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What is the Contribution of Green Innovation and Digitalization to Economic Growth: Analyzing the Role of Geopolitical Risks and Climate Policy Uncertainty

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Yeşil İnovasyon ve Dijitalleşmenin Ekonomik Büyümeye Katkısı Nedir: Jeopolitik Riskler ve İklim Politika Belirsizliği Rolünün Analizi

Öz

Bu araştırma 2002-2021 döneminde Brezilya, Rusya, Hindistan, Çin ve Güney Afrika ile Türkiye (BRICS+T) için yeşil inovasyon ve dijitalleşmenin ekonomik büyüme üzerindeki etkilerini ele almıştır. Bu çerçevede jeopolitik riskler ve iklim politika belirsizliğinin rolünü analiz etmiştir. Araştırmada değişkenler arasındaki ilişki Havuzlanmış Bewley (CPS-BP), Dinamik En Küçük Kareler Ortalama Grup (DOLS-MG), Tamamen Değiştirilmiş En Küçük Kareler (FMOLS), Kanonik Eşbütünleşik Regresyon (CCR) ile Dinamik En Küçük Kareler (DOLS) tahmincileri kullanılarak tahmin edilmiştir. Sonuçlarımız yeşil inovasyonun, dijitalleşmenin, bilgi teknolojilerinin, altyapı yatırımlarının, doğumda beklenen yaşam süresi ve ABD kaynaklı iklim politika belirsizliklerinin ekonomik büyümeyi olumlu etkilediğini göstermiştir. Artan jeopolitik riskler BRICS+T ülkelerinde büyümeyi engellemiştir.

Anahtar Kelimeler: Yeşil İnovasyon, Ekonomik Büyüme, Jeopolitik Riskler, Alt Yapı Yatırımları, İklim Politika Belirsizliği.

JEL Kodları: Q53, F43, G20

What is the Contribution of Green Innovation and Digitalization to Economic Growth: Analyzing the Role of Geopolitical Risks and Climate Policy Uncertainty

Abstract

This research examines the impact of green innovation and digitalization on economic growth in Brazil, Russia, India, China, South Africa, and Türkiye (BRICS+T) during the period 2002-2021. Within this framework, it analyzes the role of geopolitical risks and climate policy uncertainty. The relationships between variables were estimated using Pooled Bewley (CPS-BP), Dynamic Least Squares Mean Group (DOLS-MG), Fully Modified Least Squares (FMOLS), Canonical Cointegrated Regression (CCR), and Dynamic Least Squares (DOLS) estimators. Our results show that green innovation, digitalization, information technologies, infrastructure investments, life expectancy at birth, and US-originated climate policy uncertainties positively impacted economic growth. Increased geopolitical risks hindered growth in BRICS+T countries.

Keywords: Green Innovation, Economic Growth, Geopolitical Risks, Infrastructure Investments, Climate Policy Uncertainty.

JEL Codes: Q53, F43, G20

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1. Introduction

Economic globalization has undoubtedly accelerated growth; however, it has also led to the faster depletion of limited natural resources and environmental degradation (Blampied, 2021, p. 2). Environmental degradation has raised potential threats to sustainable development and has steered efforts toward green innovation as a means to reduce the environmental impact of economic activities (Rennings & Rexhauser, 2011, p. 1; Borghesi et al., 2015, p. 670; Blampied, 2021, p. 2; İzgi, 2023, p. 35). In this context, the entry into force of the 2015 Paris Climate Agreement has constituted a decisive turning point. Accordingly, the Agreement's objective of achieving low-carbon economic development has positioned green innovation as the driving force of development (Rennings, 2000, p. 321; Kemp & Oltra, 2011, p. 252; Roh et al., 2021, p. 2; Han et al., 2024, p. 4072). Green innovation encompasses the creation of scientific and technological capacity, energy conservation, prevention of environmental pollution, waste recycling, green product design, corporate environmental management, and all product and process improvements and management practices including technological innovations (Han et al., 2024, p. 4072; Chen, 2008, p. 534; Chang, 2011, p. 362; Tang et al., 2018, p. 40; Feng et al., 2022, p. 72). The purpose of this process is to reduce environmental pressure while also generating environmental benefits (Liu et al., 2023, p. 2). As a result of environmental pressures, green innovation aims to ensure sustainable development in manufacturing industries (Chang, 2011, p. 363; Rennings & Rexhauser, 2011, p. 1; Borghesi et al., 2015, p. 670; Blampied, 2021, p. 2), increase product value to balance the costs of environmental investments, enhance resource efficiency, and offer a strategic advantage by fostering competitiveness (Chen et al., 2006, p. 332; Kong et al., 2022, p. 4400; Tang et al., 2018, pp. 40–41). In the literature, green innovation, also referred to as environmental innovation or ecological innovation (Roh et al., 2021; Dong et al., 2021, p. 2), includes elements such as R&D expenditure (Jaffe & Palmer, 1997, p. 2; Shahbaz et al., 2018, p. 844), the number of approved green patents (Popp, 2006, p. 51; Aghion et al., 2019, p. 2; Liu et al., 2023, p. 2), green patent applications (Dong et al., 2021, p. 2), urban innovation capability indices (Ai et al., 2022, p. 168), and green total factor productivity (Zhang et al., 2023, p. 15045; Keller, 2004, p. 5).

Infrastructure provides various services including construction, energy, and waste management with a transformative impact on development and living standards (Tacker et al., 2019, p. 324). While supporting economic growth, infrastructure also reduces costs by facilitating communication, lowers carbon emissions through the use of green ecologies, and increases the rate of urbanization, thereby raising the demand for consumer goods (Mercure & Lam, 2015, p. 110; Irfan et al., 2022, pp. 2–3). However, the intensive use of resources in infrastructure development brings about problems such as climate change, carbon emissions, and environmental degradation, which in turn highlight green innovation as an important tool for mitigating such degradation (Yan et al., 2017, p. 2; Shahbaz et al., 2020, p. 2; Lyu et al., 2020, p. 185; Jin et al., 2021, p. 2). The concept of new infrastructure, which differs from traditional infrastructure, is defined as "digital transformation, smart upgrading, innovation and technology-oriented development, and ecological compatibility from the perspective of the green subject–object relationship" (Zhang et al., 2024, p. 2). More specifically, "new infrastructure" refers to infrastructures such as the 5G network, new energy vehicle charging stations, data centers, artificial intelligence, the industrial internet, the Internet of Things, ultra-high-voltage power grids, and intercity and urban rail transit systems (Meng et al., 2023, pp. 342–343; Tang & Zhao, 2023, p. 897; Sun et al., 2024, p. 3). New infrastructure affects green innovation in several ways. These include promoting technological progress through the efficient use of R&D inputs, establishing connections among all factors across industrial chains through resource allocation, and creating a new system of industrial production and services. It also contributes to the formation of local markets, reduces costs through economies of scale and the cross-regional flow of innovative factors, and supports the dissemination of spatial information. In addition, it decreases high-risk resource use and increases service efficiency through digital and online transformation (Meng et al., 2023, p. 343; Tang & Zhao, 2023, p. 897; Sun et al., 2024, p. 3). Economic growth enables greater investment in technologies aimed at green innovation (Sharif et al., 2023, p. 99). While technological innovation can help reduce CO_2 emissions through the economic growth it promotes, innovation may also have negative effects, such as increasing urban carbon emissions during the construction of infrastructure (Umar et al., 2020, p. 2).

