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Effects of Green Innovations, Geopolitical Risk, Renewable Energy, and Urbanization on Environmental Quality in BRICS+T

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ABSTRACT

This research examines the interplay between green innovation, geopolitical risk, renewable energy consumption, and urbanization in influencing environmental quality across BRICS+T nations from 2004 to 2022. We utilized advanced panel estimation techniques in addressing slope heterogeneity, cross-sectional dependence, and long-run equilibrium dynamics in implementing DCE, DCE-IV, and DSUR. The findings indicate that green innovation and the use of renewable energy play a crucial role in improving environmental quality by lowering CO_2 emissions and boosting the load capacity factor. Geopolitical risk and unplanned urbanization consistently undermine environmental outcomes, with both factors demonstrating statistically significant negative impacts across various models. Granger causality tests establish bidirectional relationships among geopolitical risk, urbanization, and environmental indicators, whereas green innovation and renewable energy exhibit a unidirectional influence. The results highlight the critical role of stable governance, the spread of technology, and cohesive urban planning in enhancing environmental conditions. The results underscore the necessity for unified national approaches spanning technological, political, and infrastructural areas. This research represents a pioneering effort to combine green innovation, geopolitical risk, renewable energy, and urbanization into a cohesive empirical framework centered on BRICS+T economies. This study reveals intricate interdependencies that are frequently neglected in the current environmental economics literature by utilizing strong long-run estimators and dual environmental proxies (CO_2 and LCF). The study suggests that investments should be made in renewable energy infrastructure, alongside providing institutional support for green innovation, promoting sustainable urban planning, and fostering regional cooperation. These measures aim to reduce geopolitical volatility and maintain consistent environmental governance among BRICS+T nations.

Keywords: Green Innovation, Geopolitical Risk, Renewable Energy, Urbanization, Environmental Quality
JEL Classifications: Q56, O33, Q48, R11

1. INTRODUCTION

Environmental quality has become more than just a scientific or political issue—it is a human concern that touches lives, shapes futures, and demands global attention. Today, our ecosystems face unprecedented pressure from various complex forces, including geopolitical instability, technological change, renewable energy transitions, and rapidly expanding urban landscapes. As researchers, we recognize the need to understand how these forces interact, not in isolation but as part of an intricate web that influences how societies adapt to and shape their environment. A growing body of research echoes this urgency, revealing nuanced and sometimes unexpected relationships between these variables across various economic and regional settings (Khan et al., 2024). Geopolitical risk (GPR) injects uncertainty into policy and investment landscapes. This unpredictability can stifle environmental progress by discouraging long-term planning and green investment. However, some studies also suggest that GPR can act as a catalyst, pushing countries to become more energy-independent by investing in domestic renewable energy sources (Abdallah and El Dine, 2024). For example, (Wang et al., 2024) found that in OECD countries, heightened geopolitical tension spurred energy transitions, especially when complemented by robust environmental regulations and innovation frameworks. However, in contexts where fiscal constraints dominate, GPR often leads to the reallocation of resources away from sustainability, weakening the policy and financial support needed for clean energy development.

Green innovation (GI) offers an essential avenue for reducing environmental harm without sacrificing economic progress. It embodies the idea that growth and sustainability can go hand-in-hand if fueled by the right technologies and incentives. Several studies have underscored GI's ability to lower CO_2 emissions and improve overall environmental performance (Chang et al., 2024). For instance, demonstrated how environmental innovations significantly enhanced renewable energy adoption while reducing emissions in high-pollution Asian economies. However, GI's success is not guaranteed; its potential is closely tied to the strength of institutional governance, urban management, and the ecosystem of policy support in which it operates (Chang et al., 2024). Renewable energy consumption (REC) is a well-documented pillar of environmental sustainability. Beyond its ability to reduce emissions, REC offers a pathway to energy equity, climate resilience, and cleaner air. The literature consistently confirms that expanding renewable energy use positively impacts environmental quality. However, regional disparities persist; the impact of REC often depends on the sophistication of local regulatory frameworks and the economic structure of energy markets. Effective governance and inclusive financing remain key to unlocking REC's full potential in all contexts. Urbanization presents both a challenge and an opportunity. On one hand, rapidly growing urban centers can strain natural systems, increase emissions, and deplete critical resources. Conversely, cities can serve as incubators for innovation, efficiency, and sustainable living—if guided by thoughtful planning and technology-driven infrastructure. (Li and Zhang, 2023) found that new urbanization policies in China helped reduce carbon intensity through smarter urban operations and optimized industrial layouts. This suggests that urbanization, if reimagined through a sustainability lens, can become part of the solution rather than the problem. Taken together, the research underscores that these drivers—GPR, GI, REC, and UR—do not function independently. Their interactions are shaped by national priorities, institutional strengths, and socio-economic contexts.

Environmental quality has emerged as a central issue for nations navigating rapid industrial growth, technological advancement, and socio-political complexity. BRICS+T nations—Brazil, Russia, India, China, South Africa, and Turkey—represent economies where urban expansion, energy transitions, and policy uncertainty intersect with ecological outcomes. The significance of studying these countries lies in their growing contribution to global emissions and unique developmental trajectories. This study is motivated by the need to examine how structural factors such as green innovation, geopolitical risk, renewable energy consumption, and urbanization jointly shape environmental quality in these countries over time. While prior research has addressed some of these drivers in isolation, few studies have explored their interconnected effects using a comprehensive empirical framework. This study fills that gap by offering an integrated analysis that reflects technological and political-economic dimensions.

The significance of this research is twofold. First, it contributes to empirical environmental economics by analyzing dynamic panel data across economies with distinct institutional capacities. Second, it provides policymakers with evidence on how innovation, energy strategy, urban planning, and political stability influence ecological outcomes. Understanding these relationships is crucial for designing effective and coordinated environmental policies.

This study seeks to answer the following research questions: RQ1. How does green innovation influence environmental quality in BRICS+T countries? RQ2. To what extent does geopolitical risk affect environmental performance? RQ3. What role does renewable energy consumption play in shaping ecological outcomes? RQ4. How does urbanization impact environmental quality, and does this effect vary over time and context?

Based on theoretical reasoning and existing empirical findings, the study proposes four testable hypotheses:
H_1: Green innovation has a positive effect on environmental quality.
H_2: Geopolitical risk negatively affects environmental quality.
H_3: Renewable energy consumption improves environmental quality.
H_4: Urbanization exerts a mixed effect on environmental quality, depending on urban development models and institutional factors.

This study adds to the body of knowledge in environmental economics by tackling various research gaps that have not been thoroughly examined within the context of BRICS+T countries. First, The study initially combines green innovation, geopolitical risk, renewable energy consumption, and urbanization into a cohesive empirical framework. Previous research frequently analyzes these factors individually or in specific pairings. This method restricts comprehension of their combined impacts. This research effectively captures the simultaneous influence of these variables on environmental quality. The model is designed to capture the intricate complexities and interconnections of the real world's technological, political, and structural elements. Secondly, this study emphasizes the BRICS+T economies, which are often overlooked in global environmental assessments. The current body of work primarily focuses on OECD nations or international panels. The applicability of these findings to emerging economies, which possess distinct institutional structures, policy frameworks, and environmental challenges, may be limited. This study focuses on BRICS+T countries, offering insights specifically designed for economies in swift transition, where the challenge of balancing environmental sustainability with developmental priorities is prominent. Third, the study employs load capacity factor and CO_2 emissions as two indicators of environmental quality. This dual measurement approach enables the analysis to capture ecological stress and environmental capacity effectively. Prior research predominantly depends on individual proxies like CO_2 or ecological footprint, which may fail to encompass the complete picture of environmental quality. Applying the load capacity factor provides a different perspective for assessing sustainability outcomes. Fourth, the study utilizes sophisticated panel econometric techniques that effectively tackle slope heterogeneity, cross-sectional dependence, and structural shifts. Numerous previous studies depend on conventional fixed effects or pooled regressions, which can lead to skewed results in panels characterized by interdependencies or unique country-specific effects. This research employs estimation techniques, including DCE, DSUR, and CUP-FM, ensuring reliable and pertinent outcomes to policy considerations.

