reduce uncertainty and structure incentives (North, 1990).

The institutions, through three pillars – regulative, normative, and cognitive (Scott, 1995) – determine how financial instruments are adopted and legitimized. In the context of green finance, strong institutional frameworks, including stringent regulations, sustainability-oriented norms, and stakeholders' cognitive legitimacy, ensure that green bond proceeds are allocated efficiently toward legitimate sustainability projects, minimizing risks of greenwashing, increasing investor confidence, and improving environmental performance (Banga, 2019; Delmas &

Burbano, 2011; Flammer, 2021). Empirical studies show that institutional robustness enhances investment efficiency in general by alleviating financial constraints (Dao, Marisetty, Shi, & Tan, 2020) and, more specifically, enhances green finance efficiency and supports green technological advancements (Amore & Bennedsen, 2016; Yang, Lai, Han, & Tang, 2023). Therefore, the study posits the hypothesis that

H_{4a}: Institutional quality moderates the relationship between green bonds and green innovation.

H_{4b}: Institutional quality moderates the relationship between green innovation and environmental qualities.

H_{4c}: Institutional quality strengthens the mediating role of green innovation in the green bond–environmental quality relationship.

Financial Development Theory emphasizes the role of capital markets in fostering economic and technological advancements (Levine, 1997). The sophisticated financial markets can reduce information asymmetries and transaction costs, which in turn influence investment decisions and technological innovation.

By alleviating financial constraints and improving risk diversification, financial development can optimize financial flows to innovation projects.

In the context of the green bond market, market development can enhance transparency and legitimacy, liquidity, investor participation, and then guide other green capital flows into innovation as resource and reputation advantages (Lian, Huang, & Wu, 2024). Empirical evidence shows that the financial structure, illustrated by the roles of the banking sector and the financial market, can have a positive impact on green innovation (Lv, Shao, & Lee, 2021). Based on those rationales, our study hypothesizes that

H_{5a}: Market sophistication moderates the relationship between green bonds and green innovation..

H_{5b}: Market sophistication moderates the relationship between green innovation and environmental qualities.

H_{5c}: Market sophistication strengthens the mediating role of green innovation in the green bond–environmental quality relationship.

Resource-based view (RBV) suggests that firms and economies derive competitive advantage from their unique resources, including R&D capabilities, technological know-how, and innovation-driven business models (Barney, 1991). Dynamic Capabilities Theory further argues that businesses must continuously adapt and innovate in response to external changes, such as climate policies and sustainability demands (Teece, Pisano, & Shuen, 1997). In highly sophisticated business environments, firms can effectively utilize green bond financing to develop and scale eco-innovations**,** translating them into measurable environmental benefits through the channels of knowledgeable management, green knowledge sharing, and collaborative innovation (Javeed et al., 2023; Lian et al., 2024; Sahoo, Kumar, & Upadhyay, 2023; Zairbani & Senthil Kumar, 2025).

H_{6a}: Business sophistication moderates the relationship between green bonds and green innovation..

H_{6b}: Business sophistication moderates the relationship between green innovation and environmental qualities.

H_{6c}: Business sophistication strengthens the mediating role of green innovation in the green bond–environmental quality relationship.

3. DATA AND METHODOLOGY

3.1. Data

The study encompasses data from 70 countries over the period from 2012 to 2020. This sample was chosen due to the availability of comprehensive country-level data on Environmental Performance, Green Innovation, and Green Bonds.

The measurement of variables and their data sources are indicated in Table 1.

Table 1. Measurement of variables.