Uncertainties in the global economy and politics indicate that geopolitical risk is increasing (Yuen & Yuen, 2024, p. 2). Geopolitical risk is defined as political and economic trends that can affect human well-being (Qiang et al., 2024, p. 2). Geopolitical risk caused by military and trade wars causes limitations on energy, a critical driver of economic growth and development (Thakkar & Ayub, 2022, p. 147), undermines corporate investments, and leads to a slowdown in global growth (Wang et al., 2024, p. 2). Uncertainty related to geopolitical risk harms global energy markets (Alqahtani et al., 2020, p. 239). In addition, it negatively affects economic activities, causes systemic risks in financial markets, and affects investors' confidence in clean energy markets and their investment behavior (Zuoxiang et al. 2023, p. 2; Yang et al., 2021, p. 2).

The interaction between geopolitical risk and climate uncertainty, when combined with a global issue such as climate change, increasingly affects the world economy (Liu et al., 2025, p. 2). Climate-related temperature increases raise short-term environmental investments and exert a crowding-out effect on R&D expenditures that support green innovation (He et al., 2024, pp. 1–2). Moreover, climate-related geopolitical risks threaten human life, economic growth, and security (Gu et al., 2023, p. 3). While economic policy uncertainty hinders investment in green infrastructure, geopolitical risks tend to focus on defense and crisis management arising from conflict or instability rather than addressing climate policy uncertainties (Wang et al., 2024, p. 2). Conflicts linked to geopolitical risks occurring in high-carbon-emission regions affected by climate change disrupt production and weaken global cooperation by restricting exports (Haseeb et al., 2025, p. 3).

Furthermore, geopolitical risks and economic policy uncertainty generate significant volatility in financial markets. As many conflict-prone regions are major energy suppliers, rising risks in the energy sector make international climate cooperation less likely and thereby create greater uncertainty regarding climate change (Jin et al., 2023, p. 2). An increase in geopolitical risk encourages governments to expand capital expenditures in sectors such as defense or infrastructure, which may lead to higher levels of economic growth (GDP) (Wang et al., 2024, p. 2). However, fluctuations in energy prices caused by disruptions in supply chains adversely affect economic activity (Liu et al., 2023, p. 2).

This research examines the contribution of green innovation and digitalization to economic development in the BRICS group of countries—Brazil, Russia, India, China, South Africa, and Türkiye (BRICS+T). Within this framework, it analyzes the role of geopolitical risks and US-originated climate change policy uncertainties. To accurately measure the impact of green innovation in BRICS+T countries, a general Environmental Patent Density Index (EVPI) was calculated using principal component analysis (PCA) from various indicators. Similarly, a digitalization index (DIGII) was calculated to represent the digital technological infrastructure in the study countries. This study distinguishes itself from the empirical literature by examining the impacts of green innovation and digitalization on economic growth within the context of geopolitical risks and US-originated climate change policy uncertainties. In this context, it aims to contribute to the literature in several ways.

The subsequent structure of the study has been planned as follows: In the second section, the conceptual framework of the research is presented, and the relevant empirical studies are discussed. Within this scope, the section identifies the aspects in which the research aligns with and diverges from the existing empirical literature. The third section introduces the research sample and dataset and explains the econometric methods employed. The fourth section presents the findings obtained from the applied analyses. Finally, the conclusion section interprets the results of the study and offers implications and recommendations.

2. Literature

In this part of the study, firstly the green innovation-digitalization and green innovation-digitalization-economic growth relationship will be evaluated within the framework of the research in the literature, and then the literature on geopolitical risks and climate policy uncertainty will be discussed.

2.1. Green Innovation and Digitalization

Bronzini and Piselli (2009) examined the long-run relationship between total factor productivity, R&D, human capital, and public infrastructure across regions in Italy for the period 1980-2001 using panel cointegration and Granger causality tests. Empirical evidence suggests that productivity has a significant impact on R&D activities, public infrastructure, and economic growth. Bertschek et al. (2013) examined the causal effect of broadband internet access on firm labor productivity and product innovation in Germany for the period 2001-2003 and found that broadband internet access had no effect on labor productivity but positively affected innovation activities. Shao et al. (2016) analyzed the output performance of (IT) service sectors for twelve OECD countries and the period 2000-2011 using the Malmquist productivity index and the stochastic production frontier. The findings suggest that productivity growth stems from technological advances made possible by information technology in the production process, representing a source of competitive advantage for the IT service sector. These findings are consistent with those of Bartel et al. (2007), Dedrick et al. (2013), and Acemoglu and Restrepo (2018). Jafri et al. (2021) examined the effects of physical infrastructure on energy consumption, economic growth, and air pollution for Pakistan between 1990 and 2019 using the ARDL model. They demonstrated that aircraft carriers, road infrastructure, and information and communication technologies increased energy consumption and positively impacted CO_2 emissions. Razzaq et al. (2022) analyzed the impact of green innovations and infrastructure development on resource-intensive economies for China between 1990 and 2018 using the Quantile ARDL approach. The researchers found that green innovation reduced environmental impacts while infrastructure growth increased them. Ninga et al. (2023) examined the relationship between digitalization and green innovation using capability theory for 1,166 manufacturing firms in China for the period 2008-2019. They demonstrated that corporate digitalization can positively impact green innovation. Chen et al. (2025) examined how the digital economy affected green innovation in publicly traded companies in China for the period

2010-2022, finding that the digital economy significantly supports green innovation. The results of this study are similar to those of Qiao et al. (2024), Zhao and Qian (2024), and Xu et al. (2025).

