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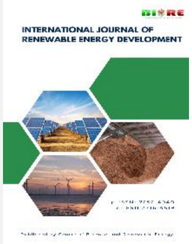

Research Article

Economic activities and CO_2 emissions: Evaluating the impacts of renewable energy, industrial growth, and financial development in CO_2-intensive economies

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Abstract. This study addresses the pressing challenge of mitigating carbon dioxide (CO2) emissions within the top ten emitting countries, which are critical to achieving global climate goals yet often analyzed separately. We investigate the intricate relationships between economic growth (GDP), renewable and non-renewable energy consumption (RE, NRE), financial development (FDI), industrial value-added (IVA), and CO2 emissions from 1990 to 2021, overcoming the limitations of single-country studies and mixed findings in existing literature. Employing a panel-based Pooled Mean Group-Autoregressive Distributed Lag (PMG-ARDL) model and Granger causality tests, we disentangle short-run and long-run dynamics, revealing that non-renewable energy significantly increases emissions while renewable energy, financial development, and industrial value-added offer mitigating effects. We provide nuanced evidence supporting the Environmental Kuznets Curve (EKC) hypothesis, suggesting a potential pathway toward sustainable growth. Furthermore, Granger causality analysis reveals significant bidirectional relationships, highlighting the interconnectedness of economic and environmental factors. We translate these findings into actionable policy recommendations, emphasizing targeted investments in clean technologies and financial strategies to foster industrial development while simultaneously curbing emissions. By providing a comprehensive analysis of these dynamics within a key group of countries, this research offers critical insights for overcoming the challenges of emissions reduction and achieving sustainable development.

Keywords: CO2 emissions; Renewable energy; industry value-add; PMG-ARDL; emitter countries

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1. Introduction

The topics of environmental degradation and carbon dioxide (CO_2) emissions have drawn considerable interest from researchers and policymakers across the globe (Adebayo and Kirikkaleli, 2021; Adeneye *et al*., 2021). Particularly noteworthy is the substantial increase in atmospheric CO2 levels, which rose by approximately 30% between the 19th and 20th centuries (Erdoğan *et al.,* 2022).

The International Energy Agency (IEA, 2017) has estimated that the energy sector is responsible for a substantial 69% of global carbon equivalent CO_2 emissions, with fuel-based energy sources, including coal, gas, and petrol, contributing to approximately 44% of this total. Furthermore, intensive industrialization, manufacturing, transportation, and refrigeration practices have engendered a notable increase in other greenhouse gas (GHG) emissions, adversely affecting environmental quality, as corroborated by Verma *et al.* (2021). Moreover, research findings have indicated that heightened GHG emissions are closely associated with increased levels of economic growth, as evidenced in the study by Wang *et al.* (2022). On a global scale, the escalation in CO2 emissions is predominantly attributed to the upsurge in industrial activities and elevated energy consumption, an assertion substantiated by the work of Callan *et al.* (2009). Recent research has underscored the importance of efficient environmental management across different climate scenarios (Nydrioti *et al.,* 2024) and the need for sector-specific assessments of carbon footprints in transportation systems (Bozoudis *et al.,* 2021). Together, these studies highlight the growing urgency for coordinated mitigation strategies in regions with high emission levels.

The global challenge of global warming is intricately linked to the emission of CO2, a predominant GHG. As industrial activities and energy consumption accelerate, certain countries emerge as major contributors to global CO2 emissions. Currently, the top ten emitter countries account for a significant portion of worldwide CO2 emissions (IEA, 2023; Global Carbon Atlas, 2023). These countries' economic activities, industrial demands, and energy policies critically influence the global carbon footprint. For instance, China, as the largest emitter, is responsible for nearly 30% of global emissions, driven by its rapid industrialization and coal dependency. The United States follows, with substantial emissions from transportation and energy sectors, despite recent strides in renewable energy adoption. Meanwhile, India's emissions continue to rise alongside its economic growth and

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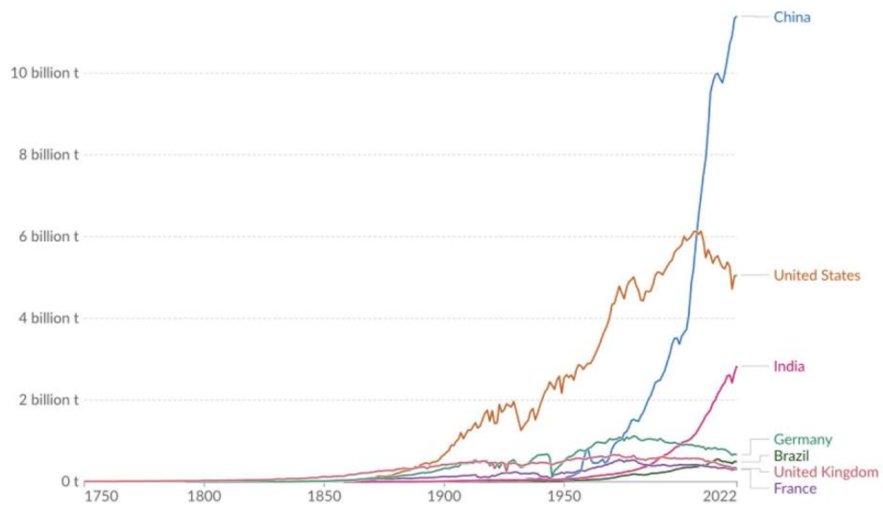

Fig 1. Yearly CO2 emissions originating from fossil fuels and industrial activities Source: Global Carbon Budget (2023)

reliance on fossil fuels. Addressing the carbon emissions of these key countries is essential for global emissions reduction targets, highlighting the need for international collaboration and sustainable policy strategies (United Nations Framework Convention on Climate Change, UNFCCC, 2023).

