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Environmental Sustainability in EU and BRICS Economies: Long-Run, Heterogeneous, and Causal Dynamics[1]

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Abstract

Environmental sustainability is a fundamental prerequisite for achieving long-term economic growth and sustainable development. This study comparatively examines the determinants of environmental degradation in EU and BRICS economies over the period 1995-2021. Specifically, it analyzes the effects of fossil energy consumption, renewable energy consumption, economic growth, industrialization, and natural resource rents on environmental degradation. To provide a comprehensive empirical framework, the PMG-DFE ARDL approach is employed to capture short- and long-run dynamics, while the CS-ARDL approach is used as a robustness check against potential cross-sectional dependence. In addition, simultaneous quantile regression is applied to examine heterogeneous effects across different emission levels, and the Emirmahmutoğlu and Köse (2011) panel causality test is used to identify directional causal relationships among the variables. The findings reveal that the determinants of environmental degradation differ between EU and BRICS economies. The long-run results indicate that fossil energy consumption, industrialization, and natural resource rents increase environmental degradation in both groups, whereas economic growth has a mitigating effect. Renewable energy reduces environmental degradation in the EU but does not exert a significant mitigating effect in BRICS economies. The error-correction coefficients show that adjustment toward the long-run equilibrium occurs faster in the EU than in BRICS. The quantile regression results further indicate that fossil energy remains the primary driver of emissions in both groups, although its effects vary across emission levels. The causality results reveal bidirectional causal linkages between environmental degradation and the explanatory variables. Overall, the findings suggest that differentiated policy strategies are needed to enhance environmental sustainability in EU and BRICS economies.

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1. Introduction

Environmental sustainability has become a global priority and a prerequisite for sustainable economic and social development. Limiting ecological degradation is essential, with carbon dioxide (CO_2) emissions mainly from fossil fuel use and industrialization representing the key driver of climate change and a major threat to ecosystems and development goals (Stern, 2008; IPCC, 2023). Thus, reducing CO_2 emissions remains central to sustainability policies (Grossman & Krueger, 1995).

In the European Union (EU), sustainability is embedded in climate and environmental frameworks such as the 8th Environmental Action Programme and the European Green Deal, which emphasize safeguarding ecosystems and adapting to climate risks (Pindaru et al., 2023; European Commission, 2024a). The BRICS bloc also underlines in its declarations the need for collective responses, framing sustainability as both an environmental and socio-economic resilience strategy (BRICS, 2024a).

Fossil fuel dependence continues to challenge sustainability. The EU seeks to reduce reliance through the “Fit for 55” package and the European Climate Law (Schlacke et al., 2022; European Commission, 2023), while BRICS countries, though still reliant on fossil fuels, stress just transition and climate finance as mitigation tools (Yao et al., 2023; BRICS, 2024b). Investments in renewable energy are at the core of both blocs’ strategies: EU reports highlight their role in reducing emissions and fostering green growth (Dvořák et al., 2017; European Commission, 2024b), whereas BRICS leverages its vast solar, wind, and hydropower potential to accelerate the transition (BRICS, 2024c).

From an economic perspective, the EU increasingly aligns growth with green policies (Eurostat, 2025), while the BRICS integrates environmental goals into their development strategies toward carbon neutrality (BRICS Policy Center, 2024). Industrialization remains a critical factor: the EU promotes the circular economy and clean production (European Commission, 2023), while the BRICS advance green industrial policies consistent with their development agendas (BRICS, 2024d). Both blocs also emphasize sustainable resource management in the EU by reducing consumption (European Commission, 2024a), and BRICS by positioning biodiversity and energy resources as strategic assets globally (Wilson, 2015; BRICS, 2024a).

Considering EU and BRICS economies together provides an opportunity to comparatively assess how environmental degradation is shaped under different development models and structural characteristics. EU countries generally have stronger institutional structures, stricter environmental policies, advanced technological capacity, and regulatory frameworks that support the transition to renewable energy. By contrast, BRICS economies display different dynamics in terms of environmental sustainability due to their high growth potential, rapid industrialization, increasing energy demand, and relatively greater dependence on natural resources.

Therefore, comparing EU and BRICS countries makes it possible to understand the effects of fossil energy consumption, renewable energy, economic growth, industrialization, and natural resources on environmental degradation not only at the general level, but also in the context of structural differences between developed and emerging economies. In this respect, the selection of these country groups strengthens the comparative contribution of the study and allows policy recommendations to be developed more realistically according to different economic structures.

Environmental degradation remains a major challenge for sustainable development. Although the determinants of environmental degradation have been widely examined in the existing literature, a significant number of studies consider variables such as energy consumption, economic growth, or natural resources separately. Research that evaluates the joint effects of fossil fuel use, renewable energy consumption, economic growth, industrialization, and natural resources on environmental sustainability within an integrated framework remains limited. Moreover, although the effects of these variables may differ depending on countries' levels of development, production structures, energy transition capacity, and institutional characteristics, relatively few studies comparatively examine two structurally distinct and important country groups such as the EU and BRICS.

This study aims to fill this gap by comparatively examining EU and BRICS economies over the period 1995-2021. Accordingly, PMG-DFE-CS ARDL, simultaneous quantile regression, and the Emirmahmutoğlu and Köse (2011) causality test are employed. The main objective of the study is to reveal the effects of fossil energy consumption, renewable energy consumption, economic growth, industrialization, and natural resources on environmental degradation within the framework of long-run dynamics, heterogeneous effects, and causal linkages. In doing so, the study seeks to explain how differences in economic structure, institutional characteristics, industrialization levels, and energy policies shape environmental sustainability outcomes in EU and BRICS countries.

Within this framework, the study addresses four main research questions. First, it examines how fossil energy consumption, renewable energy consumption, economic growth, industrialization, and natural resources affect environmental sustainability through environmental degradation in EU and BRICS countries. Second, it investigates whether the long-run effects of these variables differ between the two country groups. Third, using simultaneous quantile regression, it evaluates whether the effects of these variables are heterogeneous across countries with low and high emission levels. Fourth, by applying the Emirmahmutoğlu and

Köse (2011) causality test, it reveals whether the causal relationships among the variables differ between EU and BRICS economies.

In this respect, the study makes three main contributions to literature. First, it evaluates the joint effects of fossil energy consumption, renewable energy consumption, economic growth, industrialization, and natural resources in explaining environmental degradation by incorporating these variables into the same model. Second, by comparing EU and BRICS economies, it shows how the determinants of environmental degradation differ between developed and emerging economies. Third, by jointly analyzing long-run relationships through PMG-DFE-CS ARDL, heterogeneous effects across different emission levels through simultaneous quantile regression, and causal relationships through the Emirmahmutoğlu and Köse (2011) test, the study provides a more comprehensive, comparative, and policy-oriented perspective to the literature.

This study proceeds in five sections. Section 2 reviews the literature and identifies existing gaps. Section 3 presents the methodology, data, and model employed. Section 4 reports and discusses the empirical findings. The final section provides overall conclusions.

2. Theoretical Framework and Literature Review

Theoretical Framework

CO_2 emissions are a multidimensional indicator of environmental degradation shaped by countries' production structures, energy composition, economic growth processes, levels of industrialization, and patterns of natural resource utilization. In environmental economics literature, the relationship between economic activities and environmental quality is generally explained through the channels of production scale, technological progress, energy use, and structural transformation. Grossman and Krueger (1995) argued that the impact of economic growth on environmental indicators is not linear, suggesting that income growth initially increases environmental degradation but may support environmental improvement after a certain income threshold is reached. This approach later formed the foundation of the Environmental Kuznets Curve literature. However, Stern (2004) emphasized that the assumption that economic growth automatically generates environmental improvement is not always valid, as this relationship depends on energy structure, technological capacity, and environmental policies. Therefore, when evaluating the determinants of CO_2 emissions, attention should be directed not only to income levels but also to energy consumption structures, industrialization processes, and dependence on natural resources.

Fossil energy consumption is one of the primary determinants of CO_2 emissions. Fossil fuels such as coal, oil, and natural gas are extensively utilized in electricity generation, industrial production, transportation, and household consumption. The high carbon intensity of fossil fuels causes increases in energy consumption to directly intensify environmental degradation. Ang (2007) demonstrated the existence of a strong and long-run relationship among energy consumption, economic output, and CO_2 emissions, showing that emissions cannot be evaluated independently of economic activities. Similarly, Mudakkar et al. (2013) examined the linkages among energy consumption, industrialization, economic growth, and environmental degradation, emphasizing that energy use is a key determinant of both production capacity and environmental pressure. In this context, an increase in fossil energy consumption is expected to raise CO_2 emissions.

Renewable energy consumption, on the other hand, is considered one of the key mechanisms capable of mitigating environmental degradation. Since renewable energy sources have lower carbon intensity compared to fossil fuels, they can limit carbon emissions from energy production. Apergis and Payne (2010) demonstrated the existence of a long-run relationship between renewable energy consumption and economic growth, highlighting that renewable energy should be considered an important component of the growth process. Likewise, Balsalobre-Lorente et al. (2018) investigated the relationship among economic growth, renewable electricity consumption, natural resources, and CO_2 emissions, revealing that renewable energy use may play a significant role in reducing carbon emissions. Within this framework, renewable energy consumption is expected to exert a mitigating effect on CO_2 emissions.

The relationship between economic growth and CO_2 emissions can be explained through the channels of production scale and energy demand. Economic growth expands production, investment, consumption, and transportation activities, thereby increasing energy demand. In economies where energy supply is largely dependent on fossil fuels, this process intensifies CO_2 emissions. However, at more advanced stages of economic growth, technological progress, energy efficiency, environmental regulations, and the increasing share of the service sector may reduce emission pressures. Grossman and Krueger (1995) explained this process by suggesting that environmental degradation may initially increase and subsequently decline with rising income, whereas Stern (2004) argued that this relationship is not automatic and depends on countries' energy composition and environmental policies. Therefore, although the impact of economic growth on CO_2 emissions is generally expected to be positive, the magnitude of this effect may vary depending on countries' level of development and production structure.

Industrialization is an important structural factor that may increase CO_2 emissions. The industrial sector mainly consists of energy-intensive production activities such as manufacturing, cement, iron and steel, chemicals, energy, and mining. The widespread use of fossil fuels in these sectors increases the carbon intensity of industrialization. Mudakkar et al. (2013) examined the relationship among energy consumption, industrialization, and environmental degradation, emphasizing the impact of industrial production on energy demand and emissions. Therefore, increases in the level of industrialization are expected to raise CO_2

emissions, particularly in economies characterized by fossil fuel-based production structures. However, technological transformation, energy efficiency investments, and cleaner production processes may gradually reduce the emission-enhancing effect of industrialization over time.

The relationship between natural resources and CO_2 emissions can be explained through the channels of resource dependence, resource extraction, and environmental degradation. Since the extraction, processing, and export of natural resources require high levels of energy consumption, they may contribute to increasing CO_2 emissions. Moreover, in resource-dependent economies, production structures are often concentrated around carbon-intensive sectors, thereby intensifying environmental pressure. The resource curse approach developed by Auty (1993) suggested that natural resource abundance may not always translate into sustainable development, while Sachs and Warner (1995, 2001) demonstrated that dependence on natural resources may generate adverse effects on economic performance and institutional structures. Balsalobre-Lorente et al. (2018) and He et al. (2022) investigated the relationship among natural resources, renewable energy, economic growth, and greenhouse gas emissions, revealing that natural resources constitute a critical variable in terms of environmental sustainability. Therefore, dependence on natural resources is expected to increase CO_2 emissions; however, this effect may weaken if resource revenues are directed toward clean energy investments and environmental technologies.

Literature Review

Environmental sustainability has been extensively examined through both single-country and multi-country samples. In the literature, some studies evaluate environmental sustainability through indicators of environmental degradation, such as CO_2 emissions and ecological footprint (Sarkodie et al., 2020; Adebayo & Kirikkaleli, 2021; Chien et al., 2021; Pata, 2021; Kartal, 2022; Suki et al., 2022; Aydın et al. (2024). Other studies focus on the dimension of environmental quality by employing indicators such as greenhouse gas emissions, CO_2, and ecological footprint (Khan et al., 2020; Zafar et al., 2020; Miao et al., 2022; Mujtaba et al., 2022; Usman et al., 2022; Wang et al., 2022; Caglar et al., 2024). More recently, the load capacity factor has also begun to be used as a measure of environmental sustainability (Dam et al., 2023; Raihan et al., 2024; Çamkaya et al., 2025). At this point, the interpretation of these indicators is of considerable importance. While environmental quality indicators represent sustainability in a positive manner, environmental degradation indicators imply the opposite. This study constructs its analytical framework based on the environmental degradation approach.

Renewable and fossil energy consumption are among the main determinants of environmental sustainability; however, the effects of these two energy types differ substantially (Güney, 2019; Sarkodie et al., 2020; Abbasi et al., 2022; Kartal, 2022; Raihan & Tuspekov, 2022; Bergougui, 2024; Nam et al., 2024; Raihan et al., 2024). Renewable energy, which is based on sources such as solar, wind, biomass, and hydroelectric power, contributes to mitigating the effects of climate change by reducing CO_2 emissions and supporting ecological balance. Empirical studies generally reveal a negative relationship between renewable energy use and environmental degradation (Alola et al., 2019; Khan et al., 2020; Kirikkaleli & Adebayo, 2021; Usman et al., 2020; Zafar et al., 2020; Adebayo & Kirikkaleli, 2021; Chien et al., 2021; Pata, 2021; Ahmed et al., 2022; Adebayo, 2022; Karaaslan & Camkaya, 2022; Miao et al., 2022; Mujtaba et al., 2022; Raihan et al., 2022; Suki et al., 2022; Sun et al., 2022; Usman et al., 2022; Wang et al., 2022; Arvas et al., 2023; Dam et al., 2023; Caglar et al., 2024; Camkaya & Karaaslan, 2024; Ma et al., 2024; Li et al., 2024). For instance, Liv et al. (2024) found that renewable energy reduced CO_2 emissions in China during the 2000–2020 period, while similarly, Çamkaya and Karaaslan (2024) reported that renewable energy decreased the load capacity factor in the United States. Likewise, Zafar et al. (2020) reached similar conclusions for 53 upper-middle-income countries over the 1990-2020 period.