Fifth, the research investigates the influence of geopolitical risk within the environmental sector. This aspect is still underexplored in the current empirical literature, which emphasizes economic, institutional, or energy-related factors more prominently. The study incorporates geopolitical risk, presenting a variable pertinent to policy discussions and encapsulating elements of uncertainty, exposure to conflict, and instability in governance. This enhancement allows for a more thorough evaluation of obstacles to sustainable development.

The remainder of the article is organized into several sections. Section 2 presents the theoretical framework and specifies the empirical model, detailing the anticipated relationships among variables. Section 3 outlines the data sources, variable definitions, and econometric methods applied. Section 4 discusses the empirical results, including diagnostic tests and interpretation of model outputs. Section 5 provides a policy-focused discussion of the findings, linking results to practical implications. Section 6 concludes the study with key insights, limitations, and directions for future research.

2. LITERATURE REVIEW

2.1. Theoretical Review

Green innovations are crucial in improving environmental quality through reducing carbon emissions. Technological advancements in this area have demonstrated a clear ability to enhance energy efficiency and contribute substantially to environmental sustainability, as evidenced by the current body of literature. Similarly, JiLi et al. (2021) highlight that green innovations significantly contribute to lowering carbon emissions and enhancing environmental performance, thereby underscoring these innovations' critical role in addressing environmental degradation. Studies show that the adoption of green technologies enables countries to substantially reduce their carbon footprints, demonstrating that even incremental implementation can meaningfully improve environmental quality (Huang et al., 2021; Li et al., 2021).

The contribution of renewable energy to enhancing environmental quality is significant. As countries shift from fossil fuels to renewable energy sources, the decrease in greenhouse gas emissions is observable. Research indicates that renewable energy reduces carbon emissions while improving air quality in various regions (Gao and Fan, 2023; Shen et al., 2020). The Renewable Energy Green Innovation framework incorporates technological advancement and renewable energy consumption, which enhance initiatives to combat climate change and environmental degradation (Michele, 2023; Zhao et al., 2022). Moreover, the connection between green finance and the use of renewable energy illustrates how financial innovation can enhance environmental certification standards, which are crucial for advancing green energy technologies (Arshad et al., 2023; Huang et al., 2021).

Urbanization, often associated with heightened energy use and carbon emissions, presents avenues to improve environmental quality through strategic urban planning and innovative policy development. Swift urban growth necessitates creative approaches to address its negative effects on the environment. Research shows that urban green innovation initiatives positively impact sustainability, particularly in cities facing significant carbon emissions (Ali et al., 2022; Li et al., 2021). Developing urban infrastructure focusing on sustainable practices enhances load capacity factors by implementing energy-efficient designs, which in turn lowers energy demands and enhances air quality in metropolitan regions (Gao et al., 2022; Ghosh et al., 2024).

Geopolitical risks further exacerbate the complexities of these dynamics. Geopolitical tensions can impede the effective execution of environmental policies, as unstable regions frequently prioritize short-term economic issues over long-term sustainability objectives. The interplay between geopolitical factors and sustainable innovations can either support or obstruct environmental initiatives, contingent upon the political stability of countries involved in advancing green technology and renewable energy investments (Albaker et al., 2023; Sethi et al., 2023). Moreover, (Yi, 2023) highlights the importance of cohesive strategies in energy policy that consider geopolitical factors while promoting innovation and sustainability. The relationship among green innovations, renewable energy, urbanization, and geopolitical risk establishes a complex framework for comprehending their effects on environmental quality. The evidence consistently indicates a positive correlation between these factors and enhanced environmental outcomes; however, challenges remain, especially in reconciling development with sustainability in rapidly urbanizing areas. By advocating for green technologies and investing in renewable energy while considering geopolitical contexts, stakeholders can improve environmental quality and make meaningful contributions to sustainable development goals.

2.2. Green Innovation and Environmental Quality

Green innovation has become one of the main motivators of the search for solutions to environmental problems because it introduces sustainable methods to improve ecological outcomes. It comprises a variety of technological innovations and innovative practices that facilitate resource efficiency and minimize unfavorable environmental impacts. In an attempt to find the equilibrium between environmental sustainability and economic development, green technologies are being adopted more and more seriously. The existing literature states that, besides minimizing environmental degradation, green innovation is consistent with the overall objectives of sustainable economic development. A good amount of the research addresses the importance of the regulation of the environment in fostering green technological innovation. Li et al. (2021) prove that firms will invest in environmentally friendly technology due to stringent environmental policies, which reduce pollution and enhance ecological performance. Peng et al. (2023) take this argument one step further, showing that policy uncertainty can be an incentive, and firms can react proactively through green innovation to lock in their future. Such results uphold that coherent and consistent environmental policies are crucial for promoting innovation and sustaining long-term ecological resilience. The implementation of green innovation strategies outside of policy frameworks is largely affected by corporate governance. Cao and Chen (2019) believe that the environmental awareness level of senior management teams is a major determinant of a firm's sustainability commitment. Their research suggests that green initiatives will be high on the priority list and adopted if the leadership is responsive to ecological problems. Similarly, Yi et al. (2019) study on the effectiveness of diverse environmental policy tools supports the need for good leadership in developing organizational sustainability practices.

Green innovation has an irreplaceable role to play through financial mechanisms. Ni et al. (2023) examine financial technologies' role (green credit and investment incentives) in the diffusion of sustainable technologies in Chinese prefecture-level cities. Through their research, the need to have accessibility of a financial nature made to take place is emphasized to promote socio-friendly solutions. Green innovation initiatives have been seen to be encouraged by policy and financial incentives, apart from social mobilization, especially the youth element. Adhikari (2024) emulates how the active participation of youthful people in environmental endeavors creates a culture of innovation and eventually attains universal sustainability goals. This intergenerational pattern puts green innovation as a societal common but not a corporate or state socio-economic duty. Regional dynamics also influence the effectiveness and direction of green innovation. Ramadhan et al. (2023) explore how regional-level context-specific innovations are related to sustainability goals. Their work implies that localizing environmental strategies increases their effectiveness and sustainability results. This localized lens would be good for viewing and practicing green innovations.

There are other opportunities for developing green technologies from urbanization, particularly in growing areas such as Asia. According to Zada et al. (2025) cities are significant places to test and roll out sustainable innovations. Integrating ecological issues into urban planning can lead to great environmental gains, including reduced emissions and higher biodiversity, which requires a sustainable urban design. Entrepreneurship also contributes to the green innovation environment. He et al. (2022) explain how the business models of entrepreneurial ventures established in environmental responsibility can move. Their research highlights the role of responsible leadership in the ventures as a catalyst for innovation that will benefit both business and the community. Given the incorporation of innovation in corporate strategy, firms embed environmental priorities in their operating structures. Apart from that, Ghorbani (2023) develops a broad model to integrate green knowledge management into corporate strategy. This approach is based on finding resources and innovating to counter the environmental problem. The study supports the view that through sustainability integration in the strategic business models, there is enhanced long-term competitiveness, as well as environmental improvement.

2.3. Geopolitical Risk and Environmental Quality

Geopolitical risk is now becoming widely accepted as an important consideration in assessing environmental quality, especially in resource-poor areas with unstable political climates, such as the Asian region. Knowledge of intricate interplays between geopolitical tensions, policy reactions, and environmental degradation can facilitate the creation of sustainable development. The burgeoning literature in this domain demonstrates the deep and wide-ranging effects of political instability, international relations, and conflict on ecological systems. The correlation between geopolitical risk and environmental degradation, particularly in the exploitation of natural resources, is central to the literature. Cengiz and Manga (2022) note that greater carbon emissions often go hand in hand with growing geopolitical tensions because countries often prefer defense funding and securing resources as opposed to the role of stewardship towards the environment. Khurshid et al. (2024) proceed to support the claim that geopolitical uncertainty accelerates the mining of non-renewable energy resources, which accelerates environmental degradation. Their findings highlight the necessity to switch to renewable energy sources as a preventive strategic step against the ecological consequences of political instability.

