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

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ABSTRACT

Purpose – This study investigates the effects of green innovation, foreign direct investment (FDI), and geopolitical risk on sustainable development in an increasingly uncertain global environment. It aims to clarify whether geopolitical risk directly influences sustainable development and whether it moderates the impacts of green innovation and FDI, thereby providing new evidence on the drivers of sustainable development under external shocks.

Design/methodology/approach – The study employs a Bayesian regression approach using panel data from 33 countries over the period 2010-2021. Compared with conventional frequentist methods, the Bayesian framework is better suited to capturing parameter uncertainty and structural heterogeneity while providing probabilistic inference on the relationships among green innovation, FDI, geopolitical risk, and sustainable development.

Findings – The results indicate that green innovation exerts a positive effect on sustainable development, although its average impact remains unstable when geopolitical risk is not considered. In contrast, FDI does not consistently promote sustainable development and tends to generate adverse effects under average conditions, supporting

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the pollution hypothesis. Geopolitical risk has a significant negative impact on sustainable development with a posterior probability of 100%. Furthermore, geopolitical risk significantly strengthens the positive effect of green innovation on sustainable development, suggesting that green innovation enhances resilience to external shocks. Conversely, higher geopolitical risk intensifies the negative impact of FDI on sustainable development.

Originality/value – This study contributes to the literature by integrating geopolitical risk as both a direct determinant and a moderating factor in the relationship between green innovation, FDI, and sustainable development. It also demonstrates the advantages of Bayesian estimation in addressing uncertainty and heterogeneity in cross-country sustainability research, providing a more comprehensive understanding of sustainable development under geopolitical instability.

Practical implications – The findings suggest that policymakers should strengthen investment in green innovation and incorporate geopolitical risk into sustainable development strategies. Governments should also improve the quality and environmental orientation of FDI while enhancing resilience through policies that encourage clean technologies and sustainable investment.

Social implications – By highlighting the importance of green innovation in mitigating the adverse effects of geopolitical uncertainty, the study provides evidence that supports policies promoting environmental sustainability, economic resilience, and long-term social welfare in the face of increasing global risks.

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 and 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 sustainable development.

In parallel, endogenous growth theory emphasizes the role of knowledge, human capital, and innovation as endogenous factors determining total factor productivity (Grossman & Krueger, 1991; Romer, 1990). 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 sustainable development (Díaz-García et al., 2015; Fethi & Rahuma, 2020). However, empirical evidence remains inconclusive. Some studies find that green innovation positively affects all three pillars of sustainable development, 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; Chien et al., 2023; Koseoglu et al., 2022). In Vietnam, empirical evidence remains limited but generally supports the positive role of green innovation in promoting sustainable development, although this impact is dynamic and changes over time (Ha, 2023; Phuong et al., 2023).

In addition to green innovation, FDI is widely regarded as a critical resource for promoting economic growth and sustainable development, 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 sustainable development (Grossman & Krueger, 1991; Romer, 1990).

However, the impact of FDI on sustainable development 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 sustainable development, with outcomes strongly contingent upon institutional quality, environmental policies, and the absorptive capacity of host countries (Ayamba et al., 2020; Bhat et al., 2025; Izadi & Madirimov, 2023; Rodríguez-Chávez et al., 2024; Voica et al., 2015).

Meanwhile, the global landscape in recent years has witnessed a marked increase in geopolitical risk (GPR), manifested through armed conflicts, political tensions, and socio-economic instability. Geopolitical risk 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 geopolitical risk and sustain progress toward sustainable development. Conversely, weak institutions may amplify instability and hinder long-term development.

Empirical evidence on the relationship between geopolitical risk and sustainable development remains inconclusive. Some studies find that rising geopolitical risk deteriorates environmental quality by increasing CO_2 emissions and ecological pressure (Bashir et al., 2023; Wang et al., 2024). In contrast, other studies suggest that geopolitical risk may temporarily reduce environmental degradation by suppressing investment and production activities (Anser et al., 2021; ul Husnain et al., 2022; Nawaz et al., 2023; Zhao et al., 2021). These mixed findings indicate that the role of geopolitical risk in sustainable development is highly context-dependent and sensitive to methodological choices.