While there's considerable research on how economic growth, energy use, and environmental problems are linked (Ang, 2007; Soytas *et a*l., 2007; Apergis & Payne, 2009), some important areas are still unclear. Many studies look at single countries or regions, which gives us a partial and sometimes conflicting picture of how renewable energy, financial progress, and industry affect CO2 emissions (Al-Mulali *et al.,* 2014; Pata, 2018). For instance, some studies support the Environmental Kuznets Curve (EKC) hypothesis, suggesting that environmental degradation initially increases with economic growth but eventually decreases as economies develop (Arouri et al., 2012), while others find contradictory evidence (Nasir *et al.,* 2021). Also, most studies don't focus on the top ten CO2-producing countries, which together create most of the world's emissions and are key to meeting global climate goals. Existing studies often utilize different methodologies, analyze disparate geographical regions, or focus on specific subsets of variables, leading to inconsistent findings. This suggests a need for a thorough study that looks at economic, financial, and industrial elements within this specific group of countries.

Figure 1 illustrates CO2 emissions from fossil fuels and industry in various countries from 1750 to 2022. It shows a significant increase for China in recent decades, overtaking other nations. The U.S. experienced growth in emissions during the 20th century but has seen some stabilization and a slight reduction recently. India's emissions have risen, notably since the early 2000s. Germany, Brazil, the United Kingdom, and France have much lower emissions, with some showing a decline. This data underscores the connection between industrialization, growth, and rising CO2 emissions, particularly in China and India.

The United Nations Industrial Development Organization (UNIDO, 2019) states that the industrial sector is responsible for more than one-third of the world's primary energy consumption and significantly contributes to CO2 emissions related to energy use. The industrial sector's energy consumption is projected to exhibit an annual increase ranging from 1.8% to 3.1% over the ensuing 25 years. Graham *et al.* (2021) have underscored that the rapid expansion of the global population has come at a substantial environmental cost. Concurrently, the per capita global GDP has nearly tripled since 1960, with a corresponding fourfold increase in carbon emissions over the same period. About two-thirds of this increase has taken place over the last thirty years. By 2020, China, the United States, and India, the three largest emitters globally, were responsible for approximately 52.78% of global carbon emissions, representing a 4.32% rise from the previous decade.

Economic growth is frequently linked with environmental degradation, especially due to improvements and industrialization across both developing and industrialized nations. A country's economic progress is influenced by numerous factors, many of which can negatively impact the environment through unsustainable natural resource exploitation, air pollution, and climate change. The EKC hypothesis (Kuznets, 1955) posits that environmental degradation tends to increase during the early stages of economic growth but eventually declines as the economy reaches higher levels of development, suggesting a turning point where continued economic progress may improve environmental quality.

To adverse impacts of climate change, it is essential to adopt sustainable energy solutions, which entail the application of strategic measures aimed at managing and decreasing human-induced greenhouse gas emissions. These approaches include investing in environmentally friendly technologies, enhancing energy efficiency and conservation efforts, promoting transportation options that minimize carbon emissions, enacting policies and regulations that support sustainable energy use, and raising public awareness and education on these issues (Marunda *et al.,* 2013).

This research focuses on identifying the factors that lead to the rise in CO2 emissions and assessing the helpfulness of decisions targeted at reducing these emissions and promoting sustainable development in the ten countries with the highest emissions. It specifically examines how economic growth, different types of energy sources (RE, NRE), industrial expansion, and financial development influence the reduction of emissions. The study uses the PMG-ARDL methodology and Granger causality tests to explore the short-term and long-term interactions among these variables. Moreover, it explores the EKC hypothesis by assessing the relationship between GDP and

CO2 within the selected countries. The top ten CO_2-emitting countries were chosen because of their substantial role in global emissions, making them essential for understanding environmental challenges and climate policies. The variety in their economic conditions and energy use provides a basis for a detailed examination of how different factors influence emissions. Furthermore, their high levels of emissions create valuable opportunities to investigate effective reduction strategies. The PMG-ARDL method is chosen for this study because it effectively examines relationships between variables in both the short and long term, which is key to understanding CO2 emissions trends. It can handle a mix of stationary and non-stationary data, making it flexible for the varied economic contexts of the top ten CO_2-emitting countries. Additionally, it allows for the analysis of long-term impacts while considering short-term changes and is suitable for smaller sample sizes. Overall, PMG-ARDL improves the strength and reliability of the study's findings on emissions and economic factors.

Addressing these gaps, this study has four main goals. First, it explores how carbon emissions, economic expansion, renewable and non-renewable energy use, financial sector growth, and industry value are related in both the short-term and long-term in the top ten polluting countries from 1990 to 2021. Second, it checks if the EKC theory holds in these countries, adding to discussions about whether economic growth eventually helps the environment. Third, it uses Granger causality tests to find out how these factors affect each other, revealing how they are connected. Last, it suggests policies designed for countries that produce a lot of carbon emissions, focusing on ways to make industry and finance more sustainable. By meeting these goals, this research aims to provide more knowledge about how economic factors influence environmental results in countries that emit high amounts of pollution, addressing a key issue in current research.