Environmental security has been of academic interest in the most recent research, where scholars have underlined the negative effect of geopolitical risk on the energy transition processes. Such risks, according to Wang et al. (2024), may seriously hamper the moves toward clean energy, but strong environmental regulations may instead overrule such lags and push for sustainability. Similarly, Awal et al. (2025) emphasize the need for resilient policy frameworks to avert geopolitical uncertainties that will ensure positive environmental outcomes. Chen et al. (2025) contribute to this argument by considering how geopolitics has a two-fold effect on renewable energy consumption and energy security and the confirmation of the need for a comprehensive approach to sustainability. The environmental price of geopolitical conflicts is particularly observable in areas where such conflicts happen. The correlation between geopolitical stress and environmental degradation is explained by Khatri (2025), who states that disaster, which is expedited by political instability, increases the communities' vulnerability and adds to circles of ecological as well as social disruption. Examining in parallel with Ulussever et al. (2023), researchers focus on the Gulf Cooperation Council (GCC) countries, where geopolitical risks have severely impacted environmental conditions, thus bringing the need for policies that negotiate between ecological dilemmas and geopolitical realities to the fore. Green innovation amid a geopolitically volatile environment is a complex, developing research topic. The research of Raichuk (2024) reveals the complexity of such dynamics and the necessity of complex analytics to reveal regional disparities.

The Environmental Kuznets Curve (EKC) framework also incorporates geopolitical variables. According to Nawaz et al.

(2023) push this further to see how trade openness and economic growth influence the environmental outcomes in Asian economies against geopolitical risks. The geopolitical tensions also influence the treatment of resources and investment in sustainable activities. Such tensions, according to Husnain et al. (2022), tend to increase competition for natural resources and, consequently, overuse and environmental degradation. Like Nadia et al. (2024), geographical conflicts are reported to be the trigger of economic indiscretion, which could discourage responsible environmental investments. These interdependencies have implications for policy solutions that are comprehensive and to be accompanied by geopolitical and ecological ones. Also, evidence from E7 countries indicates that geopolitical instability may paralyze environmental governance and sustainability efforts. Similarly, Mokdadi and Saadaoui (2023) illustrate the adverse role of geopolitics and the necessity for context-specific, well-coordinated policy responses to the problem of environmental decline. International cooperation has been universally accepted as a major avenue for minimizing the environmental impact of geopolitical risk. Ghorbani (2023) looks for multilateral governance systems to cushion ecological systems against geopolitical shocks. Farooq et al. (2023) agree with this opinion by highlighting the opportunity that is presented by strategically driven coalitions that focus on renewable energy to enhance environmental security and energy security in politically volatile regions.

2.4. Renewable Energy and Environmental Quality

Renewable energy transition has become an important strategy to enhance environmental quality and to combat climate change. Renewable energy becomes a pillar to reduce greenhouse gas (GHG) emissions, enhance air and water quality, and increase ecosystem resilience as the world seeks to pursue sustainable development vigorously. This review integrates the current literature on the environmental impacts of renewable energy deployment, especially the recent progress in Asian countries. Renewable energy technologies, including solar, wind, hydro, and geothermal, are increasingly adopted as alternative sources to fossil fuels because renewable energy technologies can reduce carbon emissions and environmental devastation. Yadav et al. (2023) examine the roles of these technologies in sustainable energy production and mention significant investments to reduce national carbon footprints. This perspective is supported by a view expressed by Bashiru et al. (2024), who argue that the growth in renewable energy usage dramatically decreases GHG emissions and improves air quality.

Renewable energy provides obvious socio-economic benefits besides environmental benefits. Devadasa and Laxminarayana (2023) show that the shift to clean energy drives job creation and diversification of economies, results that are especially beneficial for developing countries. These developments contribute to the construct of resilience to climate impacts and inclusive economic growth. Bashiru et al. (2024) argue further that renewable energy is at the heart of driving the United Nations Sustainable Development Goals (SDGs), especially through promoting cleaner, equitable energy systems. The joining of renewable energy and ecological conservation can produce synergistic benefits. For instance, Susandi et al. (2024) study the integration of renewable energy and blue carbon ecosystems to build up coastal climate mitigation. Such an approach addresses two sides of the coin, energy production and biodiversity conservation, which reflects the need for a holistic environmental policy that integrates the sustainability of the energy deployment with the integrity of the ecosystem.

However, though renewable energy usually supports ecological advances, the latter can have unintended environmental consequences if not effectively regulated. Kafumu and Ojija (2025) warn that if renewable energy projects are undertaken without proper planning, they will degrade local ecosystems and result in biodiversity loss caused by changes in land use. Such concerns demonstrate the necessity of environmental evaluations and the site selection strategy to reduce ecological give-and-take related to energy development. The economic impacts of renewable energy add to its interest. Batra (2023) insists that renewable energy has not only helped reduce climate change but it has also led to energy independence, helped to minimize reliance on fuel imports, and helped to create long-term economic stability through jobs and industry. The benefits provided reinforce the argument in favor of policy support and investment in clean energy infrastructure. Study of Lee et al. (2024) discovered that the environmental benefits of renewable energy scale with consumption intensity. Based on their research, they find that increased utilization of renewable energy is associated with greater emission reductions, implying that increasing investments in renewable infrastructure would be most beneficial to the environment. These insights present large-scale deployment policies to maximize sustainability outcomes. Also highly important is the successful incorporation of renewable energy into national climate agendas. Moriarty and Honnery (2022) emphasize the need for holistic and policy-matched energy strategies for the drive to have harmonization in environmental planning. The incorporation of renewable energies into broader climate mitigation regimens enhances the effectiveness of policies and meets emission reduction targets. Policy frameworks have a very critical role to play in speeding up the entire process of adoption of renewable energy. Karim et al. (2018) stress that effective regulatory instruments and incentives for investment are critical to renewable energy growth and developable performance benchmarks. Umeh et al. (2024) also advocate for integrated energy governance frameworks that integrate renewable energy deployment with shifts in health and environment indicators. Access to energy on an equitable basis remains an important issue in the renewable transition. Ukoba et al. (2024) investigate the use of renewable technologies to provide clean energy to impoverished and rural communities while also describing the potential of renewable technologies to relieve energy poverty and enhance environmental conditions. This approach to planning serves two purposes: Advocacy for social equity and ecological stewardship. Environmental advantages obtained from renewables also apply to areas that are interconnected to the power industry, like agriculture and water-related activities. Uğurlu (2021) shows the way in which renewable energy can help to solve the problem of water quality, further pointing out the integrated nature of environmental systems and the multidimensional nature of clean energy technologies.

2.5. Urbanization and Environmental Quality

Urbanization (the transition or conversion of rural populations to urban centers) has now become one of the most important forces influencing the quality of the environment, especially for fast-growing areas like those in Asia. As urban populations keep growing, it is essential to know comprehensively the impacts of urban growth on the environment. This review assesses the complex urbanization-environment quality relationship, highlighting the adverse and possible positive effects associated with it. Air quality is a core issue of debate with regard to urbanization. Research has shown that there is a host of reports that support the fact that urbanization leads to poor air conditions, as the air quality is usually ruined by emissions associated with vehicular traffic, industrial activities, and construction activities. According to Acharya (2024), uncontrolled urban expansion in Kathmandu has resulted in rapid deterioration of air quality, mainly because policy priorities have been skewed for development at the expense of ecological conservation. Helping to substantiate this, Hussain (2024) notes how urban sprawl leads to increases in carbon dioxide and other pollutant emissions, hence severely damaging the levels of urban environmental standards.