Although green innovation, FDI, and geopolitical risk 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 geopolitical risk in the relationship between green innovation, FDI, and sustainable development 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 sustainable development in the context of geopolitical risk, 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 geopolitical risk in the nexus between green innovation, FDI, and sustainable development, while also offering important policy implications for countries seeking to attract FDI and promote green innovation in order to achieve sustainable development 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, geopolitical risk, and sustainable development. 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 geopolitical risk. Finally, Section 5 concludes and provides policy implications aimed at promoting sustainable development 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 and Brock (2004) extends this framework by integrating sustainable development 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 sustainable development.

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 sustainable development. Unlike conventional innovation, green innovation focuses on improving environmental quality, enhancing resource-use efficiency, and mitigating the negative impacts of economic activities (Díaz-García et al., 2015; Fethi & Rahuma, 2020). However, empirical evidence on the relationship between green innovation and sustainable development 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 sustainable development 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 CO_2 emissions. Similarly, Du and Li (2019) and Töbelmann and 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 sustainable development 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 sustainable development (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 sustainable development (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 sustainable development (Grossman & Krueger, 1991; Romer, 1990). 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 sustainable development (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 sustainable development has been widely examined in empirical studies. Voica et al. (2015) investigate the relationship between FDI and sustainable development in the European Union during the period 2000-2012, based on the three pillars of sustainable development: economic, social, and environmental dimensions. Using panel data for 28 EU countries, combined with FDI data from UNCTAD and sustainable development 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 sustainable development objectives, particularly in the context of Europe's transition toward a green growth model.

Ayamba et al. (2020) analyze the impact of FDI on sustainable development 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 SO_2 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 sustainable development.

Rodríguez-Chávez et al. (2024) offer a comprehensive overview of the relationship between FDI and sustainable development 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 sustainable development 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 sustainable development: 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 sustainable development. Accordingly, the authors suggest that future research should pay greater attention to nonlinear effects, sectoral heterogeneity, and country-specific contexts in Asia.

Izadi and 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 sustainable development, 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 sustainable development.

Bhat et al. (2025) investigate the dynamic effects of FDI and the institutional–legal environment on sustainable development 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 sustainable development; 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 sustainable development 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

geopolitical risk is widely regarded as a factor that can hinder countries' progress toward sustainable development through

multiple channels. From an institutional theory perspective, the quality of governance and the legal framework plays a crucial role in managing geopolitical risk and promoting sustainable development. 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 sustainable development 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 geopolitical risk may reduce environmental degradation and, consequently, promote sustainable development, as political and military tensions suppress investment and alter production and consumption patterns, leading to lower carbon emissions (Anser et al., 2021; ul Husnain et al., 2022; Nawaz et al., 2023; Zhao et al., 2021).

Empirical evidence indicates that geopolitical risk has increasingly become a major challenge to sustainable development 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., 2025; Wang et al., 2024). The review by Wang et al. (2024) shows that studies on geopolitical risk and sustainable development 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 geopolitical risk can promote sustainable development. Ahmad et al. (2024), analyzing OECD countries, find that improvements in geopolitical risk conditions enhance sustainable development 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 geopolitical risk deteriorates environmental quality through increased CO_2 emissions (Bashir et al., 2023; Wang et al., 2024).