In contrast, fossil fuel consumption exhibits a positive relationship with environmental degradation by intensifying global warming, environmental pollution, and resource depletion (Abokyi et al., 2019; Asongu et al., 2020; Li & Haneklaus, 2022; Eweade et al., 2024; Wang & Azam, 2024; Çamkaya et al., 2025a). Li and Haneklaus (2022) demonstrated that fossil fuel use increased CO_2 emissions in China during the 1992-2020 period. Eweade et al. (2024) revealed that fossil fuel consumption increased the ecological footprint in Mexico over the 1975-2020 period. Çamkaya et al. (2025a) showed that fossil fuel consumption increased the load capacity factor in E-7 countries during the 1985-2019 period. The broader category of non-renewable energy use, which includes fossil energy consumption, has also been confirmed to weaken environmental sustainability by increasing both CO_2 emissions and ecological footprint (Ulucak & Ozcan, 2020; Awosusi et al., 2022; Khan et al., 2022; Mujtaba et al., 2022; Zhang, 2024). For example, Mujtaba et al. (2022) determined that non-renewable energy use increased emissions and ecological footprint in OECD countries during the 1970-2016 period.

Economic growth is one of the most widely debated determinants of environmental sustainability. While economic growth increases energy demand and natural resource use, uncontrolled growth in most cases accelerates environmental degradation (Alola et al., 2019; Adebayo & Kirikkaleli, 2021; Ahmed et al., 2021; Abbasi et al., 2022; Li & Haneklaus, 2022; Miao et al., 2022; Mujtaba et al., 2022; Raihan et al., 2022; Raihan & Tuspekov, 2022; Wang et al., 2022; Arvas et al., 2023; Azam et al., 2023; Caglar et al., 2024; Eweade et al., 2024; Kahai & Omri, 2024; Nam et al., 2024; Raihan et al., 2024; Çamkaya et al., 2025b; Polat, 2026). For example, Nam et al. (2024) demonstrated that economic growth increased Vietnam's ecological footprint during the 1986-2022 period. Similarly, Çamkaya et al. (2025b) showed that economic growth increased the load capacity factor in France over the 1985-2021 period.

Nevertheless, in developed economies, economic growth may also play a mitigating role in environmental degradation by financing environmental protection investments, green policies, and the transition toward cleaner technologies

(Adebayo, 2022; Mohsin et al., 2022; Usman et al., 2022; Horobet et al., 2025). Mohsin et al. (2022) obtained findings supporting this argument for Asian and European countries during the 1971-2016 period.

Industrialization similarly exhibits a complex mechanism of influence in terms of environmental sustainability. In the early stages of industrialization, particularly in developing countries where environmental regulations are weak, increased production generally intensifies pollution (Ghazouani, 2022; Mentel et al., 2022; Raihan et al., 2022; Patel & Mehta, 2023; Salahodjaev et al., 2023; Hassan et al., 2025). Patel and Mehta (2023) revealed that industrialization increased CO_2 emissions in India during the 1971-2019 period, while Salahodjaev et al. (2023) reached similar conclusions for OIC member countries over the 1995-2020 period. However, industrialization may also support sustainability through the development of cleaner technologies, the expansion of renewable energy use, and improvements in resource efficiency (Abokyi et al., 2019; Ahmed et al., 2022; Rahman & Alam, 2022; Ali et al., 2023; Chen & Nguea, 2025; Hassan et al., 2025). For instance, Chen and Nguea (2025) reported that industrialization reduced pollution in Africa during the 2000-2021 period, while Hassan et al. (2025) obtained similar findings for South Asia over the 1990-2018 period.

Natural resources use further complicated discussions on environmental sustainability. Increasing global demand intensifies pressure on limited resources and renders the assumption of unlimited growth increasingly controversial (Wang & Azam, 2024). Although renewable natural resources may contribute to alleviating environmental pressures (Nam et al., 2024), empirical findings present a complex picture in this regard. Some studies highlight the positive effects of natural resources by showing that they reduce environmental degradation (Asongu et al., 2020; Khan et al., 2022; Azam et al., 2023). For example, Azam et al. (2023) found that industrialization reduced CO_2 emissions in France during the 1990-2018 period. In contrast, other studies argue that natural resource use negatively affects environmental sustainability (Ulucak et al., 2020; Zafar et al., 2020; Miao et al., 2022; Li et al., 2024; Ma et al., 2024; Bai et al., 2025). For instance, Ma et al. (2024) revealed that industrialization increased the ecological footprint in green economies during the 1990-2021 period. Similarly, Bai et al. (2025) showed that natural resources increased the ecological footprint over the 2000-2022 period.

Literature Gap

Although the relationship between environmental sustainability and environmental degradation has been extensively examined in the literature, a significant portion of existing studies investigate determinants such as fossil energy consumption, renewable energy use, economic growth, industrialization, and natural resources separately. Consequently, studies that evaluate the joint effects of these variables on environmental degradation within a holistic and comparative framework remain limited. Furthermore, the extent to which these effects differ between developed and emerging economies has not been sufficiently clarified.

This study aims to fill this gap by comparatively analyzing EU and BRICS economies over the 1995-2021 period. While EU countries are characterized by stronger institutional structures, environmental policies, and energy transition strategies, BRICS economies exhibit different dynamics, including rapid growth, intensive industrialization, increasing energy demand, and dependence on natural resources. Therefore, comparing these two country groups is important for revealing how environmental degradation is shaped under different economic structures, institutional characteristics, and energy policies. Methodologically, the study investigates long-run relationships through the PMG-DFE-CS ARDL approach, heterogeneous effects across different emission levels through simultaneous quantile regression, and directional relationships among variables through the Emirmahmutoğlu and Köse (2011) causality test. In this way, the study provides a comprehensive contribution to the environmental sustainability literature from both comparative and methodological perspectives. Based on this framework, the following hypotheses are tested.

H1: In EU and BRICS countries, increased fossil fuel consumption raises CO_2 emissions, accelerates environmental degradation, and undermines sustainability.

H2: In EU and BRICS countries, greater renewable energy use reduces CO_2 emissions, mitigates environmental degradation, and supports sustainability.

H3: In EU and BRICS countries, accelerated economic growth, through higher production and energy demand, raises CO_2 emissions and threatens sustainability.

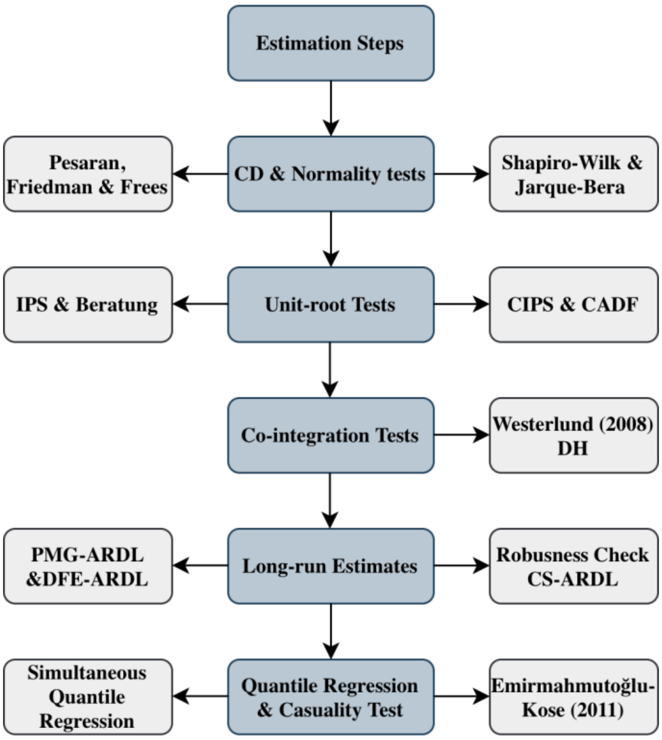
H4: In EU and BRICS countries, industrialization, driven by high energy intensity and fossil fuel dependence, increases CO_2 emissions and deepens environmental degradation.

H5: In EU and BRICS countries, intensive exploitation of natural resources increases environmental pressures, raises CO_2 emissions, and weakens sustainability.

3. Methodology

This study employs a multi-step methodology to examine the effects of fossil fuels, renewable energy, economic growth, industrialization, and natural resources on CO_2 emissions in EU and BRICS countries. Following normality (Shapiro-Wilk, Jarque-Bera), slope heterogeneity, and cross-sectional dependence (Pesaran, Friedman, and Frees) tests, both first- and second-generation unit root tests were applied to account for potential dependencies. Long-run relationships were evaluated using the Westerlund (2008) Durbin-Hausman (DH) cointegration test, while long-run coefficients were estimated through the PMG-DFE ARDL approach. In addition, a robustness check was conducted using the CS-ARDL method in order to account for the potential effects of cross-sectional dependence. Simultaneous quantile regression was applied to identify heterogeneous effects, and the analyses were further complemented by the Emirmahmutoğlu and Köse (2011) causality test to determine directional causal relationships among the variables. Figure 1 illustrates the empirical framework.

Figure 1. Structured schematic representation of the econometric modeling framework



Source: Created by author(s)

Cross-Sectional Dependence (CD) Test

Before the analysis, cross-sectional dependence (CD) was examined using three tests: Pesaran (2004), Friedman (1937, 1940), and Frees (1995). The Pesaran CD test, based on average residual correlations, is suitable for large panels and detects common shocks, though it is sensitive to outliers (Pesaran, 2004). The Friedman test, a non-parametric rank-based method, performs well in small samples and in the presence of outliers, complementing situations where normality is doubtful (Friedman, 1937, 1940; Gibbons & Chakraborti, 2014). The Frees test, relying on squared rank correlations, is effective in panels with small T and large N, addressing some limitations of other approaches (Frees, 1995; De Hoyos & Sarafidis, 2006; Larsen, 2006). Applying all three improves robustness, as each compensates for the others' weaknesses, providing a clearer view of cross-sectional linkages (De Hoyos & Sarafidis, 2006).

Slope Heterogeneity

In panel data analyses, it is important to determine whether the coefficients of variables exhibiting a long run cointegration relationship are homogeneous. The homogeneity test examines whether a change occurring in one of the countries included in the panel generates a similar level of impact on the other countries. In this context, coefficients are expected to be heterogeneous in models constructed for countries with different economic structures, whereas country groups with similar economic characteristics are expected to exhibit a more homogeneous coefficient structure.

The homogeneity assumption frequently employed in panel data analyses presume that all cross-sectional units share identical coefficients. When the homogeneity assumption is violated, homogeneous panel estimators such as fixed effects or pooled models may produce biased and inconsistent results (Pesaran & Smith, 1995). Therefore, testing whether coefficients are homogeneous is of critical importance for selecting the appropriate model specification in panel data applications.

In this regard, Pesaran and Yamagata (2008) developed the delta (Δ) and adjusted delta (Δadj) tests to examine coefficient homogeneity in panel data models. These tests are based on the differences between the mean group estimator and pooled estimators, thereby statistically determining whether the coefficients are truly identical. While Δ is used for large samples, Δadj is employed for small samples. The null hypothesis of the test states that the slope coefficients are homogeneous. According to the obtained findings, when homogeneity is rejected, heterogeneous panel estimators should be preferred (Pesaran et al., 1999). This approach contributes to obtaining reliable and consistent findings, particularly in comparative studies focusing on macroeconomic, environmental, and financial issues.

Stationary Test

In panel data analysis, the validity of unit root tests critically depends on the presence of cross-sectional dependence. First-generation tests assume cross-sectional independence, which can lead to biased outcomes when countries are exposed to common shocks. To ensure robustness, this study applies both first-generation tests, IPS (Im, Pesaran & Shin, 2003) and Breitung (2000), and second-generation tests, CADF and CIPS (Pesaran, 2007), based on the results of the CD test. The IPS test accounts for heterogeneous dynamics across panel units by estimating individual ADF regressions and combining their t-statistics into a panel-level indicator (Im et al., 2003). The Breitung test, in turn, removes fixed effects and trends, providing standardized statistics that are relatively powerful in panels with small time dimensions and large cross-sections, although it remains sensitive to heteroskedasticity and ignores cross-sectional dependence (Breitung, 2000; Baltagi, 2015; Agan, 2024). To overcome this limitation, second-generation approaches are employed. The CADF test extends the Dickey-Fuller framework by incorporating cross-sectional averages and their lagged values, thereby capturing common shocks and interdependencies (Pesaran, 2007a). Building on CADF, the CIPS test aggregates the unit-specific CADF statistics into a panel-level measure, making it particularly suitable for panels with large N and T, and providing more reliable inference under cross-sectional dependence (Pesaran, 2007a, 2007b).

Co-integration Tests

In this study, the Durbin-Hausman panel cointegration test developed by Westerlund (2008) is employed to examine the existence of a long-run relationship among the variables. The Westerlund (2008) test is classified as a second-generation panel cointegration test, as it provides reliable results particularly in panel datasets characterized by cross-sectional dependence and heterogeneity. In this respect, the test enables more consistent findings by accounting for common shocks across the countries or units constituting the panel. Moreover, provided that the dependent variable is integrated of order one, I (1), the test allows the independent variables to exhibit different levels of stationarity, either in levels or first differences.

The Westerlund (2008) Durbin-Hausman test examines the null hypothesis that there is no cointegration relationship in the panel. Rejection of the null hypothesis indicates the existence of a long-run equilibrium relationship among the variables used in the study. Conversely, failure to reject the null hypothesis implies that there is no statistically significant cointegration relationship among the variables.