Land-use changes and ecological disruption form other effects of urban expansion. Conversion of natural landscapes into built environments commonly results in loss of habitat, reduced permeability of land surfaces and reduced biodiversity. Wang and Wang (2024) study urbanization in ecologically sensitive parts of China and describe mixed results, where ‘impacts’ vary between areas degraded and others that respond with enhanced ecological governance. In the same manner, Zhu et al. (2025) demonstrate this duality in Hangzhou, where the environmentally disadvantaged zones were the newly urbanized districts, while the aged urban areas presented echoes of ecological improvement. The fact that these findings highlight the spatial variation of the environmental impacts of urbanization demonstrates the need for context-specific planning with respect to urbanization. The development of urban infrastructure as a natural extension of urbanization applies further environmental pressure. Wei and Liu (2023) explore the ecological impacts of China’s high-speed rail development, which, although more efficient public transport systems can decrease automobile dependency and greenhouse gas emissions, poorly integrated infrastructure projects can lead to greater consumption of resources and environmental pressure. Sustainable planning is therefore essential to ensure that infrastructure serves environmental objectives.

Urbanization also exerts great pressure on water resources. The population of urban centers increases, and there is, therefore, also increased demand for water, which sometimes leads to over-extraction and contamination. Ren et al. (2014) discuss this in a Chinese context where up-scaled urban areas have resulted in local waterways being polluted, a critical problem in urban water management. These results underscore the need to couple urban expansion to sustainable water governance practices. Energy consumption is another aspect on which urbanization affects the environment. According to Khan et al. (2023), urban density will lead to more energy consumption, increased emissions, and lower quality of air. However, urbanization can also support the deployment of renewable energy technologies because of the demand concentration and the infrastructure. Basri and Herianti (2024) propose that incorporating renewable solutions into the development of the urban setting would address the adverse effects of urban growth. Urban green spaces have become an important part of sustaining the quality of the environment in the cities. With the attendant increase in the size of Urban areas, the green cover often decreases, leading to a loss of ecological services like carbon sequestration, temperature regulation, and air cleaning. Putra et al. (2024) talk about this trend, and Wuisang et al. (2023) promote the conservation and development of public green spaces to increase biodiversity and urban livability. Jennings et al. (2012) develop this argument by connecting access to urban green spaces to environmental justice, pointing out how important it is to achieve equal benefits for the environment. Planning the city in an effective way with environmental provisions is crucial to neutralize the negative impact that urbanization has. Sadeghi et al. (2014) call for urban design concepts based on sustainable principles that focus on the idea of green infrastructure and ecological integration. While, concurrently, Stigt et al. (2017) support participatory urban governance strategies where the involved communities have input to influence environmentally responsible urban development. There is a need for strong frameworks of assessment for urban environmental quality to support evidence-based planning. Comprehensive models of assessment that apply multidimensional indicators to evaluate the state of environmental conditions are proposed by Shao et al. (2019) and Vo et al. (2024). These tools are important in directing urban policy and development, with ecological sustainability being the aim.

3. DATA AND METHODOLOGY OF THE STUDY

3.1. Theoretical Development and Conceptual Framework of the Study

Environmental sustainability has emerged as a critical priority in the policy agendas of both emerging and advanced economies. In this context, BRICS+T nations—Brazil, Russia, India, China, South Africa, and Turkey—represent a significant subset of fast-growing economies with considerable environmental footprints. Several structural and strategic factors, including technological change, energy transition, political uncertainty, and rapid urbanization, influence the environmental trajectory of these nations. This study is motivated by the need to understand how green innovation (GI), geopolitical risk (GPR), renewable energy consumption (REC), and urbanization (UR) jointly affect environmental quality (EQ) over the period 2004-2022. Theoretically, the Environmental Kuznets Curve (EKC) provides a foundational perspective, positing a nonlinear relationship between economic growth and environmental degradation. However, emerging literature has increasingly emphasized the role of technology and governance in shaping this dynamic. Green innovation, defined as the development and diffusion of environmentally sustainable technologies, can mitigate pollution and reduce carbon emissions by enhancing energy efficiency and replacing polluting practices (Ahakwa et al., 2023). Empirical evidence confirms that GI plays a pivotal role in environmental improvement in both developed and emerging economies (Zhang et al., 2025). Renewable energy consumption also serves as a vital determinant of environmental quality. Transitioning from fossil fuels to renewable sources—such as wind, solar, and hydroelectric—reduces greenhouse gas emissions and curbs local air pollution. In the context of BRICS+T nations, several studies confirm that increased reliance on renewable energy enhances environmental sustainability (Ahmed and Elfaki, 2024). Geopolitical risk (GPR), measured through indices capturing conflict, war threats, and political instability, can indirectly harm environmental governance by reducing foreign investment in clean technologies and hindering long-term sustainable policies. Elevated GPR is associated with reduced environmental oversight and weakened regulatory frameworks (Wang et al., 2024). Urbanization, while associated with economic development, has a dual effect on the environment. It can worsen environmental quality through increased energy demand and vehicular emissions, but also offers opportunities for efficient public services, compact infrastructure, and technological uptake. The direction of this impact depends on urban planning quality and institutional strength (Hashmi et al., 2021)

These theoretical insights support the formulation of the following general empirical model:

$$EQ\int REC, GI, GPR, UR \tag{1}$$

3.2. Model Specification

To empirically assess the effects of green innovation, geopolitical risk, renewable energy consumption, and urbanization on environmental quality in BRICS+T countries over the period 2004-2022, this study employs a dynamic panel data framework. A linear panel regression model is specified as follows:

$$EQ_{it} = \alpha_i + \beta_1 GI_{it} + \beta_2 GPR_{it} + \beta_3 REC_{it} + \beta_4 UR_{it} + \varepsilon_{it} \tag{2}$$

Where, EQ_{it} Represents environmental quality in country i at time t, proxied by CO_2 emissions per capita (inverse relationship) or Load Capacity Factor (LCF). GI_{it} Denotes green innovation, proxied by environmental patent applications or green total factor productivity. GPR_{it} Captures geopolitical risk based on the Caldara and Iacoviello index. REC_{it} Renewable energy consumption is a percentage of total energy consumption. UR_{it} Indicates urbanization, measured as the urban population (% of total population). $\alpha_{i|}$ Captures country-specific fixed effects. $\varepsilon_{it|}$ Is the error term. Table 1 displayed the variables particulars.

Table 1: Variables definition and data sources

Concept	Proxy/measurement	Source
Environmental quality	Load capacity factor (LCF), CO_2 Emissions per Capita	World Bank
Green innovations	Patents in environmental technologies, Green TFP (total factor productivity)	WIPO, national patent databases
Geopolitical risk (GPR)	GPR Index by Caldara and Iacoviello	GPR Database
Renewable energy	Share of renewable energy in total energy consumption	World Bank
Urbanization	Urban population (% of total population)	World Bank

