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The New Drivers of CO_2 Emissions in BRIC Countries: Assessing the Role of Economic Policy Uncertainty, Clean Energy Consumption and Financial Development

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BRIC Ülkelerinde CO_2 Emisyonlarının Yeni Belirleyicileri: Ekonomik Politika Belirsizliği, Temiz Enerji Tüketimi ve Finansal Gelişmenin Rolünün Değerlendirilmesi

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Abstract

Rapid economic growth (GDP) and heightened policy uncertainty have intensified environmental pressures in BRIC economies, prompting stricter environmental regulation. This study examines the drivers of ecological degradation in BRIC countries from 1997 to 2024. Per capita CO_2 emissions are the dependent variable, while real GDP per capita, clean energy consumption (CE), the economic policy uncertainty (EPU) index, and bank-based financial development (FD) serve as regressors. Cross-sectional dependence and slope heterogeneity are tested using Pesaran's CD and delta statistics; integration is assessed with CIPS and CADF unit-root tests; and long-run relationships are evaluated via the Westerlund cointegration approach. Long-run coefficients are estimated with the panel Augmented Mean Group (AMG) estimator, which accommodates common shocks and structural heterogeneity. Results show that GDP increases emissions in all BRIC economies. FD has country-specific effects, either raising or reducing emissions. CE lowers emissions at the panel level, whereas policy uncertainty worsens environmental quality in most cases. The findings support coordinated clean-energy finance, green banking standards, and predictable policy frameworks.

Keywords: *Economic policy uncertainty, clean energy, financial development, panel data analysis.*

Öz

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BRIC ülkelerinde hızlanan ekonomik büyüme ve yüksek politika belirsizlikleri son yıllarda çevresel baskıları belirgin biçimde artırmaktadır. İklim ve ekolojik sorunların hızla ivmelenmesi, politika yapıcıların daha sıkı çevre politikaları yürürlüğe koymasına imkân tanımıştır. Bu çalışma, 1997-2024 döneminde BRIC ekonomilerinde çevresel bozulmanın yeni belirleyicilerini araştırmaktadır. Kişi başına CO_2 emisyonu bağımlı değişken; kişi başına reel GSYH, temiz enerji tüketimi, ekonomik politika belirsizliği endeksi ve bankacılık temelli finansal gelişme ise açıklayıcı değişkenlerdir. Yatay kesit bağımlılığı ve eğim heterojenliği Pesaran CD ve delta testleriyle, serilerin bütünleşme dereceleri CIPS ve CADF testleriyle; uzun dönem ilişkiler Westerlund eşbütünleşme testiyle analiz edilmiştir. Uzun dönem katsayıları, ortak şokları ve yapısal farklılıkları dikkate alan Panel AMG tahmincisiyle elde edilmiştir. Bulgular, ekonomik büyümenin tüm ülkelerde emisyonları artırdığını; finansal kalkınmanın çevre üzerindeki etkisi ise ülkelere göre farklılaşmakta kimi durumda emisyon artırıcı, kimi durumda azaltmakta, temiz enerjinin panel genelinde azaltıcı etkide bulunduğunu ve belirsizliğin çoğu ülkede çevresel bozulmayı derinleştirdiğini göstermektedir. Sonuçlar, BRIC ülkelerinde temiz enerji finansmanı, yeşil bankacılık standartları ve öngörülebilir politika çerçevesinin birlikte tasarlanması gerektiğini göstermektedir.

Anahtar Kelimeler: *Ekonomik politik belirsizlik, temiz enerji, finansal kalkınma, panel veri analizi.*

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1. Introduction

Global warming and its climate impacts have been one of the most concerning issues for the international community in recent years. Increases in carbon dioxide (CO_2) emissions, which are the most significant contributor to greenhouse gas emissions (GHGs) with a share of approximately 76% in total emissions, cause environmental degradation (Coskuner et al., 2020; Syed and Bouri, 2022; Farooq et al., 2023) and this creates an important obstacle to sustainable gross domestic product (GDP) and development policies both in developed and emerging countries. CO_2 emissions can impact the ecological and natural balance through various channels, including air pollution, water pollution, deforestation, biodiversity loss, temperature increases, and heavy precipitation. They also impact human health and life in both economic and social dimensions (Jiang et al., 2019; Syed and Bouri, 2022). The United Nations identified some valuable Sustainable Development Goals (SDGs) in 2015 to address these global challenges. According to these targets, countries worldwide must implement their development plans by 2030. SDGs essentially aim to change the current patterns of GDP policies. In this way, it is planned that countries will contribute to maintaining the natural balance while addressing environmental degradation through sustainable GDP and development policies. Among the SDG targets, some are directly related to clean and green energy production and climate action (Pandey et al., 2020; Iqbal et al., 2023). For this purpose, it is crucial to understand the drivers of CO_2 emissions for both researchers and policymakers.

The first strand of these factors is GDP, which is examined in the literature under the heading of the "GDP–CO_2 emissions nexus." The rapid post-Industrial Revolution expansion in production, primarily driven by the intensive use of traditional fossil-based energy sources, has led to substantial environmental degradation (Polat et al., 2024). Because maximizing economic growth remained the primary policy priority of most countries for a prolonged period, environmental concerns were largely neglected in the early stages of this process. From the 1960s onward, however, the increasing visibility of global warming, arising from persistent environmental neglect and the associated climate and ecological changes, emerged as critical global challenges, prompting a renewed and more systematic debate on the relationship between GDP and environmental pollution. The environmental damage caused by growth and its adverse implications for sustainability have gradually rendered the transition to cleaner, more sustainable, and environmentally friendly technologies in production processes unavoidable (Aydın et al., 2024; Artan et al., 2015). In this respect, while advanced economies have, particularly since the 1990s, increasingly reoriented their production structures toward environmentally sensitive systems, many developing countries have continued to pursue output expansion at the cost of environmental degradation, mainly due to the relatively high costs of clean technologies (Artan et al., 2015). Within this context, it is widely accepted that the uncontrolled increase in pollution-related emissions poses a serious threat to the sustainability of both human development and GDP at the global level (Khan and Ozturk, 2021). In response to this alarming trajectory, the Paris Agreement, adopted at the 21st Conference of the Parties (COP21) in Paris, reiterates the explicit commitment of signatory countries to limit the rise in global temperatures to well below 2°C, and preferably to within the 1.5–1.5 °C range. Against this background, a substantial strand of the environment–energy literature focuses predominantly on economic development as the key driver of environmental quality. This perspective is theoretically grounded in the Environmental Kuznets Curve (EKC) hypothesis proposed by Grossman and Krueger (1991). According to the EKC, in the early stages of development, intensive, wasteful, and unregulated exploitation of natural resources, coupled with a high dependence on dirty, fossil fuel–based energy, leads to worsening environmental degradation. Once per capita income exceeds a certain threshold, however, it is posited that rising wealth enables economies to reallocate resources toward cleaner production technologies, such as renewable energy, thereby improving environmental quality. Nevertheless, empirical tests of this nonlinear relationship yield highly heterogeneous and sometimes contradictory evidence regarding the link between income levels and environmental degradation (Jalil and Feridun, 2011; Khan and Ozturk, 2021). As a result, although the EKC framework continues to be regarded as a useful analytical tool for examining the growth–environment nexus, several scholars argue that, given the way economic development transforms production structures, sectoral composition, and the energy mix, the income–pollution relationship must be reconsidered in the presence of other relevant determinants.

