

THE RELATIONSHIP BETWEEN GREEN INNOVATION, FOREIGN DIRECT INVESTMENT, AND SUSTAINABLE DEVELOPMENT IN THE CONTEXT OF GEOPOLITICAL RISK

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ABSTRACT

This study examines the effects of green innovation (GI), foreign direct investment (FDI), and geopolitical risk (GPR) on sustainable development (SD) in the context of increasing global uncertainty. A Bayesian regression approach is applied to panel data from 33 countries over the period 2010–2021 to better capture uncertainty and structural heterogeneity in the data. The results indicate that GI has a high probability of exerting a positive impact on sustainable development; however, its average effect remains unstable when GPR is not taken into account. In contrast, FDI does not demonstrate a clear role in promoting SD and tends to generate adverse effects under average conditions, lending support to the “pollution haven” hypothesis. GPR exhibits a pronounced negative effect on SD. Notably, GPR significantly amplifies the effectiveness of GI, suggesting that GI functions not only as an environmental driver but also as a mechanism for enhancing economic resilience to external shocks. The findings provide several policy implications for promoting SD in the countries under study.

KEYWORDS: green innovation, sustainable development, FDI, geopolitical risk

JEL classification: C11, D74, F21, O31, Q55

1. Introduction

In the context of deepening globalization and increasingly severe environmental, social, and economic challenges, sustainable development (SD) has become a central objective in the development strategies of most countries. Climate change, environmental degradation, depletion of natural resources, and rising social inequality have increasingly highlighted the limitations of the traditional growth model, which relies primarily on expanding production and exploiting natural resources. Consequently, countries are transitioning toward new development models in which economic growth must be closely aligned with environmental protection and social progress. In this transformation process, green innovation and foreign direct investment (FDI) are regarded as key driving forces facilitating the shift toward a sustainable growth model.

From a theoretical perspective, the role of technological innovation in economic growth was established early on in the neoclassical growth model of Solow (1956), in which technological progress is considered the key determinant of long-term growth. However, this model does not adequately address environmental considerations. To overcome this limitation, Taylor & Brock (2004) proposed the Green Solow model, which integrates environmental protection objectives

into the economic growth process. Within this framework, green innovation plays a crucial role in promoting environmentally friendly technological progress, improving resource-use efficiency, reducing production costs, and encouraging investment in renewable energy, thereby supporting long-term growth consistent with SD.

In parallel, endogenous growth theory emphasizes the role of knowledge, human capital, and innovation as endogenous factors determining total factor productivity (Romer, 1990; Grossman & Helpman, 1991). Green innovation, as a process of creating and diffusing sustainable technologies, generates positive spillover effects not only in economic terms but also across environmental and social dimensions. Moreover, according to Porter's theory of competitive advantage (1985), innovation is the source of sustainable competitive advantage at both the firm and national levels. Green innovation helps optimize resource utilization, reduce costs, and support countries in building long-term competitive advantages aligned with sustainable growth.

Empirical studies indicate that green innovation is increasingly viewed as an important instrument for addressing environmental degradation and promoting SD (Fethi & Rahuma, 2020; Díaz-García et al., 2015). However, empirical evidence remains inconclusive. Some studies find that green innovation positively affects all three pillars of SD, although the magnitude of these effects varies across country groups (Brandão Santana et al., 2015; Du & Li, 2019; Töbelmann & Wendler, 2020). Other studies emphasize the role of institutional and policy conditions, suggesting that green innovation is effective only within appropriate governance environments (Chang et al., 2023; Koseoglu et al., 2022; Chien et al., 2023). In Vietnam, empirical evidence remains limited but generally supports the positive role of green innovation in promoting SD, although this impact is dynamic and changes over time (Minh Phuong et al., 2023; Ha, 2023).

In addition to green innovation, FDI is widely regarded as a critical resource for promoting economic growth and SD, particularly in developing countries. According to neoclassical growth theory, FDI contributes to capital accumulation, job creation, and enhanced productive capacity, thereby providing the financial foundations necessary to achieve social and environmental objectives (Solow, 1956). Endogenous growth theory further extends this argument by viewing FDI as a channel for transferring technology, managerial expertise, and human capital, which enhances long-term productivity and supports SD (Romer, 1990; Grossman & Helpman, 1991).

However, the impact of FDI on SD remains subject to debate. The "pollution haven" hypothesis suggests that FDI may exacerbate environmental degradation in countries with weak environmental standards (Copeland & Taylor, 2004), whereas the Porter hypothesis emphasizes the role of stringent environmental regulations in steering FDI toward more environmentally friendly and economically efficient activities (Porter & Linde, 1995). Empirical studies indicate that FDI exerts a dual effect on SD, with outcomes strongly contingent upon institutional quality, environmental policies, and the absorptive capacity of host countries (Voica et al., 2015; Ayamba et al., 2020; Izadi & Madirimov, 2023; Rodríguez-Chávez et al., 2024; Bhat et al., 2025).