Variables	Acronyms	Measurement	Data sources
Environmental performance	Ln_CO_2	The carbon footprint quantifies CO_2 emissions derived from fossil fuel consumption and is a crucial metric for assessing environmental impact. The raw carbon footprint data is transformed using the natural logarithm (ln).	Footprint Data Foundation, York University Ecological Footprint Initiative, and Global Footprint Network: Ecological Footprint Accounts
Green bonds	GB	The natural log of total green bonds issuance for each country in each year.	Eikon Refinitiv
Green innovation	GI	Innovation in environment-related technologies, measured by the number of inventions per capita, serves as a key metric for evaluating countries' innovation performance. This measure also informs the development and effectiveness of governmental policies in both environmental and innovation sectors.	Organization for Economic Co-operation and Development (OECD) statistics
GDP growth	GDP	Annual percentage growth rate of GDP per capita	World Bank database & OECD database
Population	POPU	Population density (People per sq. km of land area).	Food and Agriculture Organization and World Bank database.
Foreign direct investment	FDI	Foreign direct investment, net inflows (% of GDP)	International Monetary Fund, International Financial Statistics, and Balance of Payments databases, World Bank, International Debt Statistics, and World Bank and OECD GDP estimates.
Inflation	INF	Inflation, consumer prices (Annual %)	International Monetary Fund, international financial statistics, and data files.
Renewable energy consumption	RENEW	Renewable energy consumption is the proportion of renewable energy in total final energy consumption.	World Bank database
Institutional quality	INST	The institutional quality scores are derived from the Global Innovation Index (GII), which evaluates various dimensions of a country's institutional framework that support innovation and economic growth, such as the institutional environment, regulatory environment, and business environment.	World Intellectual Property Organization (WIPO). Global Innovation Index
High institutional quality	High_Institutions	A dummy variable equals 1 if the institution's quality score is higher than the median value; otherwise, it equals 0.	World Intellectual Property Organization (WIPO). Global Innovation Index
High market sophistication	High_Market	A dummy variable equals 1 if the market sophistication score is higher than the median value; otherwise, it equals 0. The market sophistication scores are derived from the Global Innovation Index (GII), which evaluates various dimensions of a country's ability to support innovation through financial and investment conditions, trade environments, and market competitiveness.	World Intellectual Property Organization (WIPO). Global Innovation Index
High business sophistication	High_Business	A dummy variable equals 1 if the business sophistication score is higher than the median value; otherwise, it equals 0. The business sophistication scores are derived from the Global Innovation Index (GII), which evaluates various dimensions of a country's innovation ecosystem, knowledge creation, and absorptive capacity within businesses.	World Intellectual Property Organization (WIPO). Global Innovation Index

Sources: Compiled by the author based on a literature review.

3.2. Model Specifications

The study builds on the work of Sahoo et al. (2023) to explore the relationship between Green Bonds (GB), green innovation (GI), and environmental performance (EPI), with green innovation serving as a mediating factor. Model (1) serves as the baseline to evaluate Hypothesis 1, which examines the effects of Green Bonds on Environmental Performance. Model (2) investigates the mediating role of green innovation to assess the impact of Green Bonds on Green Innovation (Hypothesis 2). Model (3) examines how green innovation mediates the relationship between Green Bonds and Environmental Performance.

$$Ln\_CO_{2i,t} = \beta_0 + \beta_1 GB_{i,t} + \beta_2 Z_{i,t} + u_i + \varepsilon_{i,t} \quad (1)$$

$$GI_{i,t} = \delta_0 + \delta_1 GB_{i,t} + \delta_2 Z_{i,t} + u_i + \varepsilon_{i,t} \quad (2)$$

$$Ln\_CO_{2i,t} = \gamma_0 + \gamma_1 GB_{i,t} + \gamma_2 GI_{i,t} + \gamma_3 Z_{i,t} + u_i + \varepsilon_{i,t} \quad (3)$$

In which,

$EPI_{i,t}$ measures the environmental performance index of country i in year t.

$GB_{i,t}$ measures green bonds issuance of country i in year t.

$GI_{i,t}$ measures green innovation level of country i in year t.

$Z_{i,t}$ measures control variables of country i in year t. The control variables are $GDP_{i,t}$, $POPU_{i,t}$, $FDI_{i,t}$, $INF_{i,t}$, $RENEW_{i,t}$, $INST_{i,t}$ (as indicated in Table 1).

u_i captures country-specific fixed effects.

$\varepsilon_{i,t}$ is the error term, clustered at both country and year levels.

For confirming the presence of mediating effect, we have to be sure about few conditions: (i) if the $\beta 1$ of Model (1), the baseline model is statistically significant. For the mediating effect (ii) if δ_1 and γ_2 are significant, and γ_1 is significant, it affirms the partial mediating effect. (iii) if if δ_1 and γ_2 are significant, and γ_1 is insignificant, it confirms the complete mediating effect (Baron & Kenny, 1986). To empirically test Hypotheses 4, 5, and 6, which posit that the mediating role of green innovation in the green bond–environmental performance relationship is moderated by institutional quality, market sophistication, and business sophistication, our study incorporates a moderated mediation analysis. Specifically, we extend the baseline mediation model by introducing interaction terms between green bonds (GB), green innovation (GI), and each moderator (Institutional Quality, Market Sophistication, and Business Sophistication) separately (Hayes, 2013). By doing so, the model explicitly examines whether these contextual factors strengthen or weaken the indirect effect of green bonds on environmental quality through green innovation. This nuanced moderated mediation approach allows us to capture conditional indirect effects, providing deeper insights into how robust institutions, advanced financial markets, and sophisticated business ecosystems either enhance or limit the effectiveness of green financing mechanisms in driving eco-innovations and ultimately reducing carbon emissions.

