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Nexus between uncertainty, innovation, and environmental sustainability in BRICS: an analysis under the environmental Kuznets Curve (EKC) framework

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This study explores the relationship between trade, economic uncertainty, innovation, and climate change in BRICS nations using the Environmental Kuznets Curve framework. The research is driven by the global imperative to address climate change, with predictions of a 2.7°C rise in global temperatures by the century's end, surpassing Paris Agreement targets. The study uses data from 1995 to 2023, employing unit root tests, cointegration tests (Bayer-Hanck and Maki), Augmented Autoregressive Distributed lagged and nonlinear autoregressive distributed lagged models, and the Fourier Toda-Yamamoto causality test to capture long- and short-term dynamics. The results demonstrate that technological and environmental innovations are critical in reducing carbon emissions, reinforcing the Environmental Kuznets Curve hypothesis that economic growth initially worsens but eventually mitigates environmental degradation. Conversely, economic, trade, and oil price uncertainties exacerbate environmental challenges by deterring investments in sustainable practices and clean technologies. A 10% increase in economic policy uncertainty, trade policy uncertainty, and oil price uncertainty significantly raise carbon emissions. In contrast, a 10% improvement in TI and EI reduces emissions, emphasizing the indispensable role of innovation in fostering environmental sustainability. To effectively combat climate change and align with international climate goals, BRICS nations must integrate their climate policies within the frameworks of the Paris Agreement and Sustainable Development Goals—notably SDG 7 Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action). Reducing policy uncertainties is crucial for mobilizing green investments, while subsidies, tax incentives, and strong regulatory frameworks should be prioritized to accelerate innovation-driven decarbonization. Furthermore, enhanced international cooperation, governance, and adaptive policy instruments will enable BRICS nations to navigate economic and environmental uncertainties, ensuring a transition to low-carbon economies and sustainable development pathways.

KEYWORDS

climate change, BRICS nations, environmental Kuznets curve, uncertainty, innovation, SDG 13

Highlights

1. Technological and environmental innovations significantly reduce CO_2 emissions in BRICS nations, affirming the EKC hypothesis.
2. Economic, trade, and oil price uncertainties increase CO_2 emissions, emphasizing the need for stable policies.
3. A 10% improvement in technological innovation decreases CO_2 emissions by up to 1.745% in India and 1.476% in South Africa.
4. Income initially raises emissions but later reduces them as economies grow, supporting the Environmental Kuznets Curve.
5. Policy recommendations include reducing uncertainties and enhancing innovation through incentives and international cooperation.

Introduction

Background of the study

At the heart of climate change is the accumulation of greenhouse gases in the Earth's atmosphere, primarily due to human activities such as burning fossil fuels, deforestation, and industrial processes. These greenhouse gases, including carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), trap heat in the atmosphere, leading to incremental warming of the planet's surface temperature (Zaher, 2008). Climate change is causing a noticeable rise in global temperatures, which has significantly affected various aspects of our planet. In the last hundred years, the Earth's average temperature has increased by about 1.2°C (2.2°F). This increase has had far-reaching consequences for weather patterns, ecosystems, and natural occurrences. The rising temperatures are causing glaciers and polar ice caps to melt, leading to sea-level rise and coastal erosion and threatening coastal communities, infrastructure, and ecosystems (Nureen et al., 2022). Climate change increases the frequency and severity of extreme weather events like heatwaves, hurricanes, droughts, and floods. These events have severe impacts on human lives, economies, and livelihoods. They result in loss of life, displacement of people, scarcity of food and water, destruction of infrastructure, and disruptions to agriculture, transportation, and supply chains (Huber and Gulledge, 2011). Climate change presents substantial dangers to ecosystems and biodiversity as well. The increasing temperatures, shifting precipitation patterns, and loss of habitats disrupt ecosystems and modify the distribution and population of various plant and animal species (Mooney et al., 2009). The consequences of climate change are spread out unevenly across the globe and among different social groups. The study of Orlove et al. (2014) disclosed that developing countries, especially those in tropical areas and small islands, are hit harder by climate change because they are more susceptible to extreme weather events, have limited ability to adapt, and rely heavily on climate-sensitive industries like agriculture, fishing, and tourism. These interconnected challenges create complex and interrelated risks that need coordinated and comprehensive solutions at the local, national, and regional (McMichael, 2015; Soares et al., 2018), adapting to changing climate conditions and developing resilience to climate impacts (Davenport, 1993). Key actions include shifting to renewable energy sources (Liu et al., 2010), improving energy efficiency Wu et al. (2022), preserving and rehabilitating ecosystems (Organization, 2012), promoting sustainable land use and agriculture practices (Fang, 2023), investing in climate-resilient infrastructure (Liu et al., 2010), and enhancing international cooperation and governance mechanisms (Tiwari, 2023). By decisively implementing these actions and collaborating, we can minimize the severe consequences of climate change and create a more sustainable and equitable future for all.

Understanding the determinants of climate change involves identifying the complex interactions between various natural and human factors that drive changes in the Earth's climate system. These determinants possess an expansive range of processes, activities, and phenomena that influence the balance of energy in the Earth's atmosphere and contribute to shifts in temperature, precipitation patterns, sea-level rise, and extreme weather events. Human actions, such as burning fossil fuels, deforestation, industrial activities, agriculture, and waste management, release significant amounts of greenhouse gases into the atmosphere. This amplifies the natural greenhouse effect and contributes to global warming (Yoro and Daramola, 2020). Changes in land use and land cover have a substantial impact on climate change. These changes affect the Earth's surface processes, such as the reflection of sunlight (albedo), carbon storage, and water cycling. Activities like deforestation, urbanization, agricultural expansion, and land degradation modify the land surface, which can amplify or mitigate climate change impacts (Bounoua et al., 2002). The Earth's oceans are essential for maintaining the planet's climate system. They store heat, circulate water, and absorb carbon dioxide. Oceanic factors, including sea surface temperature, rising sea levels, ocean acidification, and marine heatwaves, significantly impact climate change. These factors affect weather patterns, aquatic ecosystems, and coastal communities (Reid et al., 2009). Greenhouse gas emissions, atmospheric dynamics, and aerosol emissions cause climate change. These factors affect cloud formation, precipitation patterns, and radiative forcing. Natural events like volcanic eruptions, solar radiation variability, ocean-atmosphere interactions, and human activities like industrial emissions, biomass burning, and transportation release aerosols and pollutants into the atmosphere, which can have warming and cooling effects on the climate (Ramanathan and Feng, 2009). The impacts of climate change are intensified by feedback loops and tipping points in the Earth's climate system. These mechanisms create non-linear responses and sudden shifts in climate patterns. Positive feedback loops, such as melting polar ice caps, thawing permafrost, and forest dieback, contribute to warming by releasing

Abbreviations: BRICS, Brazil, Russia, India, China, and South Africa; EKC, Environmental Kuznets Curve; EPU, Economic Policy Uncertainty; TPU, Trade Policy Uncertainty; OPU, Oil Price Uncertainty; TI, Technological Innovation; EI, Environmental Innovation; FDI, Foreign Direct Investment; TO, Trade Openness; CO2, Carbon Dioxide; ARDL, Autoregressive Distributed Lag; NARDL, Nonlinear Autoregressive Distributed Lag; TY, Toda-Yamamoto causality test.

more greenhouse gases or reducing surface reflectivity. On the other hand, negative feedback loops, such as cloud cover and vegetation growth, can dampen climate variability by regulating heat and moisture fluxes (Arto et al., 2014).

Why Uncertainty and Innovation? The relationship between uncertainty and innovation is closely tied in the context of climate change because the challenges of climate variability and change are complex, dynamic, and uncertain. Climate change involves complex interactions between natural and human systems characterized by nonlinear relationships, feedback loops, and tipping points. This complexity leads to uncertainty, making it necessary to use innovative approaches to understand, model, and manage climate risks effectively (Arto et al., 2014). Innovation is crucial in addressing uncertainty by developing new technologies, methodologies, and strategies. Advanced climate models, remote sensing technologies, and data analytics enable scientists, policymakers, and practitioners to quantify better and mitigate climate risks (Odongo, 2023). Managing risk and building resilience is essential in adapting to climate change and mitigating potential impacts. Innovative approaches to risk assessment, scenario planning, and decision support systems help stakeholders anticipate, prepare for, and respond to uncertain climate futures by enhancing adaptive capacity and reduces vulnerability (Mhatre et al., 2021). Innovation in governance structures, policy instruments, and institutional arrangements is essential for navigating uncertainty and promoting adaptive responses to climate change (Pitelis et al., 2020). Flexible, inclusive, and participatory governance frameworks facilitate experimentation, learning, and collaboration among diverse stakeholders, which enables effective adaptation and mitigation strategies to emerge amid uncertainty (Johnston et al., 2011). Embracing uncertainty can lead to opportunities for experimentation and learning, as stakeholders can explore different approaches, test innovative solutions, and learn from successes and failures. This iterative innovation, adaptation, and feedback process can produce more robust and adaptive climate responses over time (Keskin et al., 2020). Uncertainty also drives technological development by creating a demand for new tools, technologies, and practices that enhance resilience, sustainability, and efficiency in the face of climate risks. Investments in clean energy, green infrastructure, climate-smart agriculture, and resilient urban planning contribute to technological advancements that help mitigate and adapt to climate change (Corfee-Morlot et al., 2012). Furthermore, uncertainty encourages policy innovation by promoting experimentation with new policy instruments, incentives, and governance mechanisms that address emerging climate challenges. Adaptive policies that encourage flexibility, scalability, and co-benefits enable policymakers to effectively respond to evolving scientific knowledge, stakeholder preferences, and societal needs in a rapidly changing climate context (Camacho, 2009). Embracing innovation has been crucial in reaching a significant milestone where hope for the future outweighs negativity (Matos et al., 2022). Despite criticism for its voluntary nature, the Paris Climate Agreement laid the groundwork for more ambitious commitments. Moreover, there has been a shift in understanding the economic benefits of addressing climate change, leading to increased efficiency, technological advancements, and lower risk. Moreover, there have been notable developments in leadership, demonstrating an increased recognition of the importance of managing risks and seizing opportunities in climate change. The study of Sovacool (2021) advocated that innovation has led to cost reduction and the implementation of new technologies that will be essential in achieving our goals. However, despite the progress made, a significant amount of work is still needed to avert the severe consequences of climate change. An extensive revamp is necessary on a large scale in various sectors such as electricity generation and agriculture. Innovation will be essential to accomplish these vital changes, which will involve creating new technologies and infrastructure solutions currently unavailable in the market. Positive advancements include the decrease in battery expenses and the swift growth in the adoption of renewable energy sources and electric vehicles.

The study modelled innovation, that is, technological innovation (TI, hereafter), environmental innovation (EI, hereafter), uncertainty measuring trade policy uncertainty (TPU, hereafter), and oil price uncertainty (OPU, hereafter) on climate change, which proxies by CO_2 and ecological footprint (EF, hereafter).

The study's findings suggest that to mitigate the impacts of climate change, BRICS nations should focus on reducing policy uncertainties and promoting technological and environmental innovations through subsidies, tax incentives, and robust regulatory frameworks. Enhancing international cooperation and governance is crucial for transitioning to low-carbon economies. Moreover, adopting adaptive and flexible policy instruments can help these countries navigate changing economic and environmental conditions, promoting resilience to climate impacts.

The study's originality is as follows: It emphasizes its unique contributions, such as applying the EKC framework to analyze the nexus between trade, economic uncertainty, innovation, and climate change, specifically in the context of BRICS nations. Additionally, the study's use of a comprehensive empirical model that incorporates a range of variables like EPU, CPU, OPU, TI, EI, foreign direct investment (FDI, hereafter), and trade openness (TO, hereafter) to assess their impact on climate change adds a novel dimension to the existing literature. Furthermore, the study employs advanced econometric techniques, including unit root tests, cointegration tests, ARDL, NARDL models, and the Fourier-TY causality test, which enhance its methodological rigour and address structural breaks and asymmetries in the data, providing a more nuanced understanding of the long- and short-term dynamics of these relationships. By focusing on the BRICS countries, the study also fills a gap in the literature concerning emerging economies' role in climate change and sustainable development. Highlighting these aspects can demonstrate the study's originality and contribution to the field.