The contribution of this study is threefold. First, it concentrates on the ten largest CO_2-emitting countries, which collectively represent the bulk of global emissions, thereby generating findings with broad international significance. Second, it applies the PMG-ARDL approach, a technique that accommodates country-specific short-run dynamics while maintaining consistency in long-run equilibrium relationships. Third, in contrast to much of the existing literature, the analysis simultaneously considers financial development and industrial value-added as key determinants, offering a more comprehensive understanding of the structural factors shaping environmental outcomes. Together, these elements enrich the empirical evidence base and provide a framework that can be extended to different economic and regional settings.

The study is organized to enhance comprehension, beginning with a literature review in Section 2, followed by data, descriptive statistics, and materials and methods in Section 3. Section 4 discusses the results, and the final section provides concluding insights.

2. Literature Review

The existing literature has widely examined the factors influencing CO_2 emissions and their relationships with economic growth, energy consumption, financial development, and industrialization. However, the findings remain mixed and, at times, inconsistent, largely due to variations in methodology, data coverage, and country-specific conditions. This section reviews key theoretical and empirical contributions to these relationships, emphasizing areas of agreement as well as persistent debates within the field of environmental economics.

The present study investigates the complex interplay between economic activities, energy consumption, and CO_2 emissions, particularly within the context of the Environmental Kuznets Curve (EKC) hypothesis. The EKC posits an inverted U-shaped relationship between economic growth and environmental degradation, suggesting that environmental quality initially deteriorates with economic growth but eventually improves as economies reach higher levels of development. However, the EKC has been subject to considerable debate and criticism, with questions raised about its universality, the timing of the turning point, and the overall effectiveness of relying solely on economic growth for environmental improvement. While some studies support the EKC hypothesis for CO_2 emissions (Arouri *et al.,* 2012; Akbostanci *et al.,* 2009), others find evidence contradicting it (Pata, 2018; Nasir *et al*., 2021). This study aims to contribute to this ongoing debate by examining the long-term relationships between various factors and CO_2 emissions in a panel of high-emitting countries, allowing for a more nuanced understanding of the EKC's applicability in these specific contexts.

2.1. *Economic Growth and CO_2 Emissions*

A strong positive correlation exists between economic growth and CO_2 emissions, driven largely by increased energy consumption and industrial activity. Many studies have explored this relationship using various methodologies. Time series analyses, often applied to individual countries, have shown a strong link between GDP and CO_2 emissions (Adedoyin et al., 2020a, 2020b; Apergis et al., 2018; Mitić *et al.,* 2017). However, these analyses may not fully capture the complex interactions and cross-country effects. Panel data models, which can account for cross-sectional dependence and heterogeneity, have also been widely employed, examining the impact of various factors, such as energy consumption, industrialization, and financial development (Ang, 2008; Soytas *et al*., 2007; Sadorsky, 2009; Tugcu *et al.,* 2012; Ocal and Aslan, 2013; Alsamara *et al.,* 2018). These studies often reveal diverse findings, highlighting the need for further investigation. For instance, while some studies show a positive relationship between economic growth and CO_2, others have found that certain policies and technology advancements could mitigate the relationship (Kahia and Ben Jebli, 2021; Wang *et al*., 2019; Zheng *et al*., 2021; Rauf *et al.,* 2018). There is a clear need to further explore these relationships, and this study aims to address this issue by utilizing PMG-ARDL, which explicitly accounts for both short-term and long-term dynamics.

2.2. *Energy Consumption, Economic Growth, and Environmental Quality*

Energy consumption is a key driver of CO2 emissions. Existing research consistently highlights the detrimental effect of non-renewable energy sources (coal, oil, natural gas) on CO2 emissions (Apergis et al., 2014; Bhattacharya *et al*., 2017; Ocal and Aslan, 2013; Al-Mulali *et al*., 2014; Ito, 2017; Pao and Tsai, 2011; Apergis and Payne, 2012; Ben Jebli *et al*., 2015). However, the impact of renewable energy is less clear. While many studies demonstrate the positive role of renewable energy in reducing CO2 emissions (Apergis *et al*., 2014; Bhattacharya *et al*., 2017; Saboori *et al*., 2012; Ito, 2017; Ben Jebli *et al*., 2015), others have found less conclusive evidence or even counterintuitive results (Ocal and Aslan, 2013; Al-Mulali *et al*., 2014; Apergis and Payne, 2014; Ben Jebli *et al*., 2015). These inconsistencies highlight the importance of controlling for other factors and utilizing robust econometric techniques, which is precisely what this study does. Recent evidence from the agricultural sector in EU economies supports the existence of strong interlinkages between energy consumption, economic growth, and environmental degradation, emphasizing the need for sustainable energy transitions in production systems (Zafeiriou *et al.,* 2023).

2.3. Financial Development and Industrial Activity

The influence of financial development and industrial activity on CO_2 emissions remains an area of active scholarly debate. Several studies argue that financial development facilitates investment in environmentally friendly technologies, thereby contributing to the reduction of carbon emissions (Acheampong *et al.*, 2020; Zaidi *et al.,* 2019; Charfeddine and Kahia, 2019; Saidi and Mbarek, 2017). Additional evidence from Greece reinforces this view, as Tsepi *et al.* (2024) conducted a decomposition analysis revealing that structural, energy, and intensity factors significantly shape national CO_2 emissions patterns between 1996 and 2020. Such findings underscore the importance of technological progress and industrial transformation in determining a country's environmental trajectory. Conversely, other scholars highlight a more nuanced relationship, suggesting that financial development may, in some cases, exacerbate emissions depending on the structure of economic activities and energy use (Pata, 2018; Zakaria and Bibi, 2019). Similarly, the impact of industrial expansion on CO_2 emissions remains contested; while some studies find that industrialization intensifies environmental degradation, others emphasize the potential of industrial policies and technological innovation to mitigate these effects (Rauf *et al.*, 2018; Kahia and Ben Jebli, 2021; Wang *et al.,* 2019). The present study contributes to this ongoing discourse by employing the PMG-ARDL framework to distinguish between short-run dynamics and long-run equilibrium relationships across a panel of major CO_2-emitting economies.