Meanwhile, the global landscape in recent years has witnessed a marked increase in GPR, manifested through armed conflicts, political tensions, and socio-economic instability. GPR not only affects economic growth and investment flows but also influences countries' capacity to achieve the Sustainable Development Goals. From an institutional perspective, countries with effective governance systems are better positioned to mitigate the adverse effects of GPR and

sustain progress toward SD. Conversely, weak institutions may amplify instability and hinder long-term development.

Empirical evidence on the relationship between GPR and SD remains inconclusive. Some studies find that rising GPR deteriorates environmental quality by increasing CO₂ emissions and ecological pressure (Farooq et al., 2023; Bashir et al., 2023; Wang et al., 2024). In contrast, other studies suggest that GPR may temporarily reduce environmental degradation by suppressing investment and production activities (Anser et al., 2021; Husnain et al., 2022; Nawaz et al., 2023; Zhao et al., 2021). These mixed findings indicate that the role of GPR in SD is highly context-dependent and sensitive to methodological choices.

Although green innovation, FDI, and GPR have each been examined extensively in the literature, studies that jointly consider all three factors within a unified analytical framework remain limited. In particular, the moderating role of GPR in the relationship between green innovation, FDI, and SD at the cross-country level has not been systematically explored. Moreover, most prior studies rely on conventional econometric techniques, while Bayesian regression methods remain underutilized in multi-country settings characterized by high levels of uncertainty.

Motivated by these gaps, this study investigates the relationship between green innovation, FDI, and SD in the context of GPR, using data from 33 countries over the period 2010–2021. The application of Bayesian regression enables flexible handling of parameter uncertainty and unobserved heterogeneity, thereby providing more robust and reliable empirical evidence. This study is expected to contribute to the existing literature by clarifying the moderating role of GPR in the nexus between green innovation, FDI, and SD, while also offering important policy implications for countries seeking to attract FDI and promote green innovation in order to achieve SD goals amid rising geopolitical instability.

The remainder of the paper is structured as follows. Section 2 presents the theoretical framework and reviews relevant empirical studies on green innovation, FDI, GPR, and SD. Section 3 describes the data, variables, and Bayesian regression methodology employed. Section 4 reports and discusses the empirical results for the full sample and for country groups differentiated by levels of GPR. Finally, Section 5 concludes and provides policy implications aimed at promoting SD in an increasingly unstable geopolitical environment.

2. Theoretical background and review of empirical studies

2.1. The relationship between green innovation and sustainable development

According to Solow's neoclassical growth theory, economic growth depends on capital accumulation, labor, and technological progress. Although environmental considerations were not initially emphasized, the Green Solow model proposed by Taylor & Brock (2004) extends this framework by integrating SD objectives. Within this analytical setting, green innovation plays a pivotal role in promoting environmentally friendly technological progress, improving the efficiency of natural resource use, reducing production costs, and encouraging investment in renewable energy and sustainable infrastructure, thereby supporting long-term economic growth aligned with environmental protection.

In addition, endogenous growth theory highlights the role of knowledge, human capital, and innovation as endogenous determinants of total factor productivity. Green innovation represents the process of creating and diffusing sustainable technologies, driven by investments in research and development (R&D), education, and technology transfer. Knowledge spillover effects arising from green innovation enhance production efficiency, foster the adoption of renewable energy, and promote environmentally friendly economic practices, thereby supporting SD.

Furthermore, Porter's theory of competitive advantage (1985) argues that innovation is the source of sustainable competitive advantage at both the firm and national levels. Green innovation enables firms to differentiate their products, optimize resource use, and reduce costs, while simultaneously supporting countries in building long-term competitive advantages through investments in education, infrastructure, and innovation aligned with sustainable growth objectives.

Recent empirical studies indicate that green innovation is increasingly regarded as an important instrument for addressing environmental degradation and promoting SD. Unlike conventional innovation, green innovation focuses on improving environmental quality, enhancing resource-use efficiency, and mitigating the negative impacts of economic activities (Fethi & Rahuma, 2020; Díaz-García et al., 2015). However, empirical evidence on the relationship between green innovation and SD remains mixed and highly dependent on national contexts, measurement approaches, and research methodologies.

At the cross-country level, Brandão Santana et al. (2015) find that technological innovation positively affects all three pillars of SD in BRICS countries, whereas in G7 economies, the impact is mainly concentrated on the social dimension. Zhang et al. (2017), employing the system generalized method of moments (SGMM) for data from 30 Chinese provinces, confirm that green innovation improves environmental quality by reducing CO₂ emissions. Similarly, Du & Li (2019) and Töbelmann & Wendler (2020) provide evidence that green innovation reduces carbon emissions, although the effect is stronger in developed economies than in developing countries.