$$Ln\_CO_{2i,t} = \gamma_0 + \gamma_1 GB_{i,t} + \gamma_2 GI_{i,t} + \gamma_3 (GB_{i,t} \times GI_{i,t}) + \gamma_4 (GB_{i,t} \times GI_{i,t} \times High\_Institutions) + \gamma_5 Z_{i,t} + u_i + \varepsilon_{i,t} \quad (4)$$

$$Ln\_CO_{2i,t} = \gamma_0 + \gamma_1 GB_{i,t} + \gamma_2 GI_{i,t} + \gamma_3 (GB_{i,t} \times GI_{i,t}) + \gamma_4 (GB_{i,t} \times GI_{i,t} \times High\_Market) + \gamma_5 Z_{i,t} + u_i + \varepsilon_{i,t} \quad (5)$$

$$Ln\_CO_{2i,t} = \gamma_0 + \gamma_1 GB_{i,t} + \gamma_2 GI_{i,t} + \gamma_3 (GB_{i,t} \times GI_{i,t}) + \gamma_4 (GB_{i,t} \times GI_{i,t} \times High\_Bu\,sin\,e\,ss) + \gamma_5 Z_{i,t} + u_i + \varepsilon_{i,t} \quad (6)$$

4. RESULTS AND DISCUSSION

4.1. Descriptive Analysis

Our descriptive statistics in Table 2 offer evidence concerning the relationships between green bonds (GB), green innovation (GI), and environmental performance, particularly in terms of CO_2 emissions (Ln_CO_2). The study finds a positive and significant correlation between green bonds and green innovation ($r = 0.138$*), suggesting that green

financing actively facilitates investments in environmentally friendly technological advancements. The study also notes a small yet statistically significant positive correlation between GB and Ln_CO_2 (r = 0.306*). However, such correlation results, while informative, must be interpreted cautiously, since pairwise correlations measure simple linear associations without controlling for other influencing variables such as economic growth or population dynamics, which may confound the direct relationship between green bonds and emissions (Gujarati & Porter, 2009). This apparent positive correlation may reflect the reality that some countries issuing substantial green bonds are typically at earlier stages of the green transition, initially facing elevated emission levels due to historical dependence on carbon-intensive industries (Flammer, 2021; Tolliver et al., 2020; Wang, Wang, & Chang, 2022). Additionally, the results indicate substantial and positive associations of institutional quality, market sophistication, and business sophistication with both green bonds and green innovation. These correlations underscore the critical roles played by high institutional quality, advanced financial market structures, and knowledge-driven business environments in developing green finance and enabling greater innovative capacity. However, whether this can facilitate transitions towards sustainable economic development deserves further investigation since the simultaneous positive correlations of these variables with CO_2 emissions suggest a more complex underlying dynamic. The rigorous econometric modeling performed later in our analysis, which incorporates comprehensive controls and interaction effects, will provide clearer insights by revealing the actual direction and strength of the relationships.

4.2. Regression Results

4.2.1. The Mediating Role of Green Innovation on the Relationship between Green Bonds and CO_2 Emissions

Table 3 shows the regression results of the baseline model on the effects of green bonds (GB) and green innovation (GI) on CO_2 emissions (Ln_CO_2). Model (1) serves as the baseline model to assess Hypothesis 1, which explores the influence of green bonds on CO_2 emissions. As highlighted in Model (1), the coefficient of green bonds (GB) is negative and statistically significant (-0.000776*), underscoring the crucial role of green bonds in accelerating environmental quality. This finding is consistent with Hypothesis 1 and aligns with the studies of Flammer (2021) and Xu and Li (2023) on the impacts of green bonds on reducing CO_2 emissions.