The second strand of the literature focuses on the nexus between different types of energy consumption and CO_2 emissions. Energy consumption holds indispensable importance for both human life and welfare, as well as for economic activities around the world. It has played a critical role in the construction and development of industrialization and urbanization processes on a global scale. Its value in terms of sustainable GDP and development policies is increasing daily. Along with the globalization process, increases in population level and production/consumption processes lead to a rapid increase in global energy consumption. According to British Petroleum (BP, 2022) (hereafter BP), global energy consumption was 8.143 million tons of oil equivalent (Mtoe) in 2011 and increased approximately 1,7 times (%14) to 14,215 Mtoe in 2021. However, a large part of this energy demand is obtained from the use of traditional fossil fuels such as oil, natural gas, and coal, and leads to increases in the release of CO_2 emissions, which are the primary source of environmental degradation (Dong et al., 2018; Radmehr et al., 2021). Energy Institute (2023) statistics also show that global CO_2 emissions from fossil fuels were 21.306 billion tons in 1990 and approximately doubled to 40.6 billion tons in 2023. In other words, high shares of dirty energy in total energy consumption have led to a steady increase in CO_2 emissions throughout the above-mentioned period.

Reducing the use of fossil fuels is undoubtedly a vital solution against the environmental damage caused by CO_2 emissions. In this case, renewable energy sources, which are also defined as sustainable energy sources, are of vital importance compared to other resources (Voumik and Mimi, 2023; Dutta et al.,2018; Fei et al.,2014). They are one of the most effective sources for a cleaner energy consumption process by reducing reliance on fossil fuel usage. These sources cause little or no CO_2 emissions. Therefore, renewable energy is one of the most effective ways to mitigate global warming and is also widely accepted as an important alternative to fossil fuels, as well as an effective tool for sustainable GDP (Dong et al., 2018; Bilgili et al., 2016). There is an increasing demand for renewable energy sources worldwide, including hydroelectricity, solar, wind, biomass, and geothermal (Polat et al., 2024). Renewable energy resources have more than doubled from 453.873 Mtoe in 1990 to 953.234 Mtoe in 2023 (Energy Institute, 2023). According to the Intergovernmental Panel on Climate Change (IPCC) report, it is vital to limit temperature increases to 1.5 degrees by the middle of the century. To achieve this goal, it is aimed to reduce global CO_2 emissions by 45% by 2030 and to zero by 2050 (IPCC, 2023). At this point, renewable energy sources emerge as the most important policy tool International Energy Agency (IEA, 2016). In addition, the seventh goal of the United Nations Sustainable Development Goals (SDGs) aims to reduce CO_2 emissions and increase access to affordable, reliable, sustainable, and CE sources, thereby achieving sustainable development worldwide (Murshed et al., 2022). Ultimately, world economies are seeking pathways that lead to CE transitions within global energy systems (Murshed et al., 2022; Destek and Sinha, 2020).

The third strand of the literature examines the relationship between economic policy uncertainty (EPU) and CO_2 emissions. EPU is primarily defined as uncertainties in monetary, fiscal, and other macroeconomic policies worldwide (Pirgaip and Dinçergök, 2020). It has a significant impact on various economic indicators, including GDP, household consumption, savings, investment, FD, employment, stock and energy prices, among others (Pandey et al., 2020; Wang et al., 2020; Anser et al., 2021). In recent years, the international community has faced numerous economic and political challenges, including the COVID-19 pandemic, the China-US trade war, the United Kingdom's Brexit process, and the Russia-Ukraine war (Aslan et al., 2024). Additionally, EPU has also had a devastating effect on environmental degradation worldwide. This led to further investigation into EPU and the environment, yielding some important theoretical explanations on this issue. Some argue that EPU could lead producers to use more traditional and non-environmentally friendly methods in their production processes, thereby increasing CO_2 emissions. Others argue that EPU could hinder investment in research and development, innovation, and renewable energy sources, thereby leading to increased CO_2 emissions (Benlemlih and Yavaş, 2024; Anser et al., 2021; Syed and Bouri, 2022). Finally, a few researchers emphasize that EPU could also reduce CO2 emissions by decreasing economic activities, as it particularly affects investment and production decisions made by investors (Wang et al., 2020; Adedoyin and Zakari, 2020). For this purpose, it is an important responsibility for both researchers and policymakers to investigate the relationship between EPU and environmental degradation, and also to develop appropriate policy implications for all countries.

Another strand of the literature focuses on the nexus between FD and CO_2 emissions. Researchers have intensively studied this research question to date due to its importance for environmental economics and sustainable development policies. Scholars generally discuss two main arguments regarding the environmental effects of FD in the literature. The first view argues that FD may cause environmental degradation by increasing economic activities. Accordingly, FD may cause an increase in carbon emissions by encouraging investment increases in sectors where fossil fuel use is intensive (Kihombo et al., 2021a; Cetin et al., 2018; Shoaib et al., 2020). It can also lead to higher income levels, causing consumers to purchase more goods and services, which in turn can result in environmental damage (Sadorsky, 2010). On the other hand, the second view asserts that FD invests in energy-efficient projects and provides low-cost loans to build efficient technologies, which in turn promotes energy efficiency and environmental quality (Kihombo et al., 2021b; Zhao and Yang, 2020). According to this view, FD can channel producers towards environmentally friendly projects by reducing production costs and encouraging investment in new and efficient energy technologies such as renewable energy and green technologies (Khezri et al., 2022; Tamazian et al., 2009; Khoshnevis Yazdi and Ghorchi Beygi, 2018). In this context, FD can encourage businesses and policymakers to invest in innovative technologies that can reduce greenhouse gas emissions, improve atmospheric quality, and increase environmental sustainability (Jalil and Feridun, 2011; Abid et al., 2022).

Building on this background, BRIC countries have recorded high growth rates in recent years; however, IEA data clearly indicate that this performance has come at the cost of mounting environmental pressures. According to the IEA's 2023 assessment, China, India, and Russia rank among the top five countries worldwide in terms of energy-related CO_2 emissions, with China alone accounting for approximately 35% of global emissions and releasing about 12.6 billion tons of CO_2, thereby constituting the most significant single emitter (IEA, 2024). In the same year, India and Russia were responsible for approximately 8% and 4.9% of global emissions, respectively, while Brazil's share was around 1.2%. Taken together, this profile implies that the BRIC economies are collectively responsible for approximately 45–47% of global energy-related carbon emissions (IEA, 2024). The fact that the CO_2 emissions per unit of GDP of BRIC countries are estimated to be nearly four times higher than the averages for the EU and G7 underscores that environmental degradation has become a critical policy challenge for this group, rendering low-carbon growth, energy efficiency, and renewable-energy-oriented policy packages an urgent necessity. The present study examines, within a unified empirical framework, the relationship between environmental degradation and GDP, EC use, EPU, and FD in the BRIC economies over the period 1997–2024. In doing so, it underscores the importance of jointly considering growth, energy, financial, and policy dimensions in major emerging markets.

This study contributes to the existing literature in three main ways. First, it jointly analyses CO_2 emissions, GDP, CE deployment, EPU, and bank-based FD within a single empirical model for BRIC countries. In contrast, most previous studies have focused on only one or two of these drivers in isolation. Second, by focusing on the BRIC economies over the period 1997–2024, the study provides a distinctive perspective on a group of large emerging emitters that combine rapid growth potential with mounting environmental pressures, thereby enriching the evidence on the environment–energy–finance–policy uncertainty nexus in this specific country context. Third, the study employs a second-generation panel data approach, specifically the Augmented Mean Group (AMG) estimator, which explicitly accounts for cross-sectional dependence and slope heterogeneity, thereby capturing structural, institutional, and political differences across countries and yielding more reliable long-run coefficient estimates. In this way, the long-term effects of GDP, CE use, EPU, and FD on CO_2 emissions in BRIC countries are identified and translated into policy-relevant implications for the design of environmental, energy, and financial policies.