In this test, the existence of a long-run relationship is evaluated through the stationarity of the error terms. If a cointegration relationship exists among the variables, the error terms obtained from the model should be stationary, indicating that the variables move together in the long run. The Westerlund (2008) approach is based on the Durbin–Hausman principle, comparing different estimators of the autoregressive parameter and testing for the existence of cointegration through this comparison.

The Westerlund (2008) test produces two different statistics: the Durbin-Hausman group statistic (DHg) and the Durbin-Hausman panel statistic (DHp). The Durbin-Hausman group statistic allows the cointegration coefficients to be heterogeneous across the cross-sectional units constituting the panel. Therefore, the alternative hypothesis suggests that a cointegration relationship exists in at least some of the cross-sectional units. In contrast, the Durbin-Hausman panel statistic considers a more homogeneous structure across the panel and tests for the existence of a cointegration relationship for the panel as a whole. The DHg and DHp statistics are presented in the following equation.

$$DH_g = \sum_{i=1}^{N} \hat{S}_i \, (\tilde{\phi}_i - \hat{\phi}_i)^2 \tag{1}$$

$$DH_p = \hat{S}_N(\tilde{\phi} - \hat{\phi})^2 \tag{2}$$

Where, i denotes the cross-sectional unit, while N represents the total number of cross-sectional units in the panel. $\tilde{\phi}$ and $\hat{\phi}$ refer to different estimators associated with the error-correction process. A statistically significant difference between these two estimators indicates the existence of a long run cointegration relationship among the variables.

PMG and DFE ARDL Tests

The primary reason for employing the PMG-DFE ARDL approach in this study is its ability to estimate both short-run dynamics and long-run equilibrium relationships within a single panel data framework. The relationships between environmental degradation, energy consumption, economic growth, industrialization, and natural resources may differ in the short run depending on countries' economic conditions, energy prices, policy responses, and production structures. In contrast, a more stable equilibrium relationship among these variables is expected to emerge in the long run. The PMG-ARDL approach allows short-run coefficients, error-correction terms, and adjustment speeds to vary across countries under the assumption that long-run coefficients may be common across the panel. This characteristic provides an important advantage for country groups such as the EU and BRICS, which differ in terms of economic structure, institutional capacity, energy transition, and level of industrialization.

In addition, the DFE approach contributes to the reliability of the estimation results by controlling for country-specific unobserved fixed effects within the panel. The ARDL structure, on the other hand, accounts for the different lagged effects of the variables, thereby enabling a more flexible analysis of how environmental degradation evolves over time. Therefore, consistent with the objective of the study, the PMG-DFE ARDL method provides an appropriate methodological framework for jointly evaluating short-run fluctuations, long-run equilibrium relationships, and structural differences across countries.

The PMG-ARDL model, derived from the cointegrated ARDL framework of Pesaran (2007), serves as an alternative to GMM. It is particularly suitable when countries share common long-run relationships but differ in their short-run adjustment processes (Blackburne & Frank, 2007). Its error correction mechanism (ECM) reflects how quickly the system reverts to equilibrium following a shock, with long-run coefficients constrained to be homogeneous while short-run dynamics remain heterogeneous (Pesaran et al., 1999; Pesaran, 2007).

The DFE-ARDL differs in that it assumes full homogeneity of long-run coefficients across units, while allowing short-run coefficients and fixed effects to vary. This restriction reduces the number of estimated parameters, making the model more efficient in small samples (Pesaran et al., 1999; Blackburne & Frank, 2007). The general structure of the PMG-DFE error correction model is expressed as follows:

$$\Delta X_{it} = \phi_i\left(X_{i,t-1} - \emptyset_i' Y_{i,t-1}\right) + \sum_{j=1}^{p-1} \psi_{ij}^{*} \Delta X_{i,t-j} + \sum_{j=0}^{q-1} \vartheta_{ij}^{*} \Delta Y_{i,t-j} + \mu_i + \varepsilon_{it} \quad (3)$$

In this framework, X_{it} is the dependent variable, Y_{it} the vector of independent variables, and ϕ_i the error-correction coefficient. A negative and significant $\emptyset_i$ indicates convergence to long-run equilibrium. Long-run coefficients are assumed common across the panel, while short-run dynamics vary by country (Pesaran et al., 1999).

The DFE-ARDL model imposes homogeneity on long-run coefficients, reducing parameter estimates but risking bias if the assumption fails (Loayza & Rancière, 2006). The PMG-ARDL, by contrast, allows short-run heterogeneity while constraining long-run effects, improving long-run inference but losing efficiency in small samples (Blackburne & Frank, 2007).

In this study, both estimators are applied. The DFE offers efficiency under homogeneity, while PMG reduces bias from heterogeneity. The Hausman test is used to compare the two and determine the appropriate specification (Pesaran et al., 1999).

CS-ARDL Test

In this study, the Cross-Sectional Augmented Autoregressive Distributed Lag Model (CS-ARDL), which is an extended version of the conventional panel PMG-ARDL approach developed by Pesaran et al. (1999), is employed as a robustness check. The CS-ARDL approach was developed by Chudik and Pesaran (2015) to account for cross-sectional dependence in dynamic heterogeneous panel data models.

The CS-ARDL method enables reliable estimations in panel data analyses, particularly in the presence of cross-sectional dependence. The main advantage of this method is that it controls the effects of unobserved common factors by incorporating the cross-sectional averages of both dependent and independent variables, together with their lagged values, into the model. In this way, common shocks and spillover effects that may arise among panel units such as countries, regions, or firms are prevented from biasing the estimation results.

Another advantage of the CS-ARDL approach is that it can be applied even when the variables have different orders of integration. In other words, the variables may be integrated of order zero, I(0), or order one, I(1), without restricting the applicability of the model. However, the variables must not be integrated in order two, I(2). This characteristic makes the method more flexible compared to conventional cointegration approaches. Furthermore, the CS-ARDL model allows the simultaneous estimation of short- and long-run coefficients and, through the error-correction mechanism, demonstrates the extent to which short-run deviations converge toward the long-run equilibrium.

The CS-ARDL approach is based on the logic of the mean group estimator, which involves conducting separate estimations for each cross-sectional unit. Therefore, the model allows slope coefficients to be heterogeneous across countries or units. This feature is important because it accounts for the economic, institutional, and structural differences among the countries included in the panel. Moreover, the inclusion of lagged cross-sectional averages in the model contributes to mitigating weak exogeneity and endogeneity problems (Chudik et al., 2017). The basic CS-ARDL model employed in this study is presented in the following equation.

$$\Delta Y_{it} = C_i + \lambda_i\left(Y_{i,t-1} - \beta_i X_{i,t-1} - \phi_{1i}\overline{Y}_{t-1} - \phi_{2i}\overline{X}_{t-1}\right) + \sum_{J=1}^{p-1}\theta_{ij}\Delta Y_{i,t-j} + \sum_{J=0}^{q-1}\zeta_{ij}\Delta X_{i,t-j} + \eta_{1i}\Delta\overline{Y}_t + \eta_{2i}\Delta\overline{X}_t + \varepsilon_{i,t} \qquad (4)$$

Where, Y_{it} denotes the dependent variable, while X_{it} represents the vector of explanatory variables. Δ indicates the first-difference operator, i refers to the cross-sectional unit, and t denotes the time dimension. $\bar{Y}_t$ and $\bar{X}_t$ represent the cross-sectional averages of the dependent and independent variables, respectively. In the model, λ_i denotes the error-correction coefficient, representing the speed at which short-run disequilibria adjust toward the long-run equilibrium. $\beta_i$refers to the long-run coefficients of the explanatory variables, whereas θ_{ij} and ζ_{ij} represent the short-run coefficients of the dependent and independent variables, respectively. Finally, ε_{it} denotes the error term.

Through this model, both the long-run equilibrium relationship among the variables and the short-run dynamics can be estimated simultaneously. In addition, the inclusion of cross-sectional averages in the model enables more consistent and reliable estimations by controlling for common shocks and cross-sectional dependence that may arise among the panel units.

Simultaneous Quantile Regression Test

This study applies to the simultaneous quantile regression (SQR) method to capture effects across different points of the conditional distribution. Unlike OLS, which estimates only the mean and assumes a uniform effect, quantile regression accounts for heterogeneity by evaluating impacts at different quantiles (Koenker & Bassett, 1978).

Unlike classical quantile regression, SQR estimates multiple quantiles within a single optimization process, ensuring parameter consistency. This approach reduces variance, enhances efficiency, and improves comparability of coefficients across quantiles (Chernozhukov & Hansen, 2008; Bondell et al., 2010; Chernozhukov et al., 2010; Machado & Santos Silva, 2019). The equation of the simultaneous quantile regression model used in this study is given below (Koenker, 2004).

$$Q_{y_{i,t}|x_{i,t}}(\tau) = \alpha_\tau + x'_{i,t}\beta_\tau + \varepsilon_{i,t,\tau} \tag{5}$$

Here, $\tau \in \{0.10, 0.20, \dots, 0.80, 0.90\}$ denotes the $\tau\, th$ quantile. $y_{i,t}$ represents the vector of dependent variables at the $\tau\, th$, while $x'_{i,t}$ denotes the vector of independent variables at the τ th quantile. α_τ and β_τ βτ represent the intercept and the coefficient parameters, respectively, at the τ th quantile. $\varepsilon_{i,t,\tau}$ denotes the error term.

Panel SQR allows for the direct observation of how the effects of policy variables differ, for example, between low-income and high-income groups or between low- and high-emission levels. In this way, policymakers can design more targeted strategies tailored to specific groups across different quantiles (Khan et al., 2024). Moreover, simultaneous quantile panel regression does not require normally distributed error terms and is robust to outliers (Koenker, 2004). This flexibility makes the method suitable for a wide range of applications.

Emirmahmutoğlu and Köse (2011) Panel Causality Test

In this study, the Emirmahmutoğlu and Köse (2011) panel causality test is employed to examine the causal relationships among the variables. This method is an adaptation of the Toda and Yamamoto (1995) causality approach to the panel data framework. The test can be applied while accounting for heterogeneity among the cross-sectional units constituting the panel, even when the variables have different orders of integration. However, the maximum order of integration to be used in the model must first be determined.

Under this approach, a VAR model is estimated for each cross-sectional unit, and the causality relationship is tested through a modified Wald test. In the Emirmahmutoğlu and Köse (2011) framework, the VAR model estimated for each cross-sectional unit is presented in the following equations.

$$X_{i,t} = \alpha_i + \sum_{j=1}^{k_i+d_{max}} \beta_{ij}\, X_{i,t-j} + \sum_{j=1}^{k_i+d_{max}} \gamma_{ij}\, Y_{i,t-j} + \varepsilon_{i,t} \tag{6}$$

$$Y_{i,t} = \delta_i + \sum_{j=1}^{k_i+d_{max}} \theta_{ij}\, Y_{i,t-j} + \sum_{j=1}^{k_i+d_{max}} \lambda_{ij}\, X_{i,t-j} + u_{i,t} \tag{7}$$

Where, $X_{i,t}$ and $Y_{i,t}$ denote the variables for which the causality relationship is investigated, i represents the cross-sectional unit, t indicates time, k_i refers to the optimal lag length for each cross-sectional unit, and d_{max} denotes the maximum order of integration of the variables. In the model, the VAR specification is estimated to have a lag length of $k_i + d_{max}$; however, the causality test is conducted only on the coefficients associated with the first k_i lagged terms.

In this test, the null hypothesis states that there is no causality relationship running from one variable to another. The Wald test statistics obtained for each cross-sectional unit are subsequently transformed into a panel-wide statistic through a Fisher-type test statistic. The Fisher test statistics are presented in the following equation.

$$\lambda = -2 \sum_{i=1}^{N} \ln{(p_i)} \tag{8}$$

Where, p_i represents the probability value associated with the Wald test obtained for each cross-sectional unit. The resulting Fisher test statistic is used to evaluate the existence of a causality relationship at the panel level.

Model and dataset

To examine the effects of environmental degradation in the EU and BRICS economies, the following variables were used for the period 1995-2021: CO_2 emissions (mt, total), fossil energy consumption (kWh per capita), renewable energy consumption (kWh per capita), GDP per capita (constant 2015, USD), industry (including construction), value added (constant 2015, USD), and total natural resource rents (= 2015, LCU). Data on fossil and renewable energy consumption were obtained from the Refinitiv database (Refinitiv Datastream), while the other variables were sourced from the World Bank's World Development Indicators (WDI). A summary table of the relevant variables used in this study is presented below.

Table 1. Variables table

Acronym	Variable	Measurement	Role	Expectation	Sources	References
lco2	Environmental degradation	Carbon dioxide emissions (mt, total)	Dependant	.	WDI	Abbasi et al. (2024), Shabeer & Rasul (2024), Zhang (2024)
lfos	Fossil fuel consumption	Fossil energy consumption (kWh, per person)	Independent	Positive	Refinitiv Datastream	Nam et al. (2024), Raihan et al. (2024), Somoye et al. (2024)
lren	Renewable energy consumption	Renewable energy consumption (kWh, per person)	Independent	Negative	Refinitiv Datastream	Bergougui (2024), Li et al. (2024),

						Nam et al. (2024)
lgdp	Economic growth	GDP per capita (=2015, $)	Independent	Positive/ Negative	WDI	Mujtaba et al. (2022), Kahai & Omri (2024), Raihan et al. (2024)
lind	Industrialization	Industry (including construction), value added (= 2015, $)	Independent	Positive/	WDI	Patel & Mehta (2023), Chen & Nguea (2025), Hassan et al. (2025)
lrent	Natural resources	Total natural resource rents (=2015, LCU)	Independent	Negative	WDI	Li et al. (2024), Ma et al. (2024), Nam et al. (2024)

In this study, environmental degradation is measured by CO_2 emissions (metric tons), the largest contributor to global greenhouse gases from fossil fuel combustion and cement production (WDG, 2024). Consistent with prior literature, CO_2 is the most widely used proxy for degradation (Sarkodie et al., 2020; Adebayo & Kirikkaleli, 2021; Chien et al., 2021; Pata, 2021; Kartal, 2022; Suki et al., 2022).