3.3. Variables Definition and Expected Sign

The expected coefficients in the specified panel regression model are grounded in both theoretical reasoning and empirical evidence from recent literature. The variable GIit, representing green innovation, is expected to carry a positive sign ($\beta_1 > 0$). Green innovation encompasses the development and application of environmentally friendly technologies, such as low-carbon production methods, renewable energy solutions, and resource-efficient systems. These innovations reduce greenhouse gas emissions, mitigate resource depletion, and enhance sustainable industrial processes. For example, empirical findings demonstrate that a 1% increase in technological innovation can significantly reduce per capita CO_2 emissions in emerging economies (Zhang et al., 2025). Therefore, it is anticipated that increases in green innovation will lead to improved environmental quality. This relationship is expressed as:

$$\frac{\partial EQ_{it}}{\partial GI_{it}} = \beta_1 > 0$$

In contrast, geopolitical risk (GPR_{it}) is expected to impact environmental quality negatively, thus $\beta_2 < 0$. Geopolitical risk includes threats such as war, terrorism, and political instability, all of which can disrupt institutional focus on long-term sustainability goals. When geopolitical risk is high, governments and investors tend to deprioritize environmental regulations and shift focus toward short-term political or economic stability, often sidelining green transitions. Prior studies have found that geopolitical instability significantly hinders environmental quality by reducing foreign investment in renewable energy and weakening institutional enforcement of environmental standards (Wang et al., 2024). This anticipated relationship is captured as:

$$\frac{\partial EQ_{it}}{\partial GPR_{it}} = \beta_2 < 0$$

Renewable energy consumption (REC_{it}) is expected to be positively associated with environmental quality, hence $\beta_3 > 0$. Renewable energy sources—such as wind, solar, and hydroelectric power—produce little to no greenhouse gas emissions compared to fossil fuels, and their expansion is crucial for a sustainable energy future. In the context of BRICS+T nations, where fossil fuels often dominate the energy mix, increasing the share of renewable energy directly contributes to lowering CO_2 emissions and improving air quality. Empirical studies consistently show that higher renewable energy consumption leads to reduced environmental degradation in Asian and emerging economies (Ahmed and Elfaki, 2024). The expected relationship is represented as:

$$\frac{\partial EQ_{it}}{\partial GPR_{it}} = \beta_3 > 0$$

The coefficient β_4, associated with urbanization (URit), may take either a positive or negative sign, contingent on the nature and quality of urban development within the BRICS+T nations. Urbanization, typically measured as the share of the population living in urban areas, has a dual and context-dependent relationship with environmental quality. On one hand, urbanization can lead to environmental degradation, particularly when it is unplanned or poorly managed. In such contexts, urban expansion often results in higher energy consumption, increased vehicular emissions, greater waste generation, and overburdened infrastructure. These effects contribute to a rise in air and water pollution and a general decline in environmental quality. Numerous studies affirm that in the early stages of urban growth, especially in low- and middle-income countries, rapid urbanization tends to increase CO_2 emissions and ecological footprints (Ahakwa et al., 2023). On the other hand, urbanization—when supported by smart infrastructure, efficient public transport, green buildings, and compact city planning—can lead to improvements in environmental quality. Densely populated urban centers may reduce per capita emissions by enabling economies of scale in energy use, promoting clean technologies, and concentrating environmental governance. For instance, studies show that urban agglomeration aligned with green infrastructure development can support ecological modernization and reduce long-term emissions (Hashmi et al., 2021). As such, the expected partial derivative of environmental quality with respect to urbanization is ambiguous and depends on the interplay between urban growth and institutional capacity for sustainable management:

$$\frac{\partial EQ_{it}}{\partial UR_{it}} = \beta 4 \gtrless 0$$

The results from Table 2 indicate no evidence of multicollinearity among the independent variables in both models, as all Variance Inflation Factor (VIF) values are well below the conventional threshold of 10. In Model A (CO_2 emissions), VIF values range from 1.12 to 1.99, while in Model 2 (LCF), they range from 1.05 to 1.95. The mean VIFs of 1.60 and 1.47, respectively, confirm overall low collinearity. These findings suggest that the variables—renewable energy (RE), green innovation (GI), urbanization (UR), and geopolitical risk (GPR)—are sufficiently independent, ensuring the stability and reliability of the estimated regression coefficients.

3.4. Estimation Strategies

Phase 1 deals with the execution of Cross-sectional Dependence Tests – The study used the Xiao et al. (2023) CD test and the SH test of Bersvendsen and Ditzen (2021) to assess cross-sectional dependence. Cross-sectional dependence tests are crucial in panel data analysis to detect whether units (e.g., countries, firms) are interrelated. The CD test offers robust performance under heterogeneous slopes and allows for general forms of cross-sectional dependence. It modifies traditional CD tests to remain valid in large panels. The SH test addresses serial correlation and unbalanced panels using bias-corrected estimators. The basic equation underlying both tests involves residual correlation structures across units. These tests are particularly suitable for macro panels and empirical studies where ignoring dependence could bias inference or mislead conclusions.

Table 2: Output of VIE analysis

Statistics	RE	GI	UR	GPR
Model A: for CO_2 emission				
VIF	1.9946	1.4222	1.8769	1.1179
1/VIF	0.5013	0.7031	0.5327	0.8945
Mean VIF	1.6029			
Model 2: Load capacity factor (LCF)				
VIF	1.122	1.0476	1.9516	1.7542
1/VIF	0.8912	0.9545	0.5124	0.57
Mean VIF	1.4688			

Stage deals with Panel Unit Root Tests – Specifically, the Herwartz et al. (2018) test was applied to check the stationarity of variables. The panel unit root test is a second-generation approach that accounts for cross-sectional dependence in panel data—an improvement over first-generation tests like Levin-Lin-Chu or Im-Pesaran-Shin. It is based on a factor-augmented framework where common shocks across panel units are modeled using principal components. The basic equation incorporates both individual unit-specific dynamics and common factors, enhancing test power and robustness. It is particularly suitable for macroeconomic or financial datasets with large cross-sections and potential interdependencies among units. This makes it ideal for assessing stationarity in integrated economic panels where cross-sectional correlations exist.

Phase 3 assesses the long-run linkage in the empirical relations with the Panel Cointegration Test by following the Westerlund (2008) test used to identify long-run equilibrium relationships. Panel Cointegration Test is a second-generation cointegration method designed to account for cross-sectional dependence and heterogeneity across panel data units. It employs bootstrapping techniques to improve inference accuracy in small samples and allows for structural breaks and serial correlation. The basic model is derived from the error-correction form:

$$\Delta y_{it} = \alpha_i + \delta_{it} + \beta_i y_{it} - 1 + \sum \gamma_{ij} \Delta y_{it} - j + \int_{it} \tag{3}$$

The test is suitable for dynamic panels with structural shifts and is particularly effective for macroeconomic or financial datasets with cross-unit interactions.

Stage 4 is about documenting the elasticities of independent variables on environmental quality in BRICS+T; in this regard, the study purposively selected DCE (Dynamic Common Correlated Effects) and DCE-IV (Instrumental Variable-based Dynamic Common Correlated Effects). Dynamic Common Correlated Effects (DCE) and DCE-IV are advanced panel data estimation techniques designed to account for unobserved common factors that affect cross-sectional units over time, particularly when these units (e.g., countries, firms) are interdependent.

The DCE model extends the Common Correlated Effects (CCE) estimator to dynamic settings, where lagged dependent variables are included. It controls for unobserved common factors by including cross-sectional averages of both dependent and independent variables and their lags. The basic DCE equation is:

$$Y_{it} = \alpha_i + \rho y_i, t - 1 + \beta x_{it} + \gamma' z^{-} t + \varepsilon_{it} \tag{4}$$

Where z¯t includes cross-sectional averages of all variables to absorb unobserved common factors.

DCE-IV further addresses endogeneity by incorporating instrumental variables (IV). It applies IV techniques within the DCE framework, using external instruments or internal lags to ensure consistent estimation when explanatory variables are correlated with the error term. These methods are particularly suitable for panel datasets with cross-sectional dependence and dynamic relationships. DCE is effective when common shocks influence all units, while DCE-IV is preferable when addressing endogeneity concerns in dynamic models.

Dynamic Seemingly Unrelated Regression (DSUR) is an econometric technique used to estimate systems of equations where each equation may have different dependent variables but share potentially correlated error terms. It extends the classic Seemingly Unrelated Regression (SUR) by incorporating lagged dependent or independent variables, allowing for dynamic relationships over time. The basic form of a DSUR system for equations i = 1,2., Mi = 1, 2., Mi = 1,2., M is:

$$Y_{it} = \alpha_i + \sum j = 1p\beta_{ij} y_i, t - j + \sum k = 1K\gamma ikxkt \quad (5)$$

where y_{it} is the dependent variable, xkt are explanatory variables (which may be common across equations), and ε_{it} are contemporaneously correlated error terms across equations. DSUR is estimated using Generalized Least Squares (GLS), accounting for cross-equation error correlation and time dynamics, enhancing efficiency compared to separate OLS estimations. DSUR is particularly appropriate in macroeconomics and finance, where multiple interdependent time series are analyzed jointly. It is ideal when variables influence each other over time and when shock transmission across systems is of interest. It performs best with balanced panels and sufficient time observations.