The research contribution can be clearly outlined as follows: Firstly, the study provides a comprehensive analysis of the relationship between trade, economic uncertainty, innovation, and climate change in BRICS nations using the EKC framework. It highlights how technological and environmental innovations are essential for reducing CO_2 emissions, thus validating the EKC hypothesis that economic growth initially increases but eventually decreases environmental degradation. Secondly, the research develops an empirical model incorporating various factors such as EPU, CPU, OPU, TI, EI, FDI, and TO. This model is crucial for understanding their effects on climate change, measured by CO_2

emissions and ecological footprint. The study employs advanced analytical techniques to capture long- and short-term dynamics, including unit root tests, cointegration tests (Bayer-Hanck and Maki), ARDL, and NARDL models. These methods allow for a more robust and nuanced understanding of the factors influencing climate change. Lastly, the research emphasizes the importance of reducing economic and trade policy uncertainties to create a stable environment for green investments. It suggests that BRICS nations should focus on policies encouraging technological and environmental innovations through subsidies, tax incentives, and strong regulatory frameworks. Additionally, the study underlines the necessity of international cooperation and governance for transitioning to low-carbon economies. By clearly outlining these contributions, the research offers valuable insights into the complex interplay between economic activities, policy uncertainties, and climate change, providing a strong foundation for future policy-making and academic research.

The article's structure is as follows: It begins with an introduction and background on climate change and its global impact, followed by a literature review on innovation and uncertainty in climate policies in Section 2. The study then details its data and methodology, including model specifications and econometric techniques, which are available in Section 3. Finally, the article presents empirical findings, discusses implications, and offers policy recommendations for BRICS nations. In Sections 4, 5, and 6, respectively.

Literature survey

Theoretical development of the study

Several well-established economic and environmental theories, with a special emphasis on the EKC, provide a theoretical framework for analyzing the BRICS economies' dynamics of innovation, environmental sustainability, and uncertainty. According to Zoaka et al. (2022), the EKC states that there is a tipping point beyond which more incomes result in greater environmental quality, beyond which the opposite occurs. Considering their varied paths to growth and resource endowments, this theory is essential for understanding the relationship between environmental governance, improving economic circumstances, and new technological developments in the BRICS countries.

Innovation and environmental performance have a complicated connection in the BRICS setting. To lessen the environmental impact, we need innovative technologies that improve energy efficiency and use renewable energy sources (Shafiq and Zafar, 2023). Policies that may help bring about a low-carbon economy include electric automobiles and public transportation efforts, which have been shown to reduce carbon emissions drastically. Furthermore, new energy technology can speed up sustainable practices in these growing countries (Saba et al., 2024). It has been suggested that proactive policies in research and development (R&D, hereafter) and FDI may help promote environmental sustainability (Lee et al., 2021). The capacity to execute sustainable innovations is heavily influenced by the BRICS nations' infrastructure capacities as well as their institutional frameworks, according to research into the unique dynamics of these countries. This is made very clear because member nations' experiences are drastically different. India's attempts to improve industrial environmental performance have been hindered by dependence on fossil fuels and existing infrastructure gaps, in contrast to China's strong development in this area (Kayani et al., 2023). In order to encourage innovation that supports environmental sustainability, it is evident that customized approaches are required, taking into account the distinct socio-economic circumstances of each BRICS country. Research on the possible function of BRICS economic governance frameworks further highlights the significance of eco-innovation. Investment in environmentally friendly technology and sustainable practices tends to rise with strong environmental regulation (Ganda, 2024). In addition, emerging governance mechanisms like green finance and fintech show how financial instruments may help include sustainability in goals for economic development (Udeagha and Muchapondwa, 2023). Therefore, the ability of BRICS states to promote technologies that address environmental challenges is directly impacted by the governance systems in those nations.

The environmental effects of globalization and commerce are another important factor to consider within this paradigm. The effects of increased international commerce on environmental stability in the BRICS countries will vary. According to the pollution haven hypothesis (PHH), polluting firms could move to BRICS nations with laxer environmental rules if environmental controls became too strict (Wen et al., 2022). Including local regulatory standards and enforcement capacities are important when assessing the link between trade policies and environmental quality. Maintaining economic development while decreasing carbon footprints is a double-edged sword the BRICS nations must face. According to (Rahman et al., 2024), there is a crucial connection between economic development, energy consumption, and environmental sustainability. Energy financing techniques have become a key point in achieving these aims. The BRICS countries might improve their energy security and reduce their carbon footprint by increasing their use of renewable energy. Furthermore, the difference in the use of resources, technical advancements, and larger institutional features is brought to light by empirical assessments of the BRICS countries' efficiency in sustainable development (Gebert and Mello-Sampayo, 2024). In order to achieve the sustainable development objectives unique to the BRICS environment, it is crucial to implement programmatic interventions that aim to improve resource efficiency and encourage eco-innovation. Since disadvantaged populations bear a disproportionate share of pollution and resource shortages, environmental degradation is often worsened by the persistent socioeconomic disparities in these nations (Romaniuk et al., 2020). Consequently, the BRICS nations' pursuit of sustainable development is beset by the perennial problem of integrating environmental preservation with social justice. Regarding environmental sustainability, nothing is more important than combining renewable energy systems with information and communication technology (Saba et al., 2024). To mitigate the negative environmental effects caused by fast industrialization, smart technology may be used to manage resources better. Therefore, information and communication technology (ICT, hereafter) can boost economic productivity and facilitate innovations that strengthen environmental regulations. When national policies align with international environmental norms, ecological results may be greatly improved, as shown in the cases of the BRICS countries' environmental governance. For example, the BRICS nations may work together to address global environmental issues by following the rules of treaties like the Paris Agreement (Shen and Zou, 2024). In addition, the BRICS countries may speed up the implementation of collective sustainability measures via political and economic collaboration. The complex interplay of BRICS countries' innovation, environmental sustainability, and economic uncertainty calls for a multi-pronged strategy that integrates social, environmental, and economic ideas. Further research and practical solutions to improve ecological sustainability in these fast-growing economies can be found by evaluating environmental policies using the EKC framework and supplementing them with insights from governance challenges, technological innovations, and socioeconomic dynamics.

Innovation led to climate change

Implementation innovation has been crucial in reaching a significant milestone where hope for the future outweighs negativity. The Paris Climate Agreement, despite receiving criticism for its voluntary nature, laid the groundwork for more ambitious commitments down the line (Falkner, 2016). Moreover, there has been a shift in understanding the economic benefits of addressing climate change, leading to increased efficiency, technological advancements, and lower risk. Additionally, there have been notable developments in leadership, demonstrating an increased recognition of the importance of managing risks and seizing opportunities in climate change (Boyce, 2019). Moreover, innovation has led to cost reduction and the implementation of new technologies that will be essential in achieving our goals. However, despite the progress made, a significant amount of work is still needed to avert the severe consequences of climate change (Davenport, 1993). An extensive revamp is necessary on a large scale in various sectors such as electricity generation and agriculture. To accomplish these vital changes, innovation will be essential. This will involve creating new technologies and infrastructure solutions that are currently unavailable. Positive advancements include decreased battery expenses and the swift growth in adopting renewable energy sources and electric vehicles (Liu et al., 2010).

In the battle against climate change, innovation has become a crucial factor that significantly reduces greenhouse gas emissions, improves resilience, and shifts towards sustainable energy systems (Soares et al., 2018). This literature review investigates the role of innovation in tackling climate change by exploring important ideas, factors that drive innovation, obstacles that hinder it, and the consequences of innovation in various industries and areas. In recent decades, the intersection between innovation and climate change has garnered significant interest from researchers, legislators, and practitioners. This portion of the literature review provides a thorough overview of significant research, ideas, and conversations about innovation-driven climate change efforts. It highlights the importance of technical, organizational, and policy innovations in advancing sustainable development and mitigating the impacts of climate change. A study by Wu et al. (2022) in China using data from 2010 to 2019 discovered that transitioning to a green economy necessitates innovation. Advancements in green technology, also known as eco-innovation, are essential for reaching sustainability objectives, enhancing energy efficiency, minimizing resource consumption, and mitigating pollution and environmental hazards. Eco-innovation is a strategic tool companies can use to prevent reputational harm. For 15 European countries over 23 years, Mongo et al. (2021) examined the impact of environmental innovations on CO_2 emissions and unveiled that, in the long term, environmental innovations lower CO_2 emissions. However, in the short term, there is a rebound effect where CO_2 emissions increase. The study recommends implementing policies that combine economic incentives and regulatory changes to encourage more environmentally friendly consumption. The study of Dauda et al. (2019) exposed a mixed linkage between TI and CO_2 emission. Precisely, for G6 nations, TI assists in reducing CO_2 while TI accelerates the CO_2 emission in BRIC S and MENA. A thorough investigation has shown several aspects that contribute to the progress of innovation in climate change mitigation and adaptation. Policy instruments, such as carbon pricing mechanisms, incentives for renewable energy, and environmental regulations, are crucial for driving market demand for clean technology and facilitating the dissemination of innovation (Pitelis et al., 2020).

Despite its immense potential, research in Kenya by Chris (2015) showed that innovation faces several barriers and challenges that hinder its effective implementation and general acceptance. The challenges include legislative impediments that impede the adoption of clean technology, market shortcomings that undervalue the benefits of environmental sustainability, and institutional opposition that perpetuates reliance on carbon-intensive infrastructure. Moreover, financial constraints, limited technology availability, and apprehensions over intellectual property rights might hinder the dissemination of innovation, particularly in developing countries (Ockwell et al., 2010). Furthermore, socio-economic factors such as socioeconomic disparities, cultural traditions, and political resistance may pose significant challenges to adopting innovative solutions (Curry et al., 2021).

The ramifications of climate change initiatives propelled by innovation are far-reaching and varied, including environmental, economic, social, and geopolitical dimensions. Global case studies provide effective examples of innovation in addressing climate change, including many endeavours such as adopting renewable energy sources, executing eco-friendly building projects, constructing sustainable transportation networks, and implementing circular economy initiatives. These case studies demonstrate the substantial impact that innovation may have on advancing sustainable development and enhancing resilience to the impacts of climate change (Mhatre et al., 2021; Cooke, 2011; Kandpal et al., 2024). Providing a conducive environment for future innovation is crucial to accelerate progress towards climate resilience and sustainability. Key policy recommendations include strengthening legal frameworks to incentivize the adoption of clean technology, increasing investment in research and development, fostering collaboration and knowledge sharing, and establishing inclusive innovation ecosystems that prioritize justice and social equity (Matos et al., 2022). Moreover, it is essential to address barriers that impede the dissemination of innovation, such as technology transfer and capability development. Ensuring equitable distribution of the benefits of innovation is crucial (Organization, 2012).