The first independent variable is fossil fuel consumption (terawatt-hours per capita), including coal, oil, and gas. Fossil fuels are the main source of CO_2, intensifying global warming and environmental harm (OWD, 2025; Li & Haneklaus, 2022; Eweade et al., 2024; Mujtaba et al., 2022; Zhang, 2024). In contrast, renewable energy consumption (terawatt hours per capita) including solar, wind, hydro, and biofuels supports sustainability by reducing emissions and mitigating climate change (IEA, 2024; Bergougui, 2024; Li et al., 2024; Nam et al., 2024).

Economic growth is captured by GDP per capita (constant 2015 USD). Growth may increase resource use and pollution (Mujtaba et al., 2022; Kahai & Omri, 2024; Raihan et al., 2024), but it can also finance cleaner technologies and green policies (Adebayo, 2022; Mohsin et al., 2022; Usman et al., 2022). Industrialization, measured as value added in mining, manufacturing, construction, electricity, water, and gas (constant 2015 USD), has both negative impacts (fossil energy use, waste, pollution) (Patel & Mehta, 2023) and positive effects (innovation, clean production, awareness) (Chen & Nguea, 2025; Hassan et al., 2025).

Finally, natural resources are proxied by total natural resource rents. Overexploitation can cause biodiversity loss, pollution, and climate stress (Miao et al., 2022; Li et al., 2024; Ma et al., 2024), whereas sustainable management can enhance ecological balance (Asongu et al., 2020; Khan et al., 2022; Azam et al., 2023). Measurement of all variables has been addressed within this framework. The mathematical form of the models used in this study is given in the following equation.

$$lco2 = f(lfos,\ lren,\ lgdp,\ lind,\ lrent) \qquad (9)$$

In the model, lco_2 is the dependent variable, while lfos, lren, lgdp, lind, and lrent are independent variables. The panel econometric model estimated in this study is presented in the following equation.

$$lco2_{it} = \alpha_0 + \beta_1 lfos_{it} + \beta_2 lren_{it} + \beta_3 lgdp_{it} + \beta_4 lind_{it} + \beta_5 lrent_{it} + \varepsilon_{it} (10)$$

Where, i represents countries and t denotes time. $lco2_{it}$ is the dependent variable representing environmental degradation. $lfos_{it}$, $lren_{it}$, $lgdp_{it}$, $lind_{it}$, and $lrent_{it}$ denote the independent variables representing fossil energy consumption, renewable energy consumption, economic growth, industrialization, and natural resource rents, respectively. α_0 represents the constant term of the model, β_1–β_5 denote the slope coefficients, and ε_{it} refers to the error term. All are presented in log-log form, enabling interpretation through elasticities that capture both the direction and magnitude of effects (Polat et al., 2025). The model is estimated separately for the EU and BRICS groups. The EU country list is shown in the next table.

Table 2. EU Country Group

Cyprus	Croatia	Denmark	Hungary	Austria	Belgium	Spain	Italy
Slovenia	Slovak Republic	Bulgaria	Portugal	Greece	Czechia	Poland	Germany
Estonia	Ireland	Sweden	Finland	Romania	Netherlands	France	

The study covers 23 EU member states, shaded by CO_2 emissions from lowest to highest. Cyprus and Slovenia record the lowest emissions, while Germany and Italy are the highest contributors. Latvia, Lithuania, Luxembourg, and Malta were excluded due to missing fossil fuel and renewable energy data, as a balanced panel was required. This ensured data consistency for the analysis. The BRICS member countries are presented in Table 3.

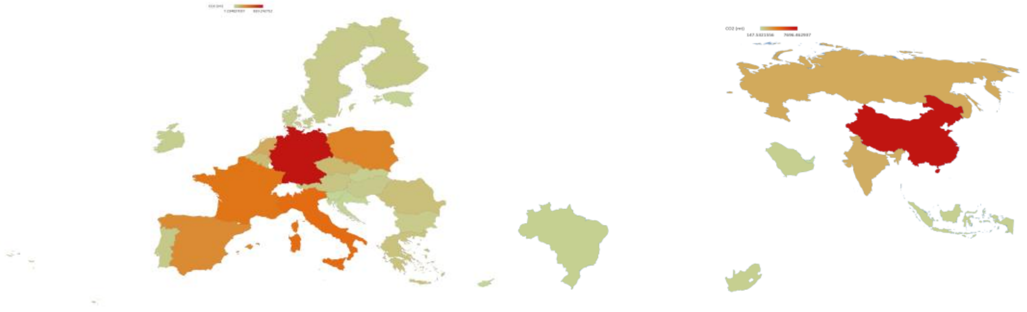
Table 3. BRICS Country Group

United Arab Emirates (UAE)	Brazil	South Africa	Iran, Islamic Rep.	Russian Federation
Egypt, Arab Rep.	Indonesia	Saudi Arabia	India	China

Table 3 lists the 10 BRICS countries analyzed, shaded by CO_2 emissions from lowest to highest. The UAE and Egypt show the lowest emissions, while China and Russia contribute the most. Ethiopia was excluded due to missing fossil fuel and renewable energy data, as a balanced panel was required.

The joint examination of EU and BRICS economies enables a comparative assessment of how environmental degradation is shaped under different development models and structural conditions. While EU countries are characterized by stronger institutional structures, stringent environmental policies, advanced technological capacity, and regulatory frameworks supporting the renewable energy transition, BRICS economies are distinguished by rapid growth, intensive industrialization, increasing energy demand, and greater dependence on natural resources. These differences suggest that the effects of fossil energy consumption, renewable energy, economic growth, industrialization, and natural resources on environmental degradation may vary across country groups. Therefore, the comparison between the EU and BRICS strengthens the comparative contribution of the study and enables the development of policy recommendations tailored to different economic structures. Map views of the EU (1) and BRICS (2) groups based on CO_2 emissions are shown below.

Figure 2. Map views of the EU (1) and BRICS (2) country groups based on CO2e



(1) (2)

Source: Created by author(s)

This study examines the effects of fossil fuels, renewable energy, economic growth, industrialization, and natural resources on environmental degradation in the EU and BRICS. Before estimation, correlation and descriptive statistics were reviewed to assess variable relationships and detect potential outliers. Results for the EU group are shown below.

Table 4. Correlation relationships, descriptive statistics and VIF (EU)

	VIF	**lco2**	**lfos**	**lren**	**lgdp**	**lind**	**lrent**
lco2	,	1					
lfos	1.30	0.201***	1				
		(0.000)					
lren	1.27	0.358***	-0.089**	1			
		(0.000)	(0.025)				
lgdp	2.02	0.173***	0.470***	0.012	1		
		(0.0000)	(0.000)	(0.766)			
lind	2.17	0.892***	0.168***	0.370***	0.523***	1	
		(0.0000)	(0.000)	(0.000)	(0.000)		
lrent	1.51	0.453***	-0.097**	0.373***	-0.091**	0.424***	1
		(0.000)	(0.016)	(0.000)	(0.023)	(0.000)	
Mean	1.66	4.336	10.312	13.198	10.001	24.669	25.316
Std. Dev.	.	1.140	0.345	8.323	0.672	1.425	2.441
Minimum	.	1.768	9.548	54.136	8.172	21.399	17.161
Maximum	.	6.846	11.121	17.026	11.453	27.592	30.717

Notes: Asterisks represent significance levels; one asterisk (*) represents 10%, two asterisks (**) represent 5%, and three asterisks (***) represent 1%. Values in parentheses are probability values.

For the EU group, correlations between lco_2 and all explanatory variables are significant at the 1% level. The correlation with lind is 89% and with lrent 45%, while lfos, lren, and lgdp show 20%, 36%, and 17%, respectively.

The potential multicollinearity problem was evaluated using the VIF test. The findings for the EU group indicate that both the variable-specific VIF values and the mean VIF value are below the threshold value of 5. These findings suggest that there is no serious multicollinearity problem in the model.

Descriptive statistics indicate no outliers for lfos, lgdp, and lind, but possible outliers for lren and lrent due to high standard deviations. To further check distributional properties, Shapiro-Wilk and Jarque-Bera normality tests were applied. Results for both the EU and the BRICS are given in the next tables.

Table 5. Normality test results

Shapiro-Wilk normality test (Shapiro & Wilk, 1965)					
Variable	**N**	**W**	**V**	**z**	**p>z**
e1	621	0.947	21.667	7.465	0.0000
e2	270	0.903	18.868	6.860	0.0000
Jarque-Bera normality test (Jarque & Bera, 1980)					
Variable	**N**	**Pr (skewness)**	**Pr (kurtosis)**	**Adj chi2 (2)**	**p >chi2**
e1	621	0.782	0.042	4.22	0.1210
e2	270	0.635	0.828	0.27	0.8730

Note: Here, e1 refers to the EU country group, while e2 refers to the BRICS country group.

Table 5 reports the Shapiro-Wilk and Jarque-Bera normality tests for the EU and BRICS. The null assumes normal distribution. For both groups, the Shapiro-

Wilk test was rejected at the 1% level, while the Jarque-Bera test could not be rejected. These mixed results cast doubt on whether residuals are normally distributed. The next table presents the correlation and descriptive statistics for the BRICS group.

Table 6. Correlation relationships, descriptive statistics and VIF (BRICS)

	VIF	lco2	lfos	lren	lgdp	lind	lrent
lco2		1					
lfos	6.38	-0.190*** (0.002)	1				
lren	3.01	0.486*** (0.000)	-0.616*** (0.000)	1			
lgdp	7.06	-0.318*** (0.000)	0.898*** (0.000)	-0.641*** (0.000)	1		
lind	1.46	0.860*** (0.000)	-0.120** (0.049)	0.294*** (0.000)	-0.066 (0.278)	1	
lrent	1.31	0.176*** (0.004)	-0.130** (0.034)	0.214*** (0.001)	-0.297*** (0.000)	0.098 (0.109)	1
Mean	3.84	6.399	9.921	17.994	8.694	30.831	33.095
Std. Dev.	.	1.147	1.144	15.982	1.067	1.023	3.404
Minimum	.	4.349	7.947	-37.861	6.431	29.047	28.680
Maximum	.	9.443	12.202	29.543	11.049	34.065	40.880

Notes: Asterisks represent significance levels; one asterisk (*) represents 10%, two asterisks (**) represent 5%, and three asterisks (***) represent 1%. Values in parentheses are probability values.

When examining the correlation findings for the BRICS country group, the correlation relationships between the dependent variable lco2 and the explanatory variables are statistically significant at the 1% significance level.

The VIF findings indicate that both the variable-specific VIF values and the mean VIF value are below the threshold value of 5. These findings suggest that there is no serious multicollinearity problem in the BRICS group model.

When the variables are reviewed to obtain prior information, it is observed that lco2, lfos, lgdp, and lind do not contain outliers. However, due to the minimum and maximum values, as well as their high standard deviations, the variables lren and lrent are likely to contain outliers.

4. ESTIMATION RESULTS AND DISCUSSION

This section presents the results for the EU and BRICS, based on analyses conducted in Stata 17. The first step was testing cross-sectional dependence, which occurs when error terms across units are correlated due to shocks from cooperation or spatial interactions. Ignoring this can bias standard errors and coefficient estimates. To address this, three tests (Pesaran, Friedman, and Frees) were applied. Their results are shown in the following table.

Table 7. Cross-sectional dependence test results

Country group	**Pesaran**	**Friedman**	**Frees**
EU	0.983	28.415	2.798*
BRICS	2.929***	49.054***	1.432*
Slope heterogeneity	$\hat{\Delta}$		$\hat{\Delta}_{Adj}$
EU	13.278***		15.428***
BRICS	6.577***		7.642***

Note: Asterisks represent significance levels; one asterisk (*) is 10%, two asterisks (**) is 5%, and three asterisks (***) is 1% significance level.

Table 7 shows the results of the Pesaran, Friedman, and Frees CD tests for the EU and BRICS. For the EU, the null of no dependence was not rejected in Pesaran and Friedman but was weakly rejected at the 10% significance level in Frees, suggesting mixed evidence. For BRICS, the null was strongly rejected at the 1% significance level in Pesaran and Friedman and weakly rejected in Frees, confirming cross-sectional dependence.

According to the findings of the slope heterogeneity test, the null hypothesis stating that “the slope coefficients are homogeneous” is rejected at the 1% significance level. This result indicates that the coefficients included in the model differ across countries and that slope heterogeneity exists in the panel. Based on these outcomes, both first- and second-generation unit root tests were applied. Results for the EU group are presented in the next table.