Several studies emphasize the importance of institutional and contextual conditions. Chang et al. (2023) show that in China, green innovation contributes to environmental improvement only when accompanied by appropriate government regulation. Meanwhile, Koseoglu et al. (2022), using the ecological footprint indicator, demonstrate that environmental technologies significantly reduce ecological pressure. Recent studies focusing on ASEAN countries and China also confirm the positive role of green innovation in promoting SD when measured by greenhouse gas emissions or the Human Development Index (HDI) (Chien et al., 2023; Chien, 2023).

In Vietnam, empirical evidence remains limited but generally supports the positive impact of green innovation on SD (Minh Phuong et al., 2023). However, Ha (2023) finds that this impact is dynamic and varies over time, reflecting the complexity of the relationship between green innovation and ecological sustainability.

2.2. The relationship between foreign direct investment and sustainable development

According to neoclassical growth theory, FDI promotes economic growth by supplementing capital, creating employment, and enhancing productive capacity, thereby providing the financial basis for achieving the social and environmental objectives of SD (Solow, 1956). However, this theoretical framework treats technological progress as exogenous and does not fully clarify the long-term role of FDI in improving the quality of economic growth.

Endogenous growth theory addresses this limitation by emphasizing the roles of knowledge, innovation, and technological spillovers. Within this perspective, FDI is viewed as a channel for transferring technology, managerial skills, and human capital, thereby enhancing long-term productivity and supporting SD (Romer, 1990; Grossman & Helpman, 1991). These spillover effects are particularly important for developing countries, where FDI can facilitate structural transformation toward more sustainable economic models.

Conversely, the “pollution haven” hypothesis argues that multinational corporations tend to relocate pollution-intensive activities to countries with lax environmental regulations, thereby exacerbating environmental degradation and hindering SD (Copeland & Taylor, 2004). In contrast, the Porter hypothesis contends that stringent environmental regulations can stimulate innovation, making FDI more environmentally friendly and contributing to greater long-term economic efficiency (Porter & Linde, 1995).

The relationship between FDI and SD has been widely examined in empirical studies. Voica et al. (2015) investigate the relationship between FDI and SD in the European Union during the period 2000–2012, based on the three pillars of SD: economic, social, and environmental dimensions. Using panel data for 28 EU countries, combined with FDI data from UNCTAD and SD indicators from Eurostat, the study applies panel OLS regression to assess the impact of sustainability indicators on FDI inflows and stocks. The findings confirm the important role of FDI as a resource supporting the achievement of SD objectives, particularly in the context of Europe’s transition toward a green growth model.

Ayamba et al. (2020) analyze the impact of FDI on SD in China over the period 1996–2016, with a focus on the relationship between FDI, economic growth, and environmental quality. Using a vector error correction model (VECM) and impulse response functions, the results indicate that FDI helps alleviate capital shortages and promotes economic growth, while its long-term impact on environmental quality remains ambiguous. The study provides evidence supporting the “pollution halo” hypothesis, suggesting that in the long run, FDI tends to facilitate technology transfer and improve environmental efficiency. However, in the short run, pollution indicators such as SO₂ emissions and industrial dust significantly affect FDI inflows. Based on these findings, the authors emphasize the importance of stringent environmental policies in guiding FDI toward supporting SD.

Rodríguez-Chávez et al. (2024) offer a comprehensive overview of the relationship between FDI and SD in Asia by combining bibliometric analysis with a systematic literature review. Drawing on recent scholarly publications, the study shows that the nexus between FDI and SD has attracted growing academic attention, particularly as Asian economies simultaneously pursue economic growth, environmental protection, and social equity. The review indicates that FDI has a dual impact on SD: on the one hand, it can stimulate economic growth, facilitate technology transfer, enhance productivity, and support the achievement of the Sustainable Development Goals (SDGs); on the other hand, in the absence of appropriate institutional frameworks, FDI may exacerbate environmental pollution, overexploitation of natural resources, and social inequality. The study highlights the critical moderating role of institutional quality, environmental policies, technological capability, and absorptive capacity in transforming FDI into a driver of SD. Accordingly, the authors suggest that future research should pay greater attention to nonlinear effects, sectoral heterogeneity, and country-specific contexts in Asia.

Izadi & Madirimov (2023) examine the impact of FDI on progress toward the Sustainable Development Goals in Eurasian countries, using panel data and advanced econometric techniques to address endogeneity and unobserved heterogeneity. The empirical results indicate that FDI generally exerts a positive effect on SD, particularly by promoting economic growth, improving infrastructure, and facilitating technology transfer, thereby enhancing social welfare and resource-use efficiency. However, the study also finds that the impact of FDI is heterogeneous across countries and depends significantly on institutional quality, financial development, human capital, and the absorptive capacity of host economies. In some cases, FDI may generate adverse environmental effects in the absence of adequate regulations and

monitoring mechanisms. Consequently, the authors stress the importance of regulatory policies, institutional improvements, and directing FDI toward environmentally friendly sectors to maximize its contribution to SD.