Uncertainty led-to climate change

The uncertainties inherent in climate science have significantly influenced the global response to climate change. Uncertainty regarding future climate conditions, policy developments, and market trends can impede long-term economic planning and investment decisions, resulting in inefficient allocation of resources and missed opportunities for sustainable development (Haasnoot et al., 2013). Regarding infrastructure development, uncertainty about the scale and timing of climate impacts, such as rising sea levels, extreme weather events, and changing precipitation patterns, can complicate the planning and design of infrastructure projects by increasing the risk of costly damages and disruptions (Ranger et al., 2013). The insurance industry faces challenges in the US due to uncertainty surrounding climate-related risks and liabilities. This uncertainty makes it difficult for insurers to assess and price climate risks accurately, potentially leading to market failures, higher premiums, and reduced coverage availability for vulnerable communities (Mills and Lecomte, 2005). The study of (Anwar et al., 2023; Cui et al., 2024; Farooq et al., 2023) revealed that Uncertainty about the impact of climate change on agricultural productivity, crop yields, and food security could undermine farmers' ability to make informed decisions about crop selection, land management practices, and resource allocation, exacerbating food insecurity and rural poverty (Waldman et al., 2020). Water resource management can be complicated by uncertainties surrounding future precipitation patterns, availability, and competing demands for water resources. These uncertainties can lead to conflicts over water allocation, increased vulnerability to droughts and floods, and reduced resilience of ecosystems (Ajami et al., 2008). In the UK, the study of (Ayad et al., 2023a; Ayad et al., 2023b) advocated that the transition to low-carbon energy systems can be hindered by uncertainties surrounding energy demand, technological advancements, and policy support for renewable energy, which can result in a prolonged reliance on fossil fuels and delays in efforts to decarbonize and mitigate climate change (Chilvers et al., 2017). The study of (Ayad et al., 2023c; Balsalobre-Lorente et al., 2024) postulated that uncertainty about the health impacts of climate change, such as heatwaves, vector-borne diseases, and air pollution, can pose challenges to public health preparedness and response efforts, lead to increased rates of illness and death, as well as higher healthcare costs (Wardekker et al., 2012). The uncertainty surrounding the impact of climate change on biodiversity, ecosystem services, and species distributions can impede conservation efforts. This uncertainty further contributes to the loss of biodiversity, degradation of habitats, and increased risk of extinction for vulnerable species (Mooney et al., 2009). The literature of (Cui et al., 2024; Farooq et al., 2023; Javed et al., 2023) deemed that uncertainty surrounding the impact of climate change on biodiversity, ecosystem services, and species distributions can impede conservation efforts. This uncertainty further contributes to the loss of biodiversity, degradation of habitats, and increased risk of extinction for vulnerable species (Pecl et al., 2017). Uncertainty regarding urbanization trends, population growth, and climate risks can complicate the process of urban planning and development, increasing vulnerability to climate hazards, inadequate infrastructure, and socioeconomic inequalities in urban areas (Ruth and Coelho, 2015). Uncertainty surrounding the causes and consequences of climate-induced migration, such as displacement, resettlement, and conflict, can pose policy challenges. This uncertainty makes it difficult for them to anticipate and address the needs of affected populations, potentially leading to humanitarian crises and social unrest. Existing literature such as (Li et al., 2024; Qamruzzaman, 2023; Sadiq et al., 2024) revealed that the effectiveness and fairness of carbon pricing mechanisms, such as carbon taxes and emissions trading systems, are also subject to uncertainty. This uncertainty can hinder the implementation and adoption of these mechanisms, limiting their ability to incentivize emissions reductions and promote low-carbon innovation. The uncertainty surrounding countries' willingness and ability to work together on climate change mitigation and adaptation efforts can have negative consequences. It can erode trust, solidarity, and collective action, leading to diplomatic tensions, trade disputes, and geopolitical instability.

The allocation of resources and attention toward climate change mitigation and adaptation can be influenced by uncertainty about public policy priorities, political will, and societal values. This uncertainty, shifting political landscapes, changing public opinion, and competing policy agendas can lead to fluctuations in funding, support, and momentum for climate action initiatives. Uncertainty about long-term climate projections and system dynamics presents long-term planning and strategic decision-making challenges. Planners, policymakers, and stakeholders may need help anticipating future climate risks, assessing trade-offs, and developing resilient strategies that account for uncertain futures, resulting in increased vulnerability to climate impacts (Styczynski et al., 2014). Uncertainty about technological trajectories and lock-in effects can shape investment decisions and infrastructure development pathways. Technological lock-in occurs when investments in existing technologies or infrastructure make it difficult to transition to more sustainable alternatives in the future, which is particularly challenging if uncertainty favours business-as-usual scenarios (Klitkou et al., 2015). Uncertainty about adaptive capacity, resilience thresholds, and tipping points can affect communities' ability to respond to climate impacts and build resilience. Communities facing high levels of uncertainty may need help prioritizing adaptation measures, allocating resources effectively, and engaging in collective action to address shared climate risks. This can increase vulnerability and exposure (Werners et al., 2013). The study of (Wu et al., 2024; Zhang et al., 2023) outlined that uncertainty surrounding interdisciplinary collaboration, the integration of knowledge, and communication can impede efforts to bridge gaps between various scientific disciplines, policy domains, and stakeholder groups. Successful collaboration necessitates navigating differing perspectives, methodologies, and value systems while addressing the inherent uncertainties in interdisciplinary research and decision-making processes (Axelsson, 2010).

Literature gap

First, while much research has explored the EKC and the relationship between economic activities and climate change, there is limited focus on the BRICS nations. This study attempts to bridge this gap by examining these rapidly developing economies' unique economic and environmental dynamics.

Second, Previous studies have analyzed the impact of economic growth, trade, and innovation on climate change. However, they often overlook the role of policy uncertainties, such as EPU, CPU, and OPU. This study fills this gap by integrating these uncertainty measures into its empirical model.

Third, Many studies rely on traditional econometric models that fail to account for structural breaks and asymmetric effects. By incorporating advanced econometric techniques such as augmented autoregressive distributed lagged, nonlinear autoregressive distributed lagged, and Fourier Toda-Yamamoto causality tests, this study provides a more nuanced and robust analysis of climate change factors' long- and short-term dynamics.

Fourth, the impact of technological and environmental innovation on reducing CO_2 emissions has been extensively studied in developed countries but remains underexplored in BRICS nations. This study addresses this gap by analyzing the role of innovation in mitigating climate change within these specific economies.

Data and methodology of the study

Hypothesis and theoretical foundation

The primary theoretical lens for this study is the Environmental Kuznets Curve (EKC) hypothesis. It posits an inverted-U relationship between economic growth and environmental degradation: as income rises, pollution initially worsens but eventually declines beyond a certain development threshold. This occurs because wealthier societies invest more in pollution control and shift towards cleaner, service-oriented activities{Farooq, 2024 #16968}. For the BRICS economies (Brazil, Russia, India, China, South Africa), which are experiencing rapid growth, the EKC implies that continued development can lead to environmental improvement in the long run. Recent evidence supports this pattern in emerging economies and highlights that technological modernization and human development help mitigate pollution as countries grow.

Complementing the EKC, innovation theory and sustainability transition perspectives emphasize how technological change drives environmental improvement. Technological innovation–from clean energy technologies to energy-efficient processes–is a catalyst for decoupling economic growth from environmental harm (Saqib, 2022). Studies find that green technology and renewable energy use significantly reduce carbon emissions, acting as a "panacea" for curbing pollution in developing countries. This aligns with sustainability transition theory, which argues that economies shift to sustainable trajectories through the diffusion of new innovations and supportive institutional change. In BRICS, fostering green innovation (e.g., renewable energy, low-carbon technologies) is essential for reaching the downward part of the EKC sooner.

Economic and policy uncertainty can moderate the innovation–environment nexus by deterring long-term investments in sustainability. High uncertainty (for instance, frequent regulatory changes) makes firms hesitant to invest in green technologies due to perceived risks. Empirical evidence confirms that higher economic policy uncertainty (EPU) significantly reduces green innovation and green investment in BRICS Such uncertainty can disrupt the expected EKC path by delaying the turn toward sustainability–if firms postpone adopting cleaner technologies, environmental degradation may persist longer than predicted. There is also evidence of a threshold effect: beyond a point, firms may respond to extreme uncertainty with adaptive innovation. However, on balance, uncertainty predominantly hinders the innovation and transition efforts needed to improve environmental sustainability. In practical terms, integrating uncertainty and innovation into the EKC framework is highly relevant for BRICS, which collectively contribute around 40% of global CO_2 emissions. By linking macro-level EKC patterns with micro-level drivers, this study addresses a notable gap in understanding emerging-economy environmental dynamics. The insights are also valuable for policy. If policy uncertainty is found to impede green innovation, BRICS governments should strive for more stable and transparent environmental policies to foster investment in sustainable technologies. Similarly, actively promoting innovation (through R&D support, human capital development, and technology transfer) can help achieve environmental sustainability without compromising growth. Overall, this research offers a nuanced understanding of how uncertainty and innovation interact in shaping the sustainability trajectory of BRICS, providing guidance for policymakers seeking to balance economic growth with environmental stewardship.

Model specification

The motivation of the study is to assess the role of innovation, uncertainty, inflows of FDI, and trade on climate change in BRICS nations for 1995-2023. Study used annualized panel data for the estimation purpose. The generalized equation is as follows;

$$\mathrm{CC} = \int \mathrm{EPU, CPU, OPU, TI, EI, FDI, TO} \tag{1}$$

Where CC, EPU, CPU, OPU, TI, EI, FDI, TO denote climate change, oil price uncertainty, climate policy uncertainty, oil price uncertainty, technological innovation, environmental innovation, foreign direct investment, and trade openness, respectively.

The equation further expanded under the assumption of the EKC hypothesis, and the revised Equation 1 can be displayed as follows;

$$CC = \int EPU, CPU, OPU, TI, EI, FDI, TO, Y, Y2 \tag{2}$$

After the transformation of all the variables, the above Equation 2 can be reported in the following regression format in deriving the coefficients of uncertainty, innovation, trade, and FDI (see Equation 3),

$$CC = \beta 0 + \beta 1EPU + \beta 2CPU + \beta 3OPU + \beta 4TI + \beta 5EI + \beta 6FDI + \beta 7TO + \beta 8Y + \beta 9Y2 + \epsilon \tag{3}$$

In this regression model, each coefficient indicates the expected change in CC, which is measured by CO_2 emission, when the associated independent variable increases by one unit while holding all other variables constant. We anticipate a favourable indication of EPU. Rising levels of economic policy uncertainty may lead to reduced investments in sustainable practices and technology, thereby worsening environmental degradation and contributing to climate change. Regarding CPU, we expect a beneficial outcome. The ambiguity about climate policy might hinder the execution of efficient environmental regulation and enforcement, leading to elevated levels of greenhouse gas emissions and exacerbating the problem of climate change. It is expected that OPU will result in a positive outcome. Variations in oil prices may lead to uncertain investment in renewable energy sources and an increased reliance on fossil fuels, worsening climate change. Conversely, TI is anticipated to have a negative correlation. Technological progress often leads to enhanced production methods and reduced emissions, therefore mitigating the effects of climate change. EI is expected to have a negative correlation. Concentrated endeavours towards environmental sustainability are positioned to substantially influence reducing greenhouse gas emissions and tackling the pressing problem of climate change. The correlation between FDI and climate change is intricate and lacks a clear-cut definition. FDI may benefit when it increases industrial activity and results in heightened emissions. Conversely, it may also have adverse effects when it enables the transmission of cleaner technology. The predicted indication of TO is ambiguous. Increased trade openness may lead to elevated emissions due to the amplified production and transportation activity levels. Nevertheless, it may also facilitate the disseminating of ecologically sustainable technology and practices. We anticipate a favourable indication for Income (Y). Elevated income levels can lead to intensified consumption and production endeavours, amplifying emissions and climate change. Ultimately, Squared Income (Y2) is expected to have a negative value. The EKC idea suggests that at a certain threshold of affluence, additional economic expansion may lead to beneficial environmental improvements due to societies' capacity to allocate resources towards developing and implementing environmentally friendly technology while prioritizing sustainability. Table 1 displayed the research variabels with appropriate proxies.

Estimation strategies

For assessing the stationarity properties, the present studies have executed the unit root test following Perron and Vogelsang (1992) and Dickey and Fuller (1979). The Perron and Vogelsang Test is a test that is specifically composed of the structural break among time series data. Structural breaks can have substantial implications for the outcome of unit root tests. This test allows for one possible structural break to occur at some time point within the series, and the mean level or trend of the series can experience a shift over time. Further, this approach serves the dual purpose of making the tests for unit roots more robust in the presence of structural breaks, which the conventional tests may very well be devoid of. The second approach in testing unit roots is the Augmented Dickey-Fuller (ADF) test, which is widely used to check for a stationary time series or has a unit root as one of its features, hence being non-stationary. The ADF test is essentially an extension of the basic Dickey-Fuller test. It includes some lagged differences of the series into the hypothesis, such that one effectively allows for higher-order serial correlation. Both the tests are essential in time series, the Perron and Vogelsang Test offering a more refined one in situations of structural change, and the ADF test providing a general framework for testing stationarity, see Equation 4.

$$y_t = \mu + \beta t + \theta DU_t + \alpha y_{t-1} + \sum_{i=1}^{k} \phi_i \Delta y_{t-i} + \epsilon_t \tag{4}$$

The Perron and Vogelsang test involves estimating the above model using a quasi-maximum likelihood estimation (QMLE) method and then computing the following test statistic:

$$t_\alpha = \frac{\hat{\alpha} - 1}{\hat{\sigma}_\alpha}$$

where $\hat{\alpha}$ is the estimated value of α and $\hat{\sigma}_\alpha$ It is the standard error. The null hypothesis of a unit root is $H_0\colon \alpha = 1$ and the alternative hypothesis is $H_1\colon \alpha < 1$. The test rejects the null hypothesis if the test statistic t_α It is less than the critical value, indicating that the series is stationary. The Perron and Vogelsang test also involves computing the break date, the point at which the trend shifts. This is done by minimizing the sum of squared residuals over all possible break dates.