Table 8. First and second-generation panel unit root test results (EU)

Variables	**Model**	**IPS^a**	**IPS^b**	**Breitung^a**	**Breitung^b**	**CIPS^a**	**CIPS^b**	**CADF^a**	**CADF^b**
lco2	**C**	-1.526	-17.111***	-0.489	-11.800***	-2.257	-4.988***	-2.029	-2.449***
	C&T	-0.272	-16.658***	2.008	-10.291***	-2.516	-5.175***	-2.072	-2.653**
lfos	**C**	-0.749	-17.417***	-0.421	-11.375***	-2.116	-5.031***	-1.880	-2.564***
	C&T	-1.339	-15.603***	1.235	-9.570***	-2.603	-5.260***	-2.004	-2.683***
lren	**C**	0.661	-19.371***	0.675	-15.587***	-2.671	-5.437***	-1.822	-2.741***
	C&T	2.743	-16.257***	-3.017	-15.221***	-2.961	-5.567***	-2.074	-2.864***
lgdp	**C**	4.123	-9.251***	8.425	-9.096***	-2.110	-3.307***	-2.098	-2.441***

	C&T	-2.327	-6.363***	1.988	-4.616***	-2.359	-3.425***	-2.462	-2.588***
lind	**C**	0.549	-10.713***	4.069	-9.217***	-1.866	-3.751***	-1.796	-2.316***
	C&T	0.319	-8.922***	2.748	-6.035***	-2.042	-4.049***	-1.883	-2.589***
lrent	**C**	-3.350***	-18.201***	-5.653***	-13.164***	-2.273**	-5.192***	-1.588	-2.761***
	C&T	-1.909**	-15.836***	-1.824**	-7.565***	-2.842***	-5.18***	-1.871	-2.835***

Notes: a indicates level values, b indicates first difference values. Asterisks represent significance levels; one asterisk (*) indicates 10%, two asterisks (**) indicates 5%, and three asterisks (***) indicates 1%.

Table 8 reports the first- and second-generation panel unit root results for the EU group. At the level, the null of a unit root could not be rejected, but at first differences it was rejected, indicating that most variables are I(1). An exception is lrent, which appeared as I(0) in first-generation tests but as I(1) in second-generation tests, suggesting it may be stationary at both levels. Overall, the results support that the series are predominantly I(1), implying cointegration. The presence of long-run relationships is further tested through cointegration methods (Table 9). The next table presents unit root results for the BRICS group.

Table 9. First and second- generation panel unit root test results (BRICS)

Variables	**Model**	**IPS^a**	**IPS^b**	**Breitung^a**	**Breitung^b**	**CIPS^a**	**CIPS^b**	**CADF^a**	**CADF^b**
lco2	**C**	0.675	-8.951***	3.0718	-7.193***	-2.180	-4.183***	-2.246	-2.881***
	C&T	1.871	-7.164***	1.4602	-4.936***	-2.579	-4.130***	-2.794	-2.784**
lfos	**C**	-1.578	-10.960***	4.3195	-7.353***	-2.117	-4.187***	-1.633	-2.516***
	C&T	-1.039	-9.328***	0.9023	-4.202***	-2.388	-4.516***	-2.101	-2.874**
lren	**C**	1.938	-7.527***	1.6963	-8.290***	-2.148	-4.501***	-1.878	-2.571***
	C&T	-0.494	-5.283***	-1.6450	-7.569***	-2.085	-4.471***	-1.679	-2.732***
lgdp	**C**	2.633	-7.677***	6.5787	-6.274***	-1.973	-3.388***	-2.123	-2.703***
	C&T	0.133	-6.522***	2.9505	-4.807***	-1.808	-3.829***	-2.138	-2.890***

lind	**C**	0.049	-10.898***	3.2433	-7.407***	-2.522	-4.437***	-1.900	-2.474**
	C&T	-0.481	-8.926***	-0.3364	-6.340***	-2.583	-4.456***	-2.675	-3.328***
lrent	**C**	-1.598**	-12.324***	-2.5896***	-8.438***	-2.117	-5.185***	-1.761	-2.778***
	C&T	-0.805	-10.629***	-0.279	-7.947***	-2.557	-5.115***	-2.364	-3.944***

Notes: a indicates level values, b indicates first difference values. Asterisks represent significance levels; one asterisk (*) indicates 10%, two asterisks (**) indicates 5%, and three asterisks (***) indicates 1%.

The findings obtained from the unit root tests conducted for the BRICS country group indicate that the variables are generally not stationary at level and that the null hypothesis of a unit root cannot be rejected. In contrast, the rejection of the null hypothesis after taking first differences reveals that the variables largely become stationary in first differences. Although some findings suggest the possibility that the natural resource rents variable may be I(0), both first- and second-generation unit root tests generally indicate that most variables are I(1). These results provide an appropriate basis for investigating a long-run relationship among the variables and making the application of cointegration analysis necessary.

The findings of the stationarity analysis generally indicate that shocks occurring in the two country groups included in the model may have persistent effects on the series and that these effects do not disappear in the short run. In other words, the non-stationarity of the variables at level suggests that economic and environmental indicators exhibit long-run dynamics over time. Nevertheless, the fact that the series are generally integrated of order one, I(1), provides a suitable basis for applying cointegration analysis to investigate possible long-run relationships among the variables.

In the next stage of the study, the Westerlund (2008) Durbin-Hausman cointegration test is applied. Since one of the main requirements of this test is that the dependent variable must be I(1), the fact that the dependent variable becomes stationary in first differences for both the EU and BRICS country groups indicates that the necessary condition for the applicability of the test is satisfied. Accordingly, the table below presents the results of the Durbin-Hausman cointegration test for the EU and BRICS country groups.

Table 10. Westerlund (2008) Durbin-Hausman cointegration test results

Country group	Tests	z- value	p-value	Decision
EU	**DHg**	3.471***	0.0003	cointegration
	DHp	2.562***	0.0052	cointegration
BRICS	**DHg**	3.861***	0.0001	cointegration
	DHp	1.245*	0.0947	cointegration

Note: Asterisks represent significance levels, one asterisk (*) is 10%, two asterisks (**) is 5%, and three asterisks (***) is 1% significance level.

The table above presents the findings of the Westerlund (2008) Durbin–Hausman cointegration test. In interpreting the findings, the presence of slope heterogeneity in the panel was considered. Therefore, the DHg statistic, which is more appropriate for heterogeneous panels, was used as the basis for evaluation.

The DHg statistics are statistically significant at the 1% significance level for both the EU and BRICS country groups. This result indicates that the null hypothesis of "no cointegration relationship" is rejected. Accordingly, there exists a long run cointegration relationship between environmental degradation and fossil energy consumption, renewable energy consumption, economic growth, industrialization, and natural resource rents in both country groups. With this relationship established, long-run coefficients were estimated using PMG, DFE and CS panel ARDL, given the mixed order of integration (I(0)/I(1)). The results are presented in the following table.

Table 11. Panel ARDL results

Variables	EU			BRICS		
	PMG	**DFE**	**CS-ARDL**	**PMG**	**DFE**	**CS-ARDL**
lfos	0.853***	0.799***	0.991***	0.770***	0.904***	0.440***
	(0.014)	[0.069]	[0.000]	(0.077)	[0.125]	[0.000]
lren	-0.022***	0.003***	-0.012	0.001	-0.002	0.015
	(0.003)	[0.0004]	[0.217]	(0.002)	[0.003]	[0.006]
lgdp	-0.236***	-0.606***	-0.306***	-0.551***	-0.452**	-0.112*
	(0.016)	[0.183]	[0.003]	(0.083)	[0.209]	[0.072]
lind	0.142**	0.453***	0.070*	-0.838***	0.470**	0.049
	(0.015)	[0.153]	[0.068]	(0.087)	[0.214]	[0.524]
lrent	0.009***	0.022**	0.006*	-0.023*	0.107**	0.019
	(0.002)	[0.012]	[0.080]	(0.014)	[0.053]	[0.244]
ECT	-0.311***	-0.159***	0.006*	-0.161***	-0.105***	-0.742***
	(0.077)	[0.045]	[0.075]	(0.081)	[0.022]	[0.000]
Hausman	0.010			18.160***		

Note: Asterisks represent significance levels; one asterisk (*) represents 10%, two asterisks (**) represents 5%, and three asterisks (***) represents 1%. Values in parentheses are standard errors. Values in square brackets represent robust standard errors.

Table 11 reports the PMG-DFE ARDL long-run coefficients for the EU and BRICS groups, together with the CS-ARDL findings employed for robustness checks. The choice between the PMG and DFE models was made based on the Hausman test results. Accordingly, for the EU group, the Hausman test indicates that the PMG-ARDL model should be preferred. According to the EU findings, a 10% increase in (lfos), (lind), and (lrent) increases environmental degradation by 8.5%, 1.4%, and 0.09%, respectively. In contrast, a 10% increase in (lren) and (lgdp) reduces environmental degradation by 0.02% and 2.4%, respectively. The negative and statistically significant error-correction term indicates the existence of a long-run equilibrium relationship among the variables and shows that the system converges to its long-run equilibrium in approximately 3.2 years.

The CS-ARDL results for the EU group generally support the findings of the baseline model. In the CS-ARDL model, the coefficient of (lfos) is positive and significant at the 1% level. Accordingly, a 10% increase in fossil fuel consumption increases environmental degradation by approximately 9.9%. This result, consistent with the PMG-ARDL findings, indicates that fossil fuel consumption is one of the main determinants of environmental degradation. Similarly, (lgdp) is negative and statistically significant in the CS-ARDL model. A 10% increase in per capita income reduces environmental degradation by approximately 3.1%. This finding suggests that income growth in EU countries supports the transition to cleaner production technologies, environmental awareness, and environmentally friendly policies. The variables of industrialization and natural resource rents are also found to be positive and weakly significant in the CS-ARDL model. By contrast, although the renewable energy variable has a negative coefficient, it is not statistically significant. This indicates that renewable energy has a mitigating effect on environmental degradation, but this effect is not supported by strong statistical evidence in the CS-ARDL model.

For the BRICS group, the Hausman test results indicate that the DFE-ARDL model should be preferred. According to the DFE-ARDL findings, all variables except (lren) are statistically significant. Accordingly, a 10% increase in (lfos), (lind), and (lrent) increases environmental degradation by 9%, 4.7%, and 1.2%, respectively. In contrast, a 10% increase in (lgdp) reduces environmental degradation by approximately 4.5%. The negative and statistically significant error-correction term indicates that the adjustment mechanism toward long-run equilibrium operates in BRICS countries and that the system converges to its long-run equilibrium in approximately 9.1 years.

The CS-ARDL results for the BRICS group partially support the baseline model findings. In the CS-ARDL model, fossil fuel consumption is positive and significant at the 1% level. Accordingly, a 10% increase in fossil fuel consumption increases environmental degradation by approximately 4.4%. This finding confirms that fossil fuel consumption is one of the main factors increasing environmental degradation in BRICS countries. In addition, (lgdp) is negative and significant at the 10% level. This result indicates that an increase in per capita income has a reducing effect on environmental degradation in BRICS countries. However, in the CS-ARDL results, the industrialization and natural resource rents variables have positive coefficients but are not statistically significant. The renewable energy variable appears to have a positive coefficient, but its level of significance is limited; therefore, strong evidence cannot be obtained regarding the mitigating effect of renewable energy on environmental degradation in BRICS countries.

Overall, the PMG/DFE-ARDL results and the CS-ARDL robustness check findings provide consistent results, particularly for fossil fuel consumption and per capita income. In both the EU and BRICS groups, fossil fuel consumption emerges as one of the most important factors increasing environmental degradation, whereas per capita income has a reducing effect on environmental degradation. This indicates that the baseline model findings are largely confirmed by CS-ARDL, which is a more robust estimation method against cross-sectional dependence. However, the effects of renewable energy, industrialization, and natural resource rents vary across country groups and estimation methods. These differences stem from structural divergences between EU and BRICS economies in terms of energy structures, levels of industrialization, dependence on natural resources, and environmental policy capacities.

To account for heterogeneity, this study employs panel simultaneous quantile regression. Unlike mean-based methods, it estimates effects across different quantiles of the dependent variable, offering more robust results against outliers and non-normality. Table 12 reports the results for the EU group.

Table 12. Panel simultaneous quantile regression analysis results (EU)

Variables	**FE**	**q10**	**q20**	**q30**	**q40**	**q50**	**q60**	**q70**	**q80**	**q90**
lfos	0.880***	0.952***	0.905***	0.882***	0.876***	0.878***	0.895***	0.889***	0.808***	0.686***
	(0.036)	[0.068]	[0.020]	[0.020]	[0.021]	[0.023]	[0.024]	[0.031]	[0.039]	[0.027]
lren	0.004	-0.006***	-0.007***	-0.007***	-0.007***	-0.005***	-0.004**	-0.002***	0.0003***	0.003***
	(0.012)	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.002]	[0.002]	[0.003]	[0.002]
lgdp	-0.303***	-0.979***	-0.954***	-0.965***	-0.990***	-1.019***	-1.014***	-1.009***	-0.970***	-0.931***
	(0.067)	[0.054]	[0.020]	[0.023]	[0.024]	[0.016]	[0.012]	[0.015]	[0.020]	[0.018]
lind	0.205***	0.970***	0.978***	0.991***	1.002***	0.986***	0.975***	0.965***	0.951***	0.924***
	(0.065)	[0.018]	[0.008]	[0.010]	[0.011]	[0.011]	[0.008]	[0.008]	[0.008]	[0.008]
lrent	0.011**	-0.010***	-0.010***	-0.016***	-0.019***	-0.027***	-0.035***	-0.044***	-0.051***	-0.059**
	(0.005)	[0.004]	[0.002]	[0.002]	[0.004]	[0.007]	[0.006]	[0.005]	[0.005]	[0.005]

c	-7.086***	-19.446***	-19.370***	-19.150***	-19.009***	-18.107***	-17.846***	-17.316***	-16.321***	-14.525***
	(1.090)	[0.215]	[0.141]	[0.140]	[0.238]	[0.312]	[0.283]	[0.399]	[0.519]	[0.378]
R^2	0.902	0.851	0.860	0.852	0.846	0.846	0.852	0.856	0.859	0.855
N	621	621	621	621	621	621	621	621	621	621

Note: Asterisks represent significance levels; one asterisk (*) represents 10%, two asterisks (**) represent 5%, and three asterisks (***) represent 1%. Values in square brackets are robust standard errors obtained with a bootstrap with 1000 replications.