2.4. Emerging Perspectives on Sustainability and Green Growth

Recent studies have broadened the discussion on sustainability by including additional aspects. For instance, Van Tran (2024) examines how economic growth, globalization, green development, and renewable energy differently affect environmental sustainability, noting that their impacts can be either positive or negative depending on the situation. Similarly, Alamry and Al-Jashaami (2024) emphasize the importance of urban governance and renewable energy in fostering sustainable city planning and management, offering insights into how policies and institutions can facilitate technological solutions. At the same time, Nguyen *et al.* (2024) investigate the relationship between the digital economy and green growth in emerging countries, demonstrating that digitalization can promote sustainable development. These studies add to the existing research by emphasizing that sustainability is a complex concept influenced not only by energy use and economic growth but also by governance and technological advances. Similarly, Michailidis *et al.* (2025) highlight the critical role of governance and policy frameworks in facilitating the renewable energy transition across developing MENA countries, underlining the importance of institutional quality and strategic planning in achieving sustainable energy development.

Existing research often employs diverse methodologies, analyzes disparate geographical regions, or focuses on specific subsets of variables, resulting in inconsistent findings. This study addresses these limitations by employing a robust PMG-ARDL model and Granger causality tests on a panel of ten of the world's largest CO2 emitters to provide a more comprehensive and nuanced understanding of the complex relationships between economic growth, energy consumption, financial development, industrial activity, and CO_2 emissions.

The existing literature demonstrates complex and often contradictory relationships between economic activity, energy consumption, and CO_2 emissions. While the EKC hypothesis offers a potential framework, its applicability remains debated. The inconsistencies in previous findings, arising from methodological differences and geographical variations, highlight the need for this study's more nuanced examination using PMG-ARDL and Granger causality tests within a well-defined panel of high-emitting countries.

3. Data and Descriptive Statistics

3.1. Data

This research examines the timeframe from 1990 to 2021, using data obtained from credible sources such as the World Bank Development Indicators (WDI, 2023), the U.S. Energy Information Administration (EIA, 2023), and the International Monetary Fund (IMF, 2023). The analysis concentrates on the ten countries that emit the most CO2[*]. The dataset includes variables such as carbon dioxide CO2 emissions (CO2em) in million metric tonnes (MM tonnes), real GDP in constant 2015 US dollars, renewable and non-renewable energy consumption (RE, NRE) measured in quadrillion British thermal units (BTU), industry value added (IVA) in US dollars, and an index for financial development. Annual data on RE, NRE, and CO2em, are sourced from the EIA (2023). Information on GDP and IVA is derived from the WDI (2023), while the financial development index (FDI) is provided by the IMF (2023). To ensure data consistency and stationarity, all variables have been logarithmically transformed, a method supported by existing literature to address heteroscedasticity issues. Data selection maximizes the number of observations based on availability.

3.2. Descriptive Statistics

The investigation begins with descriptive statistics and a graphical representation of the variables being analyzed. We examined it before the logarithmic transformation of the variables. Table 1 provides a comprehensive overview of descriptive statistics, including measures such as means, medians, and maximum and minimum values, as well as an assessment of normal distribution, for both dependent and independent variables.

According to the data in Table 1, China reported the highest level of CO2 emissions in 2021, measuring 11,466 million metric tonnes. In contrast, Indonesia had the lowest CO2 emissions, with 149 million metric tonnes in 1990, during various points of the selected period. Regarding energy consumption, the United States recorded the highest values for both renewable and non-renewable energy, with 8.861

[*] Canada, China, Germany, India, Indonesia, Iran, Japan, South Korea, Russia, and the United States.

Table 1
Descriptive statistics

Variable	Mean	Std. dev.	Min	Max
CO2em	1776.066	2232.915	149	11466
GDP	$3.42*10^{12}$	$4.64*10^{12}$	$1.88*10^{11}$	$2.05*10^{13}$
RE	1.130584	1.801374	.014	8.861
NRE	25.94394	30.16639	2.23	139
IVA	$9.47*10^{11}$	$1.17*10^{12}$	$7.95*10^{10}$	$6.27*10^{12}$
FDI	0.5841762	0.2139871	0.2238494	0.9333178

quadrillion British thermal units (QBTU) and 139 QBTU, respectively. Conversely, South Korea had the lowest renewable energy consumption, registered in 1994, while Indonesia had the lowest non-renewable energy consumption at 2.23 QBTU in 1990. Real GDP projections indicate a peak in the United States in 2021, reaching 2.05×10^{13} constant 2015 USD, whereas Iran