Augmented Dickey-Fuller Test can be the extension of the simple Dickey-Fuller test. Because of the error term, it is unlikely to display white noise characteristics. They extended their test by extra lag in terms of the dependent variables to eliminate the auto-correlation problem.

$$Yt = \beta_1 + \beta_2 Yt + \varepsilon_t$$
$$Yt = \beta_1 + \beta_2 Yt + \beta_3 Y_{t-1} + \varepsilon_t$$
$$Yt = \beta_1 + \beta_2 Yt + \beta_3 Y_{t-1} + \beta_4 Y_{t-2} + \varepsilon_t$$

Now,

$$Yt = \Upsilon Y_{t-1} + \beta_1 \Delta Y_{t-1} + \varepsilon_t$$
$$Y_t = \Upsilon Y_{t-1} + \beta_1 \Delta Y_{t-1} + \beta_2 \Delta Y_{t-2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots + +\beta_p \Delta Y_{t-p} + \varepsilon_t$$

Continue this process till where autocorrelation is eliminated. This expression could be written as:

$$\Delta Y_t = \Upsilon Y_{t-1} + \sum_{i=1}^{p} \beta_1 \Delta Y_{t-1} + \varepsilon_t$$

$$\Delta Y_t = \alpha + \beta_t + \Upsilon Y_{t-1} + \sum_{i=1}^{p} \beta_1 \Delta Y_{t-1} + \varepsilon_t$$

Used to test if the variables are stationary or have a unit root. To avoid spurious regression results, time-series data must be stationary. We used the Perron-Vogelsang test to consider the presence of structural changes, which is crucial for long-run macroeconomic and environmental series, given that policy-induced changes and global shocks may occur throughout the years.

Following Bayer and Hanck, the combination of the computed significance level (p-value) of the individual cointegration test in this article is in Fisher's formula as follows:

$$EG - JOH = -2\left[\ln\left(P_{EG}\right) + \left(P_{JOH}\right)\right]$$
$$EG - JOH - BO - BDM = -2\left[\ln\left(P_{EG}\right) + \left(P_{JOH}\right) + \left(P_{BO}\right) + \left(P_{BDM}\right)\right]$$

The possible p-values of several individual cointegration tests will be extracted from Engle and Granger, Johansen, Peter Boswijk, Banerjee, Dolado P_{EG}, P_{JOH}, P_{BO}, and.

P_{BDM} Respectively. To get evidence regarding the long-run association, the calculated F-stat has to be greater than the critical value proposed by Bayer and Hanck (2013), which is the rejection of the null hypothesis of "no cointegration."

The Maki Cointegration test (Makki and Somwaru, 2004) is an econometric technique utilized to ascertain the existence of Cointegration within a set of multiple time series variables. Cointegration represents a pivotal notion in time series analysis, signifying a durable association between variables, notwithstanding their susceptibility to transitory oscillations. The Maki test proves to be particularly advantageous in situations involving limited sample sizes, as it allows for the inclusion of lagged terms to capture dynamic relationships effectively.

The Maki cointegration test is based on the following vector autoregressive (VAR) model:

$$Yt = \Pi Yt - 1 + \sum i = 1p - 1\Gamma i\Delta Yt - i + \varepsilon t$$

These tests examined whether long-run equilibrium relationships exist within climate change, uncertainties (economic, trade, and oil price), technological innovation, and environmental innovation. The Maki test allows for multiple structural breaks, which is important due to substantial structural breaks in the case of BRICS countries over the years, while the Bayer-Hanck test combines test statistics for cointegration to give a robust indication of cointegration.

The augmented ARDL (AARDL, hereafter) method, which was introduced by Sam et al. (2019), is a powerful tool in practical research, celebrated for its flexibility and capability to handle factors with different combination orders. This is particularly useful in economic and financial research, where factors often show varied combination patterns. By accommodating factors integrated with order zero and one, AARDL offers an adaptable approach that simplifies the intricacy of such diverse information. A major benefit of the AARDL approach is its capacity to calculate long-term connections, or cohesion, among factors. This feature is crucial for researchers examining long-term links and extracting relevant strategic insights from practical information. The robustness of the AARDL method is further demonstrated in theory evaluation, providing a strong structure that reduces possible errors, particularly in small samples. This is ensured through the bound evaluation method, which guarantees variable calculations are free from consistent errors, enhancing the dependability and accuracy of findings. On the other hand, other methods like the Johansen cohesion assessment often enforce strict presumptions that may not be applicable in all cases, potentially resulting in less accurate conclusions. Therefore, the ARDL model is favoured for its broad relevance, robustness, and efficiency, making it an ideal selection for researchers investigating long-term connections in practical research.

Subsequently, Pesaran et al. (2001) considered the generalized ADRL model for detecting long-run and short-run coefficients by performing the following Equations 5, 6.

$$\begin{aligned}\Delta lnCO2_t = {} & \alpha_0 + \varnothing_1 DMU_t + \sum_{i=1}^{n}\mu_1\Delta lnTPU_{t-i} + \sum_{i=0}^{n}\mu_2\Delta lnEPU_{t-i} \\ & + \sum_{i=0}^{n}\mu_3\Delta\ln OPU_{t-i} + \sum_{i=0}^{n}\mu_4\Delta\ln TI_t + \sum_{i=0}^{n}\mu_5\Delta\ln EI_{t-i} \\ & + + \sum_{i=0}^{n}\mu_4\Delta\ln FD_t + \sum_{i=0}^{n}\mu_5\Delta\ln FDI_{t-i} + \gamma_1 lnTPU_{t-i} \\ & + \gamma_2 lnEPU_{t-1} + \gamma_3 lnOPU_{t-1} + \gamma_4\ln TI_{t-1} + \gamma_5 lnEI_{t-1} \\ & + \gamma_4\ln FD_{t-1} + \gamma_5 lnFDI_{t-1} + \omega_{1t}\end{aligned} \tag{5}$$

$$\begin{aligned}\Delta lnEF_t = {} & \alpha_0 + \varnothing_1 DMU_t + \sum_{i=1}^{n}\mu_1\Delta lnTPU_{t-i} + \sum_{i=0}^{n}\mu_2\Delta lnEPU_{t-i} \\ & + \sum_{i=0}^{n}\mu_3\Delta\ln OPU_{t-i} + \sum_{i=0}^{n}\mu_4\Delta\ln TI_t + \sum_{i=0}^{n}\mu_5\Delta\ln EI_{t-i} \\ & + + \sum_{i=0}^{n}\mu_4\Delta\ln FD_t + \sum_{i=0}^{n}\mu_5\Delta\ln FDI_{t-i} + \gamma_1 lnTPU_{t-i} \\ & + \gamma_2 lnEPU_{t-1} + \gamma_3 lnOPU_{t-1} + \gamma_4\ln TI_{t-1} + \gamma_5 lnEI_{t-1} \\ & + \gamma_4\ln FD_{t-1} + \gamma_5 lnFDI_{t-1} + \omega_{1t}\end{aligned} \tag{6}$$

Long-run and short-run coefficients with the EKC framework are as follows in Equations 7, 8.

$$\begin{aligned}\Delta lnCO2_t = {} & \alpha_0 + \varnothing_1 DMU_t + \sum_{i=1}^{n}\mu_1\Delta lnTPU_{t-i} + \sum_{i=0}^{n}\mu_2\Delta lnEPU_{t-i} \\ & + \sum_{i=0}^{n}\mu_3\Delta\ln OPU_{t-i} + \sum_{i=0}^{n}\mu_4\Delta\ln TI_t + \sum_{i=0}^{n}\mu_5\Delta\ln EI_{t-i} \\ & + + \sum_{i=0}^{n}\mu_4\Delta\ln FD_t + \sum_{i=0}^{n}\mu_5\Delta\ln FDI_{t-i} + \sum_{i=0}^{n}\mu_5\Delta\ln Y_{t-i} \\ & + \gamma_1 lnY2_{t-i} + \gamma_2 lnEPU_{t-1} + \gamma_3 lnOPU_{t-1} + \gamma_4\ln TI_{t-1} \\ & + \gamma_5 lnEI_{t-1} + \gamma_4\ln FD_{t-1} + \gamma_5 lnFDI_{t-1} + +\gamma_4\ln Y_{t-1} \\ & + \gamma_5 lnY2_{t-1} + \omega_{1t}\end{aligned} \tag{7}$$

$$\begin{aligned}\Delta lnEE_t = {} & \alpha_0 + \varnothing_1 DMU_t + \sum_{i=1}^{n}\mu_1\Delta lnTPU_{t-i} + \sum_{i=0}^{n}\mu_2\Delta lnEPU_{t-i} \\ & + \sum_{i=0}^{n}\mu_3\Delta\ln OPU_{t-i} + \sum_{i=0}^{n}\mu_4\Delta\ln TI_t + \sum_{i=0}^{n}\mu_5\Delta\ln EI_{t-i} \\ & + + \sum_{i=0}^{n}\mu_4\Delta\ln FD_t + \sum_{i=0}^{n}\mu_5\Delta\ln FDI_{t-i} + \sum_{i=0}^{n}\mu_5\Delta\ln Y_{t-i} \\ & + \gamma_1 lnY2_{t-i} + \gamma_2 lnEPU_{t-1} + \gamma_3 lnOPU_{t-1} + \gamma_4\ln TI_{t-1} \\ & + \gamma_5 lnEI_{t-1} + \gamma_4\ln FD_{t-1} + \gamma_5 lnFDI_{t-1} + +\gamma_4\ln Y_{t-1} \\ & + \gamma_5 lnY2_{t-1} + \omega_{1t}\end{aligned} \tag{8}$$

The following equation is to be executed to document the short-run coefficients.

$$\Delta lnCO2_t = \alpha_0 + \varnothing_1 DMU_t + \sum_{i=1}^{n}\mu_1 \Delta lnTPU_{t-i} + \sum_{i=0}^{n}\mu_2 \Delta lnEPU_{t-i} + \sum_{i=0}^{n}\mu_3 \Delta\, ln\, OPU_{t-i} + \sum_{i=0}^{n}\mu_4 \Delta\, ln\, TI_t + \sum_{i=0}^{n}\mu_5 \Delta\, ln\, EI_{t-i} + +\sum_{i=0}^{n}\mu_4 \Delta\, ln\, FD_t + \sum_{i=0}^{n}\mu_5 \Delta\, ln\, FDI_{t-i} + \sum_{i=0}^{n}\mu_5 \Delta\, ln\, Y_{t-i} + +\rho ECT_{t-1} + \omega_{1t}$$

$$\Delta lnEE_t = \alpha_0 + \varnothing_1 DMU_t + \sum_{i=1}^{n}\mu_1 \Delta lnTPU_{t-i} + \sum_{i=0}^{n}\mu_2 \Delta lnEPU_{t-i} + \sum_{i=0}^{n}\mu_3 \Delta\, ln\, OPU_{t-i} + \sum_{i=0}^{n}\mu_4 \Delta\, ln\, TI_t + \sum_{i=0}^{n}\mu_5 \Delta\, ln\, EI_{t-i} + +\sum_{i=0}^{n}\mu_4 \Delta\, ln\, FD_t + \sum_{i=0}^{n}\mu_5 \Delta\, ln\, FDI_{t-i} + \sum_{i=0}^{n}\mu_5 \Delta\, ln\, Y_{t-i} + +\rho ECT_{t-1} + \omega_{1t}$$

This study adopts the NARDL approach, which was developed by Shin et al. (2014) as an asymmetric extension to the standard ARDL model. The NARDL model is designed to capture both short-run and long-run asymmetries in a variable of interest while reserving all merits of the standard ARDL approach, which is dispalayed in Equation 9.

$$CO2_t = \left(\beta^+ EPU^+_{1,t} + \beta^- EPU^-_{1,t}\right) + \left(\beta^+ TPU^+_{1,t} + \beta^- TPU^-_{1,t}\right) + \left(\beta^+ OPU^+_{1,t} + \beta^- OPU^-_{1,t}\right) + \left(\gamma^+ TI^+_{1,t} + \gamma^- TI^-_{1,t}\right) + \left(\beta^+ EI^+_{1,t} + \beta^- EI^-_{1,t}\right) + \delta_i X_t + \varepsilon_t \tag{9}$$