Bhat et al. (2025) investigate the dynamic effects of FDI and the institutional–legal environment on SD in the Asia–Pacific region, within the context of the global transition toward a knowledge-based economy. Using time-series panel data for multiple countries in the region and dynamic econometric models, the authors show that FDI plays a positive role in promoting SD; however, the magnitude and persistence of this effect depend strongly on the quality of the regulatory environment. Specifically, in the short run, FDI primarily stimulates economic growth and technology transfer, while environmental and social benefits become more pronounced in the medium and long term when accompanied by effective, transparent, and stable institutional frameworks. The study also underscores the role of innovation-supporting policies, intellectual property protection, and absorptive capacity enhancement in amplifying the spillover effects of FDI. Accordingly, the authors conclude that FDI does not automatically lead to SD but must be properly guided and regulated through appropriate institutional reforms, particularly in developing economies in the Asia–Pacific region.

2.3. The relationship between geopolitical risk and sustainable development

GPR is widely regarded as a factor that can hinder countries' progress toward SD through multiple channels. From an institutional theory perspective, the quality of governance and the legal framework plays a crucial role in managing GPR and promoting SD. Countries with effective institutions that ensure transparency, accountability, and the rule of law are better equipped to mitigate the adverse effects of geopolitical instability on economic growth, social cohesion, and environmental protection. In contrast, weak institutions may exacerbate geopolitical tensions and impede the achievement of SD objectives.

From the perspective of Karl Marx's conflict theory, societies are inherently characterized by competition over scarce resources, of which geopolitical conflict represents a prominent manifestation. Such conflicts, including wars, civil unrest, and territorial disputes, can disrupt economic activity, weaken governance institutions, divert resources away from development projects, and cause environmental degradation. In particular, geopolitical competition over natural resources such as water, forests, arable land, oil, and natural gas may lead to unsustainable exploitation, resource depletion, and ecosystem degradation, thereby threatening long-term sustainability.

However, some empirical studies suggest that GPR may reduce environmental degradation and, consequently, promote SD, as political and military tensions suppress investment and alter production and consumption patterns, leading to lower carbon emissions (Nawaz et al., 2023; Husnain et al., 2022; Anser et al., 2021; Zhao et al., 2021).

Empirical evidence indicates that GPR has increasingly become a major challenge to SD in the context of deepening economic integration and globalization. Rising armed conflicts, terrorism, and geopolitical tensions can weaken international cooperation, thereby hindering progress toward the SDGs (Nguyen et al., 2023; Wang et al., 2024). The review by Wang et al. (2024) shows that studies on GPR and SD have primarily focused on environmental sustainability, with a notable increase following the Russia–Ukraine conflict, reflecting growing academic concern over the environmental implications of geopolitical instability.

Some studies argue that effective management of GPR can promote SD. Ahmad et al. (2024), analyzing OECD countries, find that improvements in GPR conditions enhance SD by fostering political and economic stability, which facilitates investment, trade, and the allocation of

resources toward sustainable initiatives. This view is consistent with Feng et al. (2024) and studies focusing on China and BRICS economies, which show that rising GPR deteriorates environmental quality through increased CO₂ emissions (Farooq et al., 2023; Bashir et al., 2023; Wang et al., 2024).

Conversely, other studies indicate that GPR may reduce environmental degradation by restraining investment, production, and consumption activities. Empirical evidence from Italy, E7 economies, emerging markets, and BRICS countries suggests that higher GPR contributes to lower CO₂ emissions or reduced ecological footprints (Nawaz et al., 2023; Husnain et al., 2022; Anser et al., 2021; Zhao et al., 2021). Overall, the empirical findings remain inconclusive, indicating that the impact of GPR on SD is highly context-dependent and sensitive to measurement choices and research methodologies.

2.4. The moderating role of geopolitical risk in the relationship between green innovation, foreign direct investment, and sustainable development

According to transaction cost theory, political uncertainty increases investors' costs of information search, negotiation, and contract enforcement, thereby reducing incentives to attract FDI into long-term projects, particularly green technological innovation initiatives (Williamson, 1981). This framework helps explain why FDI under conditions of high GPR may provide weaker support for sustainable development. From the perspective of investment under uncertainty, political instability raises expected risk and the cost of capital, prompting firms to postpone or withdraw from irreversible investments such as green innovation, which typically requires long payback periods and a stable policy environment (Dixit, 1994).

Technology spillover theory emphasizes the role of FDI in transferring advanced technologies, including clean technologies and environmental management practices (Borensztein et al., 1998). However, heightened geopolitical risk can obstruct these capital flows, thereby weakening spillover effects and constraining the positive impact of FDI on sustainable development. Finally, institutional theory highlights that a stable political environment is a prerequisite for policies promoting green innovation and for the effectiveness of incentives aimed at attracting green FDI (North, 1990). Consequently, GPR not only directly affects sustainable development but also moderates the ways in which green innovation and FDI influence sustainable development, underscoring the context-dependent nature of sustainable development analysis.