To examine the mediating effect of green innovation, the study utilizes Model (2) to evaluate the impact of GB on GI (Hypothesis 2), and subsequently investigates how green innovation mediates the relationship between green bonds and CO_2 emissions through Model (3). The regression results of Model (2) show a strong positive relationship between green bonds (GB) and green innovation (GI) (8.126***), emphasizing their role in channeling resources toward innovative eco-friendly technologies and practices. This finding is consistent with Hypothesis 2 and aligns with existing literature, such as Chang et al. (2019); Dong et al. (2024); Flammer (2021); Lee et al. (2023) and Lin, Du, and Ren (2022) which underscores sustainable financial instruments like green bonds mobilize dedicated investments for fostering innovation. The statistically significant positive coefficient of GB on GI, as indicated by the coefficient δ_1 in Model (2), serves as an essential prerequisite for validating the mediating role of green innovation (GI).

Table 2. Descriptive statistics.

Panel A: Summary statistics for the main variables					
Variable	**Obs.**	**Mean**	**Std. dev.**	**Min**	**Max**
Ln_CO_2	612	16.821	2.214	9.437	22.032
GB	630	8.971	10.415	0	25.767
GI	527	122.938	1030.087	0	22981.737
GDP	597	1.101	4.364	-55.189	23.305
POPU	612	628.534	2685.895	2.633	20734.058
FDI	604	15.211	127.586	-1303.108	1709.827
INF	586	3.329	12.274	-3.233	254.949
RENEW	603	28.851	23.53	0.1	87.8
INST	590	68.872	17.626	16	95.8
High_Institution	630	0.532	0.499	0	1
High_Market	630	0.532	0.499	0	1
High_Business	630	0.532	0.499	0	1

Panel B: Pairwise correlation matrix												
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**
(1) Ln_CO_2	1.000											
(2) GB	0.306*	1.000										
(3) GI	0.068	0.138*	1.000									
(4) GDP	0.007	-0.204*	-0.032	1.000								
(5) POPU	0.026	-0.027	-0.012	-0.203*	1.000							
(6) FDI	-0.224*	0.001	-0.006	-0.003	0.001	1.000						
(7) INF	0.071	-0.091*	-0.023	-0.021	-0.010	-0.055	1.000					
(8) RENEW	-0.556*	-0.187*	-0.046	0.010	-0.201*	0.021	-0.041	1.000				
(9) INST	0.139*	0.387*	0.114*	-0.085*	0.252*	0.124*	-0.300*	-0.332*	1.000			
(10) High_Institution	-0.010	0.296*	0.099*	-0.064	0.184*	0.094*	-0.157*	-0.283*	0.871*	1.000		
(11) High_Market	0.134*	0.320*	0.084	-0.072	0.184*	0.085*	-0.137*	-0.300*	0.710*	0.662*	1.000	
(12) High_Business	0.111*	0.294*	0.097*	-0.003	0.182*	0.092*	-0.127*	-0.295*	0.705*	0.707*	0.579*	1.000

Note: * p<0.05, ** p<0.01, *** p<0.001.

Coming to Model 3, the negative association between green innovation and Ln_CO_2 (-3.84e-06*) suggests that advancements in green innovation are instrumental in reducing environmental footprints. Although the effect size is modest, it is statistically meaningful, reinforcing the theoretical assertion that innovation plays a critical role in achieving environmental goals, such as CO_2 mitigation. Meanwhile, green bonds witness an insignificant negative influence on CO_2 emissions. Therefore, the estimated coefficients (β_1, δ_1, γ_2) are statistically significant, and the coefficient γ_1(GB on Ln_CO_2) is insignificant, which confirms the complete (full) mediating effects of green innovation on the impact of green bonds on environmental performance and verifies Hypothesis 3 and consistent with Hu, Chen, Dinis, and Xiang (2023). Consequently, the overall regression result highlights that green bonds enhance environmental performance primarily through the promotion of green innovation.

Table 3. Regression results on the baseline model.