The asymmetric shocks of EPU, TPU, OPU, TI, and EI can be extracted using the following decomposition functions.

$$EPU_t = \sum_{j=1}^{t} EPU^+_j = \sum_{j=1}^{t} max\ (\Delta EPU_{j,0}$$

$$EPU_t = \sum_{j=1}^{t} EPU^-_j = \sum_{j=1}^{t} min\left(\Delta EPU_{j,0}\right)$$

$$TPU_t = \sum_{j=1}^{t} TPU = \sum_{j=1}^{t} max\ (\Delta TPU_{j,0}$$

$$TPU_t = \sum_{j=1}^{t} TPU^-_j = \sum_{j=1}^{t} min\left(\Delta TPU_{j,0}\right)$$

$$OPU_t = \sum_{j=1}^{t} OPU^+_j = \sum_{j=1}^{t} max\ (\Delta OPU_{j,0}$$

$$OPU_t = \sum_{j=1}^{t} OPU^-_j = \sum_{j=1}^{t} min\left(\Delta OPU_{j,0}\right)$$

$$TI_t = \sum_{j=1}^{t} TI^+_j = \sum_{j=1}^{t} max\left(\Delta TI_{j,0}\right)$$

$$TI_t = \sum_{j=1}^{t} TI^-_j = \sum_{j=1}^{t} min\left(\Delta TI_{j,0}\right)$$

$$EI_t = \sum_{j=1}^{t} EI^+_j = \sum_{j=1}^{t} max\left(\Delta EI_{j,0}\right)$$

$$EI_t = \sum_{j=1}^{t} EI^-_j = \sum_{j=1}^{t} min\left(\Delta EI_{j,0}\right)$$

Since the ARDL model estimates short-run (coefficient) and long-run (consistency) when the variables of both I (0) and I (1) order, it was used. This is particularly useful in economic and environment studies where mixed-order integration often occurs. The NARDL approach expands the asymmetric impact from the ARDL framework, thus demonstrating how positive and negative variations of uncertainties and innovations affect climate change in different ways. Asymmetries are particularly relevant in this study due to the characteristics of climate policy and economic shocks.

The Fourier-TY causality tests were developed by Nazlioglu et al. (2016) to compensate for this omission with the extension of the trigonometric term, and the VAR model can be reproduced in the following ways:

$$y_t = \alpha(t) + \beta_1 y_{t-1} + \ldots + \beta_{p+d} y_{t-(p+d)} + \varepsilon t$$

where $\alpha(t)$ Explain the possible structural changes in the dependent variable (y), β_1 stands for the coefficients, and εt stands for the white noise error term in the equation. The above equation can be transformed with Fourier functions to capture the unknown structural changes in the following manner.

$$y_t = \alpha(t) + \beta_1 y_{t-1} + \ldots + \beta_{p+d} y_{t-(p+d)} + \vartheta_1 \sin\frac{2k\pi t}{T} + \vartheta_2 \cos\frac{2k\pi t}{T} + \varepsilon t$$

Where k refers to the frequency, t denotes the time trend, T shows the number of observations, and %_ and %_ measure the amplitude and displacement of the frequency. The null hypothesis for the Fourier–TY test is no causality between variables (H_0: $\beta_1 = \beta_2 \ldots\ldots\ldots\ldots\ldots \beta_p = 0$). This test was performed to identify the causal interactions among economic, trade, and oil price uncertainties, innovation variables, and climate change indicators, considering the behaviour of structural breaks. The Fourier function can capture cyclical variations and structural transformation through time, making it suitable for analyzing long-term environmental and economic interaction.

Estimation and interpretation

Table 2 displays the results of the variables' order of integration by performing the stationary test introduced by (Perron and Vogelsang, 1992) and the ADF test. Following the test statistics, the null of non-stationary was rejected after the first difference operation, which is valid for all variables in all selected nations.

The study implemented the cointegration test following Bayer and Hanck (2013) and maki (Maki, 2012) cointegration, and the results are displayed in Table 3. The test statistics of combined cointegration revealed statistical significance at 5%, establishing the presence of long-run linkage between innovation, uncertainty, and climate change in BRICS nations. According to the test statistics derived with the Makki test, the test statistics are statistically significant in all three circumstances, indicating the confirmation of long-run association.

The study executed a standard Wald test under three environments with the linear and nonlinear framework to document the long-run cointegration. The results of Wald test of $F_{overall,}$ t_{DV}, and F_{IDV} are reported in Table 4 and found to be statistically significant at a 1% level. Thus, it is concluded that long-run relations exist under symmetric and asymmetric evaluation.

TABLE 1 Variables, symbols, measurement units, and data sources.

Variable	Symbol	Measurement unit	Data source
Carbon Emissions	CO_2	Metric tons *per capita*	World Bank, Global Carbon Atlas
Economic Policy Uncertainty	EPU	Index Value (Standardized Score)	Baker, Bloom and Davis EPU Index
Climate Policy Uncertainty	CPU	Index Value (Standardized Score)	Climate Policy Uncertainty Database
Oil Price Uncertainty	OPU	Index Value (Standardized Score)	IMF, Federal Reserve Economic Data (FRED)
Technological Innovation	TI	Patent Counts, R&D Expenditure (% GDP)	World Intellectual Property Organization (WIPO), OECD
Environmental Innovation	EI	Green patents, Eco-Innovation Index	OECD, European Commission
Foreign Direct Investment	FDI	Net Inflows (% of GDP)	World Bank, UNCTAD
Trade Openness	TO	(Exports + Imports)/GDP (%)	World Bank, WTO
Gross Domestic Product	Y	GDP *per capita* (Constant 2010 US$)	World Bank, IMF
Squared GDP	Y^2	GDP *per capita* squared	Calculated from GDP data
Ecological Footprint	EE	Global Hectares per Capita	Global Footprint Network

Once the cointegration has been disclosed in both symmetric and asymmetric frameworks, we move to gauge the elasticities of independent variables on climate change.

The coefficients of TI revealed that they are negatively associated with carbon emission, and fostering TI may improve environmental sustainability (see, Table 5). The validation of TI has beneficial effects in controlling the adverse of climate change through the reduction of CO_2 prevails in BRICS nations and is supported by the existing literature (Chen and Lee, 2020; Rahman et al., 2022; Cheng et al., 2021; Dunyo et al., 2024; Khan et al., 2024). A 10% improvement in TI will reduce CO_2 by 1.452% in Brazil, 1.166% in Russia, 1.745% in India, 1.097% in China, and 1.476% in South Africa, respectively.

Environmental innovation exposed positive towards environmental improvement through the mitigation of CO_2 in BR by 0.1826%, RU by 0.1486%, IND by 0.113%, CHN by 0.0779%, and SA by 0.036% due to 1% changes surrounding the environmental innovation. Our findings align with those offered by (Zhang, 2021; Sarfraz et al., 2022; Geng et al., 2023). Study findings postulate that EI, specifically green innovation, has been recognized as a crucial approach to decreasing environmental deterioration and alleviating the impacts of CO_2 emissions in these countries. Green innovation refers to creating and using eco-friendly technology, goods, and services that minimize the negative effects of economic activity on the environment.

The study found a positive relationship between EPU and CO_2. This means that when there is increased uncertainty in economic policy, it worsens environmental degradation. Specifically, a 10% increase in EPU leads to a 1.095% increase in CO_2 emissions in Brazil, 0.936% in Russia, 0.775% in India, 1.097% in China, and 0.510% in South Africa. These findings align with previous research that emphasizes how uncertainty in economic policy can hinder investment in green technologies and innovation, thus worsening environmental outcomes (Ajami et al., 2008; Wardekker et al., 2012; Narassimhan et al., 2018). This emphasizes the need for stable and predictable economic policies to promote an environment conducive to sustainable development and climate change mitigation in BRICS countries.

The coefficients of TPU positively correlate with CO_2. Specifically, a 10% increase in TPU leads to a 0.977% increase in CO_2 emissions in Brazil, a 1.085% increase in Russia, a 0.339% increase in India, a 0.309% increase in China, and a 0.309% increase in South Africa. These findings indicate that higher levels of trade policy uncertainty contribute to more significant environmental degradation. These results align with previous research [(Bouwer and Aerts, 2006; Mills and Lecomte, 2005; Kuo and Means, 2021)], which suggests that uncertainty in trade policies can disrupt international trade flows and investment in environmentally friendly technologies. Therefore, reducing trade policy uncertainty is crucial for promoting environmental sustainability and reducing carbon emissions in the BRICS nations.

The study found a positive relationship between OPU and CO_2. This means that when there is higher uncertainty in oil prices, it leads to worse environmental outcomes. The research shows that a 10% increase in OPU results in a 0.813% increase in CO_2 emissions in Brazil, 0.801% in Russia, 1.302% in India, 0.850% in China, and 0.433% in South Africa. These findings are consistent with previous studies [(Lerch, 2017; Su et al., 2021; Wang et al., 2022)] that suggest that uncertainty in oil prices can cause volatility in energy markets, thereby affecting investment in renewable energy and green technologies. As oil price uncertainty increases, countries may rely more on fossil fuels, worsening environmental degradation. Hence, reducing oil price uncertainty is critical for promoting investment in clean energy and sustainable environmental practices in BRICS countries.

The coefficients for Y indicate a positive relationship with carbon emissions, suggesting that as income increases, so do carbon emissions. Specifically, a 10% increase in income leads to a 0.926% increase in CO_2 emissions in Brazil, 0.157% in Russia, 0.709% in India, 0.364% in China, and 0.291% in South Africa. This finding supports the initial phase of the EKC hypothesis, which suggests that economic growth is initially associated with higher emissions due to increased industrial activity and energy consumption. However, as economies develop, the Y2 coefficients negatively affect carbon emissions, indicating that economic growth leads to reduced environmental degradation at higher income levels.

TABLE 2 Results of unit root test.

Variables	Perron and vogelsang test				ADF test	
	First difference		After the first diff		First difference	After the first diff
Level	Test Statistics	D-SB	Test Statistics	D-SB	Test Statistics	Test Statistics
For Brazil						
CO2	−0.797	2005	−10.3862	2002	−0.8196	−4.5807
EE	−2.674	1996	−9.0067	2007	−2.8684	−5.6119
EPU	−0.1914	2004	−10.5167	2001	−1.3423	−6.8758
TPU	−0.5225	2006	−6.6039	2012	−2.401	−8.998
OPU	−0.5442	1994	−6.1347	2016	−1.6906	−7.6005
TI	−0.6566	2008	−9.6828	2011	−1.0732	−8.925
EI	−2.0692	2000	−8.5106	2019	−0.5703	−5.2281
FD	−1.4814	2017	−9.899	2016	−1.7598	−7.8844
FDI	−0.3747	2003	−8.0433	2008	−0.7707	−5.7755
Y	−1.7572	2010	−10.0554	2019	−0.8349	−7.7255
For Russia						
CO2	−1.122	1995	−8.5406	2019	−1.8259	−7.6733
EE	−2.0171	2001	−10.1774	2002	−1.0734	−8.692
EPU	−2.7952	2018	−7.3505	2011	−2.7697	−6.1821
TPU	−1.269	2006	−9.9373	2002	−1.8627	−7.6016
OPU	−0.2833	2007	−7.7298	2003	−0.0602	−3.9411
TI	−2.7623	2006	−6.3798	2011	−0.7845	−6.4263
EI	−1.5263	2019	−9.711	2011	−1.5183	−3.3799
FDI	−1.2389	2003	−9.291	2009	−2.6401	−4.3724
FDI	−2.839	2001	−8.4496	2000	−2.8474	−7.2888
Y	−0.0072	2016	−8.1012	2010	−0.9905	−8.0108
For India						
CO2	−0.7967	2007	−7.1614	1997	−2.9503	−5.0511
EE	−1.3521	2008	−7.7311	2003	−2.0257	−3.2029
EPU	−2.6424	2007	−7.301	2009	−0.9222	−4.6556
TPU	−2.0361	2020	−7.4166	2018	−0.6328	−5.8976
OPU	−2.3624	1998	−10.3867	1994	−1.9533	−7.6376
TI	−2.3882	1999	−9.5616	2006	−0.4253	−6.5599
EI	−0.0513	1994	−9.0301	2001	−0.9797	−5.5046
FDI	−2.0068	2011	−10.9299	1999	−0.4586	−3.6748
FDI	−2.9048	2009	−8.3519	2010	−1.5341	−4.213
Y	−2.4282	2000	−10.9227	2006	−0.233	−3.1984
For China						
CO2	−1.0788	2019	−10.8886	2017	−1.786	−5.0434
EE	−1.6214	2005	−10.0444	2013	−1.8177	−6.4614

(Continued on following page)

TABLE 2 (*Continued*) Results of unit root test.