The final phase deals with the causality assessment by implementing the DH causality test. The Dumitrescu-Hurlin (D-H) causality test is a panel data econometric technique used to assess Granger causality across cross-sectional units (e.g., countries, firms) in a panel dataset. Unlike traditional time series Granger causality tests, the D-H test is well-suited for heterogeneous panel data, where the causal relationship may differ across units.

The core model is:

$$Y_i, t = \alpha_i + \sum k = 1K\gamma_i, ky_i, t - k + \sum k = 1K\beta_i, kx_i, t - k + \varepsilon_i, t \quad (6)$$

Where: y_i, t and $x_i t$ are the dependent and independent variables for cross-section i at time t, β_i, k captures the causal effect of x on y,

- The null hypothesis: H_0: $\beta_{i,k} = 0$ for all i, i.e., no causality,
- The alternative allows causality in at least some cross-sections.

4. ESTIMATION AND INTERPRETATION

4.1. Pre-estimation

The results from the CD test presented in Panel A (Table 3) confirm significant cross-sectional dependence across all variables, including renewable energy (RE), green innovation (GI), urbanization (UR), geopolitical risk (GPR), CO_2 emissions, and load capacity factor (LCF), with all test statistics highly significant ($P < 0.01$), which indicates that shocks or disturbances in one country are likely correlated with those in others, underscoring the need for estimators that account for such interdependencies. Panel B further corroborates this through the SH test, where both the Delta and Adjusted Delta statistics for CO_2 and LCF models are highly significant. These findings justify the application of second-generation panel estimation techniques that accommodate cross-sectional dependence and slope heterogeneity.

The unit root test results in Panel A (Table 4) confirm that all variables—RE, GI, UR, GPR, CO_2, and LCF—are non-stationary at level but become stationary after first differencing, indicating they are integrated of order one, I(1). This justifies the use of cointegration analysis. Panel B presents the cointegration test, which shows statistically significant LM statistics under all three specifications (no shift, mean shift, and regime shift) for both CO_2 and LCF models. These findings robustly confirm the existence of a long-run equilibrium relationship among the studied variables, validating the use of long-run panel estimators for empirical analysis.

4.2. Empirical Model Estimations: CO_2

For renewable energy (RE), the study reveals, Table 5, a consistent and statistically significant negative relationship with CO_2 emissions across all estimation techniques (DCE = −0.1536; DCE-IV = −0.0869; DSUR = −0.1079). These coefficients confirm the mitigating role of renewable energy in improving environmental quality among BRICS+T countries. The magnitude of the effect, particularly under DCE and DSUR methods, underscores that the transition to cleaner energy sources significantly offsets carbon emissions. This relationship reflects the direct mechanism by which renewable energy displaces fossil fuel consumption, reduces dependency on high-emission energy infrastructure, and introduces carbon-neutral technologies into national grids. However, the relatively weaker impact under the DCE-IV estimator points to potential challenges such as the intermittency of renewables, infrastructural deficiencies, and policy inconsistency that may dilute the full environmental benefits of renewable energy deployment. To fully harness the mitigating effects of RE, policymakers must prioritize investment in energy storage technologies, grid modernization, and regional cooperation for transboundary energy sharing. A robust institutional framework that ensures subsidy realignment and incentivizes private-sector investment in renewables can further enhance this decarbonization pathway. Thus, strengthening the renewable energy landscape is a central lever in achieving long-term carbon neutrality in emerging economies.

For green innovation (GI), the findings consistently show a significant inverse relationship with CO_2 emissions (DCE = −0.0879; DCE-IV = −0.1556; DSUR = −0.1013), confirming the emissions-reducing effect of technological advancement. These results support the proposition that innovation in clean technologies—such as carbon capture, electrification, and circular economy practices—plays a critical role in

Table 3: Output of CD test and SH test

Panel A: CD test of Juodis and Reese (2022)						
Statistics	**RE**	**GI**	**UR**	**GPR**	**CO_2**	**LCF**
Test stat value	10.4554***	10.6307***	11.5073***	11.0778***	12.9785***	8.8432***
Probability	***	***	***	***	***	***
CD exist	YES	YES	YES	YES	YES	YES
Panel B: SH test of Bersvendsen and Ditzen (2021)						
Models	**Delta Statistic**	**Adjusted Delta Statistic**	**SH exits**			
$Model_{CO2}$	4.8682***	5.2299***	Yes			
$Model_{LCF}$	4.3987***	4.186***	Yes			

Table 4: Results of integration and cointegration test

Panel A: Integration (or unit-root) test of Herwartz and Siedenburg -2008						
Statistics	**RE**	**GI**	**UR**	**GPR**	**CO_2**	**LCF**
At level	0.4177	−0.6539	1.2095	−0.2748	1.1087	−0.6652
First difference	8.045***	6.9062***	5.6664***	4.0072***	7.3367***	7.0618***
Panel B: Cointegration test of Westerlund and Edgerton (2008)						
Models	**No shift**		**Mean shift**		**Regiem shift**	
	LMr statistic	**LMΦ statistic**	**LMr statistic**	**LMΦ statistic**	**LMr statistic**	**LMΦ statistic**
$Model_{CO2}$	−2.0415***	−3.8568***	−2.8724***	−4.4369***	−4.2035***	−4.7033***
$Model_{LCF}$	−3.2262***	−4.5325***	−2.3559***	−3.2487***	−3.7101***	−3.0338***

Table 5: Results of DCE, DCE-IV and DSUR- Empirical model estimations: CO_2

Variables	Coeff	Standard error	t-Stat	Coeff	Standard error	t-Stat	Coeff	Standard error	t-Stat
		DCE			DCE-IV			DSUR	
RE	−0.15363	0.0351	−4.3769	−0.08695	0.0173	−5.026	−0.10788	0.0398	−2.7105
GI	−0.08792	0.0438	−2.0073	−0.15559	0.0319	−4.8774	−0.10133	0.0242	−4.18719
UR	0.12729	0.0448	2.8412	0.15735	0.036	4.3708	0.16653	0.0347	4.7991
GPR	0.15203	0.027	5.6307	0.1181	0.0235	5.0255	0.08611	0.0279	3.0863
C	−17.154	0.24013	−71.4363	0.16019	0.24013	0.667	0.07936	0.24013	0.3304877
R^2		0.912			0.9069			0.8921	
Adj R^2		0.9456			0.9431			0.9273	
Anderson canon. corr. LM statistics		14.8514			14.8514			14.8514	
Cragg-Donald Wald F statistics		1825.6918			1825.6918			1825.6918	
Stock-Yogo weak ID test critical values		17.0075			17.0075			17.0075	

DIV: environmental quality measured by CO_2 emission. RE, GI, UR, and GPR stands for renewable energy, green innovation, urbanization, and geopolitical risk, respectively

promoting environmental sustainability. The stronger effect observed under the DCE-IV method suggests that when endogeneity is controlled, the impact of green innovation becomes even more pronounced, likely due to its indirect multiplier effects across sectors. Green innovation facilitates structural shifts in production and consumption by increasing energy efficiency, reducing waste, and enabling low-carbon alternatives. Nonetheless, these benefits are often delayed due to high R&D costs, limited commercialization channels, and regulatory inertia. Addressing these constraints requires targeted innovation policies such as green patent incentives, public-private research partnerships, and the alignment of national innovation systems with climate goals. Integrating sustainability criteria into industrial policy and financing frameworks can accelerate technology transfer and diffusion, particularly in energy-intensive sectors. Therefore, green innovation should be viewed not only as a technological solution but as a transformative force capable of realigning economic systems with ecological boundaries.