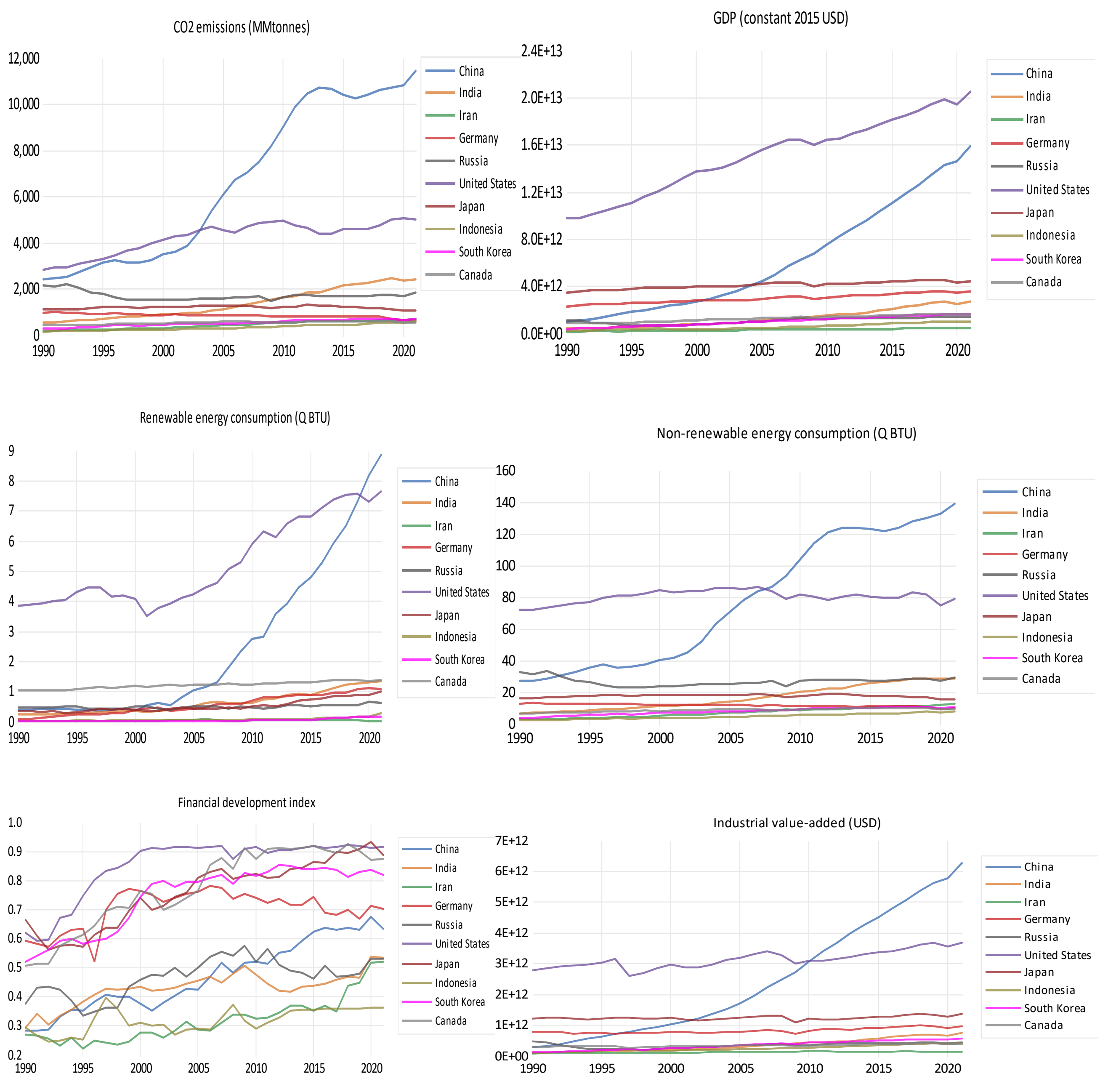

Fig 2. Plots of the analysis variables

recorded the lowest value at 1.88×10^{11} USD in 1990. Japan achieved the highest financial development index of 0.93 in 2020, while Iran had the lowest index value of 0.22 in 1995. Concerning industrial value-added, China reached the highest figure with 6.27×10^{12} USD in 2021, while Iran registered the lowest at 7.95×10^{10} USD in 1990.

Figure 2 presents trends in CO2 emissions, GDP, renewable and non-renewable energy use, financial development, and industrial growth for the ten largest CO2-emitting countries from approximately 1990 to 2020. China's emissions saw a dramatic increase, surpassing all others, while India also showed substantial growth. The USA experienced relative stability, initially leading but then growing more slowly, while other countries exhibited lower and more stable or declining emissions. In terms of GDP, China exhibited the most significant growth from a low baseline, followed by consistent growth in the USA and notable increases in India. The remaining countries showed moderate growth, with some experiencing stagnation. China led in renewable energy expansion starting around 2008, while the USA reported steady growth. Other nations had lower and more variable renewable energy usage. For non-renewable energy, China and India had the most substantial increases, while the USA maintained a stable high consumption, and other countries presented varied levels. The financial development index indicated strong growth for China and the USA, with a notable acceleration in India post-2000, while Germany, Japan, and Indonesia showed moderate improvements. In industrial growth, China experienced significant increases post-2000, with the USA sustaining high output and India growing gradually, while other countries like South Korea improved noticeably, and Iran remained comparatively low.