Recent empirical studies provide evidence on the moderating role of GPR in green technology transfer channels. Cheng et al. (2024) demonstrate that geopolitical risk significantly undermines the diffusion of green technologies through both FDI and import trade at the provincial level in China, while also showing that endogenous factors, such as the level of green technological capability, marketization, and intellectual property rights protection, can mitigate these adverse effects.

Although not directly measuring sustainable development indices, a study on Saudi Arabia by Hajimineh and Moghani (2025) finds that GPR not only increases carbon emissions directly but also amplifies the negative environmental impacts of FDI and trade, indicating an adverse moderating effect on the environmental dimension of economic globalization. Moreover, global evidence suggests that political risk more broadly constitutes a barrier to green innovation, particularly in unstable political environments where firms curtail investments in environmentally friendly technologies, leading to changes in the quality of domestic green innovation. Using global data, Yang et al. (2022) show that political risk significantly weakens

green technological upgrading, especially in developed economies and countries with high levels of political organization.

Overall, the existing evidence indicates that geopolitical risk is a critical moderating factor in the nexus between FDI, green innovation, and sustainable development. GPR not only directly influences sustainable development prospects through policy stability and the investment climate but also reshapes the channels through which FDI and green technologies diffuse and contribute to sustainability objectives. Therefore, a comprehensive political–economic analysis of the impacts of FDI and green innovation should explicitly incorporate the moderating role of geopolitical risk as an essential factor, rather than treating it merely as a peripheral control variable.

3. Data and research methodology

Based on the theoretical framework and empirical evidence discussed in the previous sections, the proposed research model is specified as follows:

$$SD_{i,t} = \beta_i + \beta_1 FDI_{i,t} + \beta_2 GI_{i,t} + \beta_3 GPR_{i,t} + \beta_4 Z_{i,t} + \varepsilon_{i,t} \quad (1)$$

where $i = 1, 2, \dots, N$ denotes countries and $t = 1, 2, \dots, T$ denotes time periods.

To examine the moderating role of geopolitical risk in the relationship between green innovation, foreign direct investment (FDI), and sustainable development, the study incorporates the interaction terms $GI \times GPR$ and $FDI \times GPR$ into the empirical model presented below:

$$SD_{i,t} = \beta_i + \beta_1 FDI_{i,t} + \beta_2 GI_{i,t} + \beta_3 GPR_{i,t} + \beta_4 GI_{i,t} \times GPR_{i,t} + \beta_5 FDI_{i,t} \times GPR_{i,t} + \beta_6 Z_{i,t} + \varepsilon_{i,t} \quad (2)$$

where SD represents the sustainable development variable, FDI denotes foreign direct investment, GI represents green innovation, GPR is geopolitical risk, and Z is a vector of control variables, including economic growth (GDP), fiscal decentralization (FD), natural resources (NRR), renewable energy consumption (REC), urbanization level (URB), trade openness (OPEN), government size (SIZE), and population growth (POP). Detailed measurements of these variables are presented in Table 1.

Table 1. Variable description

Variable	Description	Measurement	Research	Data sources
SD	Sustainable development	Sustainable development goals index	Oanh (2023), Dinh et al. (2024), Nguyen et al. (2025)	Sustainable Development Report
FDI	Foreign direct investment	Foreign direct investment, net inflows (% of GDP)	Oanh (2023), Izadi & Madirimov (2023)	WDI
GI	Green innovation	The ratio of environmental-related technology patents to total technology patents (%)	Chien et al. (2023), Nguyen et al. (2025)	OECD
GPR	Geopolitical risks	The geopolitical risk index,	Hoang et. al (2024)	www.matteoia-coviello.com

Variable	Description	Measurement	Research	Data sources
		developed by Dario Caldara and Matteo Iacoviello.		
GDP	Economic growth	GDP growth rate (%)	Wang et al. (2023)	WDI
FD	Fiscal decentralization	Local spending/total government spending ratio (%)	Yang et al. (2020), Hui & Martinez-Vazquez (2021)	IMF
NRR	Natural resources rent	Total natural resources rents (% of GDP)	Dastgeer et al. (2023)	WDI
REC	Renewable energy consumption	% of total final energy consumption	Sueyoshi et al. (2022), Dastgeer et al. (2023)	
URB	Urbanization	Urban population (% of total population)	Chen & Liu (2020), Li & Xu (2023)	
OPEN	Trade openness	Sum of exports and imports of goods and services (% of GDP)	Yang et al. (2020), Hui & Martinez-Vazquez (2021), Nguyen et al. (2025)	
SIZE	Government size	Government revenue (% of GDP)	Jin & Jakovljevic (2023), Nguyen et al. (2025)	
POP	Population	Population growth rate (%)	Vo & Vo (2021)	

Due to data limitations for the variables included in the research model, this study employs a balanced panel dataset of 33 countries over the period 2010–2021. The data for the variables used in the model are collected from multiple sources, as presented in Table 1.