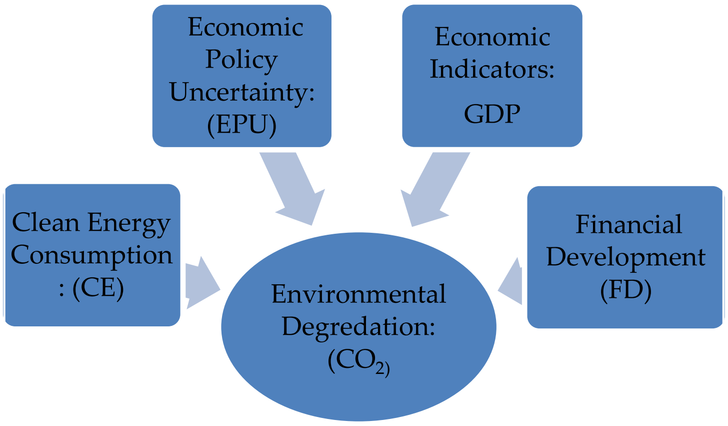

Figure 1. Factors Affecting Environmental Degradation

As summarized in the conceptual framework presented in Figure 1, this study examines, for the sample of BRIC countries, how CO_2 emissions, considered a key indicator of environmental degradation, are related to GDP, EPU, CE, and FD.

The remainder of the paper is organized as follows. The “2- Literature Review” section 2 presents the theoretical and empirical background of the study. The “3- Methods” section 3 describes the empirical methodology employed. The “4- Empirical Analysis” section 4 reports the main results, while the “5- Discussion” section interprets these findings in light of the existing literature and conceptual framework. Finally, the “6 - Conclusion and Policy Implications” section 6 provides an overall synthesis of the study and outlines the policy recommendations derived from the results.

2. Literature Review

The literature on environmental impacts is both extensive and continuously evolving, shaped by a range of theoretical approaches over time. In response to the recent increase in CO_2 emissions, many scholars have sought to identify the fundamental drivers of this process. Borozan (2024) highlights that uncovering the determinants of CO_2 emissions is a highly complex task, emphasizing that there is still no widely accepted, unified theoretical and empirical framework in this field. Consequently, the empirical literature has identified a broad set of determinants of CO_2 emissions, which vary depending on the geographical scope of the analysis, the period under consideration, data availability, and the econometric or statistical methods employed.

2.1. Economic Growth and Environmental Degradation

Studies on the GDP–environment nexus, building on Kuznets's original insight, generally suggest that the relationship between income and environmental degradation follows an inverted U-shaped pattern, known as the Environmental Kuznets Curve (EKC). Much of the empirical literature is organized around this framework. For Pakistan, Mirza and Kanwal (2017) employ Johansen cointegration, Autoregressive Distributed Lag (ARDL), and VECM for the period 1971–2009 and find bidirectional causality between GDP and CO_2 emissions. At a broader scale, Acheampong (2018) applies a PVAR–system Generalized Method of Moments (GMM) approach to 116 countries (1990–2014) and reports no significant causality in most regions, but an adverse effect of GDP on carbon emissions at the global level and in the Caribbean–Latin America region, together with a positive effect of emissions on growth. For China, Caporale et al. (2021) employ fractional integration and cointegration over 1978–2015 and document a long-run equilibrium relationship, implying that appropriate public policies can reduce CO_2 emissions without impeding growth, while Chen and Yan (2022) use the LMDI method for 2002–2016 and confirm an inverted U-shaped growth–emissions relationship. Evidence for 25 EU member states (2000–2020) from a panel ARDL model shows only short-run causality from CO_2 emissions to GDP growth (Androniceanu and Georgescu, 2023), whereas FMOLS and DOLS estimates for G20 economies (1990–2020) indicate that the effect of GDP on CO_2 turns from positive to negative across quantiles, suggesting that growth can reduce emissions under certain conditions (Naseem et al., 2024). Using a novel Transfer Entropy (TE) time-series framework for the United States (2000–2023), Chamakhi et al. (2025) further find bidirectional causality between GDP and CO_2 emissions, reinforcing the view that the growth–environment linkage is dynamic and context-specific. This study examines the following hypotheses:

H1: GDP increases environmental degradation in BRIC countries.

H2: CE reduces environmental degradation in BRIC countries.

H3: Increased EPU increases environmental degradation in BRIC countries.

H4: The effect of FD on environmental degradation is heterogeneous in BRIC countries.

2.2. EPU and Environmental Degradation

Since the seminal contribution of Baker et al. (2016), a rapidly expanding empirical literature has examined how EPU shapes environmental outcomes. Country-specific and panel studies for the United States, the United Kingdom, major emitters and large country groups over the period 1960–2022, using time-series and panel techniques such as ARDL, panel ARDL, PMG-ARDL, GMM, panel cointegration, MMQR and panel causality, generally suggest that EPU can either exacerbate or mitigate CO_2 emissions depending on the economic and institutional context (Jiang et al., 2019; Adedoyin and Zakari, 2020; Wang et al., 2020; Anser et al., 2021; Liu and Zhang, 2022; Iqbal et al., 2023 Farooq et al., 2023; Durani et al., 2023; Aslan et al., 2024; Mohanty et al., 2025). While some studies for the United States, the United Kingdom and a group of major emitters over 1960–2017 find that higher EPU is associated with higher CO_2 emissions in the short and/or long run, often via delayed green investment and sector-specific channels (Jiang et al., 2019; Adedoyin and Zakari, 2020; Wang et al., 2020; Anser et al., 2021), an increasingly large set of panel analyses for China, BRICS, G7, G20 and other country groups over the 1990s–2020s document a negative long-run EPU–CO_2 relationship, indicating that heightened policy uncertainty can also restrain emissions by dampening output and energy demand or accelerating the restructuring of energy portfolios (Liu and Zhang, 2022; Iqbal et al., 2023; Farooq et al., 2023; Durani et al., 2023; Aslan et al., 2024; Mohanty et al., 2025). Overall, the EPU-environment nexus appears to be strongly non-linear and context-dependent, with the sign and magnitude of the effect varying across countries, periods, model specifications, and sectors.

2.3. Clean Energy and Environmental Degradation

CE sources, such as solar, wind, hydropower, geothermal, biomass, and nuclear, are widely viewed as central to decarbonization and sustainable development; however, the empirical evidence on their impact on CO_2 emissions is not entirely uniform. A broad set of time-series and panel studies for the Organization for Economic Co-operation and Development (OECD), BRICS, G7, G20, Sub-Saharan African, South Asian and individual economies over 1965–2024, employing ARDL, panel ARDL, FMOLS/DOLS, panel cointegration, GMM, AMG and Granger/Toda–Yamamoto causality frameworks, generally finds that higher CE or renewable energy use is associated with lower CO_2 emissions in the long run (Bilgili et al., 2016; Dong et al., 2018; Maji, 2019; Rahman and Alam, 2021; Jamil et al., 2021; Li and Haneklaus, 2022; Zahoor et al., 2022; Balsalobre-Lorente et al., 2023; Perone, 2024). These studies show that, for many OECD, BRICS, G7, and emerging economies, a 1% increase in CE consumption can result in a statistically significant reduction in emissions, with geothermal, biomass, hydropower, and solar energy often identified as the most effective sources. However, a smaller group of papers reports neutral or even positive effects of renewable energy on CO_2, particularly in settings where the CE share is still low, the technology mix is inefficient, or waste and biomass are not adequately managed, as in the cases of Tunisia, parts of Sub-Saharan Africa, and some G7 members (Apergis et al., 2010; Jebli et al., 2015; Adams and Nsiah, 2019; Cai et al., 2018; Xue et al., 2022; Bhowmik et al., 2025). Taken together, the evidence suggests that while the dominant pattern supports a mitigating role of CE, the magnitude and even the sign of its impact on CO_2 remain highly heterogeneous across regions, time horizons, and policy frameworks.