2.2. The Relationship Between Green Innovation, Digitalization and Economic Growth

Liu et al. (2020) conducted a study covering the period 2003–2016 in China and revealed that government resource allocation policies focused on economic growth significantly affect green innovation. Shen et al. (2021), in their research carried out in the same country for the years 2004–2016, presented strong evidence that economic growth has a clear and positive impact on green technological innovation. Wang et al. (2021), examining the period 2004–2015, reported consistent findings indicating that expectations of economic growth increase both air pollution and green technological innovation. Meirun et al. (2021) analyzed the relationship between green innovation and economic growth by employing the bootstrap autoregressive distributed lag (bootstrap ARDL) technique for the period 1990–2018. Although the study identified a positive relationship between green innovation and economic growth, it also showed that carbon emissions have a markedly negative effect on this relationship. Fernandes et al. (2021) investigated the effects of sustainable technology transfer, green innovation, and green growth on economic growth through a panel data analysis covering 32 OECD member countries from 1990 to 2013. The findings demonstrated that sustainable technology transfer and sustainable innovation strongly support green growth, which in turn makes a positive and significant contribution to economic growth. Yang et al. (2022), using data from 30 provinces in China for the period 2011–2019, examined the relationships among digitalization, technological innovation, and green economic development using panel data analysis and the entropy method. Their results indicated that digitalization has a strong positive effect on green economic development, whereas the impact of technological innovation was not as positive as expected. Wang (2023) analyzed the mediating role of green innovation in the effect of environmental regulations on economic growth by applying a panel threshold regression model for China covering the years 2005–2020. The study provided robust evidence that green innovation enhances the effectiveness of environmental regulations and contributes positively to economic growth. Yu et al. (2023), using threshold panel regression analysis with data from 285 Chinese cities over the period 2006–2018, found that economic growth pressures have a statistically significant and negative impact on green technological innovation. Chen et al. (2024) applied principal component analysis (PCA) to Chinese data for the years 2012–2019 and demonstrated that developments in the digital economy significantly promote corporate green innovation. Wu et al. (2024), in their empirical analysis for China covering 2011–2019, concluded that green innovation substantially improves energy efficiency; however, the effect of digital economic development on promoting green innovation remains relatively weak. Khan et al. (2025), using a long-term data set for the period 1990–2023 and employing the ARDL bounds testing approach along with FMOLS and DOLS estimators, found that green innovation, foreign direct investment, and medium–high technology exports support sustainable economic growth in a positive and statistically significant manner. Chen and Xing (2025), through a study based on panel data from 279 Chinese cities for the period 2010–2022, reported that digital transformation significantly enhances sustainable economic growth by promoting green innovation. Gharbi et al. (2025), examining 27 European Union member countries for the years 2000–2022 using PMG-ARDL and PMG-NARDL models, showed that both green innovation and digitalization have long-term positive and statistically significant effects on green economic growth.

2.3. Economic Growth, Geopolitical Risks and Climate Policy Uncertainty

Chu et al. (2023) examined the effects of economic policy uncertainty, geopolitical risk, and economic complexity on carbon emissions for the E7 economies for the period 1995-2018. Empirical results prove that economic complexity, economic policy uncertainty, and geopolitical risk are detrimental to carbon emissions in the short term, but beneficial in the long term. Li et al. (2024) empirically examined the effects of geopolitical risk, economic policy uncertainty, natural resources, and renewable energy on the ecological footprint of BRICS countries for the period 2000-2021. According to the findings, it was found that while renewable energy resources reduce the ecological footprint, economic policy uncertainty and non-renewable energy use increase the ecological footprint. The increasing acceleration of the globalization process has connected national economies through trade. A stable and peaceful environment is becoming more important for the development of the global economy. However, increasing geopolitical risks and climate-related fluctuations are rapidly evolving into some problems. In this context; Yuen and Yuen (2024) investigated the effects of geopolitical risk, economic and political uncertainty, and CO2 emissions on government spending on renewable energy projects using ARDL, CS-ARDL, and FMOLS techniques. The results showed that powerful governments continue to increase their R&D investments in the face of ongoing geopolitical tension, economic and political uncertainty. Haseeb et al. (2025) analyzed the effects of geopolitical risk, economic and trade policy uncertainty, and financial development on greenhouse gas emissions for China for the 1997-M1/2024-M12 period using quantile-quantile regression and cross-quantile regression methods. Empirical findings indicate that geopolitical risk, economic policy uncertainty, and trade policy uncertainty have an impact on emissions. Hashmi et al. (2025) analyzed the impact of climate policy uncertainty on greenhouse gas emissions for the G7 countries using moment quantile regression. The results documented that climate policy uncertainty increases greenhouse gas emissions. Anser et al. (2021), examining the impact of geopolitical risks on CO2 emissions in the BRICS countries, found that geopolitical risks increased CO2 emissions. Gu et al. (2023), using mixed-frequency VAR (MF-VAR) to examine the relationship between climate risk, geopolitical risk, and energy market risk, demonstrated that increases in climate risk and geopolitical risk are associated with increases in energy markets.

3. Data and Methods

3.1. Data

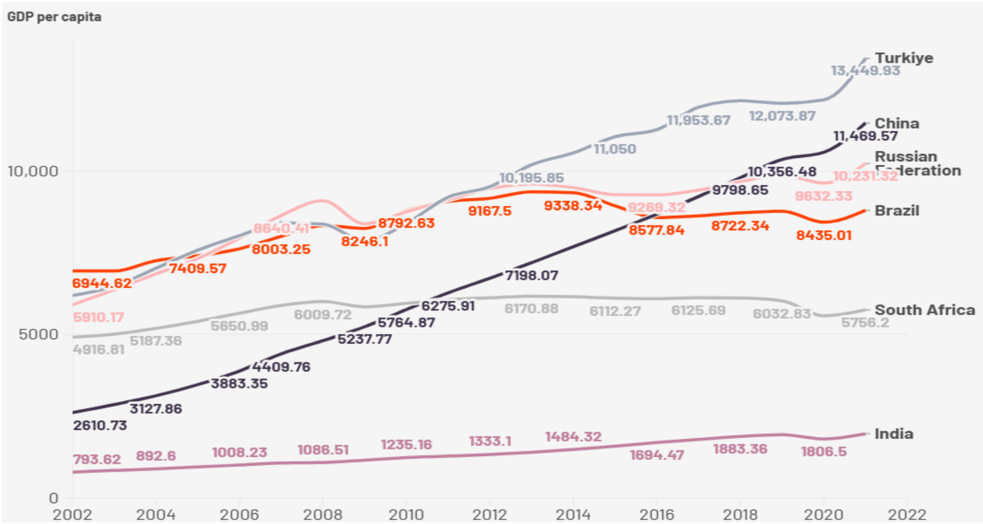
This research examined the impacts of green innovation and digitalization of economies on economic growth for the founding countries of the BRICS group (BRICS+T): Brazil, Russia, India, China, South Africa, and Türkiye (BRICS+T) during the period 2002-2021. In the study, the econometric relationship between the variables was examined through annual data. In this context, it analyzed the role of geopolitical risks and climate policy uncertainty. Technological innovation supports both environmental improvement and economic growth (Meirun et al., 2021; Bousnina et al., 2025). Environmentally friendly technologies, sustainable technology transfer, and innovation contribute to economic development through green growth (Fernandes et al., 2021; Wang, 2023; Wani et al., 2024; Bouattour et al., 2025). On the other hand, resource allocation that supports growth policies is critical for green innovation (Liu et al., 2020). There is a persistent and significant relationship between the digitalization of economies and economic growth (Suhendra et al., 2025). The development of digital infrastructure promotes economic development (Zhang et al., 2022; Correa & Esquivias, 2025).

Figure 1 illustrates the research design. The study examines the impacts of green technological innovation and digitalization on economic growth in the context of geopolitical risks and climate change policy uncertainties. In this framework, trade liberalization, infrastructure investments, and human capital development were used as control variables.