Variables	(1)	(2)	(3)
	Ln_CO_2	GI	Ln_CO_2
GI			-3.84e-06*
			(-1.925)
GB	-0.000776*	8.126***	-0.000695
	(-1.738)	(2.709)	(-1.431)
GDP	0.00684***	4.674	0.00717***
	(5.036)	(1.165)	(4.838)
POPU	0.000749***	-0.564	0.000771***
	(2.981)	(-1.283)	(2.911)
FDI	-0.000167	-0.0694	-0.000174
	(-0.435)	(-0.100)	(-0.445)
INF	0.00261	1.607	0.00292
	(1.575)	(0.313)	(1.595)
RENEW	-0.0184***	14.70	-0.0184***
	(-9.757)	(0.847)	(-8.248)
INST	0.00284**	17.73	0.00436***
	(2.381)	(0.951)	(3.321)
Constant	17.20***	-1.382	17.38***
	(144.5)	(-0.863)	(131.5)
Country fixed effects	Yes	Yes	Yes
S.E clustered by	Country. & year	Country & year	Country & year
Observations	552	479	470
Adjusted R^2	0.999	0.171	0.999

Note: t Statistics in parentheses.
* p<0.05, ** p<0.01, *** p<0.001.

4.2.2. The Influence of Institutional Quality, Market Sophistication, and Business Sophistication on the Green Bond–Green Innovation–Environmental Performance Nexus – The Heterogeneity Test

Our baseline model confirms that green innovation is a critical transmission mechanism in the green bonds–CO_2 emissions nexus. This insight underscores innovation's pivotal role in translating green financial instruments into tangible environmental outcomes. However, considerable heterogeneity exists regarding how effectively this mediation operates across different contexts. Specifically, the strength and consistency of the green bond–innovation–emissions nexus likely vary depending on enabling conditions such as institutional quality, market sophistication, and business sophistication. Unpacking this heterogeneity is essential, both theoretically and practically, to inform targeted policy frameworks and guide stakeholders striving to achieve ambitious global climate objectives, including those highlighted in recent SDG 13 as well as COP28 and COP29 commitments.

When institutional quality is introduced as a moderator, as indicated in the Panel A of Table 4, high institutional quality significantly strengthens the negative relationship between green bonds and CO_2 emissions (r = -0.00262***) in Model (4a) and Model (4c), signifying that robust institutional frameworks substantially enhance the efficiency of green bond usage, reducing risks such as greenwashing and enhancing environmental outcomes (Amore &

Bennedsen, 2016; Delmas & Burbano, 2011). Moreover, high institutional quality strengthens the positive relationship between green bonds and green innovation (r = 15.73**) in Model (4b). However, the three-way interaction term (GB × GI × High_Institution) is not statistically significant in Model (4c). This indicates that although strong institutions directly foster environmental performance improvements by effectively managing green finance as well as strengthen the positive influence of green bonds on fostering green innovation, their influence does not further amplify the mediating role of green innovation on the relationship between green bonds and CO_2 emissions. Therefore, green innovation fully mediates the green bond–CO_2 emissions nexus at the baseline, but this mediation effect is not further significantly strengthened under high institutional environments. Thesse findings aligns with Institutional Theory (North, 1990; Scott, 1995) highlighting that strong institutional environments directly mitigate environmental risks by ensuring transparent and accountable allocation of green bond proceeds, thus reducing reliance on innovation as an intermediary mechanism (Amore & Bennedsen, 2016; Delmas & Burbano, 2011; Flammer, 2021).

Similarly, as indicated in Panel C of Table 4, contexts with high business sophistication, characterized by extensive knowledge absorption, innovation linkages, and highly qualified knowledge workers strengthen the negative relationship between green bonds and CO_2 emissions and the positive relationship between green bonds and green innovation. Yet, the lack of significance in the three-way interaction terms suggests that the mere presence of innovative business environments is not sufficient to ensure the mediation pathway from green bonds through innovation to environmental outcomes. Resource-Based View (Barney, 1991) and Dynamic Capabilities Theory (Teece et al., 1997) help explain this phenomenon. Although firms in sophisticated environments possess advanced capabilities for innovation, these capabilities might not be fully directed toward sustainable outcomes without clear policy guidance and institutional incentives. Consequently, the standalone innovative capabilities inherent in business sophistication do not necessarily strengthen the indirect link between green bonds and CO_2 emissions reduction.