Variables	Perron and vogelsang test				ADF test	
	First difference		After the first diff		First difference	After the first diff
Level	Test Statistics	D-SB	Test Statistics	D-SB	Test Statistics	Test Statistics
EPU	−1.3022	1995	−6.8422	2004	−1.8133	−8.7204
TPU	−2.3188	2003	−9.19	2002	−0.0187	−8.9902
OPU	−0.3161	2000	−8.8241	2007	−2.7516	−7.8311
TI	−2.9551	2021	−6.7074	2012	−1.8387	−6.2408
EI	−1.0135	2010	−6.7883	2011	−2.7857	−7.1301
FDI	−2.7753	2001	−7.9945	2019	−2.2075	−7.8158
FDI	−0.0077	1995	−6.7054	2004	−0.7267	−4.6996
Y	−1.7199	2018	−6.7037	2000	−0.8514	−7.9475
For south Africa						
CO2	−0.5179	2012	−7.7809	2012	−0.7138	−8.3443
EE	−1.5673	2012	−8.9527	2007	−1.7849	−8.6117
EPU	−1.9318	1999	−9.352	2009	−1.5179	−6.4443
TPU	−2.4399	2009	−10.8476	2008	−2.7405	−4.7212
OPU	−2.4096	2008	−6.8787	1997	−0.996	−3.4376
TI	−0.2967	2008	−9.1027	2018	−0.5734	−7.0096
EI	−1.6714	2011	−7.7122	1998	−1.7304	−7.6093
FDI	−0.0482	2010	−9.7164	2010	−0.6713	−3.1449
FDI	−2.2711	2012	−6.2923	2016	−2.0376	−6.9998
Y	−1.4643	2004	−10.9317	2011	−2.2877	−4.4685

This is likely due to expanded investment in cleaner technologies and stricter environmental regulations. This transition underscores the importance of sustainable economic policies and green investments to offset economic growth with environmental preservation in BRICS countries (Wang et al., 2018; Ulucak and Danish, 2024).

The coefficients for Y^2 indicate a negative relationship with carbon emissions, suggesting that as income levels increase beyond a certain point, there is a decrease in carbon emissions. Specifically, a 10% increase in the squared term of income leads to a reduction of CO_2 emissions by 0.228% in Brazil, 0.403% in Russia, 0.805% in India, 0.592% in China, and 1.048% in South Africa. These findings support the latter phase of the EKC hypothesis, which suggests that countries experience a decline in environmental degradation after reaching a certain level of economic growth (Zhou et al., 2019; Kor and Qamruzzaman, 2024). This decline can be attributed to increased public awareness, better environmental regulations, and investments in green technologies and sustainable practices. These results corroborate these results, emphasizing that economic development eventually leads to more resources being allocated toward reducing emissions and enhancing environmental quality. Consequently, policies promoting sustainable economic growth can help BRICS nations balance economic development and environmental sustainability.

Following the nonlinear framework introduced by Shin, the present study has implemented the empirical investigation with the asymmetric decomposition of TI, EI, EPU, OPU, and TPU., Table 6 displayed the results of asymmetric long-run coefficients (see panel–A), short-run coefficient (see panel–B), and residual diagnostic test in Panel C, respectively.

For technological innovation, the asymmetric coefficients of TI that are a positive (negative) shock revealed a negative tie with CO_2 emission in BRICS in the long-run and short-run duration. Study findings suggest that augmentation (contraction) in TI results in lessening (surging) of CO_2 injection in the ecosystem, implying that fostering the TI in the national innovation system can assist in achieving environmental sustainability both in the long-run and short-run. It is supported by the study of (Udeagha and Ngepah, 2022; Adebayo et al., 2023). For environmental innovation, the asymmetric coefficients of EI, representing positive and adverse shocks, exhibit a significant negative association with CO_2 emissions in BRICS nations, both in the long-run and short-run duration. The study findings indicate that an increase (decrease) in environmental innovation leads to a decrease (increase) in CO_2 emissions. This indicates that stimulating environmental innovation within the national innovation system can be crucial in achieving environmental sustainability. This assertion is supported by previous studies (Mhatre et al., 2021; Cooke, 2011; Kandpal et al., 2024).

TABLE 3 Combined cointegration test.

Test statisitcs		Brazil	Russia	India	China	SA	Brazil	Russia	India	China	SA	CV
EG-JOH	1	11.232	14.568	14.193	13.745	11.738	12.503	14.704	12.398	11.912	13.467	11.229
	2	11.157	11.091	11.172	10.974	11.091	11.046	11.01	11.052	11.124	10.962	10.895
	3	11.299	10.783	11.317	10.782	10.981	11.389	11.261	11.398	10.944	10.727	10.637
	4	10.725	10.789	10.992	10.897	10.857	10.993	10.831	10.935	10.99	10.922	10.576
	5	10.562	10.602	10.559	10.594	10.72	10.551	10.717	10.534	10.688	10.59	10.419
EG-JOH-BO-BDM	1	38.264	34.352	34.032	31.265	26.219	28.889	37.202	33.597	32.278	35.527	21.931
	2	23.006	26.288	24.624	24.697	29.399	25.775	28.952	29.378	25.189	26.021	21.106
	3	22.275	24.071	23.721	23.409	22.328	22.185	22.991	22.581	23.692	22.563	20.486
	4	21.468	21.652	21.208	21.944	21.75	22.277	21.217	21.204	22.235	21.725	20.143
	5	20.886	20.873	20.856	20.934	20.895	20.951	20.876	20.897	20.938	20.946	19.888

Panel B: Maki Cointegration with structural Break		
For Brazil		
Model	Model [1]	Model [2]
Level shift with Trend	−9.6832 [2001:2002:2008]	−7.6798 [1994:2002:2013]
Regime shifts	−12.7351 [2000:2001:2007]	−13.4773 [2000:2008:2013]
Regime Shifts with Trend	−10.4053 [1995:2007:2019]	−16.7942 [2002:2000:2019]
For Russia		
Model	test Statistics	Break Year
Level shift with Trend	−9.4004 [1997:2008:2019]	−9.3783 [1998:2008:2011]
Regim shifts	−11.1194 [1992:2002:2016]	−11.7017 [1996:2007:2008]
Regim Shifts with Trend	−13.6684 [1991:2007:2019]	−14.1025 [1995:2003:2013]
For India		
Model	test Statistics	Break Year
Level shift with Trend	−9.3925 [2001:2007:2012]	−7.066 [1993:2008:2006]
Regim shifts	−12.6235 [1995:2004:2019]	−9.5436 [2003:2001:2009]
Regim Shifts with Trend	−15.3779 [1999:2009:2008]	−11.6442 [2001:2001:2008]
For China		
Model	test Statistics	Break Year
Level shift with Trend	−7.6952 [1992:2002:2010]	−9.4369 [1992:2006:2005]
Regim shifts	−13.6476 [1993:1999:2018]	−10.2527 [1998:2009:2019]
Regim Shifts with Trend	−12.7798 [2002:2003:2014]	−18.6923 [2004:2001:2010]
For South Africa		
Model	test Statistics	Break Year
Level shift with Trend	−7.3029 [1996:2003:2015]	−8.5482 [2001:2006:2018]
Regim shifts	−10.9421 [1998:2005:2019]	−10.2834 [2003:2004:2005]
Regim Shifts with Trend	−17.4475 [1996:2000:2012]	−14.0351 [2002:2005:2009]

TABLE 4 Long-run cointegration under linear and nonlinear framework.

Model		Brazil	Russia	India	China	SA
Linear framework	$F_{overall}$	8.057***	12.615***	13.857***	11.674***	10.889***
	t_{DV}	−5.921***	−5.216***	−7.08***	−4.833***	−5.859***
	F_{IDV}	8.573***	8.802***	7.719***	9.165***	10.472***
Nonlinear framework	$F_{overall}$	12.092***	9.16***	11.724***	9.669***	12.577***
	t_{DV}	−6.371***	−5.387***	−5.645***	−5.865***	−6.597***
	F_{IDV}	6.483***	12.077***	6.587***	10.653***	8.866***

TABLE 5 Result of augmented ARDL estimation.

	Brazil	Russia	India	China	SA
Panel – A: long-run coefficients					
TI	−0.1452 (0.0056) [-25.7847]	−0.1166 (0.0081) [-14.4017]	−0.1745 (0.0091) [-19.0277]	−0.1097 (0.0068) [-15.9556]	−0.1476 (0.0109) [-13.4311]
EI	−0.1826 (0.0043) [42.3798]	−0.1486 (0.0072) [-20.4658]	−0.113 (0.0049) [-22.8375]	−0.0779 (0.0051) [-14.9916]	−0.036 (0.0032) [-11.2305]
EPU	0.1095 (0.0066) [16.5034]	0.0936 (0.0114) [8.2072]	0.0775 (0.0073) [10.6024]	0.1097 (0.0032) [33.9216]	0.051 (0.0031) [16.1647]
TPU	0.0977 (0.0033) [29.3276]	0.1085 (0.0035) [30.4418]	0.0339 (0.0115) [2.9297]	0.0309 (0.0069) [4.4368]	0.0309 (0.0065) [4.739]
OPU	0.0813 (0.0084) [9.6155]	0.0801 (0.0058) [13.7864]	0.1302 (0.008) [16.1415]	0.085 (0.011) [7.6658]	0.0433 (0.0044) [9.7]
Y	0.0926 (0.0077) [11.9173]	0.0157 (0.0026) [5.9078]	0.0709 (0.0039) [17.8692]	0.0364 (0.0064) [5.6317]	0.0291 (0.0063) [4.585]
Y2	−0.0228 (0.0072) [-3.1658]	−0.0403 (0.0091) [-4.4273]	−0.0805 (0.0054) [-14.807]	−0.0592 (0.0075) [-7.8008]	−0.1048 (0.0115) [-9.0593]
Panel – B: short-run coefficients					
ΔTI	−0.048 (0.0107) [-4.4859]	−0.0176 (0.0075) [-2.3466]	−0.0173 (0.0095) [-1.821]	−0.0554 (0.0025) [-22.161]	−0.0308 (0.009) [-3.4222]
ΔEI	−0.0577 (0.0116) [-4.9741]	−0.0707 (0.0068) [-10.397]	−0.0556 (0.0063) [-8.8253]	−0.0231 (0.0063) [-3.6666]	−0.0247 (0.0053) [-4.6603]
ΔEPU	0.0593 (0.0054) [10.9814]	0.0467 (0.0095) [4.9157]	0.0444 (0.002) [22.2112]	0.0439 (0.0023) [19.0869]	0.0517 (0.0113) [4.5752]
ΔTPU	0.0117 (0.0047) [2.4893]	0.0562 (0.0104) [5.4038]	0.0325 (0.0026) [12.5033]	0.0629 (0.004) [15.725]	0.0701 (0.0036) [19.4722]
ΔOPU	0.0589 (0.0085) [6.9294]	0.0222 (0.0111) [2]	0.0387 (0.0055) [7.0363]	0.0682 (0.0063) [10.8253]	0.0607 (0.0053) [11.4528]
ΔY	0.0168 (0.0063) [2.6666]	0.0116 (0.0034) [3.4117]	0.0704 (0.003) [23.4666]	0.0157 (0.0079) [2.0137]	0.0439 (0.0099) [4.4343]
ΔY2	0.0296 (0.0116) [2.5517]	0.0679 (0.0077) [8.8181]	0.0548 (0.0088) [6.2272]	0.0198 (0.0035) [5.6571]	0.0492 (0.0073) [6.7397]
ECT (−1)	−0.6229 (0.0931) [-6.6915]	−0.1517 (0.1489) [-1.0193]	−0.5473 (0.1023) [-5.3505]	−0.5468 (0.1543) [-3.5442]	−0.1439 (0.1616) [-0.8905]
Panel – C: Residual Diagnostics test					
x^2_{Auto}	0.852	0.797	0.805	0.836	0.529
x^2_{Het}	0.574	0.641	0.758	0.604	0.709
x^2_{Nor}	0.561	0.568	0.786	0.531	0.715
x^2_{RESET}	0.805	0.863	0.881	0.887	0.89

In the case of economic policy uncertainty, the asymmetric coefficients of EPU indicate a positive (negative) tie with CO_2 emissions in BRICS nations, observed in both the long-run and short-run duration. The study findings suggest that higher (lower) economic policy uncertainty contributes to an increase (decrease) in CO_2 emissions, stressing the importance of reducing economic policy uncertainty to achieve environmental sustainability. These findings align with previous research (Wardekker et al., 2012; Narassimhan et al., 2018). Regarding trade policy uncertainty, the asymmetric coefficients of TPU reveal a positive (negative) association with CO_2 emissions in BRICS nations, both in the long-run and short-run duration. The study findings imply that increased (decreased) trade policy uncertainty leads to higher (lower) CO_2 emissions, highlighting the need for stable trade policies to promote environmental sustainability. This

TABLE 6 Results of the asymmetric investigation.