3.2. Research methodology

This study applies Bayesian regression techniques to process data from 33 countries during the period 2010-2021. Within the Bayesian paradigm, inference is obtained by updating prior knowledge with observed data to form a posterior distribution, from which parameter uncertainty is directly assessed. Interpretation therefore focuses on the full probability distribution of parameters rather than on asymptotic properties tied to sample size, allowing Bayesian methods to remain effective even when data are limited in scope. In this framework, the dataset is regarded as given, while model parameters are treated as stochastic quantities. Prior distributions encode existing information or beliefs about parameters before any observations are taken, representing the researcher’s initial state of knowledge. As empirical evidence is introduced, these priors are updated to yield more precise estimates. The posterior distribution, derived from the combination of priors and observed data, thus supports inference

that incorporates both data-driven information and prior beliefs, offering a flexible and robust approach for addressing data incompleteness and heterogeneity.

4. Results and discussion

Table 2 reports substantial variation across the variables included in the research model. The Sustainable Development Goals Index (SDGI) has a mean value of 4.32 with a relatively low standard deviation (0.079), indicating that the level of sustainable development is fairly stable and exhibits limited dispersion across countries. Green innovation (GI) records an average value of approximately 0.126; however, its standard deviation is relatively large compared to the mean, suggesting considerable cross-country heterogeneity in green innovation performance. Foreign direct investment (FDI) displays a low mean value (0.032) but a very wide range, extending from negative values to a maximum exceeding 1, which reflects substantial disparities in countries' ability to attract FDI inflows.

Geopolitical risk (GPR) has an average level of 0.243 and a high standard deviation, highlighting pronounced differences and volatility in geopolitical environments across countries. Among the control variables, economic growth (GDP) and population growth (POG) exhibit relatively low mean values, whereas fiscal decentralization (FD), trade openness (trade), and urbanization (URBAN) show comparatively higher averages, reflecting clear trends toward economic integration and urban development. Renewable energy consumption (REC) and natural resource rents (NRR) present modest mean values but considerable dispersion, indicating their potential yet uneven roles in promoting sustainable development.

Table 2. Descriptive statistics

Variable	Obs	Mean	Std. dev.	Min	Max
SDGI	396	4.32097	0.07892	4.09722	4.46080
GI	396	0.12627	0.03746	0.05041	0.26616
FDI	396	0.03209	0.09385	-0.40086	1.06574
GPR	396	0.24273	0.40874	0.00564	2.62763
GDP	396	0.02424	0.03390	-0.10940	0.13363
FD	396	0.34709	0.15919	0.03000	0.82510
URB	396	0.75722	0.13604	0.30417	0.98117
TRADE	396	0.78156	0.37344	0.23393	1.86429
SIZE	396	0.36156	0.11286	0.12461	0.57498
POP	396	0.00625	0.00634	-0.01854	0.02010
REC	396	0.18818	0.13537	0.01300	0.61400
NRR	396	0.02534	0.03404	0.00008	0.18511

The regression results reported in Table 3 indicate that green innovation exerts a positive effect on sustainable development, with a posterior probability of 59.79%. Consistent with the classical Solow growth theory and the Green Solow model proposed by Taylor & Brock (2004), green innovation represents a form of technological progress oriented toward environmentally sustainable solutions. By investing in research and development to generate cleaner technologies, improve energy efficiency, and reduce environmental externalities, economies can enhance productivity and achieve sustainable growth while mitigating environmental degradation. Through the promotion of green innovation, higher productivity can be attained alongside improved environmental sustainability and resilience. This finding is also in line with endogenous growth theory and empirical evidence reported by Töbelmann & Wendler (2020), Koseoglu et al. (2022), and Chien et al. (2023).

In contrast, FDI is found to exert a negative effect on sustainable development in the sampled countries, with a posterior probability of 59.01%. This result lends support to the “pollution haven” hypothesis. FDI projects, particularly those concentrated in pollution-intensive or hazardous industries, may pose significant risks to human health and the environment. Industrial pollution, including air and water contamination and the disposal of toxic waste, can adversely affect local communities by impairing respiratory health, degrading water quality, undermining food safety, and ultimately weakening sustainable development outcomes. This finding is consistent with the results reported by Farooq et al. (2023) and Nawaz et al. (2023).