2.4. Financial Development and Environmental Degradation

The literature on FD and environmental quality begins with the premise that deeper financial systems foster higher consumption and investment, thereby supporting GDP but with ambiguous implications for CO_2 emissions (Tamazian et al., 2009; Bouyghrissi et al., 2022). Empirical studies for BRIC, transition, Asian, African, Middle Eastern, European, and G7 economies over 1965–2022, using panel models, GMM, (N)ARDL, ARDL cointegration, wavelet analysis, and various causality tests, provide mixed evidence on the FD–CO_2 nexus. A first strand finds that FD can reduce emissions, either by facilitating cleaner technologies and efficiency-enhancing investments or by improving capital allocation, as shown for BRIC, Malaysia, Tunisia, large panels of developing countries, and the United States, where a 1% rise in FD is associated with small but significant declines in CO_2 over 1990–2022 (Tamazian et al., 2009; Shahbaz et al., 2013; Farhani and Ozturk, 2015; Khan and Ozturk, 2021; Bilgili et al., 2025). A second group of studies reports no robust linkage between financial development and emissions, particularly in parts of Europe, Africa, and the Gulf region, suggesting that financial deepening does not automatically translate into either greener or dirtier production (Ozturk and Acaravcı, 2013; Jamel and Maktouf, 2017; Adams and Klobodu, 2018; Salahuddin et al., 2018). A third, equally important strand documents a positive impact of FD on CO_2, especially where credit expansion fuels carbon-intensive activities and where institutional quality is weak, as evidenced in India, Greece, China, Turkey, East and South Asia, G7, and selected emerging markets over 1971–2020 (Boutabba, 2014; Işık et al., 2017; Ahmad et al., 2018; Doğanlar et al., 2021; Batool et al., 2022; Qalati et al., 2023; Saboori et al., 2024). Overall, these heterogeneous findings underscore that the environmental consequences of FD are highly contingent on country-specific structural characteristics, regulatory quality, and the direction in which finance is channeled.

3. Methodology

This section outlines the empirical strategy employed to investigate the impact of GDP, CE, EPU, and FD on environmental degradation in BRIC countries during the period 1997-2024. The analysis proceeded in several stages. First, the presence of cross-sectional dependence among the variables was examined using the Pesaran CD test. Having detected cross-sectional dependence, second-generation panel unit root tests, namely CIPS and CADF, were applied, which revealed that the variables were non-stationary. Subsequently, in light of this unit root evidence, the Westerlund (2007) second-generation panel cointegration test was implemented. The test results indicated the existence of a cointegration relationship, and the long-run coefficients were then estimated using the panel AMG estimator.

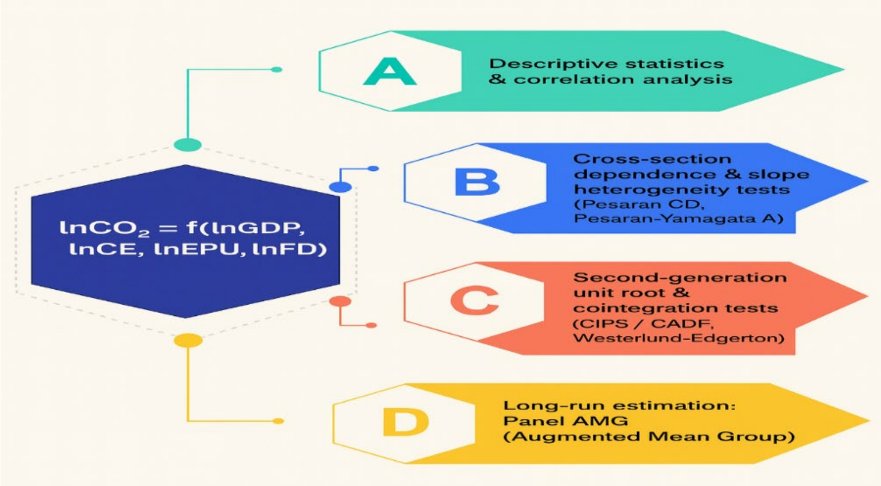

Figure 2. Methodology Framework

3.1. Cross-Section Dependence (CD) Tests

In this study, the presence of cross-sectional dependence among the variables was examined before proceeding with the empirical analysis, considering the specific characteristics of the panel data set. In panel models, mutual interactions across countries or units—such as trade linkages, financial flows, or transboundary environmental effects—may violate the assumption of cross-sectional independence, thereby undermining the reliability of conventional estimators. For this reason, we employ the widely used Pesaran CD test (Pesaran, 2004) to assess whether cross-sectional dependence is present in the panel. The Pesaran CD test is a parametric procedure that evaluates whether the average pairwise correlations across cross-sectional units are equal to zero and is particularly suitable for panels with both a large cross-sectional dimension (N) and a long time dimension (T). While the test can be sensitive to outliers, it is specifically designed to reveal the presence of standard shocks or interconnections among units. It yields a test statistic that is asymptotically standard normal, and statistically significant values indicate the existence of cross-sectional dependence in the panel (Pesaran, 2004). The CD (Cross-section Dependence) test examines whether the mean of the pairwise correlation coefficients across units is zero. The corresponding test statistics are computed using the following equation (Pesaran, 2004).

$$CD = \sqrt{\frac{2T}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij} \qquad (1)$$

In the above equation, j denotes the correlation between the error terms of units ‘i’ and ‘j’, N represents the number of cross-sectional units in the panel, and T denotes the time dimension. The null hypothesis (H_0) states that there is no cross-sectional dependence among the units. In contrast, the alternative hypothesis (H_1) implies the presence of cross-sectional dependence (Pesaran, 2004).

3.2. Slope Heterogeneity

In panel data analysis, the standard assumption holds that slope coefficients are homogeneous across cross-sectional units, implying that all units share the same response to a given explanatory variable. However, in applications involving heterogeneous entities such as countries or firms, the impact of the regressors on the dependent variable frequently differs from one unit to another. This phenomenon, commonly referred to as slope heterogeneity in the literature, challenges the validity of the assumption of homogeneity. When this assumption does not hold, homogeneous panel estimators—such as pooled OLS or fixed-effects models with common slopes—can produce biased and inconsistent estimates (Pesaran and Smith, 1995). Consequently, testing whether slope coefficients are homogeneous or heterogeneous represents a crucial step in panel data applications, as it directly informs the choice of the appropriate econometric model.

In this context, Pesaran and Yamagata (2008) propose the delta (Δ) and adjusted delta (Δ_adj) tests to assess slope homogeneity in panel data models. These tests are based on the discrepancy between the group mean and pooled estimators, providing a formal statistical criterion for determining whether slope coefficients are indeed identical across units. When the null of homogeneity is rejected, a heterogeneous panel specification should be adopted (Pesaran et al., 1999). This approach proves particularly valuable in macroeconomic, environmental, and financial applications, where cross-country or cross-firm comparisons require reliable and consistent inference.