Figure 1: Research Design

The research variables are shown in Table 2. Real GDP per capita (US$) was used as a proxy for economic growth in the research. Figure 2 shows the change graph of the GDP per capita data of the research countries for the period 2002-2021. According to World Bank (2025) data, the countries with the highest GDP per capita during the period were Türkiye, China, and Russia. There was an increasing trend in the GDP of these three countries throughout the period. The countries with the lowest GDP per capita were India and South Africa. While GDP per capita in India was USD 793,616 in 2002, it remained at USD 1.965,309 in 2021. On the other hand, GDP per capita in Turkey and China was 6192,186 and 2610,730 USD in 2002, and increased to 13449,929 and 11469,571 USD in 2021.

Figure 2: GDP per capita in the research countries (2002-2021)



Source: Data from the World Bank (2025), edited by researchers.

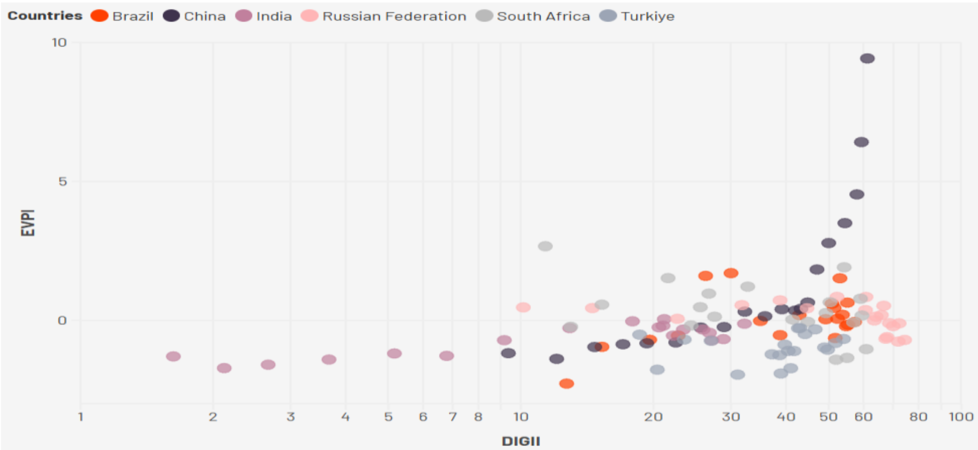
As an indicator of environmental (green) innovation, an Environmental Patent Intensity Index (EVPI) was constructed. To develop this index, Principal Component Analysis (PCA) was applied to four variables related to environmental patents—patents per capita, the share of inventions, the share of technologies, and the patent index. Examination of the resulting eigenvalues and explained variance ratios shows that the first component (Comp1) accounts for 55.9% of the total variance. Accordingly, the EVPI was derived using this first principal component (Table 1).

Table 1: Calculation of EVPI using PCA method

Component	Eigenvalue	Explained Variance (%)	Cumulative Variance (%)
Comp1	2.236	55.91	55.91
Comp2	1.473	36.83	92.74
Comp3	0.231	5.77	98.51
Comp4	0.059	1.49	100.00
Inventions per capita	0.5771		
Invention percentage	0.5299		
Percentage of technologies	0.4797		
Patent index	0.3950		

In the study, the digitalization index (DIGII) is employed as a proxy indicator for infrastructure investment. The calculation of DIGII was based on the study of Lee and Brahmasrene (2014). This composite index includes (1) readness, (2) use, and intensity stages of technological development in research countries (Saia, 2023). The index is constructed by taking the arithmetic mean of fixed broadband subscriptions per 100 people, fixed telephone subscriptions per 100 people, individuals using the Internet per 100 people, and mobile cellular subscriptions per 100 people. Figure 3 presents the trends of EVPI and DIGII in the study countries over the period 2002–2021. During this period, China appears to be significantly more advanced in green innovation compared with the other countries. In contrast, the development of environmental technologies in India has remained relatively limited. The countries with the highest levels of digitalization are Russia, China, and South Africa, whereas India exhibits the lowest digitalization levels.

Figure 3: Periodic Changes in EVPI and DIGII in the Study Countries (2002–2021))



Source: Data from the World Bank (2025) and OECD (2025) edited by researchers.

In the study, the Geopolitical Risk Index (GPR) developed by Caldara and Iacoviello (2022) is employed to represent geopolitical risks. To capture climate policy uncertainty, the U.S.-based Climate Policy Uncertainty Index (CPU) proposed by Gavriilidis (2021). is used. As control variables, gross fixed capital formation (as a percentage of GDP), life expectancy at birth, and trade openness are included in the analysis.

Table 2: Research variables

Variable	Explanation	Type	Data Source
LnGDP	Real GDP per capita	Natural logarithm is taken.	WDI
EVPI	Environmental patent density index	PCA is applied using patents per capita, invention percentage, percentage of technologies, and the index.	OECD
LnDIGII	Digitalization index (calculated as the arithmetic mean of fixed broadband subscriptions per 100 people, fixed telephone subscriptions per 100 people, individuals using the Internet per 100 people, and mobile cellular subscriptions per 100 people).	Natural logarithm is taken.	WDI
LnGPR		Natural logarithm is taken.	Caldara and Iacoviello (2022)
LnCPU	Climate policy uncertainty index originating from the USA	Natural logarithm is taken.	Gavriilidis (2021)
LnLEB	Life expectancy at birth	Natural logarithm is taken.	WDI
LnK	Gross fixed capital accumulation (percentage of GDP) was used as a proxy for infrastructure investments.	Natural logarithm is taken	WDI

LnOP	Trade liberalization (ratio of total goods imports and exports to GDP).	Natural logarithm is taken	WDI

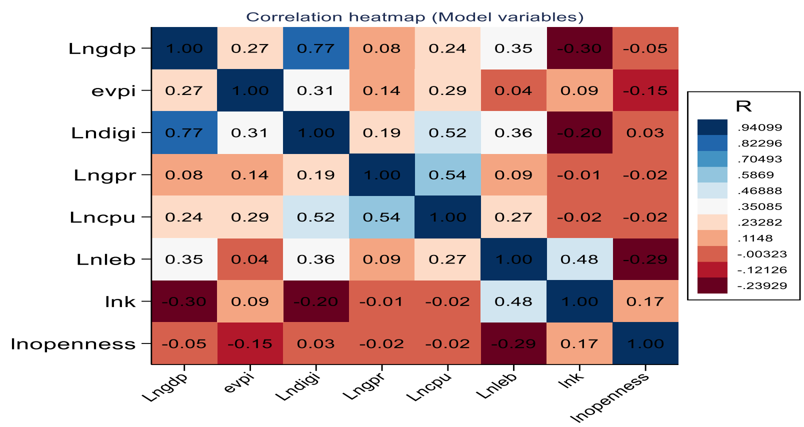
Table 3 presents descriptive statistics for the research variables. The mean value of the natural logarithm of real GDP per capita, representing economic growth, was calculated as 8.638, the maximum value as 9.506, and the minimum value as 6.676. The mean values of the logarithms of the EVPI and digitalization index were calculated as 0.010 and 3.441, the maximum values as 9.421 and 4.308, and the minimum values as 2.279 and 0.485. The mean values of the natural logarithms of the GPR and CPU indices were calculated as 1.519 and 4.664, the maximum values as 1.728 and 5.387, and the minimum values as 1.392 and 4.177. The panel data sample consisted of 20 years and 6 countries.