The table above presents the findings of the simultaneous quantile regression analysis conducted for the EU country group. According to the results, lfos is statistically significant across all quantiles and increases lco2. This indicates that fossil fuel consumption is an important determinant even in countries with low CO_2 emissions, although its effect diminishes somewhat in high-emission countries. lren is statistically significant in all quantiles. At lower and middle quantiles (q10-q80), lren reduces lco_2, but in the upper quantiles (q80 and q90), the sign changes, and lren increases lco_2. This suggests that renewable energy is effective at reducing emissions in low-CO_2-intensive countries, but in high-CO_2-intensive countries, it does not improve environmental sustainability. One reason is that countries such as Germany, Italy, and France, among the EU's highest CO_2 emitters, have large production volumes. In these cases, the impact of renewable energy use is relatively limited compared to fossil fuel consumption. lgdp is statistically significant across all quantiles and reduces lco_2. This shows that in the EU group, where environmental regulations are well-developed and public awareness is high, economic growth is aligned with emission-reducing policies. lind is statistically significant across all quantiles and increases lco2. This finding highlight that the industrial sector still plays a significant role in CO_2 emissions, especially through energy-intensive production processes. However, the relatively small differences across quantiles indicate that this relationship is fairly homogeneous. lrent has a statistically significant effect on lco_2. At q10, lrent increases lco_2, but from q20 to q90, the sign changes, and lrent reduces lco2. This suggests that in low CO_2-intensity countries such as Cyprus and Slovenia, where natural resources are heavily utilized and rents are high, environmental performance worsens. The following table presents the results of the simultaneous quantile regression analysis for the BRICS country group.

Table 13. Panel simultaneous quantile regression analysis results (BRICS)

Variables	FE	q10	q20	q30	q40	q50	q60	q70	q80	q90
lfos	0.798***	0.821***	1.031***	0.928***	0.867***	0.921***	0.955***	0.932***	0.934***	0.948***
	(0.048)	[0.170]	[0.174]	[0.120]	[0.088]	[0.045]	[0.027]	[0.034]	[0.026]	[0.017]
lren	0.007***	0.005**	0.006***	0.006*	0.011**	0.016***	0.018***	0.020***	0.022 ***	0.019***
	(0.001)	[0.002]	[0.002]	[0.003]	[0.005]	[0.003]	[0.001]	[0.001]	[0.001]	[0.001]

lgdp	-0.328*** (0.043)	-1.074*** [0.171]	-1.271*** [0.176]	-1.162*** [0.144]	-1.032*** [0.123]	-0.998*** [0.054]	-1.004*** [0.030]	-0.958*** [0.040]	-0.959*** [0.042]	-1.030*** [0.026]
lind	0.625*** (0.036)	0.997*** [0.036]	0.987*** [0.029]	1.010*** [0.026]	1.016*** [0.037]	0.962*** [0.023]	0.948*** [0.015]	0.920*** [0.019]	0.896*** [0.015]	0.902*** [0.009]
lrent	-0.019* (0.010)	-0.033*** [0.007]	-0.027*** [0.008]	-0.027*** [0.007]	-0.033*** [0.010]	-0.049*** [0.007]	-0.050*** [0.005]	-0.054*** [0.005]	-0.063*** [0.006]	-0.069*** [0.004]
c	-17.439*** (0.666)	-22.479*** [0.790]	-22.682*** [0.673]	-23.233*** [0.663]	-23.704*** [0.956]	-22.319*** [0.726]	-22.136*** [0.463]	-21.282*** [0.631]	-20.219*** [0.572]	-19.624*** [0.293]
R²	0.952	0.763	0.741	0.731	0.731	0.757	0.789	0.820	0.836	0.870
N	270	270	270	270	270	270	270	270	270	270

Note: Asterisks represent significance levels; one asterisk (*) represents 10%, two asterisks (**) represents 5%, and three asterisks (***) represents 1%. Values in square brackets are robust standard errors obtained with a bootstrap with 1000 replications.

The table above presents the findings of the simultaneous quantile regression analysis for the BRICS countries. According to the results, lfos is statistically significant across all quantiles and increases environmental degradation. lren is statistically significant in all quantiles and increases lco2. Notably, the elasticity of lren in increasing lco2 becomes stronger at the medium-to-upper quantiles (q40-q90). This marginal effect of renewable energy use on environmental degradation does not support environmental sustainability. lgdp is statistically significant in all quantiles and reduces lco2. lind is statistically significant in all quantiles and increases lco2. lrent is statistically significant in all quantiles and increases lco2, with its elasticity in exacerbating environmental degradation growing stronger toward the upper quantiles.

The panel quantile regression results show that fossil fuels remain the primary determinant of emissions in both groups: while their impact decreases across quantiles in the EU, it remains more homogeneous in BRICS. Renewable energy plays a mitigating role in lower quantiles in the EU but shows an emission-increasing effect across all quantiles in BRICS. Economic growth reduces emissions in both groups, whereas industrialization increases them. Natural resource rents exhibit a dual effect in the EU, while in BRICS they consistently exacerbate emissions. These differences highlight that the EU is more advanced in its energy transition, whereas BRICS remains more dependent on fossil fuels. In the simultaneous quantile regression analysis, these findings evaluated across different quantiles provide deeper insights into the concept of environmental degradation. Additionally, to understand the directional relationships among the variables affecting environmental degradation, the Emirmahmutoğlu and Köse (2011) panel causality test was conducted. The table below presents the Emirmahmutoğlu and Köse (2011) panel causality test results for the EU country group.

Table 14. Emirmahmutoğlu and Köse (2011) Panel Causality Results (EU)

Direction of causality	**Fisher stat.**	**p-value**	**Decision**
lfos→ lco2	100.625***	0.0000	Causality exists
lren→ lco2	113.324***	0.0000	Causality exists
lgdp→ lco2	131.394***	0.0000	Causality exists
lind→ lco2	104.440***	0.0000	Causality exists
lrent→ lco2	127.617***	0.0000	Causality exists
lco2→ lfos	133.118***	0.0000	Causality exists
lco2→ lren	125.120***	0.0000	Causality exists
lco2→ lgdp	84.675***	0.0004	Causality exists
lco2→ lind	82.301***	0.0008	Causality exists
lco2→ lrent	76.063***	0.0035	Causality exists

Note: Asterisks represent significance levels, one asterisk (*) is 10%, two asterisks (**) is 5%, and three asterisks (***) is 1% significance level.

The table above presents the findings of the Emirmahmutoğlu and Köse (2011) panel causality test for the EU country group. The findings are statistically significant at the 1% significance level. They indicate the existence of bidirectional causality between the dependent variable, lco2, and the independent variables, lfos, lren, lgdp, lind, and lrent. In other words, these variables emerge both as determinants of environmental degradation and as variables affected by environmental degradation. This result reveals that the relationship between environmental degradation and energy consumption, economic growth, industrialization, and natural resource rents in EU countries is characterized by mutual interaction. The table below reports the results of the Emirmahmutoğlu and Köse (2011) panel causality test for the BRICS country group.

Table 15. Emirmahmutoğlu and Köse (2011) Panel Causality Results (BRICS)

Direction of causality	**Fisher stat.**	**p-value**	**Decision**
lfos→ lco2	100.625***	0.0000	Causality exists
lren→ lco2	113.324***	0.0000	Causality exists
lgdp→ lco2	131.394***	0.0000	Causality exists
lind→ lco2	104.441***	0.0000	Causality exists
lrent→ lco2	127.617***	0.0000	Causality exists
lco2→ lfos	133.118***	0.0000	Causality exists
lco2→ lren	125.120***	0.0000	Causality exists
lco2→ lgdp	84.676***	0.0004	Causality exists
lco2→ lind	82.301***	0.0008	Causality exists
lco2→ lrent	76.063***	0.0000	Causality exists

Note: Asterisks represent significance levels, one asterisk (*) is 10%, two asterisks (**) is 5%, and three asterisks (***) is 1% significance level.

The table above presents the results of the Emirmahmutoğlu and Köse (2011) panel causality test for the BRICS country group. When evaluated at the 1% significance level, the findings reveal the existence of bidirectional causality between the dependent variable, lco2, and the independent variables, lfos, lren, lgdp, lind, and lrent. In other words, there is a mutual interaction between environmental degradation and fossil energy consumption, renewable energy consumption, economic growth, industrialization, and natural resource rents in BRICS countries. This result indicates that these variables are not only factors affecting environmental degradation but are also influenced by changes in environmental degradation.

The results of the Emirmahmutoğlu and Köse (2011) panel causality test generally point to a similar causality structure across the EU and BRICS country groups. In both groups, bidirectional causality is detected between lco2 and lfos, lren, lgdp, lind, and lrent. This finding demonstrates that the relationship between environmental degradation and energy consumption, economic growth, industrialization, and natural resource use is not unidirectional, but rather mutual and dynamic. Therefore, in both EU and BRICS countries, policies aimed at reducing environmental degradation should not address energy consumption or economic growth separately; instead, energy transition, industrial policies, natural resource management, and sustainable growth strategies should be evaluated within a holistic framework.

5. CONCLUSION

This study comparatively analyzes the main determinants of environmental degradation in EU and BRICS country groups over the 1995-2021 period. The findings obtained using PMG-DFE ARDL, CS-ARDL, panel simultaneous quantile regression, and the Emirmahmutoğlu and Köse (2011) panel causality test show that the effects of energy consumption, economic growth, industrialization, and natural resource use on environmental degradation differ across country groups. In this respect, the study provides a comparative framework between EU and BRICS economies by considering not only long-run coefficients but also robustness, distributional heterogeneity, and causal interactions.

The overall findings reveal that fossil fuel consumption is the strongest determinant of environmental degradation in both EU and BRICS countries. This result confirms the critical role of the energy mix in terms of environmental sustainability. In contrast, the mitigating effect of per capita income on environmental degradation indicates that income growth may support environmental quality when combined with clean technology use, environmental awareness, and more effective environmental policies. Industrialization and natural resource rents generate stronger environmental pressures, particularly in BRICS countries. This suggests that production structures, energy-intensive industrial activities, and dependence on natural resources constitute key areas of vulnerability for environmental sustainability in emerging economies.

The CS-ARDL findings applied for robustness checks show that the baseline results are consistent, particularly with respect to fossil fuel consumption and per capita income. The panel quantile regression results indicate that the effects of the variables are not homogeneous across different levels of environmental degradation. This finding suggests that environmental policies cannot be designed uniformly for all countries; rather, different policy instruments are required for economies with low, medium, and high levels of environmental degradation. In addition, the results of the Emirmahmutoğlu and Köse (2011) causality test reveal bidirectional relationships between environmental degradation and energy consumption, economic growth, industrialization, and natural resource rents in both EU and BRICS countries. Therefore, environmental degradation is not merely an outcome of economic and energy-related variables but also a dynamic process that affects the future trajectory of these variables. Accordingly, the relationship between environmental degradation and economic and energy-related determinants is not unidirectional, but mutual, endogenous, and self-reinforcing over time.

The findings of this study are largely consistent with the previous literature. The results indicating that fossil fuel consumption increases environmental degradation are in line with the findings reported by Sarkodie et al. (2020), Adebayo and Kirikkaleli (2021), Khan et al. (2020), and Zafar et al. (2020). The limited or unstable mitigating effect of renewable energy on environmental degradation, particularly in BRICS countries, also suggests that renewable energy investments alone are not sufficient; rather, these investments should be considered together with technological capacity, energy storage infrastructure, grid modernization, and the reduction of fossil fuel dependence. The mitigating effect of economic growth on environmental degradation in the EU group indicates that income growth may strengthen the transition toward cleaner production technologies and environmental awareness. However, the more complex nature of this effect in BRICS countries reveals that environmental outcomes may differ depending on the quality of growth, production structure, and energy composition. This result is also consistent with the findings emphasized by Adebayo (2022), Mohsin et al. (2022), and Nam et al. (2024). The fact that industrialization generates more limited environmental effects in EU countries but stronger effects in BRICS countries supports the findings of Patel and Mehta (2023) and Salahodjaev et al. (2023). The variation in the effect of natural resource rents across country groups is also consistent with the heterogeneous structure of the natural resources-environment nexus highlighted by Azam et al. (2023) and Ma et al. (2024).

This study contributes to the literature by comparatively examining the EU and BRICS country groups and by jointly employing PMG-DFE ARDL, CS-ARDL, panel simultaneous quantile regression, and the Emirmahmutoğlu and Köse panel causality analysis. While a substantial portion of previous studies focuses on a single country, a single country group, or only mean-based estimation methods, this study evaluates the determinants of environmental degradation in both developed and emerging economies within a comparative, distributional, and causal framework. In this respect, the study demonstrates that the energy-growth-environment relationship should be analyzed not only through long-run coefficients but also across different levels of environmental degradation and within a framework of reciprocal causality.

From a policy perspective, the findings point to the need for differentiated and targeted strategies for both country groups. First, since fossil fuel consumption is the strongest determinant of environmental degradation, policies aimed at reducing fossil fuel dependence should be prioritized in both EU and BRICS countries. In EU countries, the scope of carbon pricing mechanisms should be expanded to accelerate the ongoing energy transition process, fossil fuel subsidies should be gradually phased out, and energy efficiency standards in the industrial, transportation, and residential sectors should be tightened. In particular, financial support, green credit mechanisms, and tax incentives that promote the transition from carbon-intensive production processes to low-carbon technologies should be strengthened in high-emission sectors.

For BRICS countries, the policy priority should not only be to increase renewable energy capacity but also to develop the complementary infrastructure that enables this capacity to translate into environmental quality. In this context, electricity grids should be modernized, investments in energy storage systems should be increased, renewable energy sources should be integrated into industrial production, and fossil fuel-based electricity generation should be gradually reduced. In addition, direct and indirect subsidies for high-carbon energy sources such as coal and oil should be reduced, while low-carbon alternatives such as solar, wind, geothermal energy, and green hydrogen should be supported instead. However, this transition should not be carried out abruptly or in a costly manner; rather, it should be implemented together with just transition policies that reduce employment losses and energy security risks.