3.3. Unitroot Tests

In panel data analysis, the reliability of unit root tests critically depends on whether there is cross-sectional dependence among the series. First-generation panel unit root tests are built on the assumption of cross-sectional independence; when this assumption is violated, the resulting inference may be misleading. Therefore, in settings where cross-sectional units such as countries or regions are likely to be exposed to common shocks or strong interlinkages, it is more appropriate to rely on second-generation panel unit root tests. Accordingly, the present study employs the CIPS (Cross-sectionally Augmented IPS) and CADF (Cross-sectionally Augmented Dickey–Fuller) tests proposed by Pesaran (2007a).

The CADF test extends the conventional Dickey–Fuller regression by augmenting it with the cross-sectional mean of the series and its lagged values, thereby embedding cross-sectional dependence directly into the model. Through this specification, common shocks and interdependencies across panel units are explicitly considered. The corresponding CADF regression equation is given below (Pesaran, 2007a).

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \delta_i \Delta \bar{y}_t + \sum_{j=1}^{p} \emptyset_{ij} \Delta y_{i,t-j} + \varepsilon_{it} \tag{2}$$

In this specification, y_{it}, denotes the value of the series for unit 'i' at time t, α_i is the unit-specific intercept, and $\bar{y}_t$ represents the cross-sectional mean of the series at time 't'. The coefficients δ_i ve γ_i capture the loadings on the common factor components, $\emptyset_{ij}$ are the coefficients on the lagged dependent variable, and ε_{it} is the error term. In addition, 'p' denotes the lag length and Δ is the first-difference operator. The null hypothesis H_0 states that the series contains a unit root (Pesaran, 2007a).

The CIPS test, in turn, is constructed by taking the cross-sectional average of the individual CADF statistics, thereby allowing inference at the panel level. By doing so, unit-specific results are aggregated into a statistic that represents the panel as a whole. The CIPS test statistic is defined as follows (Pesaran, 2007b).

$$CIPS = \frac{1}{N} \sum_{i=1}^{N} CADF_i \tag{3}$$

Here, $CADF_i$ denotes the test statistic estimated for each cross-sectional unit. The CIPS test is sensitive to the standard factor structure and cross-sectional dependence, and it delivers highly reliable results, especially in panel data settings with large N and T. In this framework, the null hypothesis H_0 again states that the series contains a unit root (Pesaran, 2007a).

3.4. Westerlund (2007) Cointegration Test

In this study, the existence of long-run relationships in the panel data set is examined using the panel cointegration test developed by Westerlund and Edgerton (2007). Owing to its ability to account for heterogeneity across panel units and potential cross-sectional dependence, this approach provides more reliable evidence than conventional cointegration tests. Westerlund and Edgerton (2007) propose a panel cointegration procedure that automatically selects the optimal lag length and uses a bootstrap technique to obtain inference that is robust to cross-sectional dependence. The main advantage of this method is that it can simultaneously capture both dynamic and structural dependence within panel data sets. The Westerlund and Edgerton (2007) model is computed as follows:

$$\Delta y_{it} = \alpha_i + \delta_i t + \pi_i\left(y_{i,t-1} - \theta_i' x_{i,t-1}\right) + \sum_{j=1}^{p_i} \gamma_{ij} \Delta y_{i,t-j} + \sum_{j=0}^{q_i} \lambda_{ij} \Delta x_{i,t-j} + \varepsilon_{it} \tag{4}$$

In this framework, π_i denotes the error-correction (cointegration) coefficient, θ_i' is the vector of long-run slope parameters, α_i is the individual fixed effect, δ_i captures the deterministic time trend, and ε_{it} represents the disturbance term. The null hypothesis H_0 states that there is no cointegration in the panel ($\pi_i = 0$ for all i). Four test statistics are computed: two are group-mean statistics, and two are panel statistics. Specifically, G_t is the group-mean t-statistic and G_a is the group-mean average statistic, while P_t is the panel t-statistic and P_a is the panel average statistic (Westerlund and Edgerton, 2007).

Compared with conventional ADF- and Phillips–Perron-type tests, Westerlund's procedures generally exhibit higher power, particularly in panels where short-run dynamics are pronounced. The Westerlund and Edgerton test can also be effectively applied in data sets with relatively short time dimensions and a large number of cross-sectional units. By embedding the error-correction mechanism directly into the specification, the test evaluates the existence of cointegration while explicitly accounting for the dynamic structure of the model. In addition, the use of a bootstrap approach allows the test to deliver more robust and reliable inference in the presence of cross-sectional dependence.

3.5. Augmented Mean Group (AMG) Test

One of the key challenges frequently encountered in panel data analysis is the presence of cross-sectional dependence and structural heterogeneity across countries. Conventional panel estimators typically assume that all units share identical slope coefficients; under cross-sectional dependence and heterogeneity, this assumption can lead to biased and inconsistent estimates. To address these issues, Eberhardt and Bond (2009) and Bond and Eberhardt (2013) propose the Augmented Mean Group (AMG) estimator, which has emerged as a powerful tool in such settings. The AMG approach incorporates a common dynamic process into the specification for all cross-sectional units. Then it estimates separate long-run coefficients for each unit, before taking the arithmetic mean of these coefficients. In this manner, it explicitly accounts for both cross-sectional dependence and unit-specific heterogeneity, allowing the long-run relationships in the panel to be identified reliably.

A key advantage of the AMG estimator is that it models the impact of standard shocks without imposing homogeneity on the underlying structural parameters, thereby preserving cross-country (or cross-firm) differences in adjustment and behaviour. This feature makes the method particularly attractive in empirical applications in macroeconomics, energy economics, and environmental economics, where unobserved common factors and heterogeneous responses are the norm rather than the exception. Consistent with this, the literature emphasizes that AMG tends to deliver more robust and reliable estimates of long-run equilibrium relationships than standard homogeneous panel estimators (Eberhardt and Teal, 2010; Pesaran et. al., 2013). Overall, the AMG estimator provides researchers with a flexible and powerful framework for analysing panels characterised by pronounced cross-sectional dependence and heterogeneity.

This study employs the Augmented Mean Group (AMG) estimator because, in the presence of potential cross-sectional dependence and slope heterogeneity, AMG accommodates unobserved common factors through the "common dynamic process" augmentation and yields consistent estimates, particularly in small-N panels. Since the dataset has a small cross-sectional dimension and a moderate time span, AMG provides a methodologically appropriate and statistically robust framework for inference. The estimator is also well established in applications with small country groups; for example, Ozgun (2025) estimates long-run coefficients for a four-country sample using AMG.

4. Data Set and Model

This study examines the relationship between environmental degradation and key economic and financial indicators in BRIC economies from 1997 to 2024. To capture environmental pressures, per capita carbon dioxide (CO_2) emissions (in tons) are used as the dependent variable. The set of explanatory variables includes real GDP per capita (in 2015 constant US dollars) as a proxy for GDP, per capita renewable energy consumption (in terawatts) as a measure of CE use, and an EPU index. In addition, domestic credit to the private sector by banks (as a percentage of GDP) is employed to represent FD.

Data on CO_2 emissions, GDP per capita, and FD are drawn from the World Bank's World Development Indicators (WDI). The EPU series is obtained from Baker et al. (2016), while renewable energy consumption is sourced from Refinitiv Datastream. Through this approach, environmental degradation is examined within a multidimensional framework that integrates its socio-economic and structural determinants.