Table 3: Descriptive Statistics

	LnGDP	EVPI	LnDIGII	LnGPR	LnCPU	LnLEB	LnK	LNOP
Mean	8.638	0.010	3.441	1.519	4.664	4.248	3.188	3.791
Median	8.889	-0.199	3.667	1.534	4.596	4.274	3.090	3.870
Maximum	9.506	9.421	4.308	1.728	5.387	4.358	3.785	4.263
Minimum	6.676	-2.279	0.485	1.392	4.177	3.987	2.568	3.095
Std. Dev.	0.719	1.497	0.740	0.083	0.371	0.091	0.333	0.276
Jarque-Bera	41.699	1255.131	109.067	2.448	8.303	33.756	7.081	17.833
Prob	0.000	0.000	0.000	0.293	0.015	0.000	0.028	0.000
Obs	119	119	119	119	119	119	119	119

Figure 4 examines the correlation between the research variables using the correlation heatmap analysis technique. The results show a negative correlation between economic growth, physical capital investment, and trade liberalization, and a positive correlation between the other explanatory variables. The correlation between the explanatory variables is within acceptable limits.

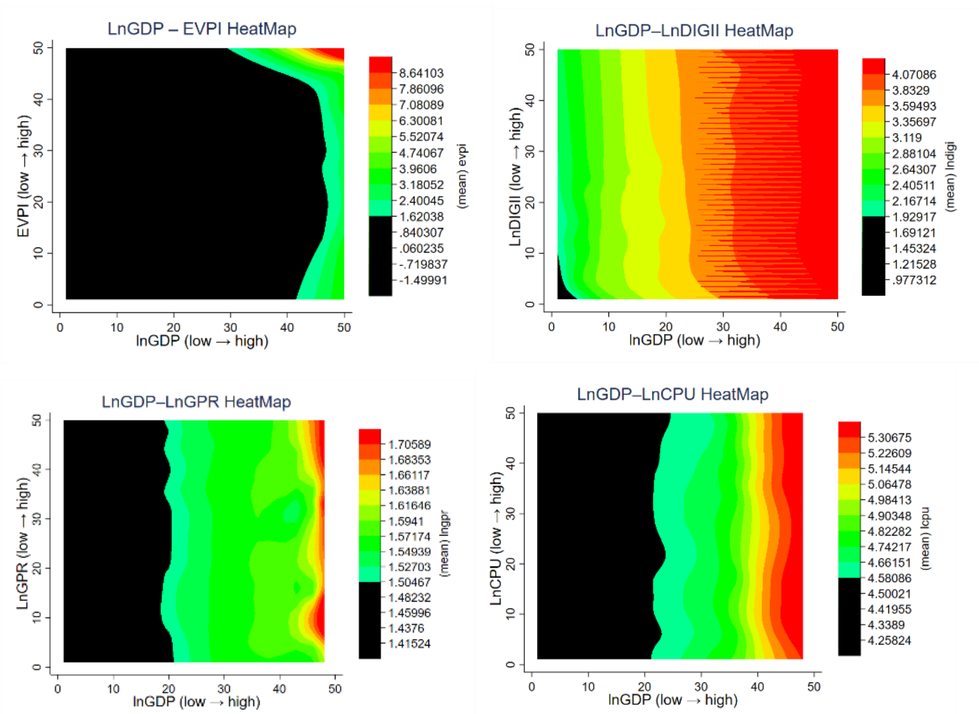
Figure 4: Correlation heatmap analysis

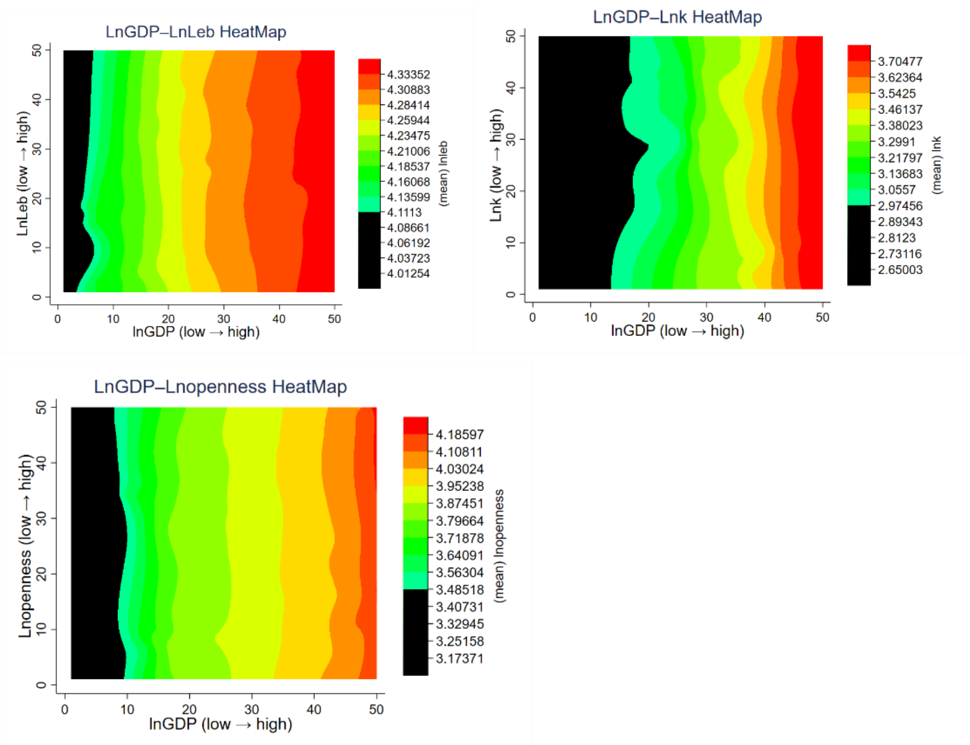


Source: Created by the authors

In the study, quantile-binned heat maps were used to visually examine the relationship structure between the variables. In Figure 5, two-dimensional cells were created by dividing economic growth and related variables into 50 quantitative slices; the mean of the relevant variable in each cell is shown by color intensity. The EVPI series is extremely low in concentration in low and mid-level economic growth, while there is a high concentration of EVPI in the upper right corner of the chart. This outlook shows that green innovation tends to increase as economic development increases, but technological innovation intensifies at a very high growth level. There is an extremely strong positive relationship on the economic growth and digitalization graph. While the concentration of digitalization is low at a low level of economic growth, the concentration of digitalization increases as economic growth increases. This outlook shows that economic development and digitalization are directly proportional. Geopolitical risks and climate policy uncertainties tend to increase as economic growth increases. The increase in climate policy uncertainty is more pronounced, especially at a very high level of economic growth. Although geopolitical risks appear positive, they show a more heterogeneous and fluctuating concentration, showing that the link between global risks and tensions and growth may be more cyclical. When the graph is examined, it is observed that life expectancy at birth, physical capital accumulation and commercial openness increase significantly from left to right. In this respect, there is a positive relationship between control variables and economic growth.