In contrast, as indicated in Panel B of Table 4, examining contexts characterized by high market sophistication reveals nuanced findings. In environments with high market sophistication, green bonds can directly reduce CO_2 emissions (the coefficient of GB × High_Institution is -0.00321*** in Model (5c)) and significantly promote green innovation (The coefficient of GB on GI is +11.67* in Model (5b)). However, the significant positive three-way interaction (the coefficient of GB × GI × High_Institution is 7.26e-05*) indicates that its moderating role of high institutional quality in GB-GI-CO_2 emissions appears weaker. This outcome might reflect situations where sophisticated financial markets enhance liquidity and financing diversity for green innovation projects, yet do not necessarily guarantee effective translation into carbon reductions. This finding aligns with Financial Development Theory (Levine, 1997) which emphasizes that, although well-developed markets can mobilize capital efficiently, they might also inadvertently lead to allocations that focus primarily on economic rather than ecological objectives, undermining the environmental impacts of green financing (Zhang, Mohsin, Rasheed, Chang, & Taghizadeh-Hesary, 2022).

The weakened mediating effect of green innovation on the green bond–CO_2 emissions nexus under conditions of high market sophistication can be thoughtfully explained through the lens of the Environmental Kuznets Curve (EKC) and the Theory of Diminishing Returns. The EKC framework posits that environmental degradation initially increases with economic growth but subsequently decreases after reaching a certain threshold (Grossman & Krueger, 1995). In highly sophisticated markets, substantial initial environmental improvements driven by green bonds and green innovations may have already been realized, positioning these countries at or beyond the turning point of the EKC. Thus, further incremental investments in green technologies may yield progressively smaller marginal returns in terms of emissions reduction (Dinda, 2004; Stern, 2004). Similarly, from the standpoint of the Theory of Diminishing Returns, once economies achieve a certain level of market sophistication and technological advancement, additional investments in green innovation may face diminishing incremental effectiveness, as low-hanging fruits have already been captured (Ricardo, 1817; Stern, 2004). In such contexts, increased green bond issuance or intensified

innovation activities might not proportionally enhance environmental performance without complementary regulatory frameworks or institutional interventions explicitly aimed at environmental sustainability rather than economic optimization alone (Levine, 1997). Consequently, without targeted policy interventions and institutional alignment, sophisticated markets may inadvertently prioritize economic efficiency or financial returns over strict environmental gains, thereby diluting the environmental effectiveness of green innovation and green financing mechanisms (Zhang et al., 2022).

Table 4. Regression results on the extended model.

Panel A: The influence of institutional quality			
Variables	**(4a)**	**(4b)**	**(4c)**
	Ln_CO2	**GI**	**Ln_CO2**
GB	0.000865	0.0910	0.00133
	(1.234)	(0.198)	(1.297)
GI			0.0121
			(1.489)
GB x GI			-2.18e-05
			(-0.0415)
High_Institutions	0.0528**	-121.3	0.0667**
	(2.350)	(-1.540)	(2.159)
High_Institutions x GB	-0.00262***	15.73**	-0.00293***
	(-3.120)	(2.402)	(-2.663)
High_Institutions x.GI			-0.0120
			(-1.480)
High_Institutions x GB x GI			1.71e-05
			(0.0326)
GDP	0.00633***	-0.740	0.00646***
	(4.758)	(-0.280)	(4.209)
POPU	0.000771***	-0.328	0.000822***
	(3.116)	(-0.996)	(2.992)
FDI	2.77e-05	0.147	-0.000183
	(0.0688)	(0.184)	(-0.469)
INF	0.00365*	-2.876	0.00287*
	(1.878)	(-0.695)	(1.656)
RENEW	-0.0183***	2.149	-0.0185***
	(-9.946)	(0.198)	(-8.355)
Constant	17.29***	225.4	17.59***
	(213.5)	(0.848)	(188.0)
Country fixed effects	Yes	Yes	Yes
S.E clustered by	Country & year	Country & year	Country & year
Observations	561	488	475
Adjusted R^2	0.999	0.173	0.999
Panel B: The influence of high market sophistication			
Variables	**(5a)**	**(5b)**	**(5c)**
	Ln_CO2	**GI**	**Ln_CO2**
GB	0.000919	2.311*	0.00163*
	(1.236)	(1.734)	(1.906)
GI			0.00166*
			(1.947)
GB x GI			-7.74e-05**
			(-2.031)
High_Market	0.0448***	-129.6**	0.0406**
	(2.881)	(-2.102)	(2.530)
High_Market x GB	-0.00251***	11.67*	-0.00321***
	(-2.944)	(1.878)	(-3.436)
High_Market x GI			-0.00155*
			(-1.799)
High_Market x GB x.GI			7.26e-05*
			(1.884)