In this study, the primary reason for constructing the panel dataset with only four cross-sections (the original BRIC countries) is that long-term and comparable data particularly for the EPU variable are available exclusively for these countries. Accordingly, the analysis exhibits a structure with a relatively small cross-section and a medium-length time dimension due to data limitations. Considering this, the AMG estimator was chosen, as it is known to yield more reliable results in panels with a small number of cross-sections. The AMG estimator is methodologically suitable for the data structure of this study because it allows for heterogeneity across countries and produces consistent coefficients in small-N panels by accounting for the common factor structure. Moreover, since a low N can make p-values in panel cointegration tests such as CIPS/CADF and Westerlund more fragile, the present study employs the Westerlund (2007) cointegration test and uses robust standard errors in the AMG estimator to reduce potential biases stemming from the limited cross-sectional dimension. In sum, to ensure that the employed tests generate reliable inferences despite the small-N structure, an approach that provides both methodological compatibility and statistical robustness has been adopted. The variables used in the analysis are summarized in the table below, which reports their abbreviations, measurement units, data sources, and roles in the model.

Table 1. Table of variables

Acronym	Variable	Measurement	Role	Sources
co2	Environmental degradation	Carbon dioxide (CO2) emissions (per	Dependent	WDI
gdp	Economic growth	GDP per capita (constant 2015 US$)	Independent	WDI
epu	Economic Policy Uncertainty	Index	Independent	Baker et al.
ce	Clean energy	Renewable energy	Independent	Refinitiv
fd	Financial development	Domestic credit to the private sector by	Independent	WDI

In this study, the effects of GDP, CE, EPU, and FD on environmental degradation are examined using the variable representations defined above. The empirical specification of the model employed in the analysis is presented in the following equation.

$$co2 = f(gdp, ce, epu, fd) \tag{5}$$

In the above equation, co_2 is the dependent variable of the model, while GDP, CE, EPU and FD denote the explanatory variables. One of the most effective ways to obtain preliminary insights into the relationships among these variables is through correlation analysis. This approach quantitatively captures the degree of linear association between pairs of variables, thereby providing initial evidence on potential interactions among them (Polat et al., 2025; Tosunoğlu and Uçal, 2025). Before proceeding to more advanced econometric techniques, this method allows us to establish a comprehensive picture of the fundamental linkages in the data. The correlation matrix for the relevant variables, together with their descriptive statistics, is reported in the table below.

Table 2. Correlational relationships and descriptive statistics (N= 112)

	co2	**gdp**	**ce**	**epu**	**fd**
co2	1				
gdp	0.587	1			
ce	-0.136	0.509	1		
epu	0.398	0.636	0.386	1	
fd	0.108	0.316	0.829	0.280	1
Mean	5.571	6052.767	1350.076	140.826	65.969
Std. Dev.	4.532	3522.946	1578.165	99.560	44.666
Min	0.878	667.598	213.686	28.335	1.617
Max	14.619	13121.68	7988.452	577.142	194.166

According to the correlation results, the association between the dependent variable (co_2) and the explanatory variables is as follows. The correlation between gdp and co_2 is positive and relatively strong, at around 0.59, while the correlation between epu and co_2 is also positive, at roughly 0.40. Thus, the link between GDP and environmental degradation emerges as the strongest among the explanatory variables, followed by EPU. In addition, the correlation between ce and co_2 is negative and weak in magnitude. Overall, these findings support the existence of meaningful relationships between the dependent variable and the regressors included in the empirical model.

The descriptive statistics reported in the table are examined to obtain preliminary information on the variables and to assess whether the data may contain outliers. Outliers typically correspond to extreme observations that differ markedly from the bulk of the data, and they tend to be reflected in sensitive summary measures, such as very wide gaps between the minimum and maximum values, considerable standard deviations, and means that are shifted away from the central mass of the distribution. In econometric models, such observations can lead to biased coefficient estimates, reduce the explanatory power of the model, and contribute to violations of classical assumptions (Tosunoğlu, 2024). Examination of the descriptive statistics suggests that some variables may contain extreme values. To mitigate the potential distortions that these observations could introduce into the estimation results, the analysis relies on the panel AMG estimator and the Westerlund cointegration tests, both of which are robust to cross-sectional dependence and parameter heterogeneity. Moreover, heteroskedasticity- and autocorrelation-robust standard errors are employed to limit the influence of outliers on inference, thereby enhancing the statistical reliability of the results.

Another key diagnostic for panel data concerns cross-sectional dependence, specifically whether the error terms across countries are independent of one another. In practice, such dependence may arise from common shocks, economic and political interlinkages, or spatial spillovers. Ignoring cross-sectional dependence can result in misleading inference, particularly through downward- or upward-biased standard errors, and thus unreliable significance tests for the estimated coefficients. To avoid such pitfalls, cross-sectional dependence is routinely assessed using formal tests. In this study, the Pesaran CD test is applied to examine cross-sectional dependence among the panel units. Additionally, it is crucial to determine whether slope parameters can be considered homogeneous across countries. If slope coefficients are indeed heterogeneous, failing to account for structural differences across economies can compromise the validity of the estimates. For this reason, slope homogeneity is tested using the procedure proposed by Pesaran and Shin (1999) and Pesaran and Smith (1995), as modified by Pesaran and Yamagata (2008). The corresponding test statistics for cross-sectional dependence and slope homogeneity are reported in the table below.

4.1. Findings and Discussion

As a preliminary step in the empirical analysis, cross-sectional dependence and slope heterogeneity tests are conducted. These tests are essential for identifying the underlying characteristics of the panel structure and for selecting appropriate estimation techniques. The corresponding results are reported in Table 3.

Table 3. Cross-sectional dependence and slope heterogeneity test results

Pesaran CD Test	
co2	9.804***
gdp	11.719***
ce	10.874***
epu	3.775***
fd	7.612***
resid	-2.985***
Slope heterogeneity	
$\hat{\Delta}$	9.875***
$\hat{\Delta}_{Adj}$	11.141***

Notes: The stars indicate levels of statistical significance: one star (*) denotes significance at the 10% level, two stars (**) at the 5% level, and three stars (***) at the 1% level. In the slope heterogeneity test, robust standard errors were estimated.

The cross-sectional dependence test results reported in Table 3 show that the null hypothesis of no cross-sectional dependence is rejected at the 1% significance level for all variables. Likewise, the same null is rejected at the 1% level when the test is applied to the residuals, confirming the presence of cross-sectional dependence in the panel. In addition, the slope heterogeneity test rejects the null hypothesis of homogeneous slope coefficients at the 1% level, indicating that the underlying relationships differ across countries. Taken together, these findings suggest that both cross-sectional dependence and slope heterogeneity must be considered in the empirical specification, and that unit root properties should be examined using second-generation panel unit root tests. Accordingly, the CIPS and CADF tests, which explicitly allow for cross-sectional dependence, are employed, and their results are summarized in Table 4.

Table 4. CIPS and CADF unit root test results

Variables	Model	$CIPS^a$	$CIPS^b$	$CADF^a$	$CADF^b$
co2	**c**	-1.142	-3.533***	-1.078	-2.368*
	c/t	-1.336	-3.667***	-0.988	-3.317***
gdp	**c**	-1.245	-2.937***	-2.057	-2.193
	c/t	-1.563	-4.089***	-2.099	-3.322**
ce	**c**	-2.700***	-5.745***	-1.764	-2.803**
	c/t	-2.926**	-5.792***	-2.082	-4.029***
epu	**c**	-2.242*	-3.819***	-2.370	-3.398***
	c/t	-3.526***	-3.611***	-2.672	-3.074**
fd	**c**	-1.145	-4.325***	-0.837	-1.886
	c/t	-1.126	-4.580***	-2.404	-4.155***

Notes: In this context, superscript a denotes level values, while superscript b represents first-differenced values. The stars indicate levels of statistical significance: one star (*) denotes significance at the 10% level, two stars (**) at the 5% level, and three stars (***) at the 1% level.