Geopolitical risk is also identified as a factor that undermines sustainable development in the countries under study. This outcome can be interpreted through the lens of Karl Marx’s conflict theory, which posits that social order is maintained through dominance and power rather than consensus and harmony. Geopolitical conflict represents one manifestation of such struggles. Both internal and external geopolitical tensions can disrupt economic activities, weaken social cohesion, and hinder environmental protection efforts, thereby obstructing sustainable development. Wars, civil unrest, and territorial disputes may divert resources away from development projects and exacerbate environmental degradation. Armed conflicts, civil wars, and terrorism not only inflict direct harm on individuals and communities but also disrupt economic activity, displace populations, erode governance institutions, and complicate the implementation of long-term development strategies. Moreover, geopolitical tensions over environmental resources, such as water, forests, arable land, oil, and natural gas, can further contribute to environmental degradation and ecological conflict. Competition for access to natural resources, combined with unsustainable extraction practices, may lead to resource depletion, pollution, and habitat destruction, thereby intensifying environmental challenges and threatening ecosystem sustainability. These findings are consistent with the study’s initial hypotheses and align with the evidence reported by Farooq et al. (2023), Bashir et al. (2023), Ahmad et al. (2024) and Wang et al. (2024).

Table 3. Bayesian Regression Results of Model 1

SDGI	Mean	Std. dev.	MCSE	Median	Probability		
					Mean	Std. Dev.	MCSE
GI	0.1607	0.0572	0.0006	0.1614	0.5979	0.0458	0.0005
FDI	-0.0049	0.0214	0.0002	-0.0051	0.5901	0.4918	0.0049
GPR	-0.0241	0.0057	0.0001	-0.0241	1.0000	0.0000	0.0000
GDP	0.0247	0.0616	0.0006	0.0253	1.0000	0.0000	0.0000
FD	0.0064	0.0134	0.0001	0.0064	0.6846	0.4647	0.0046
URB	0.2028	0.0198	0.0002	0.2029	1.0000	0.0000	0.0000
TRADE	0.0343	0.0065	0.0001	0.0343	1.0000	0.0000	0.0000
SIZE	0.1926	0.0271	0.0003	0.1928	1.0000	0.0000	0.0000
POP	-3.6597	0.3937	0.0039	-3.6618	1.0000	0.0000	0.0000
REC	0.2072	0.0185	0.0002	0.2070	1.0000	0.0000	0.0000
NRR	-0.5990	0.0649	0.0006	-0.5999	1.0000	0.0000	0.0000
CONS	4.0412	0.0156	0.0002	4.0411			
<i>Avg acceptance rate</i>			<i>0.8226</i>	<i>Avg efficiency: min</i>			<i>0.0570</i>

The results further reveal that the posterior probabilities associated with FDI and green innovation are relatively modest, remaining below 60%, which indicates uncertainty regarding both the direction and magnitude of their effects. By contrast, geopolitical risk exhibits an effect on sustainable development with a posterior probability of nearly 100%. This suggests that GPR

may not only exert a direct influence on the SDGI but also shape the transmission mechanisms through which green innovation and FDI affect sustainable development. From a theoretical perspective, an unstable geopolitical environment can weaken the effectiveness of green innovation by disrupting technological supply chains, constraining knowledge flows, and increasing compliance costs. At the same time, it may alter the incentives, composition, and time horizons of FDI flows, thereby affecting their contribution to sustainable development objectives. Consequently, incorporating the interaction terms $GI \times GPR$ and $FDI \times GPR$ into the model enables a direct examination of the moderating role of geopolitical risk and helps clarify whether, and under what conditions, green innovation and FDI can effectively promote sustainable development. The corresponding results are presented in Table 4.

Table 4. Bayesian regression results of Model 2

SDGI	Mean	Std. dev.	MCSE	Median	Probability		
					Mean	Std. Dev.	MCSE
GI	0.0988	0.0626	0.0006	0.0989	0.9435	0.2309	0.0023
FDI	-0.0202	0.0265	0.0003	-0.0202	0.7777	0.4158	0.0042
GPR	-0.0489	0.0303	0.0003	-0.0490	0.9475	0.2230	0.0022
FDI×GPR	0.2962	0.2965	0.0030	0.2943	0.8396	0.3670	0.0037
GI×GPR	0.5913	0.2583	0.0026	0.5909	0.9884	0.1071	0.0010
GDP	0.0299	0.0628	0.0006	0.0294	0.6845	0.4647	0.0046
FD	0.0055	0.0133	0.0001	0.0055	0.6667	0.4714	0.0046
URB	0.2055	0.0192	0.0002	0.2054	1.0000	0.0000	0.0000
TRADE	0.0347	0.0064	0.0001	0.0347	1.0000	0.0000	0.0000
SIZE	0.1882	0.0265	0.0003	0.1882	1.0000	0.0000	0.0000
POP	-3.6856	0.3959	0.0039	-3.6842	1.0000	0.0000	0.0000
REC	0.2119	0.0190	0.0002	0.2114	1.0000	0.0000	0.0000
NRR	-0.5757	0.0661	0.0007	-0.5754	1.0000	0.0000	0.0000
cons	4.0471	0.0159	0.0002	4.0470			
<i>Avg acceptance rate</i>			<i>0.8189</i>	<i>Avg efficiency: min</i>			<i>0.1100</i>

The results indicate that geopolitical risk plays an important role in moderation; however, the magnitude and degree of certainty of this moderating effect differ across the two channels.