Panel A: The influence of institutional quality			
Variables	**(4a)**	**(4b)**	**(4c)**
	Ln_CO2	**GI**	**Ln_CO2**
GDP	0.00633***	0.173	0.00628***
	(4.748)	(0.0699)	(4.210)
POPU	0.000765***	-0.298	0.000821***
	(3.091)	(-0.968)	(2.970)
FDI	2.31e-05	0.259	-0.000217
	(0.0587)	(0.380)	(-0.610)
INF	0.00343*	-1.055	0.00257
	(1.806)	(-0.256)	(1.533)
RENEW	-0.0186***	6.175	-0.0193***
	(-10.05)	(0.539)	(-8.569)
Constant	17.31***	116.3	17.63***
	(216.0)	(0.438)	(195.1)
Country fixed effects	Yes	Yes	Yes
S.E clustered by	Country & year	Country & year	Country & year
Observations	561	488	475
Adjusted R^2	0.999	0.171	0.999
Panel C: The influence of high business sophistication			
Variables	**(6a)**	**(6b)**	**(6c)**
	Ln_CO2	**GI**	**Ln_CO2**
GB	-7.00e-06	0.355	0.000735
	(-0.0108)	(0.605)	(0.932)
GI			0.00189
			(0.657)
GB x GI			-0.000103
			(-0.795)
High_Business	0.0467***	-123.7**	0.0594***
	(2.783)	(-2.385)	(2.641)
High_Business x GB	-0.000981	15.73**	-0.00185*
	(-1.149)	(2.390)	(-1.947)
High_Business x GI			-0.00179
			(-0.619)
High_Business x GB x GI			9.82e-05
			(0.756)
GDP	0.00566***	-2.052	0.00572***
	(4.085)	(-0.711)	(3.605)
POPU	0.000752***	-0.350	0.000807***
	(3.034)	(-1.019)	(2.929)
FDI	4.71e-05	0.122	-0.000186
	(0.117)	(0.158)	(-0.480)
INF	0.00319*	-2.415	0.00241*
	(1.851)	(-0.592)	(1.692)
RENEW	-0.0189***	0.961	-0.0188***
	(-9.843)	(0.0916)	(-8.220)
Constant	17.32***	264.3	17.61***
	(211.9)	(0.963)	(194.1)
Country fixed effects	Yes	Yes	Yes
S.E clustered by	Country & year	Country & year	Country & year
Observations	561	488	475
Adjusted R^2	0.999	0.173	0.999

Note: t Statistics in parentheses.
* p<0.05, ** p<0.01, *** p<0.001.

4.2.3. Robustness Test as Ecofootprint as an Alternative Measurement of Environmental Performance

To ensure the robustness of our findings, we further validate the results by employing the Ecological Footprint (EF) as an alternative measure of environmental quality. The Ecological Footprint (EF) quantifies the demand placed by humans on the Earth's ecosystems by measuring the biologically productive area required to produce the resources consumed and assimilate the waste generated, given current technological capabilities and resource management

practices (Footprint Data Foundation, 2024). Therefore, it provides a broader indicator of environmental sustainability beyond just carbon emissions.

Table 5 presents the robustness of the main findings by reporting alternative measures of environmental quality.

Table 5. Robustness results.