4. Methods

This study covers the period 1990–2021 and focuses on the top ten CO2-emitting countries. Annual data on CO2 emissions (measured in million metric tonnes), renewable energy (RE), and non-renewable energy (NRE) consumption (in quadrillion BTU) were collected from the U.S. Energy Information Administration (EIA, 2023). Data on real GDP (constant 2015 US dollars) and industry value-added (IVA) were sourced from the World Bank's World Development Indicators (WDI, 2023), while the financial development index (FDI) was obtained from the International Monetary Fund (IMF, 2023). All variables were transformed into natural logarithms to ensure stationarity and comparability across countries. The present study investigates the dynamic short- and long-run relationships among CO_2 emissions, real GDP, renewable and non-renewable energy consumption, financial development, and industrial value-added for these top emitter countries spanning the period 1990-2021. Additionally, the validity of the Environmental Kuznets Curve (EKC) hypothesis has been evaluated. Guided by relevant literature in the field, the empirical model's functional form has been delineated to examine these relationships comprehensively:

$$CO_{2em} = f(GDP, GDP^2, RE, NRE, IVA, FDI) \quad (1)$$

This study aims to examine the relationships among CO2em (lnCO2em), real GDP (lnGDP) and its square (lnGDP^2), renewable energy (lnRE), non-renewable energy (lnNRE), industrial value-added (lnIVA), and financial development (FDI) for a panel consisting of the top ten emitting countries during the period from 1990 to 2021. The empirical analysis employs the Pooled Mean Group-Autoregressive Distributed Lags (PMG-ARDL) method, cointegration techniques, and Granger causality tests.

This study chose specific factors to examine based on what past research and existing theories suggest are important. Carbon emissions are the main outcome being studied, as they indicate environmental health. Economic output, along with its squared value, is included to see if the EKC hypothesis is valid. The amounts of renewable and non-renewable energy used are considered to understand how different energy sources affect emissions. Industrial output is also examined because industry contributes heavily to emissions, especially in countries that produce a lot of carbon. Lastly, financial sector growth is included because it can direct investments into cleaner technologies, which can change long-term environmental results. These factors have also been used in similar studies, which justifies their use in this research (Ang, 2008; Ben Jebli *et al.*, 2016; Zaidi *et al.*, 2019).

The log-linear framework is given as follows:

$$lnCO_{2em\,it} = \alpha_{0i} + \alpha_{1i} lnGDP_{it} + \alpha_{2i} lnGDP^2 + \alpha_{3i} lnRE_{it} + \alpha_{4i} lnNRE_{it} + \alpha_{5i} lnIVA_{it} + \alpha_{6i} lnFDI_{it} + \mu_{it} \quad (2)$$

With $i = 1, \ldots, 10$ connotes the specific state and $t = 1990, \ldots, 2021$ defines the period. The state-specified effect is given byα_{0i} and ε_{0i}suggests the specification error.

The primary aim of our study is to investigate the short- and long-term relationships among CO2 emissions, economic growth, consumption of renewable and non-renewable energy, industrial value-added, and financial development utilizing the PMG-ARDL estimation method and the Granger causality approach. The Pooled Mean-Group estimator, introduced by Pesaran *et al.* (2001), provides two key methodologies for estimating non-stationary dynamic panels with group-specific parameter heterogeneity: the Mean-Group (MG) and Pooled Mean-Group (PMG) estimators.

The PMG-ARDL model is selected for its ability to address the core requirements of this analysis. It accounts for cross-country heterogeneity by permitting unique short-run dynamics, which is vital given the diverse profiles of the world's largest CO_2 emitters. Furthermore, the model robustly estimates long-run cointegrating relationships among variables, regardless of their stationarity properties. A key feature is the error correction term (ECT), which reveals the speed of adjustment back to long-term equilibrium, thereby illuminating the dynamic response of these economies to disturbances.

Granger causality testing complements the PMG-ARDL analysis by determining the directional relationships between the variables. Establishing whether one variable Granger-causes another yields critical insights into temporal precedence, which is necessary to develop effective and evidence-based emission reduction strategies.

The methodological framework follows a sequence of steps. First, panel unit root tests (ADF, PP, and CIPS) are applied to determine the integration order of the variables. Second, Pedroni (1999, 2004) and Westerlund (2005) cointegration tests are employed to examine whether long-run relationships exist among the series. Third, the PMG-ARDL estimator of Pesaran *et al.* (2001) is used to estimate both short-run and long-run elasticities, as this method accommodates heterogeneity across countries while imposing long-run homogeneity. Finally,