Urbanization (UR), conversely, displays a positive and significant correlation with CO_2 emissions across models (DCE = 0.1273; DCE-IV = 0.1573; DSUR = 0.1665), indicating that, in the BRICS+T context, urban growth has been environmentally burdensome. This result reflects the reality that rapid urbanization, if unmanaged, leads to increased energy demand, vehicular emissions, industrial sprawl, and pressure on waste and water systems. The strongest coefficient under DSUR suggests that the long-run and cross-sectional dimensions of urbanization are particularly damaging to air quality. The results highlight that current urban expansion lacks adequate environmental planning, with urban infrastructure lagging behind population growth. To reverse this trajectory, cities must adopt a low-carbon urban development model by investing in public transportation, promoting green building standards, and implementing urban greening strategies. Integrated land-use planning, smart city technologies, and digital infrastructure can help balance growth with environmental constraints. Moreover, fiscal decentralization paired with performance-based urban environmental management systems can empower municipalities to adopt more sustainable practices. Thus, unless urbanization is accompanied by deliberate sustainability planning, it will continue to exacerbate carbon emissions and derail climate progress.

Geopolitical risk (GPR) also exerts a statistically significant and positive effect on CO_2 emissions (DCE = 0.1520; DCE-IV = 0.1181; DSUR = 0.0861), revealing that political instability and external threats undermine environmental performance. The coefficients, while declining slightly from DCE to DSUR, still suggest a strong detrimental influence. Geopolitical risk disrupts energy markets, discourages green foreign direct investment, and shifts policy priorities away from long-term climate goals to short-term national security concerns. This instability also erodes institutional trust, delays environmental legislation, and weakens the enforcement of existing regulations. In times of geopolitical turmoil, governments often revert to carbon-intensive emergency measures, such as subsidizing fossil fuel production or pausing environmental reforms. Therefore, minimizing geopolitical risk is crucial not just for national security but also for environmental stability. Strategies should include diversifying energy supply chains, regional diplomatic cooperation on climate issues, and integrating environmental security into foreign policy agendas. Enhancing institutional resilience and maintaining environmental policy continuity during crises can safeguard sustainability progress. In conclusion, political and regulatory stability is a precondition for sustained decarbonization and ecological integrity in BRICS+T nations.

4.3. Empirical Model Estimations: LCF

Referring to output displayed in Table 6. For renewable energy (RE), the estimated coefficients across all three estimators—DCE = 0.1711, DCE-IV = 0.08664, and DSUR = 0.17907—consistently exhibit a positive and statistically significant relationship with load capacity factor (LCF), an inverse proxy for environmental degradation. These findings reinforce the conclusion that increased deployment of renewable energy sources substantially enhances environmental quality. The mechanisms driving this effect are multifaceted. First, renewable energy technologies directly reduce carbon emissions by substituting fossil fuel-based energy systems with cleaner alternatives such as solar, wind, hydro, and geothermal. These sources generate little to no greenhouse gas emissions and significantly cut local air pollution. Second, the integration of renewable energy supports decarbonization in sectors beyond power generation, particularly in transportation and industry, when linked to electrification initiatives. Third, renewable energy projects promote energy efficiency through modern infrastructure and decentralized grids, helping to optimize resource consumption. To capitalize on these benefits, policymakers in BRICS+T countries must accelerate investments in renewable infrastructure, remove fossil fuel subsidies, and adopt feed-in tariffs or green tax credits. Strategic planning, such as smart grid deployment and cross-border renewable energy trade agreements, will further scale the impact. Overall, renewable energy offers a robust pathway to environmental sustainability when embedded in long-term national energy transitions.

In the case of green innovation (GI), the positive and significant coefficients across DCE = 0.10973, DCE-IV = 0.09123, and DSUR = 0.12252 point to its strong contribution to environmental improvement via LCF. Green innovation functions through the creation and diffusion of new technologies that reduce environmental footprints—such as energy-efficient machinery, pollution control systems, green architecture, and low-carbon industrial processes. These technologies facilitate cleaner production, minimize waste, and lower emissions intensity per unit of output. Moreover, green innovation fosters systemic transformation by encouraging research and development, strengthening environmental regulations, and nurturing eco-industrial clusters. To harness this effect, BRICS+T governments should increase public and private R&D funding, create intellectual property protections for green technologies, and support innovation incubators focused on climate solutions. International collaboration—especially in the form of joint ventures, patent sharing, and climate finance—can catalyze wider technology transfer and deployment. These proactive steps will ensure that innovation supports the shift toward a sustainable development trajectory.

Conversely, the coefficients for urbanization (UR) are negative and statistically significant (DCE = −0.10764; DCE-IV = −0.10492; DSUR = −0.0788), suggesting that current urbanization patterns in BRICS+T nations are deteriorating environmental quality. This adverse association reflects the consequences of unplanned or sprawling urban growth, often marked by congestion, vehicular pollution, deforestation, increased energy demand, and inefficient waste management. Such trends are common in fast-growing cities where infrastructural development fails to keep pace with

Table 6: Results derived from DCE, DCE-IV, and DSUR- Empirical model estimations: LCF

Variables	Coeff	Standard error	t-Stat	Coeff	Standard error	t-Stat	Coeff	Standard error	t-Stat
	DCE			DCE-IV			DSUR		
RE	0.17111	0.0344	4.9741	0.08664	0.02	4.332	0.17907	0.0291	6.1536
GI	0.10973	0.038	2.8876	0.09123	0.0206	4.4286	0.12252	0.0317	3.8649842
UR	−0.10764	0.0402	−2.6776	−0.10492	0.0365	−2.8745	−0.0788	0.0254	−3.102362
GPR	−0.07979	0.0373	−2.1391	−0.14411	0.0233	−6.1849	−0.12425	0.0339	−3.665192
R^2		0.8917			0.8892			0.8913	
Adj R^2		0.9449			0.9236			0.934	
Anderson canon. corr. LM statistics		12.9137			12.9137			12.9137	
Cragg-Donald Wald F statistics		1526.4948			1526.4948			1526.4948	
Stock-Yogo weak ID test critical values		18.7496			18.7496			18.7496	

population expansion. However, urbanization can also serve as a lever for sustainability if appropriately managed. The focus must shift toward smart cities, green infrastructure, public transit systems, and compact, energy-efficient urban design. Initiatives like green building codes, vertical zoning, and low-emission urban transport can reduce the environmental burden. Moreover, investments in waste recycling, wastewater treatment, and digital monitoring systems will help mitigate the ecological impact. In short, to reverse the negative effects, urban growth must be aligned with climate-resilient urban planning and sustainable development principles.

Lastly, the results for geopolitical risk (GPR) reveal a consistent and significant negative influence on LCF, with coefficients of DCE = −0.07979, DCE-IV = −0.14411, and DSUR = −0.12425. These findings highlight the destabilizing role of political uncertainty, regional conflict, and governance volatility on environmental quality. High geopolitical risk deters long-term green investments, undermines regulatory stability, and weakens institutional commitment to environmental policy enforcement. In such climates, businesses prioritize short-term survival over environmental compliance, and governments often redirect resources away from sustainability toward defense or crisis management. Addressing this challenge requires institutional strengthening, regional peacebuilding, and risk-informed climate governance. Mechanisms such as green budgeting frameworks, environmental policy continuity guarantees, and risk-adjusted climate financing can insulate environmental agendas from political turbulence. Additionally, fostering public participation, transparency, and cross-border environmental cooperation can help depoliticize sustainability goals and reinforce the resilience of environmental governance structures. Therefore, minimizing geopolitical uncertainty is crucial for unlocking consistent and sustainable improvements in environmental quality across BRICS+T nations.