Figure 5: Quantile-binned heatmaps for LnGDP and explanatory variables





Source: Created by the authors

3.2. Econometric Method

In the study, the economic relationship between the variables was analyzed using panel data analysis technique. The empirical literature was followed when examining the relationship between the variables within the research framework (Meirun et al., 2021; Fernandes et al., 2021; Wang, 2023; Wani et al., 2024; Bousnina et al., 2025; Bouattour et al., 2025; Correa & Esquivias, 2025; Suhendra et al., 2025; Zhang et al., 2022). The linear representation of the model established in this context, which gives the panel data relationship between the variables, is shown below:

$$LnGDP_{it} = \beta_0 + \beta_1 EVPI_{it} + \beta_2 LnDIGII_{it} + \beta_3 LnGPR_{it} + \beta_4 LnCPU_{it} + \beta_5 LnLEB_{it} + \beta_6 LnK_{it} + \beta_7 LnOP_{it} + \varepsilon_{it} \quad (1)$$

Here, i and t represent the unit and time (year) dimension. β_0 and β represent the constant education and coefficient parameters, and ε represents the error term. Figure 6 illustrates the analysis process for the study. Within the scope of the study, cross-sectional dependence (CSD), unit root, and slope heterogeneity analyses were first applied to the series. In the next stage, the existence of a long-term relationship between the variables was examined using the cointegration tests of Kao (1999), Pedroni (1999, 2004), and Westerlund-Edgerton (2008).

Figure 6: Analysis Process

Long-run coefficients were estimated using the Pooled Bewley (CPS-BP) estimator introduced by Asnani et al. (2025), adapted to heterogeneous panel data by Chudik et al. (2026), and the Dynamic Least Squares Mean Group (DOLS-MG) estimator proposed by Pedroni (2001). To ensure robustness of the estimation results within the analysis framework, the Fully Modified Least Squares (FMOLS) estimator proposed by Phillips and Hansen (1990), the Canonical Cointegrated Regression (CCR) proposed by Park (1992), and the Dynamic Least Squares (DOLS) estimator developed by Stock and Watson (1993) were used. In the next stage of the research, the short-run causality relationship between the variables was addressed using the Granger-based heterogeneous causality test proposed by Dumitrescu-Hurlin (2012) for heterogeneous panel data models.

3.3. Analysis Findings

As presented in Table 4, the presence of cross-sectional dependence (CSD) among the variables was examined using the LM test proposed by Breusch and Pagan (1980), along with the scaled LM and bias-adjusted scaled LM tests developed by Pesaran, Ullah, and Yamagata (2008). The probability values of the LM test were found to be significant for all variables except LnGPR and LnCPU. In the later stage of the research, the heterogeneity of the estimated model was examined using the Delta tests proposed by Swamy (1970) and Pesaran-Yamagata (2008). The test results are shown in Table 5. Swamy's (1970) probe values for the s test were found to be statistically significant (p≤0.000). Likewise, Delta and adjusted Delta statistics for the Pesaran-Yamagata (2008) test were significant. In this respect, the model estimated according to the results of both test statistics exhibits heterogeneous features.

Table 3: CSD analysis

	LM		Scaled LM		S.D. Scaled LM	
	Statistics	Prob	Statistics	Prob	Statistics	Prob
LnGDP	225.646	0.000***	38.458	0.000***	38.458	0.000***
EVPI	25.453	0.044**	1.908	0.056*	1.706	0.080*
LnDIGII	274.591	0.000***	47.394	0.000***	47.236	0.000***
LnLEB	273.979	0.000***	47.282	0.000***	47.125	0.000***
LnK	52.206	0.000***	6.792	0.000***	6.635	0.000***
LnOP	50.891	0.000***	6.552	0.000***	6.394	0.000***

***, ** and * represents significance at p≤0.01, p≤0.05 and p≤0.10 levels.

Table 4: Slope-Heterogeneity Test

	Statistics	Prob
Swamy's (1979) sKi square	66651.66	0.000***
Pesaran-Yamagata (2008)		
Δ	6.254	0.000***
Δadj	8.462	0.000***

***, ** and * represents significance at p≤0.01, p≤0.05 and p≤0.10 levels.

The stationarity of LnGPR and LnCPU was investigated using the traditional first-generation panel unit root tests-namely the ADF–Fisher, PP–Fisher and LLC tests introduced by Im, Pesaran, and Shin (2003), Levin et al (2002), Maddala and Wu (1999), and Choi (2001). The test results are presented in Table 5. LnCPU contains a unit root at the level according to all test results. LnGPR is stationary at the level according to the IPS test results, while it contains a unit root according to the LLC, ADF-Fisher, and PP-Fisher test results. When the test results are considered together, the LnCPU and LnGPR series contain a unit root at the level and become stationary when their first differences are taken. In the presence of CSD, traditional unit root analyses lose their reliability. Therefore, the stationarity of the other series was examined using the CIPS test statistics proposed by Pesaran (2007), which produced reliable results in the presence of CSD. In addition, the form of the IPS test that takes CSD into account was used. The results of the CIPS and IPS analysis given in Table 6 showed that all series contained unit roots at the level, and when the first differences were taken, they became stationary.

Table 5: LLC, IPS, ADF-Fisher, and PP-Fisher Unit root analysis

	LLC		IPS		ADF-Fisher		PP-Fisher	
	Level	Difference	Level	Difference	Level	Difference	Level	Difference
LnGPR	-0.459	-7.437***	-1.672**	-6.541***	17.785	59.312***	17.785	59.275***
LnCPU	2.525	-9.569***	3.081	-7.540***	1.270	68.619***	1.270	69.835***

***, ** and * represents significance at p≤0.01, p≤0.05 and p≤0.10 levels.

Table 6: CIPS and IPS Unit root analysis

	CIPS		IPS	
	Level	Difference	Level	Difference
LnGDP	-1.098	-2.922***	3.632	-3.836***
EVPI	-1.736	-3.746***	1.645	-6.262***
LnDIGII	-2.525**	-2.252**	-0.167	-3.275***
LnLEB	-3.574***	-3.877***	-1.103	-1.584*
LnK	-1.991	-3.093***	-1.075	-4.672***
LnOP	-0.628	-3.104***	0.131	-5.676***

***, ** and * represents significance at p≤0.01, p≤0.05 and p≤0.10 levels.

In Table 7, the test results applied regarding the long-term relationship between the variables are presented. The ADF test statistic for the Kao test confirmed the existence of cointegration between economic growth and explanatory variables. Rho and ADF statistics were significant from the panel and group tests of the Pedroni test. From the Westerlund-Edgerton test statistics, the tau_n (τ) statistic shows that the variables are co-integrated, while the phi_n (ϕ) statistic is meaningless. When all tests are taken into consideration, it can be said that the variables are cointegrated in the long run.