	Brazil	Russia	India	China	SA
TI^+	−0.1364 (0.0113) [11.9715]	−0.1176 (0.0028) [40.6405]	−0.1219 (0.0118) [10.2652]	−0.111 (0.0105) [-10.519]	−0.189 (0.0094) [19.9935]
TI^-	−0.0614 (0.0031) [-19.3632]	−0.0804 (0.0055) [-14.5079]	−0.021 (0.0114) [1.8437]	−0.1536 (0.0035) [-43.8789]	−0.0282 (0.0054) [-5.1367]
EI^+	−0.133 (0.0085) [-15.6273]	0.0457 (0.0109) [4.1801]	0.1144 (0.0025) [44.1038]	0.0836 (0.0083) [9.9791]	0.0768 (0.0067) [11.4075]
EI^-	0.0859 (0.0041) [20.4826]	0.1262 (0.0095) [13.2609]	0.1315 (0.0074) [17.7584]	0.078 (0.0105) [7.431]	0.1223 (0.0091) [13.3909]
EPU^+	0.0984 (0.0096) [10.1488]	0.0923 (0.0084) [10.9439]	0.0535 (0.0045) [11.7529]	0.1038 (0.007) [14.6598]	0.0822 (0.0021) [38.7021]
EPU^-	0.049 (0.0105) [4.6603]	0.0609 (0.0046) [13.1428]	0.039 (0.0117) [3.3308]	0.0685 (0.0043) [15.7621]	0.026 (0.0078) [3.3128]
TPU^+	0.0923 (0.0074) [12.4446]	0.089 (0.0078) [11.3858]	0.0581 (0.0022) [25.342]	0.0873 (0.0026) [33.2363]	0.0223 (0.0103) [2.163]
TPU^-	0.044 (0.0042) [10.2704]	0.0689 (0.0101) [6.8062]	0.0914 (0.0029) [30.9634]	0.0298 (0.0068) [4.3534]	0.0504 (0.0075) [6.7097]
OPU^+	0.0395 (0.0058) [6.795]	0.042 (0.0044) [9.5056]	0.0374 (0.0111) [3.3627]	0.0159 (0.0064) [2.4618]	0.0198 (0.0061 [3.2024]
OPU^-	0.0986 (0.0076) [12.9408]	0.0446 (0.0037) [11.9764]	0.0799 (0.0024) [32.7726]	0.0799 (0.0024) [32.7726]	0.1068 (0.0054) [19.6645]
Panel – B: short-run coefficients					
ΔTI^+	−0.0154 (0.0053) [-2.9056]	−0.0398 (0.0037) [-10.7567]	−0.0428 (0.0047) [-9.1063]	−0.0701 (0.0117) [-5.9914]	−0.0124 (0.0035) [-3.5428]
ΔTI^-	−0.054 (0.0077) [-7.0129]	−0.0503 (0.0118) [-4.2627]	−0.0468 (0.0046) [-10.1739]	−0.0258 (0.0058) [-4.4482]	−0.0183 (0.0058) [-3.1551]
EI^+	0.0526 (0.0089) [5.9101]	0.041 (0.0023) [17.826]	0.0259 (0.0101) [2.5643]	0.0587 (0.0069) [8.5072]	0.0328 (0.0051) [6.4313]
EI^-	0.0623 (0.0089) [7]	0.0664 (0.011) [6.0363]	0.0667 (0.0099) [6.7373]	0.0456 (0.0044) [10.3636]	0.0333 (0.0093) [3.5806]
EPU^+	0.0566 (0.003) [18.8666]	0.0264 (0.0115) [2.2956]	0.0095 (0.0037) [2.5675]	0.0641 (0.0115) [5.5739]	0.0441 (0.0076) [5.8026]
EPU^-	0.07 (0.0104) [6.7307]	0.0387 (0.0038) [10.1842]	0.0294 (0.0068) [4.3235]	0.0569 (0.0077) [7.3896]	0.0078 (0.0033) [2.3636]
TPU^+	0.0368 (0.0036) [10.2222]	0.0212 (0.003) [7.0666]	0.0495 (0.0063) [7.8571]	0.0185 (0.0032) [5.7812]	0.023 (0.0026) [8.8461]
TPU^-	0.0644 (0.0067) [9.6119]	0.0669 (0.0091) [7.3516]	0.0644 (0.0025) [25.76]	0.0529 (0.0107) [4.9439]	0.0664 (0.0079) [8.405]
OPU^+	0.0411 (0.0082) [5.0121]	0.0366 (0.007) [5.2285]	0.0251 (0.0054) [4.6481]	0.0196 (0.0117) [1.6752]	0.0476 (0.004) [11.911]
OPU^-	0.0326 (0.0109) [2.9908]	0.0557 (0.0028) [19.8928]	0.0506 (0.0062) [8.1612]	0.0664 (0.005) [13.285]	0.0629 (0.0027) [23.2962]
ECT (-1)	−0.7061 (0.0948) [-7.4483]	−0.2683 (0.1153) [-2.3274]	−0.5212 (0.1763) [-2.9568]	−0.4342 (0.154) [-2.8195]	−0.2399 (0.0881) [-2.7232]
Panel C: Residual Diagnostics test					
x^2_{Auto}	0.841	0.576	0.568	0.679	0.597
x^2_{Het}	0.552	0.882	0.628	0.846	0.822
x^2_{Nor}	0.877	0.888	0.713	0.758	0.708
x^2_{RESET}	0.491	0.709	0.864	0.814	0.628

conclusion is consistent with prior studies (Mills and Lecomte, 2005; Kuo and Means, 2021). For oil price uncertainty, the asymmetric coefficients of OPU demonstrate a positive (negative) link with CO_2 emissions in BRICS nations, followed in both the long-run and short-run duration. The study findings recommend that higher (lower) oil price uncertainty contributes to increased (decreased) CO_2 emissions, emphasizing the importance of stable oil prices in achieving environmental sustainability. This conclusion is supported by existing research (Lerch, 2017; Su et al., 2021).

The following section assesses asymmetric linkage by executing a standard Wald test with a null of "symmetry." Table 7 reported the test statistics derived from the Wald test and revealed statistical significance at a 1% level, indicating the presence of asymmetric linkages between independent variables and climate changes.

Table 8 displays the results of the Fourier TY causality test, which investigates the causal relationships between different variables in BRICS nations.

CO_2 emissions Granger cause EPU, TPU, and TI in the long run, suggesting that changes in CO_2 emissions precede changes in these variables. EPU Granger causes CO_2 emissions in both the short and long run, indicating a causal relationship between economic policy uncertainty and CO_2 emissions. TPU Granger causes CO_2 emissions in the short run but not in the long run. OPU does not show a significant causal relationship with CO_2 emissions. TI and EI Granger cause CO_2 emissions in both the short and long run, indicating that technological and environmental innovation advancements affect CO_2 emissions. These results suggest significant causal relationships exist between economic policy uncertainty, trade policy uncertainty, technological innovation,

TABLE 7 Results of long-run and short-run symmetry test.

	Brazil	Russia	India	China	SA
W_{LR}^{EPU}	13.509***	3.487***	8.284***	4.121***	5.962***
W_{LR}^{TPU}	4.416***	3.787***	6.048***	3.403***	2.788***
W_{LR}^{OPU}	6.786***	11.075***	3.221***	6.702***	3.256***
W_{LR}^{TI}	6.833***	4.695***	2.781***	9.392***	7.536***
W_{LR}^{EI}	2.597***	4.276***	7.955***	10.055***	10.208***
W_{SR}^{EPU}	12.803***	7.301***	9.641***	13.744***	12.001***
W_{SR}^{TPU}	7.561***	11.648***	7.336***	7.664***	5.384***
W_{SR}^{OPU}	12.897***	2.653***	12.726***	3.426***	8.916***
W_{SR}^{TI}	12.784***	7.532***	12.104***	7.541***	9.653***
W_{SR}^{EI}	12.202***	12.517***	11.874***	11.773***	13.208***

environmental innovation, and CO_2 emissions in BRICS nations. Notably, changes in economic policy uncertainty and technological and environmental innovation advancements precede changes in CO_2 emissions. These findings highlight the importance of policy measures and innovation strategies in addressing environmental challenges and promoting sustainability in BRICS nations.

Discussion

The study's findings reveal a noteworthy correlation between EPU and the levels of CO_2 emissions and ecological footprint in BRICS nations. It can be inferred that heightened uncertainty in economic policy tends to worsen environmental degradation. Given the increasing uncertainty surrounding economic policies, it is likely that firms and investors will choose to postpone or scale back their investments in sustainable practices and green technologies, which, unfortunately, will result in a rise in CO_2 emissions and a significant expansion of our ecological footprint. This correlation supports previous research that has established a connection between EPU and adverse environmental consequences (Cui et al., 2024; Dauda et al., 2019; Farooq et al., 2023). Studies have demonstrated, for instance (Li et al., 2024; Makki and Somwaru, 2004; Pinninti, 2013; Selmey and Elamer, 2023), that in times of economic uncertainty, companies may place greater emphasis on immediate profits rather than long-term sustainability, which often leads to a greater dependence on carbon-intensive practices and a decrease in investments towards environmentally friendly technologies. In a study conducted by Wu et al. (2024), it was discovered that uncertainty harms investments in green technologies and inhibits innovation in environmental sustainability. This, in turn, contributes to increased environmental degradation. The findings of this research shed light on the importance of addressing uncertainty to promote a more sustainable future. On the other hand, the literature presents a different perspective, indicating that the connection between EPU and environmental outcomes may not always be negative. It has been suggested that EPU may result in more rigorous environmental regulations as governments strive to stabilize the economy by adopting stricter environmental policies. This can potentially decrease CO_2 emissions and significantly minimize the ecological footprint. Nevertheless, in the case of BRICS nations, the study's findings indicate a significant negative effect of EPU on environmental sustainability (Degirmenci et al., 2024).

The study results revealed that TPU is a significant factor related to environmental degradation regarding CO_2 emissions and ecological footprint in BRICS countries. Our analysis from an EKC perspective suggests that CO_2 emissions increase with increases in TPU throughout these nations, demonstrating additional environmental devastation due to heightened uncertainty in trade policies (Ayad et al., 2023a). Literature (Sadiq et al., 2024; Zhang et al., 2023; Aydin et al., 2024) established that the uncertainties surrounding trade policy impede international trade flows and reduce incentives for investment in green technologies or sustainable practices. Investors and firms will be less willing to invest in capital-heavy projects—such as those supporting green technology, many of which need relatively predictable policy environments for success, which leads to even more dependence on traditional and dirtier technologies and fuels, leading to a growth in emissions of CO_2. However, the uncertainty in the trade environment makes economic agents opt for short-term gains over longer-term sustainability, due to which resource allocation burden creates inefficiencies because of high TPU. These can lead to higher emissions in the short run, as cost-cutting measures (like those pursued during a recession) presented themselves more cheaply than aver them e mission energy sources. Moreover, uncertainty in trade policies can curtail international cooperation on environmental criteria since countries are less likely to increase their regulations without guaranteeing similar actions from trading partners.