4.4. DH Granger Causality Test

The results of the Dumitrescu–Hurlin (D-H) panel Granger causality test, see Table 7, offer compelling insights into the dynamic interlinkages between renewable energy consumption (REC), green innovation (GI), geopolitical risk (GPR), urbanization (URC), and environmental quality, here represented by both carbon dioxide emissions (CO_2) and load capacity factor (LCF). These two proxies serve as inverse indicators of environmental degradation—higher CO_2 suggests poorer environmental quality, while higher LCF implies environmental improvement. The test indicates a bidirectional causal relationship between REC and CO_2 (REC ↔ CO_2). This mutual influence suggests that as renewable energy adoption increases, CO_2 emissions tend to decrease—an expected outcome supported by the decarbonizing nature of renewables (Simeon et al., 2024). Conversely, higher CO_2 levels may prompt policies and societal demands that accelerate renewable energy investments, reinforcing a feedback loop. Interestingly, LCF shows unidirectional causality from REC (REC → LCF), meaning renewable energy usage positively drives environmental quality without reciprocal feedback. This directional influence is consistent with literature emphasizing how renewable energy enhances ecological resilience, reduces air pollution, and supports long-term sustainability (Regmi, 2023). The unidirectional relation implies that improvements in environmental quality do not necessarily cause further changes in renewable energy use—highlighting the need for proactive renewable energy policies regardless of current environmental conditions.

In the context of green innovation, the test reveals unidirectional causality from GI to both CO_2 and LCF (GI → CO_2, GI → LCF), with no feedback observed. This finding highlights the instrumental role green innovation plays in driving environmental progress. Green innovation reduces CO_2 emissions through cleaner technologies and production methods, aligning with studies showing GI's capacity to decouple economic growth from environmental degradation (Chang et al., 2024). Its effect on LCF further suggests that GI contributes to enhancing ecological capacity and system stability. However, the absence of reverse causality indicates that improvements in environmental indicators do not inherently foster further innovation—suggesting that without continuous investment and institutional support, green innovation may plateau despite environmental gains.

When examining geopolitical risk, a bidirectional relationship exists with both CO_2 and LCF (GPR ↔ CO_2, GPR ↔ LCF). This reciprocal causality reflects a complex interdependence: geopolitical tensions can disrupt environmental governance and deter green investment, while worsening environmental conditions (e.g., climate-induced resource scarcity) may exacerbate geopolitical instability (Abdallah and El Dine, 2024; Wang et al., 2024). The dual influence underscores the necessity of integrated policy frameworks that simultaneously address political stability and environmental targets. Without addressing geopolitical volatility, progress toward sustainability may remain fragile and inconsistent.

Urbanization (URC) also demonstrates strong bidirectional causality with both CO_2 and LCF (URC ↔ CO_2, URC ↔ LCF).

Table 7: Results of DH Granger causality test

Null hypothesis	W-statistic	Zbar-statistic	Remarks	Null hypothesis	W-statistic	Zbar-statistic	Remarks
CO_2<==/==>REC	6.2359	6.5726	<---->	LCF<==/==>REC	7.4952	7.8999	-->
REC<==/==>CO_2	7.1849	7.5728		REC<==/==>LCF	1.3538	1.4269	
CO_2<==/==>GI	8.3018	8.75	-->	LCF<==/==>GI	8.1742	8.6156	-->
GI<==/==>CO_2	1.2306	1.297		GI<==/==>LCF	2.1402	2.2557	
CO_2<==/==>GPR	8.3517	8.8026	<---->	LCF<==/==>GPR	8.4527	8.9091	<---->
GPR<==/==>CO_2	8.645	9.1118		GPR<==/==>LCF	6.4006	6.7462	
CO_2<==/==>URC	5.4346	5.728	<---->	LCF<==/==>URC	7.2157	7.6053	<---->
URC<==/==>CO_2	10.1934	10.7438		URC<==/==>LCF	5.8947	6.213	
<==/==>CO_2	1.9585	2.0642		0<==/==>LCF	7.5844	7.9939	

Urban growth leads to increased energy demand and emissions, yet it also offers opportunities for green infrastructure, efficient public transit, and compact development (Li and Zhang, 2023). Conversely, environmental degradation in urban settings can influence migration patterns, infrastructure pressure, and urban planning. The mutual feedback suggests that urban and environmental strategies must be co-designed; sustainable cities are not only built with green materials but also through coherent environmental policy and urban governance.

5. CONCLUSION AND POLICY SUGGESTIONS

5.1. Conclusion

This study investigated the dynamic effects of green innovation, geopolitical risk, renewable energy consumption, and urbanization on environmental quality in BRICS+T countries from 2004 to 2022. The results reveal several key insights. Green innovation and renewable energy have a statistically significant positive effect on environmental quality, both in terms of reducing CO_2 emissions and improving the load capacity factor, by confirming their essential role in environmental improvement. Conversely, geopolitical risk and unplanned urbanization consistently deteriorate environmental outcomes, emphasizing the vulnerability of environmental systems to instability and structural strain. These findings support the proposition that environmental quality in emerging economies is determined not just by policy intentions but also by technological readiness, governance stability, and urban management capacity. The study's provisions clarify the need for an integrated environmental policy that aligns technological progress with energy transition and urban development. It also identifies the importance of geopolitical stability as a necessary condition for sustaining environmental policy commitments. Despite its contributions, this research has limitations. It relies on proxies such as patent data for green innovation and does not capture the full spectrum of technological activities. It also focuses on macro-level panel data, which may mask micro-level dynamics within countries. Future studies should consider disaggregated data and explore how local governance, behavioral shifts, and sectoral policies mediate these relationships. In addition, the study could be extended to examine the impact of institutional quality, climate finance, and international cooperation mechanisms. Insights from these avenues would strengthen the theoretical and practical understanding of the environmental pathways in emerging economies. Ultimately, the results call for deliberate, coordinated, and context-sensitive approaches to ecological sustainability, particularly in transitional economies where the stakes are high and the trade-offs are complex.

5.2. Policy Recommendations

First, governments in BRICS+T countries should expand public investment in renewable energy infrastructure. This includes grid modernization, support for decentralized systems, and incentives for private sector participation through green tariffs, subsidies, and tax credits. Addressing intermittency and storage capacity through smart grid deployment and battery technologies will maximize renewable energy's long-term benefits.

Second, policymakers must institutionalize green innovation through national research funding, technology transfer programs, and regulatory support. Establishing dedicated innovation hubs, providing patent protection for eco-technologies, and encouraging university-industry collaboration will help mainstream green innovation and diffuse its environmental benefits.

Third, urban planning must be realigned with climate goals. Local authorities should implement compact city models, invest in efficient public transportation, promote vertical development, and enforce green building codes. Integrating digital infrastructure, waste recycling, and ecosystem restoration into urban governance can mitigate the negative effects of urbanization on environmental quality.

Fourth, national governments must create environmental policy buffers to reduce vulnerability to geopolitical risk. This involves embedding environmental objectives into foreign policy, establishing continuity clauses for climate legislation, and participating in multilateral energy security agreements. Building regional cooperation for environmental diplomacy can also reduce exposure to external shocks.

Fifth, policy frameworks should promote adaptive governance. Environmental regulations need built-in flexibility to respond to political, economic, and environmental uncertainties. Institutions must be empowered with technical capacity and autonomy to enforce rules, even during periods of instability.

5.3. Future Research Directions and Limitations

The study is limited to panel data from 2004 to 2022 and may not capture long-term lags of policy impacts. Future studies should explore micro-level or city-level analyses for more localized insights. The study uses proxies like CO_2 and LCF; future research could incorporate ecological footprint or biodiversity indices. Further research should also explore sectoral breakdowns (e.g., transport, manufacturing) to assess source-specific environmental impacts. Finally, the dynamic nature of geopolitical risks demands adaptive methodologies—future work can integrate real-time data or scenario-based forecasting for more agile policy evaluation.

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