Table 7: Cointegration analysis

Pedroni (1999, 2004)	Panel	Group
v- statistics	-1.001	
rho- statistics	2.876***	3.828***
t- statistics	-0.473	0.003
ADF- statistics	3.774***	4.715***
Kao (1999)	statistics	Prob
ADF	-3.380	0.000***
Westerlund-Edgerton (2008)		
τ	-2.298	0.010***
ϕ	-1.198	0.115

***, ** and * represents significance at p≤0.01, p≤0.05 and p≤0.10 levels.
The regime-shift option was selected when applying the Westerlund-Edgerton test.

Table 8 presents the long-run coefficient estimation results. The effects of both the EVPI and the digitalization index on economic growth are found to be positive across all estimators. These findings indicate that green innovation stimulates economic growth (Meirun et al., 2021; Bousnina et al., 2025). Accordingly, increasing investment in environmentally friendly technologies and prioritizing green growth strategies are essential for promoting economic development in BRICS+T countries (Fernandes et al., 2021; Wang, 2023; Wani et al., 2024; Bouattour et al., 2025). Furthermore, policies centered on green innovation not only support economic development but also contribute to mitigating the impacts of climate change (Nan et al., 2022; Banelienė et al., 2023; Van Trung et al., 2025). In addition, expanding investments in green technologies may play a significant role in reducing the adverse environmental consequences associated with increased production and economic expansion (Nan et al., 2022). The estimation results also show that rising levels of digitalization exert a positive influence on economic growth (Zhang et al., 2022; Correa & Esquivias, 2025; Neffati, 2025; Suhendra et al., 2025). Our findings highlight the pivotal role of information technologies in driving economic development (Alsebai, 2025). They also point to the potential for digital infrastructure and technology-related investments to enhance economic efficiency (Neffati, 2025:19). The results further indicate that greater investment in infrastructure contributes positively to economic growth (Maruf & Mansur, 2019). In this regard, the evidence suggests that a rising stock of physical capital is associated with higher levels of productivity and output in the countries under study (Olawale, 2024). Moreover, the analysis shows that U.S.-based climate policy uncertainty exerts a positive influence on economic growth in the BRICS+T economies. The effect of life expectancy at birth on economic growth is also found to be positive for all estimators except CPS-BP (2026). In contrast, rising geopolitical risks have a detrimental impact on growth in these countries. These results underline the need for policymakers to incorporate geopolitical risk considerations into the design of growth strategies. Regarding trade openness, the findings are mixed: while the DOLS and DOLS-MG estimators produce a negative coefficient (Neffati, 2025), the FMOLS estimator yields a positive effect, and the CPS-BP (2026) and CCR estimators suggest no statistically significant relationship.

Table 8: Estimation of long-term coefficients

	CPS-BP (2026)		DOLS-MG		FMOLS		CCR		DOLS	
	βeta	t-statistics	βeta	t-statistics	βeta	t-statistics	βeta	t-statistics	βeta	t-statistics
EVPI	0.023	2.66***	0.022	6.448***	0.01	7.00***	0.01	2.16**	0.02	4.85***
LnDIGII	0.157	2.79***	0.192	13.63***	0.19	50.38***	0.19	26.37***	0.19	16.63***
LnGPR	-0.856	-4.26***	-0.038	-6.838***	-0.06	-17.52***	-0.06	-5.73***	-0.04	-4.67***
LnCPU	0.372	3.36***	0.071	10.97***	0.04	17.88***	0.04	5.85***	0.07	10.80***
LnLEB	-0.472	-1.51	2.665	24.06***	3.30	51.69***	3.11	19.60***	2.66	19.62***
LnK	0.564	2.99***	0.226	4.665***	0.15	29.24***	0.14	11.88***	0.23	4.18***
LnOP	-0.276	-1.47	-0.051	-14.09***	0.06	-3.44***	0.05	-0.81	-0.05	-10.74***

***, ** and * represents significance at p≤0.01, p≤0.05 and p≤0.10 levels.
CSD correction was applied to the CPS-BP estimator.

In the subsequent stage of the study, the short-run causal relationships among the variables were analyzed using the Granger causality test (DH) developed by Dumitrescu and Hurlin (2012) for heterogeneous panels (Table 9). The results showed that there was no Granger causality towards LnGDP from the explanatory variables, but one-way Granger causality from LnGDP to LnCPU, LnLEB, and LnOP. Growth policies for research countries are an important determinant of human capital accumulation and international trade policies. Our results show that the development policies implemented in developing countries are related to the environmental policies originating from the USA. Within the framework of the analyses, one-way Granger causality was determined from LnLEB to EVI and from LnDIGI to LnCPU. Our findings point to human capital accumulation as a key driver of green technologies. It has been revealed that digitalization is closely related to global climate policies. The results of the analysis showed that there was a bidirectional Granger causality between LnDIGI, LnK and LnOP. Our findings show that digitalization, physical capital investment, and international trade policies are compatible for BRICS+T. Similarly, there is bidirectional Granger causality between LnK and LnLEB. Our findings have shown that investments in basic infrastructure and physical capital are important for the development of human capital accumulation. It was determined that there was bidirectional Granger causality between LnCPU and LnGDP, LnCPU and LnLEB, and LnOP and LnLEB.

Table 9: DH (2012) Granger causality test

	LnGDP	EVPI	LnDIGII	LnGPR	LnCPU	LnLEB	LnK	LnOP
	W-statistics	W-statistics	W-statistics	W-statistics	W-statistics	W-statistics	W-statistics	W-statistics
LnGDP	1.000	1.239	1.627	1.473	4.170***	11.830***	1.873	8.114***
EVPI	0.829	1.000	0.687	0.875	2.658**	0.678	0.991	0.719
LnDIGI	1.641	1.699	1.000	1.472	3.801***	2.849**	2.741**	6.760***
LnGPR	0.684	1.799	1.418	1.000	4.228***	3.460***	3.856***	0.921
LnCPU	0.880	0.942	2.119	11.036***	1.000	5.714***	2.293	3.950***
LnLEB	0.716	2.451*	1.222	1.695	4.950***	1.000	2.910**	4.739***
LnK	0.810	2.239	3.038***	0.513	1.278	9.127***	1.000	1.993
LnOP	1.566	1.694	2.494*	0.810	0.386	3.841***	1.309	1.000

***, ** and * represents significance at p≤0.01, p≤0.05 and p≤0.10 levels.

4. Conclusion and Recommendations

This research examined the contribution of green innovation and digitalization to economic growth in BRICS+T countries. In this context, the role of geopolitical risks and climate policy uncertainty originating from the USA is analyzed. Our research results showed that variables are related in the long run. Our results revealed that green innovation is in favor of economic growth in the long run. In this respect, encouraging environmentally friendly technologies and investments in research countries will contribute to sustainable economic development through green growth. These investments are important both in terms of increasing productivity and reducing GHG gases released into the environment as a result of production activities. Because BRICS+T countries, especially China, India and Russia, are among the most polluting countries in the world. In this respect, prioritizing green innovation can play a key role in these countries' fight against climate change.