According to the second-generation unit root tests reported in Table 4, the null hypothesis of a unit root is rejected when the series is stationary and cannot be rejected when the series follows a unit root process. Both the intercept-only (c) and intercept-and-trend (c/t) specifications are considered at levels and first differences, and the integration order of each variable is determined by jointly evaluating these cases. The CIPS statistics indicate that clean energy (ce) and economic policy uncertainty (epu) are stationary in levels, i.e., I(0), whereas CO_2 emissions (co2), economic growth (gdp), and financial development (fd) become stationary after first differencing, i.e., I(1). By contrast, the CADF results suggest that all variables are integrated of order one, I(1). The fact that at least some of the series are I(1) is consistent with the presence of long-run equilibrium relationships among them and motivates the use of panel cointegration techniques. Given these findings, the existence of cointegration is examined using the second-generation panel cointegration test proposed by Westerlund (2007), which employs robust standard errors obtained via a bootstrap procedure with 400 replications. The corresponding cointegration test results are presented in Table 5.

Table 5. Westerlund (2007) cointegration test results

Westerlund (2007)		
Stat.	**Value**	**p-value (robust)**
G_t	-1.388*	0.099
G_a	-1.790**	0.050
P_t	-1.871***	0.000
P_a	-2.294**	0.050

Notes: The stars indicate levels of statistical significance: one star (*) denotes significance at the 10% level, two stars (**) at the 5% level, and three stars (***) at the 1% level. In the Westerlund cointegration analysis, estimations were conducted using robust standard errors obtained through the bootstrap method with 400 replications.

According to Westerlund (2007), the null hypothesis of no cointegration is rejected. The results indicate that the null is rejected at the 10% significance level for the group statistics and at the 5% level for the panel statistics, providing evidence of a long-run cointegrating relationship among the variables. Given the presence of cointegration, the long-run coefficients can be consistently estimated. For this purpose, the present study employs the panel AMG estimator, which is robust to cross-sectional dependence and allows for heterogeneous effects at both the country and panel levels. The corresponding panel AMG estimation results are reported in Table 6.

Table 6. Panel AMG test results

	gdp	**ce**	**epu**	**fd**
Brazil	0.0002***	-0.0010***	0.0008***	0.0123***
	(0.00004)	(0.00013)	(0.00027)	(0.00288)
China	0.0015***	-0.0012***	-0.0010	-0.0191***
	(0.00008)	(0.00015)	(0.00094)	(0.00675)
India	0.0011***	-0.0008***	0.0008***	0.0029**
	(0.00010)	(0.00018)	(0.00029)	(0.00085)
Russia	0.0006***	0.0055***	0.0010	-0.0499***
	(0.00015)	(0.00189)	(0.00078)	(0.01459)
Panel	0.0009***	-0.0010***	0.0008***	-0.0120
	(0.00032)	(0.00013)	(0.00008)	(0.01725)

Note: The stars indicate levels of statistical significance: one star (*) denotes significance at the 10% level, two stars (**) at the 5% level, and three stars (***) at the 1% level. Standard errors were estimated robustly. The values given in parentheses are robust standard errors.

The panel AMG estimates point to a persistent long-run association among the variables. At the panel level, economic growth (GDP), clean energy (CE), and economic policy uncertainty (EPU) exert statistically significant effects on environmental degradation proxied by CO_2 emissions at the

1% level. Country specific results further indicate that the impacts of GDP and CE are highly consistent, remaining significant at the 1% level across all countries. By contrast, the role of EPU is country dependent: it is positive and strongly significant in Brazil, and also significant in India, while it is statistically insignificant in China and Russia. In contrast, FD is statistically significant in all countries but with opposite signs: it is positive and significant at the 1% level in Brazil and positive and significant at the 5% level in India, while it is negative and significant at the 1% level in China and Russia. Overall, these findings underscore the robustness of the core growth, energy and environment link in the long run, while suggesting that the influence of EPU varies with country specific institutional and macroeconomic conditions.

GDP is found to exacerbate environmental degradation in Brazil, China, India, and Russia, as well as for the BRIC panel as a whole. This result suggests that growth processes, operating through higher energy use and more intensive exploitation of natural resources, tend to raise emissions and aggravate environmental damage, consistent with the early stage of the Environmental Kuznets Curve (EKC) hypothesis. CE consumption, by contrast, reduces environmental degradation in Brazil, China, and India, but increases emissions in Russia; at the panel level, CE use is associated with lower CO_2 emissions. These findings support the view that renewable energy investment plays a crucial role in reducing carbon emissions, while the cross-country heterogeneity likely reflects differences in energy policy frameworks, technological capabilities, and the composition of national energy portfolios.

EPU has a detrimental effect on environmental quality in Brazil and India, and it also emerges as an emissions-raising factor at the panel level. This implies that in more uncertain policy environments, environmental standards may be deprioritised and environmentally friendly investments postponed, underscoring the importance of policy stability for environmental sustainability. Finally, the impact of FD is clearly heterogeneous: it intensifies environmental degradation in Brazil and India but mitigates it in China and Russia. This pattern suggests that the environmental consequences of financial deepening depend on the level of FD and on how financial systems allocate resources. In other words, whether financial deepening supports environmental sustainability is contingent on institutional quality, the regulatory framework, and the direction of capital flows.

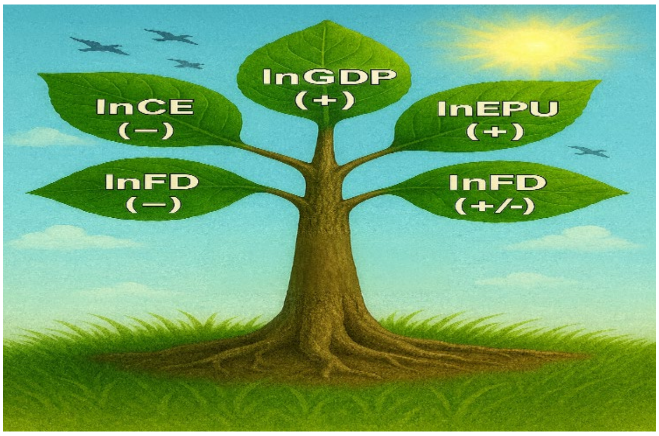

Figure 3. Graphical display of estimation results

5. Conclusion and Policy Implications

Global warming has become one of the most pressing threats to human life and the stability of ecosystems. A central driver of this process is carbon dioxide (CO_2) emissions, which severely undermine environmental quality. Although a vast body of research has examined the economic and institutional determinants of CO_2 emissions, the direction and strength of the link between emissions and economic policy uncertainty (EPU)—a macro-level institutional indicator—remain relatively underexplored. This study addresses that gap by focusing on the BRIC economies, which play a pivotal role in the world economy and account for a large share of global output and emissions. Specifically, it examines the relationship between environmental degradation, GDP, CE, EPU, and FD in BRIC countries over the period 1997–2024, using the panel AMG estimator. The use of the AMG approach allows the analysis to accommodate cross-sectional dependence and slope heterogeneity, providing a framework that captures long-run relationships while explicitly accounting for cross-country differences rather than imposing homogeneity across the panel.

The panel AMG estimates point to a persistent long-run association among the variables. At the panel level, GDP, CE, and EPU exert statistically significant effects on environmental degradation, proxied by CO_2 emissions, at the 1% level. Country-specific results further indicate that the impacts of GDP and CE are highly consistent, remaining significant at the 1% level across all countries. By contrast, the role of EPU is country-specific: it is positive and strongly significant in Brazil and also significant in India, while it is statistically insignificant in China and Russia. Economic growth is found to increase CO_2 emissions in Brazil, China, India, and Russia, as well as in the BRIC panel as a whole. This pattern is consistent with the extensive empirical literature documenting a positive growth emissions nexus in the earlier stages of development and is in line with the initial phase of the Environmental Kuznets Curve (EKC) framework, as reported by Mirza and Kanwal (2017), Caporale et al. (2021), and Chen and Yan (2022). At the same time, compared with evidence from the G20 suggesting that the impact of growth on emissions may turn negative at higher income quantiles (Naseem et al., 2024), the findings here imply that BRIC economies remain closer to a high-growth, high-emissions regime.