Second, the fact that industrialization increases environmental degradation more strongly, particularly in BRICS countries, indicates that industrial policies should be integrated with environmental policies. In BRICS countries, mandatory energy efficiency targets should be established for energy-intensive sectors, clean technology investments should be supported in high-carbon production facilities, and waste heat recovery, circular economy practices, and resource efficiency programs should be expanded in industrial zones. In EU countries, the relatively lower level of industry-induced emissions suggests that existing regulations are effective to some extent; however, carbon border adjustment mechanisms, green industrial strategies, and clean technology R&D support should be further strengthened.

Third, the positive effect of natural resource rents on environmental degradation demonstrates that how natural resource revenues are used is critical for environmental sustainability. Particularly in BRICS economies with high dependence on natural resources, resource revenues should be directed toward renewable energy infrastructure, energy efficiency projects, clean technology R&D expenditures, and environmental rehabilitation programs rather than supporting fossil fuel-based growth. In this context, green transition funds financed through natural resource revenues may serve as an effective policy instrument for reducing environmental degradation. For EU countries, although the effect of natural resource rents is more limited, circular economy, recycling, and raw material efficiency policies should be prioritized in resource use.

Fourth, the mitigating effect of per capita income on environmental degradation indicates that growth can be aligned with environmental quality. However, this result does not imply that economic growth automatically generates environmental improvement. For income growth to support environmental quality, growth must be directed toward low-carbon investments, green technologies, sustainable transportation systems, and energy-efficient production processes. Therefore, green financing instruments, sustainable bonds, environmentally friendly investment incentives, and transformation loans for carbon-intensive sectors should be expanded in both EU and BRICS countries.

Fifth, the causality findings showing bidirectional relationships among all variables reveal that policy approaches focusing on a single variable will be insufficient. Energy policies, growth strategies, industrial policies, and natural resource management should be designed simultaneously. For instance, merely increasing renewable energy investments may not be sufficient to reduce environmental degradation; rather, a comprehensive policy package is required that reduces fossil fuel consumption, improves energy efficiency in industry, directs natural resource revenues toward green investments, and strengthens environmental regulations. Therefore, in EU countries, existing Green Deal and carbon neutrality targets should be supported by stricter implementation mechanisms, while in BRICS countries, gradual but binding low-carbon transition roadmaps compatible with economic growth objectives should be established.

Finally, this study has some limitations. First, because the analysis requires a balanced panel dataset, some countries with missing data were excluded from the sample. For the EU group, the analysis covers 23 member countries; however, Latvia, Lithuania, Luxembourg, and Malta could not be included in the sample due to missing data on fossil fuel consumption and renewable energy consumption. Similarly, for the BRICS group, the analysis was conducted for 10 countries; however, Ethiopia was excluded from the sample due to missing fossil fuel and renewable energy data. Second, the study period is limited to 1995-2021. The main reason for this limitation is that data on natural resource rents end in 2021 and that a balanced panel structure was intended to be maintained for all variables. Therefore, the study does not cover the post-COVID-19 recovery process, recent energy crises, or the potential effects of geopolitical developments on environmental degradation. Future studies may analyze these periods using more recent and expanded datasets. In addition, incorporating variables such as environmental policy stringency, green innovation, institutional quality, sectoral energy consumption, and energy efficiency into the model may contribute to a more detailed understanding of the energy-growth-environment nexus in EU and BRICS countries.

REFERENCES

Abbasi, K. R., Shahbaz, M., Zhang, J., Irfan, M., & Alvarado, R. (2022). Analyze the environmental sustainability factors of China: The role of fossil fuel energy and renewable energy. *Renewable Energy*, 187, 390-402.

Abokyi, E., Appiah-Konadu, P., Abokyi, F., & Oteng-Abayie, E. F. (2019). Industrial growth and emissions of CO2 in Ghana: the role of financial development and fossil fuel consumption. *Energy Reports*, 5, 1339-1353.

Adebayo, T. S. (2022). Renewable energy consumption and environmental sustainability in Canada: does political stability make a difference?. *Environmental Science and Pollution Research*, 29(40), 61307-61322.

Adebayo, T. S., & Kirikkaleli, D. (2021). Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools. *Environment, Development and Sustainability*, 23(11), 16057-16082.

Agan, B. (2024). Sustainable development through green transition in EU countries: New evidence from panel quantile regression. *Journal of Environmental Management*, 365, 121545.

Ahmed, Z., Ahmad, M., Murshed, M., Shah, M. I., Mahmood, H., & Abbas, S. (2022). How do green energy technology investments, technological innovation, and trade globalization enhance green energy supply and stimulate environmental sustainability in the G7 countries?. *Gondwana Research*, 112, 105-115.

Ahmed, F., Ali, I., Kousar, S., & Ahmed, S. (2022). The environmental impact of industrialization and foreign direct investment: empirical evidence from Asia-Pacific region. *Environmental Science and Pollution Research*, 29(20), 29778-29792.

Ahmed, Z., Cary, M., Shahbaz, M., & Vo, X. V. (2021). Asymmetric nexus between economic policy uncertainty, renewable energy technology budgets, and environmental sustainability: Evidence from the United States. *Journal of Cleaner Production*, 313, 127723.

Ali, U., Guo, Q., Nurgazina, Z., Sharif, A., Kartal, M. T., Depren, S. K., & Khan, A. (2023). Heterogeneous impact of industrialization, foreign direct investments, and technological innovation on carbon emissions intensity: Evidence from Kingdom of Saudi Arabia. *Applied Energy*, 336, 120804.

Alola, A. A., Yalçiner, K., Alola, U. V., & Saint Akadiri, S. (2019). The role of renewable energy, immigration and real income in environmental sustainability target. Evidence from Europe largest states. *Science of The Total Environment*, 674, 307-315.

Ang, J. B. (2007). CO2 emissions, energy consumption, and output in France. *Energy policy*, 35(10), 4772-4778.

Apergis, N., & Payne, J. E. (2010). Renewable energy consumption and economic growth: evidence from a panel of OECD countries. *Energy policy*, 38(1), 656-660.

Arvas, M. A., Demirtas, C., Yildirim, E. S., & Ilikkan Ozgur, M. (2023). Does economic policy uncertainty cause environmental pollution? fresh evidence from developed countries. *Environmental Science and Pollution Research*, 30(49), 107921-107937.

Asongu, S. A., Agboola, M. O., Alola, A. A., & Bekun, F. V. (2020). The criticality of growth, urbanization, electricity and fossil fuel consumption to environment sustainability in Africa. *Science of the Total Environment*, 712, 136376.

Awosusi, A. A., Adebayo, T. S., Kirikkaleli, D., & Altuntaş, M. (2022). Role of technological innovation and globalization in BRICS economies: policy towards environmental sustainability. *International Journal of Sustainable Development & World Ecology*, 29(7), 593-610.

Aydın, Ş., Öztutuş, F., & Polat, İ. H. (2024). The Impact of Financial Development, Foreign Direct Investment and Geopolitical Risk on CO2 Emissions: Evidence from Turkey. *Fiscaoeconomia*, 8(3), 1617-1640.

Azam, W., Khan, I., & Ali, S. A. (2023). Alternative energy and natural resources in determining environmental sustainability: a look at the role of government final consumption expenditures in France. *Environmental Science and Pollution Research*, 30(1), 1949-1965.

Bai, Y., Eweade, B. S., Aghazadeh, S., Bamidele, R. O., & Xu, Y. (2025). Pathways to environmental sustainability: Do fintech, natural resources, and environmental patents matter in E− 7 nations?. *Renewable Energy*, 247, 122987.

Baltagi, B. H. (Ed.). (2015). The Oxford handbook of panel data. *Oxford University Press*.

Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., & Farhani, S. (2018). How economic growth, renewable electricity and natural resources contribute to CO2 emissions?. *Energy policy*, 113, 356-367.

Bergougui, B. (2024). Moving toward environmental mitigation in Algeria: Asymmetric impact of fossil fuel energy, renewable energy and technological innovation on CO2 emissions. *Energy Strategy Reviews*, 51, 101281.

Blackburne III, E. F., & Frank, M. W. (2007). Estimation of nonstationary heterogeneous panels. *The Stata Journal*, 7(2), 197-208.

Bondell, H. D., Reich, B. J., & Wang, H. (2010). Noncrossing quantile regression curve estimation. *Biometrika*, 97(4), 825-838.

Breitung, J. (2001). The local power of some unit root tests for panel data. In Nonstationary panels, panel cointegration, and dynamic panels (pp. 161-177). Emerald Group Publishing Limited.

BRICS. (2024a). 11th BRICS Environment Ministers Meeting: Environment Declaration. Avaible at https://brics.br/en/news/ministers-approve-brics-environment-declaration

BRICS. (2024b). Joint Statement on Climate Finance and Just Transition. Avaible at http://www.brics.utoronto.ca/docs/250707-climate-finance.html

BRICS. (2024c). BRICS Energy and Renewable Transition Report. Avaible at https://brics.br/en/news/brics-working-group-discusses-ways-in-which-energy-security-and-sustainable-transition-can-advance-together

BRICS. (2024d). Environment, Climate, Energy and Disaster Risk Reduction Action Plan 2024–2027. Avaible at https://brics.br/en/documents/environment-climate-energy-and-disaster-risk-reduction

BRICS Policy Center. (2024). The Climate Ambition of BRICS Countries: Executive Summary. Rio de Janeiro: BRICS Policy Center. Avaible at https://bricspolicycenter.org

Camkaya, S., & Karaaslan, A. (2024). Do renewable energy and human capital facilitate the improvement of environmental quality in the United States? A new perspective on environmental issues with the load capacity factor. *Environmental Science and Pollution Research*, 31(11), 17140-17155.

Camkaya, S., Kaya, Y., Brika, S. K., Barut, A., & Ali, K. (2025a). Do Fossil Fuel Consumption, Eco-Friendly Technology and Financial Development Have an Impact on Environmental Quality Under the LCC Hypothesis? Evidence From E-7 Countries. *Geological Journal*, 1-21.

Camkaya, S., Kaya, Y., & Karabayir, M. E. (2025b). Do renewable and nuclear R&D expenditures affect environmental quality in France? An assessment from the perspective of the LCC hypothesis and SDGs. *Energy*, 320, 135179.

Chen, J., Wu, W., & Nguea, S. M. (2025). Combining the effects of industrialization and oil prices on CO2 emissions: What role do renewable energy, urbanization and financial crisis play?. *Sustainable Development*, 33(2), 2780-2796.

Chernozhukov, V., Fernández-Val, I., & Galichon, A. (2010). Quantile and probability curves without crossing. *Econometrica*, 78(3), 1093-1125.

Chernozhukov, V., & Hansen, C. (2008). Instrumental variable quantile regression: A robust inference approach. *Journal of Econometrics*, 142(1), 379-398.

Chien, F., Ajaz, T., Andlib, Z., Chau, K. Y., Ahmad, P., & Sharif, A. (2021). The role of technology innovation, renewable energy and globalization in reducing environmental degradation in Pakistan: a step towards sustainable environment. *Renewable Energy*, 177, 308-317.

Chudik, A., Mohaddes, K., Pesaran, M. H., & Raissi, M. (2017). Is there a debt-threshold effect on output growth?. *Review of Economics and Statistics*, 99(1), 135-150.

Chudik, A., & Pesaran, M. H. (2015). Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. *Journal of econometrics*, 188(2), 393-420.

Coad, A., & Rao, R. (2008). Innovation and firm growth in high-tech sectors: A quantile regression approach. *Research policy*, 37(4), 633-648.

Caglar, A. E., Daştan, M., Bulut, E., & Marangoz, C. (2024). Evaluating a pathway for environmental sustainability: The role of competitive industrial performance and renewable energy consumption in European countries. *Sustainable Development*, 32(3), 1811-1824.

Dam, M. M., Işık, C., & Ongan, S. (2023). The impacts of renewable energy and institutional quality in environmental sustainability in the context of the sustainable development goals: A novel approach with the inverted load capacity factor. *Environmental Science and Pollution Research*, 30(42), 95394-95409.

De Hoyos, R. E., & Sarafidis, V. (2006). Testing for cross-sectional dependence in panel-data models. *The stata journal*, 6(4), 482-496.

Dvořák, P., Martinát, S., Van der Horst, D., Frantál, B., & Turečková, K. (2017). Renewable energy investment and job creation; a cross-sectoral assessment for the Czech Republic with reference to EU benchmarks. *Renewable and Sustainable Energy Reviews*, 69, 360-368.

Emirmahmutoglu, F., & Kose, N. (2011). Testing for Granger causality in heterogeneous mixed panels. *Economic Modelling*, 28(3), 870-876.

European Commission. (2023). The European Climate Law and Fit for 55 package. Brussels: European Commission. Avaible at https://climate.ec.europa.eu

European Commission. (2024a). 8th Environment Action Programme: Progress Report. Brussels: European Commission. Avaible at https://environment.ec.europa.eu

European Commission. (2024b). Climate Action Progress Report 2024. Brussels: European Commission. Avaible at https://climate.ec.europa.eu

Eurostat. (2025). Sustainable development in the European Union: Monitoring report on progress towards the SDGs in an EU context, 2025 edition. Luxembourg: Publications Office of the European Union. Avaible at https://ec.europa.eu/eurostat

Eweade, B. S., Karlilar, S., Pata, U. K., Adeshola, I., & Olaifa, J. O. (2024). Examining the asymmetric effects of fossil fuel consumption, foreign direct investment, and globalization on ecological footprint in M exico. *Sustainable Development*, 32(4), 2899-2909.

Frees, E. W. (1995). Assessing cross-sectional correlation in panel data. Journal of econometrics, 69(2), 393-414.