The study's finding emphasizes the crucial role of TI in mitigating carbon dioxide (CO_2) emissions in the BRICS nations. Based on the analysis, it is evident that a positive shock in TI has a significant negative effect on CO_2 emissions, both in the long-run and short-run durations. On the other hand, a negative shock in TI is associated with a rise in CO_2 emissions. Based on the data, it can be inferred that changes in TI directly impact CO_2 emissions. Specifically, when TI is increased, there is a noticeable decrease in CO_2 emissions. Conversely, when TI is decreased, CO_2 emissions tend to increase. Furthermore, the study's findings suggest that promoting technological innovation within the national innovation system can be crucial in achieving short-term and long-term environmental sustainability. This is of utmost significance for the BRICS nations, as they are undergoing rapid economic expansion and industrial development. Consequently, their energy consumption and CO_2 emissions have witnessed a substantial rise. By fostering technological advancements, these countries have the potential to decrease their dependence on fossil fuels and shift towards more sustainable energy sources. This transition would help alleviate the detrimental effects of CO_2 emissions on the environment. The study's findings align with prior research that highlights the critical importance of technological innovation in mitigating environmental degradation and fostering sustainable development see for instance (Khan et al., 2024; Adebayo et al., 2023; Udeagha and Ngepah, 2022; Cheng et al., 2021; Chen and Lee, 2020). As per a study published in the esteemed journal Nature, it has been observed that technological innovation plays a crucial role in bringing about immediate reductions in CO_2 emissions by promoting cleaner technologies (Zhang, 2021; Tan and Cao, 2023). In another study, the significance of technological innovation in mitigating carbon emissions in China and Brazil was emphasized (Junsheng et al., 2024).

TABLE 8 Fourier TY causality test.

	CO2	EPU	TPU	OPU	TI	EI
Panel; A: for Brazil						
CO2		11.195***	4.877*	6.357**	1.475	7.287**
EPU	2.461		3.516	10.899***	7.216**	0.75
TPU	0.698	5.532*		5.369*	4.796*	3.487
OPU	3.342	1.767	5.97*		3.339	4.37*
TI	3.682	3.407	8.234***	10.627***		11.774***
EI	7.414**	6.395**	7.667**	8.974***	11.269***	
Panel; B: for Russia						
CO2		4.658*	8.756***	0.401	11.361***	5.179*
EPU	2.221		3.263	4.777*	7.31**	5.5*
TPU	11.045***	2.111		4.637*	8.558***	4.679*
OPU	5.902*	6.564**	12.235***		9.057***	9.368***
TI	9.762***	6.52**	4.315*	11.756***		8.889***
EI	8.697***	7.664**	11.208***	3.924	1.189	
Panel C: for India						
CO2	0	6.245*	5.162	1.123	6.76*	11.39***
EPU	7.677*	0	6.947*	8.659**	2.177	6.405*
TPU	11.995***	2.261	0	5.899	5.332	3.475
OPU	6.206*	1.603	3.299	0	9.492**	0.532
TI	7.654*	1.113	10.513***	7.585*	0	11.489***
EI	4.076	0.719	11.752***	3.489	10.76***	0
Panel D: for China						
CO2	0	11.526***	2.738	0.677	4.364	7.279*
EPU	10.673***	0	3.521	1.001	8.148**	6.014*
TPU	10.223***	1.985	0	5.871	3.114	10.575***
OPU	3.293	7.34*	2.323	0	11.972***	8.887**
TI	5.48	8.246**	8**	7.267*	0	1.994
EI	4.294	11.212***	4.926	9.261**	4.384	0
Panel E: for South Africa						
CO2	0	2.033	10.703***	8.215**	11.885***	6.579*
EPU	0.722	0	11.478***	3.101	1.347	1.313
TPU	7.703*	7.728*	0	9.031**	11.213***	10.15***
OPU	9.342**	10.769***	3.071	0	4.887	3.588
TI	4.759	6.088*	8.646**	3.356	0	9.689**
EI	7.158*	11.284***	9.724**	4.439	8.023**	0

TI has been one of the prime drivers of environmental sustainability among the BRICS nations. The member nations exhibit rapid economic growth and industrialization, with the balance between development and the environment remaining a key challenge (Huang, 2024; Shabir et al., 2023). However, the adverse impacts of economic activities on the ecosystem can be absorbed and offset to some extent by strategic uses of technological innovations. One of the most identifiable ways technological innovations have promoted environmental sustainability is the development and adoption of clean energy technology. BRICS countries have substantially invested a lot in other sources of energy apart from fossil, such as solar, wind, and hydropower, to lower carbon emissions (Mngumi et al., 2024). For instance, China has emerged as the global leader in solar power and has the largest ever-installed capacity for solar power in the world. For instance, India has ambitions to increase its renewable capacity and target 450 GW by 2030. This will reduce greenhouse gas emissions and create new workforces in the green energy sector, hence sustainable economic growth. Innovative technological dimensions in energy use, waste management, and water treatment can singly subdue the ecological footprints of the BRICS countries.

The BRICS nations play a crucial role in global greenhouse gas emissions due to their rapid economic expansion and industrial development. Environmental innovation, especially green innovation, has been recognized as a crucial strategy for addressing environmental degradation and minimizing the impact of CO_2 emissions in these countries. Green innovation involves creating and applying eco-friendly technologies, products, and services that aim to minimize the environmental consequences of economic activities (Agboola et al., 2022; Li et al., 2022). Research has demonstrated that the implementation of green innovation has the potential to decrease significantly CO_2 emissions, which can be achieved through the promotion of renewable energy sources, the enhancement of energy efficiency, and the reduction of dependence on fossil fuels (Gebert and de Mello-Sampayo, 2024). The study by Usman et al. (2021) stated that incorporating renewable energy sources like solar and wind power can greatly diminish our reliance on fossil fuels, leading to a substantial decrease in CO_2 emissions. In addition, green innovation has the potential to drive sustainable development by generating fresh economic prospects and employment in the clean energy industry. This, in turn, can help alleviate poverty and enhance living standards (Dutz and Sharma, 2012). This is of utmost significance for the BRICS nations, where the swift expansion of their economies has frequently resulted in the deterioration of the environment (Sadiq et al., 2022). Nevertheless, the efficacy of environmental innovation in addressing the impact of CO_2 emissions on environmental degradation in BRICS nations is not devoid of obstacles. The BRICS nations encounter notable obstacles when it comes to embracing green technologies. These challenges include substantial initial expenses, inadequate infrastructure, and restricted funding availability (Khattak et al., 2021). In addition, the BRICS nations exhibit different levels of dedication to environmental preservation, which can influence the efficacy of environmental advancements in mitigating CO_2 emissions (Sarfraz et al., 2021). For example, certain BRICS nations, like China, have made remarkable progress in reducing their carbon footprint by adopting green technologies and implementing effective policies. However, other nations, such as India, continue to encounter significant obstacles in this area (Miranda et al., 2021; Degirmenci and Aydin, 2024).

Conclusion and policy suggestions

Conclusion

This study investigated the nexus between technological innovation, CO2 emissions, and environmental sustainability in the BRICS nations: Brazil, Russia, India, China, and South Africa. Through comprehensive analysis and interpretation of empirical data, several key findings have emerged, shedding light on the crucial role of technological innovation in mitigating CO_2 emissions and advancing environmental sustainability within these dynamic economies. Our investigation demonstrated significant negative associations between TI and CO_2 emissions across the BRICS nations. Through both long-run and short-run analyses, it became apparent that advancements in technological innovation are inversely correlated with CO_2 emissions, indicating that augmentations in technological innovation lead to reductions in CO_2 emissions. This finding underscores the importance of promoting technological innovation as a strategic approach to addressing environmental challenges and achieving sustainability objectives. Additionally, our study uncovered similar EI trends, with positive associations observed between EI and environmental improvement, as evidenced by reductions in CO_2 emissions across the BRICS nations, which indicates that investments in environmental innovation, particularly in green technologies and practices, are instrumental in curbing CO_2 emissions and fostering environmental sustainability. These findings align with existing literature and underscore the critical role of innovation in shaping environmental outcomes. Likewise, the EPU, TPU, and OPU analysis revealed subtle relationships with CO_2 emissions across the BRICS nations. While EPU demonstrated significant positive associations with CO_2 emissions, TPU exhibited mixed results, influencing CO_2 emissions in the short run but not consistently in the long run. OPU, on the other hand, did not show significant causal relationships with CO_2 emissions, highlighting the need for targeted policy interventions in these areas to address environmental challenges effectively. Drawing from these key findings, it becomes apparent that technological innovation holds immense potential for reducing CO_2 emissions and advancing environmental sustainability in the BRICS nations. By facilitating investments in research and development, fostering collaboration between public and private sectors, and implementing supportive policy frameworks, governments in these nations can harness the power of innovation to drive meaningful progress towards sustainability goals.

Policy suggestion

Instead of depending only on theoretical debates about technological and environmental advances, the BRICS states should adopt tangible policy actions to implement the suggestions.

First, the BRICS states must develop and adopt a national innovation plan incorporating technical and environmental advances with clear implementation frameworks. These plans should include measurable goals, financial incentives supported by the government, and stringent compliance monitoring. Carbon capture, renewable energy, and energy efficiency are all examples of green technologies that may benefit from a specialized budget. To help bring environmentally friendly ideas to market, public-private partnerships (PPPs) should be promoted.

Second, in order to encourage investment in sustainable practices and lessen policy uncertainty, regulatory frameworks should be enhanced. For companies' long-term survival, governments should enact legally enforceable climate laws. The regulatory approval procedures for clean technology can be made more efficient, green investments can be taxed, and companies that produce too much carbon may be penalized. The member states of the BRICS may provide market-based incentives for long-term economic development by charging carbon prices and reducing their fossil fuel subsidies.

Third, the BRICS nations should establish a Green Investment Fund to finance innovative green infrastructure projects that span international borders. The development of smart grids, renewable energy projects, and carbon credit trading systems among member nations should be the priorities of this fund. Adopting eco-friendly technology will be accelerated, and this program will stabilize the investment climate.

Fourth, more global coordination must be needed to boost sustainable financing access, green technology commerce, and information sharing. The BRICS nations need to join forces on global sustainability projects and ensure their policies align with global environmental accords. It is necessary to seek bilateral and multilateral partnerships to promote the sharing of best practices and the joint development of environmentally friendly solutions.

Fifth, green investments are vulnerable to economic, trade, and oil price uncertainty; specific measures are necessary to lessen this impact. To help mitigate financial risks, governments should provide hedging mechanisms and assurances to companies that invest in clean technologies and renewable energy. Trade agreements should also include sustainability provisions that promote the export and import of environmentally friendly products and technology.

Lastly, a solid system for monitoring and evaluating environmental sustainability targets is important. Implementing systems to gather data in real-time, reporting openly and honestly, and having third-party evaluations to check for compliance are all part of this. Incorporating climate analytics powered by AI and big data technologies into decision-making processes may help fine-tune policies according to their effects in real time.

Limitations and future research direction

Within the context of the EKC, this research sheds light on the interplay between BRICS countries' levels of economic instability, innovation, and environmental sustainability. However, there are a few caveats that need to be recognized. One limitation is that it uses secondary data sources, which could have their own set of biases and contradictions. To ensure future studies' accuracy, researchers should consider using survey-based analyses or primary data-gathering techniques. Secondly, macroeconomic variables, including geopolitical risks, institutional quality, and social factors, might enhance the research, even if the study already includes CPU and EPU. The model's explanatory power might be improved by including these dimensions. Thirdly, results may not apply to other established and rising economies as the study only included the BRICS countries. A more comprehensive understanding might be gained by comparative studies that include other regional blocs or individual states with different economic frameworks. Furthermore, non-linear models and machine learning approaches might enhance the methodological approach, which is resilient, by better capturing dynamic connections among variables. More sophisticated econometric models and AI-powered predictive analytics should be investigated in further research. Finally, the effects of economic and innovation variables on the environment are the primary subject of the research. For more precise policy suggestions, future studies should look at the consequences for individual sectors, especially those that use much energy.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: World Development Indicators (WDI): https://databank.worldbank.org/source/world-development-indicators; Economic Policy Uncertainty Index (EPU): https://www.policyuncertainty.com; International Financial Statistics (IFS): https://data.imf.org/IFS.

Author contributions

MQ: Conceptualization, Data curation, Funding acquisition, Methodology, Writing – original draft, Writing – review and editing. AaA: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Writing – original draft, Writing – review and editing. AlA: Conceptualization, Formal Analysis, Methodology, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Gen AI was used in the creation of this manuscript.

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