Variables	(1)	(2)	(3)	(4)
	Ln_Ecofootprint	Ln_Ecofootprint	Ln_Ecofootprint	Ln_Ecofootprint
GB	0.000158	0.00172***	0.00104*	0.00134**
	(0.435)	(2.590)	(1.837)	(2.507)
GI	-4.26e-06**	0.00896	0.00348***	0.00372
	(-2.194)	(0.963)	(2.805)	(1.067)
GB x GI		-0.000537	-0.000156***	-0.000190
		(-1.157)	(-2.844)	(-1.209)
High_Institution		0.0292		
		(1.055)		
High_Institution x GB		-0.00236***		
		(-3.072)		
High_Institution x GI		-0.00871		
		(-0.935)		
High_Institution x GB x GI		0.000525		
		(1.133)		
High_Market			0.0249**	
			(2.098)	
High_Market x GB			-0.00144**	
			(-2.280)	
High_Market x GI			-0.00327***	
			(-2.626)	
High_Market x GB x GI			0.000147***	
			(2.665)	
High_Business				0.0226
				(1.564)
High_Business x GB				-0.00195***
				(-2.856)
High_Business x .GI				-0.00345
				(-0.990)
High_Business x GB x .GI				0.000178
				(1.133)
GDP	0.00363***	0.00393***	0.00374***	0.00380***
	(3.194)	(3.438)	(3.281)	(3.185)
POPU	0.000343*	0.000358*	0.000355*	0.000356*
	(1.897)	(1.956)	(1.928)	(1.941)
FDI	-0.000126	-0.000126	-0.000146	-0.000130
	(-0.497)	(-0.494)	(-0.541)	(-0.510)
INF	0.00152	0.00178	0.00157	0.00173
	(1.307)	(1.508)	(1.365)	(1.596)
RENEW	-0.00588***	-0.00467**	-0.00562***	-0.00459**
	(-3.059)	(-2.348)	(-2.853)	(-2.343)
Constant	18.03***	18.01***	18.03***	17.98***
	(165.0)	(150.8)	(161.1)	(160.2)
Country fixed effects	Yes	Yes	Yes	Yes
S.E clustered by	Country_Year	Country_Year	Country_Year	Country_Year
Observations	470	470	470	470
Adjusted R^2	0.999	0.999	0.999	0.999

Note: t Statistics in parentheses.
* p<0.05, ** p<0.01, *** p<0.001.

5. CONCLUSION AND IMPLICATIONS

Green bonds emerge as a critical tool to support environmental advancements; however, the growing concern over how to secure sufficient funding through green bonds and the optimal strategies for allocating these funds has spurred considerable interest in the academic literature, which seeks to unravel the connection between green bonds and environmental performance. Nevertheless, much of the existing research has largely focused on the direct

relationship between green finance and environmental outcomes at the firm level, often neglecting the complex, integrated dynamics involving green bonds, green innovation, and environmental performance.

This study aims to bridge this gap by examining the interconnected relationships among these elements, using a global sample of 70 countries spanning from 2012 to 2020. By positioning green innovation as a mediating mechanism, the research seeks to elucidate how it enhances the impact of green bonds on environmental performance. The findings of this study not only enrich theoretical perspectives on that nexus but also offer valuable insights into the efficiency of resource allocation at different institutional, market, and business sophistication frameworks.

Our findings confirm that green innovation effectively mediates the link between green bonds and CO_2 emission reductions, highlighting innovation as essential for translating green finance into tangible environmental outcomes. However, this mediation varies notably based on institutional quality, market sophistication, and business sophistication. Our findings reveal that strong institutional frameworks enhance the direct impact of green bonds on emissions reductions but do not amplify the mediation effect of green innovation. Meanwhile, business sophistication supports green finance and innovation but requires targeted policy incentives to ensure that innovation translates into environmental benefits. Additionally, in highly developed markets, green bonds and innovation remain drivers of CO_2 reductions, but their mediating effect weakens. This aligns with the Environmental Kuznets Curve (EKC) Hypothesis and the Theory of Diminishing Returns, suggesting that at some point after, additional green finance will be linked with declining environmental benefits unless there are stricter regulatory interventions. These insights further support demands for institutional quality, regulatory oversight, and well-aligned financial policies to maximize the environmental impact of green bonds. Policy makers should prioritize institutional strengthening to ensure that green bonds directly finance credible sustainability projects, thereby minimizing the risks associated with greenwashing, bolstering investor confidence, and enhancing environmental outcomes. For businesses, targeted policy incentives are essential to align business innovation fully with environmental objectives. The experiences of highly sophisticated innovation ecosystems, such as the U.S. and Japan, which increasingly emphasize regulatory incentives alongside corporate innovation investments, underline the importance of integrated policy measures to unlock the full sustainability potential of advanced business environments. Investors in highly sophisticated markets should cautiously evaluate green bond investments, actively demanding stringent transparency and sustainability metrics to avoid scenarios where capital flows predominantly drive economic rather than environmental objectives.

While this study provides novel insights into the green bonds–green innovation CO_2 nexus, **the** data availability of green bond and green innovation pose challenges in fully capturing the long-term impact of green finance on environmental outcomes. Future research could address this issue by integrating more granular, project-level green finance data and incorporating advanced machine learning techniques to refine impact assessments. Moreover, future research should examine how specific policy interventions, carbon pricing mechanisms, and regulatory frameworks shape the effectiveness of green bonds in promoting environmental sustainability.

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