Conversely, other studies indicate that geopolitical risk 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 geopolitical risk contributes to lower CO_2 emissions or reduced ecological footprints (Anser et al., 2021; ul Husnain et al., 2022; Nawaz et al., 2023; Zhao et al., 2021). Overall, the empirical findings remain inconclusive, indicating that the impact of geopolitical risk on sustainable development 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 geopolitical risk 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 & Pindyck, 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 weaken 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, geopolitical risk 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 geopolitical risk 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 (2023) finds that geopolitical risk 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. Geopolitical risk 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

3.1. Research model and data

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, …, N denotes countries and t = 1, 2,…, 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×GPR and FDI×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 sustainable development represents the sustainable development variable, FDI denotes foreign direct investment, GI represents green innovation, geopolitical risk is geopolitical risk, and 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 Appendix 1 *(see Appendix 1 online)*.

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 Appendix 1.

3.2. Research methodology

This study employs a Bayesian regression framework to analyze panel data from 33 countries over the period 2010-2021. Compared with the traditional frequentist paradigm, which typically relies on large sample sizes and repeated sampling assumptions, the Bayesian approach offers a more flexible alternative. In the fields of social sciences and macroeconomics, it is particularly advantageous because model parameters are treated as random variables rather than fixed quantities (Briggs & Nguyen, 2019; Kruschke, 2014). This methodological choice is supported by two main considerations. First, Bayesian techniques are well suited to panel datasets with a relatively short time dimension (T = 12 years) and do not impose strict stationarity requirements, thereby retaining the inherent economic information within the data (Gary, 2003). Second, instead of focusing solely on point estimates, the Bayesian framework generates posterior distributions, enabling a probabilistic interpretation of the effects of explanatory variables (Thach, 2020).

Under the Bayesian perspective, statistical inference is conducted by combining prior beliefs with observed data to obtain posterior distributions, which provide a direct measure of parameter uncertainty. As a result, interpretation emphasizes the entire distribution of parameters rather than relying on asymptotic properties associated with large samples, making the approach suitable even in contexts with limited data. Within this framework, the observed dataset is considered fixed, while parameters are modeled as stochastic. Prior distributions reflect initial knowledge or assumptions about these parameters before incorporating empirical evidence. As new data is introduced, the priors are updated, leading to more refined estimates. The resulting posterior distributions integrate both prior information and observed data, offering a comprehensive and adaptable basis for inference, particularly in the presence of data limitations and heterogeneity. In this study, given the lack of well-established prior information from

existing literature, non-informative priors are adopted to maintain objectivity. This specification reduces the influence of prior assumptions, allowing the empirical data to play a central role in determining the posterior outcomes (Nalborczyk et al., 2019).

4. Results and discussion

Appendix 2 *(see Appendix 2 online)* 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.

The regression results reported in Table 1 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 and Brock (2004), green innovation represents a form of technological progress oriented towards 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. From a practical perspective, this result can be explained by the fact that economies actively promoting green innovation tend to experience more efficient resource utilization and lower environmental costs, which directly contribute to sustainable development outcomes. In reality, countries with higher levels of investment in clean technologies and energy efficiency often achieve a better balance between economic growth and environmental protection. This reflects how green innovation not only enhances productivity but also reduces negative externalities, thereby reinforcing its positive role in supporting long-term sustainability. This finding is also in line with endogenous growth theory and empirical evidence reported by Chien et al. (2023), Koseoglu et al. (2022), and Töbelmann and Wendler (2020).

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 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 Ahmad et al. (2024), Bashir et al. (2023), and Wang et al. (2024).

Table 1. 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			
Avg acceptance rate			*0.8226*	*Avg efficiency: min*			*0.0570*

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 geopolitical risk 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×GPR and FDI×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 2.

Table 2. 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
FDIxGPR	0.2962	0.2965	0.0030	0.2943	0.8396	0.3670	0.0037
GIxGPR	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			
Avg acceptance rate			*0.8189*	*Avg efficiency: min*			*0.1100*

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×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 geopolitical risk 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×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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Data Availability

Data available upon reasonable request (contact corresponding author).

AI Usage Statement

This paper used ChatGPT to support grammar correction and structural editing. All idea development, literature review, data collection, analysis, and interpretation were carried out entirely by the authors, who take full responsibility for the study.

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