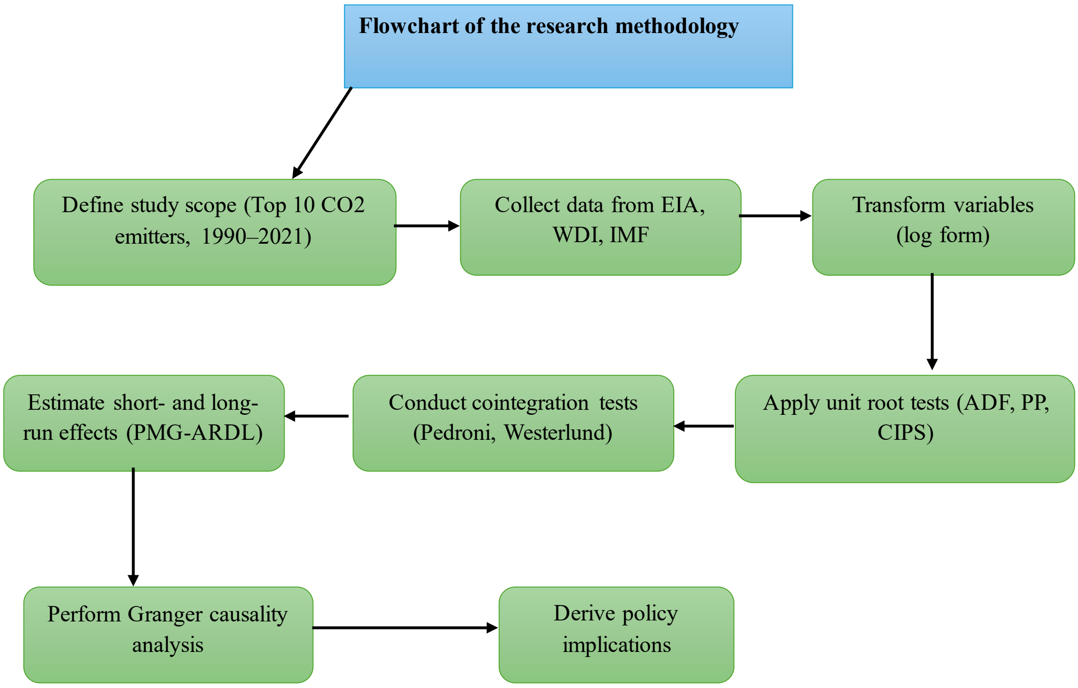

Figure 3. The flowchart of the empirical methodology

Granger causality tests are applied to explore the direction of causality among the variables. The flowchart presented in Figure 3 summarizes the methodology of the study.

To ensure our findings are reliable, we tested different versions of our model. We looked at versions without financial growth, or where financial growth was switched with how open countries are to trade. We also checked if different timeframes changed the outcomes. The main findings stayed the same: non-renewable energy increases carbon emissions, renewable energy and financial growth help lower emissions, and the EKC idea is supported. However, when we removed industrial value, the model was not as good at explaining the results, which shows that industry is important for understanding emission changes in countries that emit a lot.

5. Results

5.1. Cross-sectional Dependence (CD) tests

Prior to a panel data analysis, it is essential to address the issue of cross-sectional dependence (CD). The CD test is utilized to identify the presence of cross-sectional dependency problems within the panel data. Consequently, three diagnostic tests for cross-sectional dependence, Breusch-Pagan Chi-square, Pearson LM Normal, and Pearson CD Normal, are presented in Table 2. The null hypothesis of cross-sectional independence assumes that countries in the panel are mutually exclusive and uncorrelated. This is opposed to the alternative hypothesis, which suggests the presence of mutual dependence across the entire panel.

Table 2 presents the results of the CD tests. The Breusch-Pagan Chi-square test statistics reject the null hypothesis of cross-sectional independence. In contrast, the statistics from the Pearson LM Normal and Pearson CD Normal tests indicate insufficient evidence to reject the null hypothesis of no cross-sectional dependence in the residuals. Consequently, this outcome implies a significant discrepancy between the rankings of the groups, necessitating the use of a first-generation panel unit root test (PURT).

5.2. Panel unit root test

To establish the order of integration for each variable, three PURTs are employed: the Augmented Dickey-Fuller (ADF, 1979) and Phillips-Perron (PP, 1988) tests, both of which are first-generation tests, and the Cross-Sectionally Augmented IPS (CIPS; Pesaran, 2007) test, regarded as a second-generation test. The ADF and PP tests play a crucial role in panel data analysis, as non-stationarity may result in spurious regressions and undermine the reliability of statistical inference. The CIPS test is specifically designed for panel data and employs an augmented IPS statistic approach to address cross-sectional

Table 2
Cross-sectional Dependence (CD) tests

Test	Statistic	Prob.
Breusch-Pagan Chi-square	60.31576	0.0631*
Pearson LM Normal	0.560330	0.5753
Pearson CD Normal	1.233219	0.2175

"*" indicates statistical significance at the 1% level.

Table 3
Panel unit root test

PP						
At Level	lnCO2em	lnGDP	lnRE	lnNRE	lnIVA	lnFDI
t-Statistic	0.2983	0.5165	0.2047	0.3843	0.2572	0.9994
Prob.	0.9804	0.1391	0.0001***	0.9376	0.8890	0.1823
At First Diff.	d(lnCO2)	d(lnGDP)	d(lnRE)	d(lnNRE)	d(lnIVA)	d(lnFDI)
t-Statistic	0.0000	0.0003	0.0001	0.0000	0.0001	0.0000
Prob.	0.0000***	0.0000***	0.0002***	0.0000***	0.0000***	0.0000***
ADF						
At Level	lnCO2em	lnGDP	lnRE	lnNRE	lnIVA	lnFDI
t-Statistic	0.4272	0.5362	0.2111	0.1870	0.2711	0.9766
Prob.	0.8895	0.6179	0.3246	0.8115	0.8192	0.1383
At First Diff.	d(lnCO2em)	d(lnGDP)	d(lnRE)	d(lnNRE)	d(lnIVA)	d(lnFDI)
t-Statistic	0.0000	0.0003	0.0005	0.0000	0.0001	0.0000
Prob.	0.0000***	0.0000***	0.0002***	0.0004***	0.0001***	0.0000***
CIPS						
At Level	lnCO2em	lnGDP	lnRE	lnNRE	lnIVA	lnFDI
Z-t bar stat	18.289	13.743	-0.217	1.203	18.289	0.942
Prob.	1.000	1.000	0.414	0.114	1.000	0.827
At 1st Diff	d(lnCO2em)	d(lnGDP)	d(lnRE)	d(lnNRE)	d(lnIVA)	d(lnFDI)
Z-t bar stat	-16.841	-18.222	-16.334	-17.883	-17.542	-5.547
Prob.	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***

Notes: "***" indicates statistical significance at the 1% level.

dependence. In our case, the first generation is more significant given the degree of independence in residuals.