The effects of CE are more nuanced. CE consumption in Brazil, China, and India reduces CO_2 emissions, but is associated with higher emissions in Russia. At the panel level, renewable energy use is found to mitigate environmental degradation. This is broadly consistent with the large set of country and panel studies reporting that higher renewable or CE use helps to curb emissions in the long run (Bilgili et al., 2016; Dong et al., 2018; Maji, 2019; Rahman and Alam, 2021; Jamil et al., 2022; Li and Haneklaus, 2022; Zahoor et al., 2022; Balsalobre-Lorente et al., 2023; Perone, 2024). At the same time, the Russian case mirrors findings from studies that detect either an insignificant or even positive association between renewable energy (or waste- and biomass-based energy) and CO_2 emissions in specific contexts (Apergis et al., 2010; Ben- Jebli et al., 2015; Adams and Nsiah, 2019; Cai et al., 2018; Xue et al., 2022; Bhowmik et al., 2025). Overall, these results reinforce the view that while CE is generally conducive to environmental sustainability, its effectiveness depends critically on the design of national energy policy, technological capacity, and the composition of the energy mix. When considering the country-specific effects of CE, its negative and significant coefficients in Brazil and India confirm that scaling up CE is an effective instrument for reducing emissions. By contrast, the positive and significant coefficient for Russia suggests that CE policies need to be designed in a way that genuinely accelerates substitution away from fossil fuels toward cleaner energy sources.

EPU is found to raise emissions in Brazil and India and at the panel level, suggesting that higher uncertainty may push environmental priorities down the policy agenda and delay green investment decisions. This aligns with studies reporting a positive EPU–CO_2 relationship in several large emitting economies and sectors (Jiang et al., 2019; Anser et al., 2021). By contrast, panel evidence documenting a negative long-run association between EPU and emissions (Liu and Zhang, 2022; Iqbal et al., 2023; Farooq et al., 2023; Durani et al., 2023; Aslan et al., 2024; Mohanty et al., 2025) highlights that the EPU–EPU-environment nexus is highly context-dependent, varying with country group, time horizon, and modelling strategy. The BRIC results suggest that, in these economies, EPU does not appear to curb emissions solely through demand compression; instead, it may slow down the transition towards cleaner technologies by creating a less favourable environment for long-term, irreversible green investments. Although this study does not directly observe the specific channel through which EPU operates, the cross-country coefficient pattern reveals that the EPU–CO_2 relationship is closely tied to the composition of investment and the pace of the low-carbon transition, indicating that uncertainty may influence emissions by delaying cleaner capital accumulation and reallocating investment. When considering the country-specific effects of EPU, the finding that EPU is positive and statistically significant in Brazil and India suggests that heightened uncertainty may weaken decarbonisation momentum by postponing green investment. In this context, enhancing policy predictability and stabilising the regulatory framework are essential for achieving emissions-reduction targets.

The environmental implications of FD are also heterogeneous. FD is associated with higher emissions in Brazil and India, but with lower emissions in China and Russia. This pattern suggests that the impact of financial deepening is mediated by how financial systems allocate capital, the quality of regulation, and institutional features, as well as the extent to which financial resources are channeled towards green versus carbon-intensive activities. The findings therefore corroborate the mixed evidence in the literature: they are consistent with studies showing that FD can support emission reductions when it facilitates cleaner technologies and efficiency-enhancing projects (Tamazian et al., 2009; Shahbaz et al., 2013; Farhani and Ozturk, 2015; Khan and Ozturk, 2021; Bilgili et al., 2025), while also aligning with work documenting that credit expansion can fuel higher emissions in settings where financial flows predominantly finance polluting activities and institutional quality is weaker (Boutabba, 2014; Işık et al., 2017; Ahmad et al., 2018; Doğanlar et al., 2021; Batool et al., 2022; Qalati et al., 2023; Saboori et al., 2024). Taken together, the evidence suggests that environmental degradation in BRIC economies is jointly shaped by EG, energy choices, policy uncertainty and the structure of the financial system, and that the signs and magnitudes of these effects are broadly consistent with the complex and context-specific relationships documented in the existing literature on growth–environment, CE–emissions, EPU–environment and finance–emissions linkages. When considering the country-specific effects of FD, the fact that FD exhibits opposite signs across countries (positive in Brazil and India; negative in China and Russia) indicates that the environmental implications of financial deepening depend critically on how financial resources are allocated. Accordingly, financial policies particularly in Brazil and India should be complemented with sustainable finance instruments that strengthen the redirection of capital toward green projects.

From a policy perspective, the findings suggest that environmental sustainability in BRIC countries cannot be achieved through isolated interventions, but rather requires a coherent, multidimensional strategy. First, growth strategies should be reoriented away from fossil-fuel-intensive expansion towards investment paths that prioritise CE deployment and energy efficiency. Expanding the supply of renewables and accelerating the diffusion of clean technologies requires a comprehensive package of tax incentives support, green financing instruments, and targeted subsidies. Second, the positive link between EPU and emissions highlights that policy stability and predictability are crucial institutional prerequisites for environmental progress. Designing economic and environmental policies that are transparent, internally consistent, and framed within a medium- to long-term horizon, while avoiding frequent and abrupt changes in environmental regulation, is likely to reduce uncertainty and strengthen the credibility of climate commitments. Third, the fact that FD can have either beneficial or adverse environmental consequences depending on country-specific conditions points to the importance of "greening" the financial system. Regulatory frameworks that encourage green bonds, sustainability-linked lending standards, and climate-risk-sensitive disclosure and reporting practices can help steer financial flows towards low-carbon investments and away from carbon-intensive activities.

Despite its contributions, the study has several limitations. The sample period, 1997–2024, may not fully capture longer-run structural transitions, and the results should therefore be interpreted in light of the specific shocks and regime changes that have characterized this timeframe. In addition, data on EPU within the BRIC group are available only for Brazil, Russia, India, and China, which restricts the analysis to this four-country panel and limits the immediate generalizability of the findings beyond the set of economies considered. Finally, because the empirical model includes only the linear term of real GDP per capita and omits higher-order terms such as the squared GDP term, the EKC hypothesis is not explicitly tested; as a result, the non-linear dynamics of the growth–environment relationship can only be inferred indirectly.

Future research could refine and extend the present analysis in several directions. One avenue would be to disentangle the different dimensions of uncertainty—such as risk, ambiguity, and model misspecification—and to construct tailored indicators for each, examining their potentially divergent effects on a broader set of environmental outcomes, including ecological footprint, local air quality measures, and indicators of green innovation. Another promising direction would be to apply more flexible and up-to-date panel econometric techniques, and to replicate similar analyses for alternative country groupings or individual economies, thereby enhancing the robustness and external validity of the findings. Incorporating non-linear income terms to test the EKC hypothesis more directly and augmenting the empirical model with additional explanatory variables, such as globalization, trade openness, institutional quality, tourism intensity, or green technology indicators, would also help broaden the scope of the results. Finally, comparative panel studies that jointly cover advanced and emerging economies could shed further light on how the uncertainty–environment nexus varies with income level, global integration, and institutional characteristics, providing a richer basis for international policy design.

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