Friedman, M. (1937). The use of ranks to avoid the assumption of normality implicit in the analysis of variance. *Journal of the american statistical association*, 32(200), 675-701.

Friedman, M. (1940). A comparison of alternative tests of significance for the problem of m rankings. *The annals of mathematical statistics*, 11(1), 86-92.

Ghazouani, T. (2022). The effect of FDI inflows, urbanization, industrialization, and technological innovation on CO2 emissions: Evidence from Tunisia. *Journal of the Knowledge Economy*, 13(4), 3265-3295.

Gibbons, J. D., & Chakraborti, S. (2014). Nonparametric statistical inference: revised and expanded. CRC press.

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The quarterly journal of economics*, 110(2), 353-377.

Güney, T. (2019). Renewable energy, non-renewable energy and sustainable development. *International Journal of Sustainable Development & World Ecology*, 26(5), 389-397.

Hassan, M. U., Siddique, H. M. A., Sumaira, & Alvi, S. (2025). Impacts of industrialization, trade openness, renewable energy consumption, and urbanization on the environment in South Asia. *Environment, Development and Sustainability*, 1-24.

He, Y., Li, X., Huang, P., & Wang, J. (2022). Exploring the road toward environmental sustainability: natural resources, renewable energy consumption, economic growth, and greenhouse gas emissions. *Sustainability*, 14(3), 1579.

Horobet, A., Radulescu, M., Bouraoui, T., Mnohoghitnei, I., Balsalobre-Lorente, D., & Belascu, L. (2025). Financial development and environmental degradation: insights from European countries. *Applied Economics*, 57(32), 4679-4694.

IEA (2025). International Energy Agency. Avaible at https://www.iea.org/energy-system/renewables.

Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of econometrics*, 115(1), 53-74.

IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*.

IPCC (2023). Intergovernmental Panel on Climate Change . Climate Change 2021 - The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Jarque, C. M., & Bera, A. K. (1980). Efficient tests for normality, homoscedasticity and serial independence of regression residuals. *Economics letters*, 6(3), 255-259.

Kahia, M., & Omri, A. (2024). Oil rents and environmental sustainability: Do green technologies and environmental technological innovation matter?. *Journal of Open Innovation: Technology, Market, and Complexity*, 10(3), 100366.

Karaaslan, A., & Camkaya, S. (2022). The relationship between CO2 emissions, economic growth, health expenditure, and renewable and non-renewable energy consumption: Empirical evidence from Turkey. *Renewable Energy*, 190, 457-466.

Kartal, M. T. (2022). The role of consumption of energy, fossil sources, nuclear energy, and renewable energy on environmental degradation in top-five carbon producing countries. *Renewable Energy*, 184, 871-880.

Khan, I., Muhammad, I., Sharif, A., Khan, I., & Ji, X. (2024). Unlocking the potential of renewable energy and natural resources for sustainable economic growth and carbon neutrality: A novel panel quantile regression approach. *Renewable Energy*, 221, 119779.

Khan, S. A. R., Zhang, Y., Kumar, A., Zavadskas, E., & Streimikiene, D. (2020). Measuring the impact of renewable energy, public health expenditure, logistics, and environmental performance on sustainable economic growth. *Sustainable development*, 28(4), 833-843.

Khan, I., Zakari, A., Ahmad, M., Irfan, M., & Hou, F. (2022). Linking energy transitions, energy consumption, and environmental sustainability in OECD countries. *Gondwana Research*, 103, 445-457.

Kirikkaleli, D., & Adebayo, T. S. (2021). Do renewable energy consumption and financial development matter for environmental sustainability? New global evidence. *Sustainable Development*, 29(4), 583-594.

Koenker, R. (2004). Quantile regression for longitudinal data. *Journal of multivariate analysis*, 91(1), 74-89.

Koenker, R., & Bassett Jr, G. (1978). Regression quantiles. *Econometrica: journal of the Econometric Society,* 33-50.

Larsen, M. D. (2006) Longitudinal and Panel Data: Analysis and Applications in the Social Sciences, Journal of the American Statistical Association, 101:473, 402-402.

Li, A., Li, S., Chen, S., & Sun, X. (2024). The role of Fintech, natural resources, and renewable energy consumption in Shaping environmental sustainability in China: A NARDL perspective. *Resources Policy*, 88, 104464.

Li, B., & Haneklaus, N. (2022). The role of clean energy, fossil fuel consumption and trade openness for carbon neutrality in China. *Energy Reports*, 8, 1090-1098.

Loayza, N. V., & Ranciere, R. (2006). Financial development, financial fragility, and growth. *Journal of money, credit and banking*, 1051-1076.

Machado, J. A., & Silva, J. S. (2019). Quantiles via moments. *Journal of econometrics*, 213(1), 145-173.

Ma, F., Saleem, H., Ding, X., Nazir, S., & Tariq, S. (2024). Do natural resource rents, green technological innovation, and renewable energy matter for ecological sustainability? Role of green policies in testing the environmental kuznets curve hypothesis. *Resources Policy*, 91, 104844.

Mentel, U., Wolanin, E., Eshov, M., & Salahodjaev, R. (2022). Industrialization and CO2 emissions in Sub-Saharan Africa: the mitigating role of renewable electricity. *Energies*, 15(3), 946.

Miao, Y., Razzaq, A., Adebayo, T. S., & Awosusi, A. A. (2022). Do renewable energy consumption and financial globalisation contribute to ecological sustainability in newly industrialized countries?. *Renewable Energy*, 187, 688-697.

Mohsin, M., Naseem, S., Sarfraz, M., & Azam, T. (2022). Assessing the effects of fuel energy consumption, foreign direct investment and GDP on CO2 emission: New data science evidence from Europe & Central Asia. *Fuel*, 314, 123098.

Mudakkar, S. R., Zaman, K., Khan, M. M., & Ahmad, M. (2013). Energy for economic growth, industrialization, environment and natural resources: Living with just enough. *Renewable and Sustainable Energy Reviews*, 25, 580-595.

Mujtaba, A., Jena, P. K., Bekun, F. V., & Sahu, P. K. (2022). Symmetric and asymmetric impact of economic growth, capital formation, renewable and non-renewable energy consumption on environment in OECD countries. *Renewable and Sustainable Energy Reviews*, 160, 112300.

Nam, L. P., Hang, N. T. B., Van Song, N., & Eluriagac, L. M. T. (2024). Examining the non-linear impact of fossil and renewable energy consumption on Vietnam's ecological footprint: insights from the asymmetric ARDL approach. *Discover Energy*, 4(1), 10.

OWD (2024). Our World in Data. Avaible at https://ourworldindata.org/fossil-fuels.

Pata, U. K. (2021). Linking renewable energy, globalization, agriculture, CO2 emissions and ecological footprint in BRIC countries: A sustainability perspective. *Renewable Energy*, 173, 197-208.

Patel, N., & Mehta, D. (2023). The asymmetry effect of industrialization, financial development and globalization on CO2 emissions in India. *International Journal of Thermofluids*, 20, 100397.

Pesaran, M. H. (2004). General diagnostic tests for cross section dependence in panels. Cambridge Working Papers. *Economics*, 1240(1), 1.

Pesaran, M. H. (2007a). A simple panel unit root test in the presence of cross-section dependence. *Journal of applied econometrics*, 22(2), 265-312.

Pesaran, M. H. (2007b). A pair-wise approach to testing for output and growth convergence. *Journal of econometrics*, 138(1), 312-355.

Pesaran, M. H., Shin, Y., & Smith, R. P. (1999). Pooled mean group estimation of dynamic heterogeneous panels. *Journal of the American statistical Association*, 94(446), 621-634.

Pesaran, M. H., & Smith, R. (1995). Estimating long-run relationships from dynamic heterogeneous panels. *Journal of econometrics*, 68(1), 79-113.

Pesaran, M. H., & Yamagata, T. (2008). Testing slope homogeneity in large panels. *Journal of econometrics*, 142(1), 50-93.

Pindaru, L. C., Nita, A., Niculae, I. M., Manolache, S., & Rozylowicz, L. (2023). More streamlined and targeted. A comparative analysis of the 7th and 8th Environment Action Programmes guiding European environmental policy. *Heliyon*, 9(9).

Polat, İ. H. (2026). The New Drivers of CO_2 Emissions in BRIC Countries: Assessing the Role of Economic Policy Uncertainty, Clean Energy Consumption and Financial Development. *İktisadi İdari ve Siyasal Araştırmalar Dergisi*, (29), 292-315.

Polat, İ. H., Tosunoğlu, M., & Aslan, T. (2025). Analyzing the Ageing Population and Healthcare Expenditures from an Environmental Sustainability Perspective for The Eu Countries: A Spatial Approach. *Kafkas University Journal of Economics and Administrative Sciences Faculty*, 16(31), 168-200.

Rahman, M. M., & Alam, K. (2022). Impact of industrialization and non-renewable energy on environmental pollution in Australia: Do renewable energy and financial development play a mitigating role?. *Renewable Energy*, 195, 203-213.

Raihan, A., Muhtasim, D. A., Farhana, S., Pavel, M. I., Faruk, O., Rahman, M., & Mahmood, A. (2022). Nexus between carbon emissions, economic growth, renewable energy use, urbanization, industrialization, technological innovation, and forest area towards achieving environmental sustainability in Bangladesh. *Energy and Climate Change*, 3, 100080.

Raihan, A., & Tuspekova, A. (2022). Role of economic growth, renewable energy, and technological innovation to achieve environmental sustainability in Kazakhstan. *Current Research in Environmental Sustainability*, 4, 100165.

Raihan, A., Voumik, L. C., Zimon, G., Sadowska, B., Rashid, M., & Akter, S. (2024). Prioritising sustainability: how economic growth, energy use, forest area, and globalization impact on greenhouse gas emissions and load capacity in Poland?. *International Journal of Sustainable Energy*, 43(1), 2361410.

Refinitiv Eikon Datastream (2024). Avaible at https://www.refinitiv.com

Sachs, J. D., & Warner, A. (1995). Natural resource abundance and economic growth.

Sachs, J. D., & Warner, A. M. (2001). The curse of natural resources. *European economic review*, 45(4-6), 827-838.

Salahodjaev, R., Djalilov, B., Kobiljonov, I., Otajonov, S., & Kasimova, N. (2023). Industrialization and CO2 emissions: accounting for the role of renewable energy in OIC member states. *International Journal of Energy Economics and Policy*, 13(5), 37-43.

Sarkodie, S. A., Adams, S., Owusu, P. A., Leirvik, T., & Ozturk, I. (2020). Mitigating degradation and emissions in China: the role of environmental sustainability, human capital and renewable energy. *Science of the Total Environment*, 719, 137530.

Schlacke, S., Wentzien, H., Thierjung, E. M., & Köster, M. (2022). Implementing the EU Climate Law via the 'Fit for 55'package. *Oxford Open Energy*, 1, oiab002.

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52(3-4), 591-611.

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. *World development*, 32(8), 1419-1439.

Stern, N. (2008). The economics of climate change. *American economic review*, 98(2), 1-37.

Suki, N. M., Suki, N. M., Sharif, A., Afshan, S., & Jermsittiparsert, K. (2022). The role of technology innovation and renewable energy in reducing environmental degradation in Malaysia: a step towards sustainable environment. *Renewable Energy*, 182, 245-253.

Sun, Y., Anwar, A., Razzaq, A., Liang, X., & Siddique, M. (2022). Asymmetric role of renewable energy, green innovation, and globalization in deriving environmental sustainability: Evidence from top-10 polluted countries. *Renewable Energy*, 185, 280-290.

Toda, H. Y., & Yamamoto, T. (1995). Statistical inference in vector autoregressions with possibly integrated processes. *Journal of econometrics*, 66(1-2), 225-250.

Ulucak, R., & Ozcan, B. (2020). Relationship between energy consumption and environmental sustainability in OECD countries: the role of natural resources rents. *Resources Policy*, 69, 101803.

Usman, O., Akadiri, S. S., & Adeshola, I. (2020). Role of renewable energy and globalization on ecological footprint in the USA: implications for environmental sustainability. *Environmental Science and Pollution Research*, 27(24), 30681-30693.

Usman, O., Alola, A. A., & Saint Akadiri, S. (2022). Effects of domestic material consumption, renewable energy, and financial development on environmental sustainability in the EU-28: Evidence from a GMM panel-VAR. *Renewable Energy*, 184, 239-251.

Wang, J., & Azam, W. (2024). Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries. *Geoscience Frontiers*, 15(2), 101757.

Wang, J., You, S., Agyekum, E. B., Matasane, C., & Uhunamure, S. E. (2022). Exploring the impacts of renewable energy, environmental regulations, and democracy on ecological footprints in the next eleven nations. *Sustainability*, 14(19), 11909.

WDG (2024). World Bank Metadata Glossary. Avaible at https://databank.worldbank.org/metadataglossary/

WDI (2025). World Devleopment Indicators. Available at https://databank.worldbank.org/source/world-development-indicators

Westerlund, J. (2008). Panel cointegration tests of the Fisher effect. *Journal of applied econometrics*, 23(2), 193-233.

Wilson, J. D. (2015). Resource powers? Minerals, energy and the rise of the BRICS. *Third World Quarterly,* 36(2), 223-239.

Yao, S., Li, T., & Li, Y. (2023). Promoting sustainable fossil fuels resources in BRICS countries: Evaluating green policies and driving renewable energy development. *Resources Policy*, 85, 103990.

Zafar, M. W., Shahbaz, M., Sinha, A., Sengupta, T., & Qin, Q. (2020). How renewable energy consumption contribute to environmental quality? The role of education in OECD countries. *Journal of Cleaner Production*, 268, 122149.

Zhang, J. (2024). Energy access challenge and the role of fossil fuels in meeting electricity demand: Promoting renewable energy capacity for sustainable development. *Geoscience Frontiers*, 15(5), 101873.