For the interaction term $FDI \times GPR$, the posterior mean coefficient is positive, with a posterior probability of approximately 83.96%. This finding suggests a relatively high likelihood that geopolitical risk alters both the direction and intensity of the impact of FDI on sustainable development. In other words, as geopolitical risk increases, the average negative effect of FDI tends to be attenuated and, in some cases, may even shift toward a more positive contribution. Nevertheless, given the remaining degree of uncertainty, this result implies that the moderating role of GPR on FDI is not sufficiently robust and remains contingent upon complementary conditions, such as institutional quality and the green orientation of FDI inflows.

By contrast, the interaction term $GI \times GPR$ provides very strong Bayesian evidence. The posterior mean coefficient is large and positive, with a posterior probability reaching 98.84%. This result confirms that geopolitical risk significantly amplifies the positive impact of green innovation on sustainable development. In countries or periods characterized by heightened geopolitical instability, green innovation not only functions as an environmental driver but also becomes a mechanism for enhancing economic resilience, helping to sustain and improve sustainable development trajectories in the face of external shocks. These findings suggest that green innovation acts as a “strategic shield,” enabling countries to mitigate the adverse effects

of geopolitical instability on sustainable development. In contrast, FDI can contribute positively to sustainable development under high-risk conditions only when it is properly guided and accompanied by effective screening, regulatory, and incentive-based policies for green investment.

Overall, these findings not only help explain inconsistencies in previous empirical results but also underscore the importance of explicitly incorporating geopolitical risk into the analytical framework of sustainable development, particularly in an era of intensifying global uncertainty. In addition, the results show that factors such as economic growth, fiscal decentralization, urbanization, trade openness, government size, and renewable energy consumption promote sustainable development, whereas population growth and natural resource dependence tend to undermine it.

5. Conclusions and recommendations

This study examines the effects of green innovation, foreign direct investment, and geopolitical risk on sustainable development in a context of rising global uncertainty, employing a Bayesian regression approach to better capture uncertainty and structural heterogeneity in the data. The empirical results indicate that the relationships among these factors are neither linear nor homogeneous but depend critically on geopolitical conditions.

Specifically, green innovation exhibits a high probability of exerting a positive influence on sustainable development; however, its average effect remains unstable when geopolitical risk is not taken into account. Meanwhile, FDI does not display a clear role in promoting sustainable development and even tends to generate adverse effects under average conditions, reflecting substantial heterogeneity in the quality and orientation of international investment flows. In contrast, geopolitical risk shows a pronounced negative impact on sustainable development, highlighting the importance of political stability and a favorable international environment for achieving long-term development goals.

Notably, the inclusion of interaction terms sheds light on the critical moderating role of geopolitical risk. The Bayesian regression results provide compelling evidence that green innovation becomes more effective in fostering sustainable development as geopolitical risk increases, indicating that green innovation is not only an environmental driver but also a tool for enhancing economic resilience to external shocks. Conversely, although the interaction between FDI and geopolitical risk displays a positive sign, it is characterized by substantial uncertainty, suggesting that FDI can contribute to sustainable development only under appropriate institutional and policy conditions.

Based on these findings, the study derives several important policy implications for countries facing rising geopolitical uncertainty.

First, green innovation should be regarded as a strategic pillar of sustainable development, particularly in high-risk environments. Governments should prioritize investment in green research and development, promote clean technology transfer, and build innovation ecosystems to strengthen economic adaptability and resilience. Integrating green innovation objectives into economic security and long-term development strategies can help mitigate the adverse effects of geopolitical shocks.

Second, FDI attraction policies should shift their focus from quantity to quality. In a context of geopolitical risk, countries should not expect FDI to automatically promote sustainable development; instead, more rigorous screening, guidance, and monitoring mechanisms for foreign investment projects are required. Priority should be given to FDI flows associated with

green technologies, high environmental and social standards, and strong spillover potential for domestic firms.

Third, the results highlight that geopolitical stability and risk governance constitute fundamental conditions for achieving sustainable development. Governments should therefore strengthen their capacity to anticipate, manage, and mitigate geopolitical risks through the diversification of international economic relations, institutional strengthening, and enhanced policy coherence. These efforts not only directly improve sustainable development outcomes but also create favorable conditions for green innovation and FDI to operate more effectively.

Finally, from both academic and policy perspectives, the study emphasizes the need to adopt a context-dependent approach to sustainable development rather than applying “one-size-fits-all” solutions. Combining Bayesian analysis with considerations of geopolitical uncertainty provides a more flexible and realistic analytical framework, thereby supporting policymakers in designing sustainable development strategies that are better suited to an increasingly uncertain world.

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