The analysis results reveal that digitalization and information technologies serve as key drivers of economic development. Similarly, the estimation results indicate that increasing infrastructure investment positively influences economic growth. Accordingly, our findings provide evidence that greater accumulation of physical capital stock is associated with improvements in productivity and output. One of the most significant barriers to global economic activity is the destructive impact of climate change–induced extremes on economic performance. In particular, the economic costs of weather- and water-related disasters have increased noticeably in recent years. Therefore, U.S. climate policies are critically important for shaping environmental policy worldwide. The forecast results showed that climate policy uncertainties originating from the USA positively affected economic growth in the research countries. Similarly, the effect of life expectancy at birth on economic growth was positive across all estimates, except CPS-BP (2026). On the contrary, increasing geopolitical risks have hindered growth in BRICS+T countries.

Our results revealed that the growth policies implemented in the research countries are extremely sensitive to global risks and uncertainties. Therefore, governments and policymakers in these countries should take geopolitical risks into account in their growth policies. Our results also indicate that the integration of BRICS+T economies into the global world is extremely strong. The impact of trade liberalization on economic growth was negative according to the results of DOLS and DOLS-MG estimators (Neffati, 2025), positive according to the results of FMOLS estimators, and insignificant according to the results of CPS-BP (2026) and CCR estimators. In the next stage of the research, the short-term causality relationship between the variables was examined using the DH (2012) Granger-based causality test. The results showed that there is no Granger causality towards economic growth, but there is a one-way Granger causality from economic growth to U.S.-induced climate policy uncertainties, life expectancy and trade liberalization. Growth policies for research countries are an important determinant of human capital accumulation and international trade policies. Our results show that the development policies implemented in developing countries are related to the environmental policies originating from the USA. In addition, evidence has been found that human capital accumulation is a key driver of green technologies. It has been revealed that digitalization is closely related to global climate policies. Our analysis results show that digitalization, physical capital investment, and international trade policies are integrated for BRICS+T. Similarly, it has been determined that there is a bidirectional Granger causality between physical capital investment and human capital accumulation. Our findings have shown that investments in basic infrastructure and physical capital are important for the development of human capital accumulation. It has been determined that there is a bidirectional Granger causality between US-induced climate policy uncertainties, geopolitical risks, and life expectancy at birth, and between trade liberalization and life expectancy at birth.

Research findings indicate that sustainable growth in BRICS+T countries can only be achieved through a green technology-based transformation. Therefore, increasing environmentally friendly innovation capacity, strengthening digital infrastructure, and strategically directing physical capital investments stand out as key steps to support economic dynamism. Given the growth-repressing impact of geopolitical risks, policies that ensure energy supply security, secure supply chains, and prioritize international cooperation are essential. The growth-supporting impact of US-driven climate policy uncertainties suggests that BRICS+T countries should develop more flexible environmental policies that protect them against external shocks. Furthermore, the positive impact of life expectancy on growth demonstrates that investments in health and education focused on human capital yield long-term economic gains. The growth consequences of trade liberalization, in turn, necessitate countries to adopt a foreign trade strategy that takes into account their sectoral competitiveness.

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Extended Summary

What is the Contribution of Green Innovation and Digitalization to Economic Growth: Analyzing the Role of Geopolitical Risks and Climate Policy Uncertainty

Economic globalization has undoubtedly increased growth rates, but it has accelerated the transition to green innovation due to the potential threats to sustainable development caused by environmental degradation. Green innovation also aims to achieve sustainable development, offset the costs of environmental investments by increasing product value, increase resource efficiency, and provide a competitive advantage. While infrastructure is crucial for supporting economic growth, the intensive use of resources brings with it challenges such as climate change, carbon emissions, and environmental degradation. Uncertainties in the global economy and policies have increased geopolitical risk. Geopolitical risk imposes limitations on energy, a critical driver of economic growth and development, undermines corporate investments, and leads to a slowdown in global growth. The interaction between geopolitical risk and climate uncertainty, combined with climate change, is increasingly impacting the global economy. However, climate-related geopolitical risks threaten human life, economic growth, and security. Economic policy uncertainty hinders investment in green infrastructure, while geopolitical risks, in turn, focus on defense and crisis management stemming from conflict or instability rather than addressing climate policy uncertainty. Geopolitical risks related to conflicts occurring in regions with high carbon emissions stemming from climate change disrupt production and restrict exports, weakening global cooperation. Furthermore, geopolitical risks and economic policy uncertainty create significant uncertainties in financial markets. Because many conflict-prone regions are energy suppliers, increasing risks in the energy sector make international climate cooperation less likely, thereby creating greater uncertainty about climate change. Increased geopolitical risk encourages governments to increase capital expenditures in sectors such as defense and infrastructure, which can lead to higher economic growth (GDP). However, fluctuations in energy prices due to disruptions in supply chains negatively impact economic activity. A review of the literature reveals that advances in information technologies create competitive advantage, increasing productivity but also increasing energy consumption and CO_2 emissions. It has been determined that corporate digitalization and economic growth can positively impact green innovation and, consequently, contribute significantly to a sustainable economy. Studies have found that economic complexity, economic policy uncertainty, climate policy uncertainty, and geopolitical risk increase carbon emissions. Furthermore, the finding that renewable energy sources reduce the ecological footprint is a positive finding. In the face of ongoing geopolitical tensions, powerful governments continue to increase R&D investments. This research examines the contribution of green innovation and digitalization to economic development in the founding countries of the BRICS group (BRICS+T): Brazil, Russia, India, China, South Africa, and Turkey. Within this framework, it analyzes the role of geopolitical risks and climate change policy uncertainties originating from the US. To accurately measure the impact of green innovation in the BRICS+T countries, an overall Environmental Patent Intensity Index (EVPI) was calculated from various indicators using principal component analysis (PCA). Similarly, the digitalization index (DIGII) was calculated to represent the digital technological infrastructure in the study countries. The study distinguishes this study from the empirical literature by examining the impacts of green innovation and digitalization on economic growth in the context of geopolitical risks and US-induced climate change policy uncertainties.

Our research results demonstrate that the variables are correlated in the long run. Our results demonstrate that green innovation is beneficial to economic growth in the long term. Therefore, encouraging environmentally friendly technologies and investments in the study countries will contribute to sustainable economic development through green growth. These investments are important for both increasing productivity and reducing GHG emissions from production activities. BRICS+T countries, especially China, India, and Russia, are among the world's most polluting countries. Therefore, prioritizing green innovation can play a key role in these countries' fight against climate change. The analysis results indicate that digitalization and information technology are crucial for sustainable economic development.