The findings presented in Table 3 indicate that all variables exhibit a unit root at their level. However, they become stationary after the first differencing, demonstrating that all variables are integrated of order one, I(1), at the 1% significance level.

5.3. Panel cointegration test results

The stationary tests proved that all variables are I (1) and the long-run cointegration can be examined through various cointegration techniques such as Pedroni (1999, 2004) and Westerlund (2005). To achieve this, Pedroni's cointegration test (1999, 2004) is utilized. By incorporating multiple testing procedures, including modified versions of the Phillips-Perron and Augmented Dickey-Fuller tests, Pedroni (1999, 2004) applied multiple testing procedures to enhance the robustness and reliability of the cointegration analysis. For the Westerlund (2005) test, the applied statistic is based on the variance-ratio, which is a statistical technique utilized to evaluate the presence of cointegration among time series variables. Unlike the traditional Engle-Granger and Johansen cointegration tests, this method accommodates heteroscedasticity in the error terms. This is on structural dynamics rather than residual dynamics, which results in the panel cointegration test statistics being calculated as follows:

$$VR = \sum_{i=1}^{N}\sum_{t=1}^{T} \hat{E}_{it}^{2}\, \hat{R}_i^{-1} \quad (3)$$

$$VR = \sum_{i=1}^{N}\sum_{t=1}^{T} \hat{E}_{it}^{2} \left(\sum_{i=1}^{N} \hat{R}_i\right)^{-1} \quad (4)$$

The Westerlund (2005) test is particularly advantageous in scenarios where the error variances vary across observations, rendering it a robust approach for cointegration analysis. Both tests assume an absence of cointegration as their null hypothesis.

Table 4 presents the results of the Pedroni cointegration tests. The findings indicate that the null hypothesis of no cointegration can be rejected at a significance level of 1%. This

Table 4
Pedroni cointegration test results

	Statistic	p-value
Modified Phillips–Perron t	9.2094	0.0000***
Phillips–Perron t	4.6943	0.0000***
Augmented Dickey-Fuller t	4.0677	0.0000***

Notes: "***" indicates statistical significance at the 1% level.

Table 5
Westerlund cointegration test results

	Statistic	p-value
Variance ratio	20.3619	0.0000***

Notes: "***" indicates statistical significance at the 1% level.

suggests a long-term cointegrating relationship among the variables analyzed. Table 5 presents the results of the Westerlund cointegration test, indicating that the variance ratio statistic provides evidence supporting the presence of a long-term relationship among the variables. This conclusion is drawn as the calculated statistic rejects the null hypothesis of no cointegration at the 1% significance level.

5.4. PMG-ARDL estimates

Once the variables have been confirmed, the PMG-ARDL model is utilized to estimate the coefficients reflecting both short-term and long-term dynamics. This methodology integrates aspects of the ARDL and PMG models in a panel econometric setting, effectively addressing cross-sectional dependence in the dataset. The PMG-ARDL model is capable of estimating relationships over both long and short terms, even when the series exhibit non-stationarity, and can also serve to forecast future values of the examined variables.

Table 6 displays the results of the PMG-ARDL estimations, depicting the relationship between CO2 emissions (as the dependent variable) and various independent variables, including real GDP, the square of real GDP, renewable and non-renewable energy, industrial value-added, and the financial development index. This analysis covers the top ten CO2-emitting countries from 1990 to 2021. The coefficients obtained from the estimations can be interpreted as elasticities, as the variables were transformed using natural logarithms.

The findings presented in Table 6 indicate that the lagged error correction term (ECT) is expected to be negative and statistically significant at -0.14. This suggests that the economy adjusts toward long-run equilibrium at a rate of 14% per year across the ten countries studied that emit CO2. In the short-term analysis, the coefficient for non-renewable energy consumption is positive and statistically significant at the 1% level. This indicates that any changes in fossil fuel energy consumption are likely to result in increased pollution levels in the short term.

The PMG-ARDL results indicate that all estimated coefficients are statistically significant at the 1% level. Specifically, the coefficient of real GDP is positive, while its square term is negative. The findings demonstrate the emergence of an inverted U-shaped correlation between CO2 emissions and economic advancement. This implies the substantiation of the EKC theory within the surveyed panel of nations. This outcome diverges from the observations made by Ben Jebli and Ben Youssef (2015a) regarding Tunisia's scenario, as assessed through the ARDL methodology. However, it aligns with the conclusions drawn by Alsamara *et al*. (2018) concerning the Gulf Cooperation Council (GCC) nations, investigated through panel cointegration methodologies. This result can be explained by the fact that these selected countries often have more advanced technological capabilities and greater financial resources to invest in cleaner technologies and sustainable practices. As a result, they can adopt and implement technologies that help reduce CO2 emissions and improve environmental quality.

Table 6
PMG-ARDL estimates

Variable	Coefficient	Std. Error	t-Statistic	Prob.
	Long Run Equation			
lnGDP	0.375025	0.035938	10.43534	0.0000***
lnGDP2	-0.002094	0.000511	-4.095731	0.0001***
lnRE	-0.020191	0.003845	-5.251226	0.0000***
lnNRE	0.950952	0.024478	38.84901	0.0000***
lnIVA	-0.172348	0.033865	-5.089213	0.0000***
lnFDI	-0.057779	0.013746	-4.203361	0.0000***
	Short Run Equation			
ECT	-0.143565	0.082858	-1.732659	0.0845*
D(lnCO2em(-1))	0.066685	0.027818	2.397197	0.0173**
D(lnGDP)	-0.174537	3.355437	-0.052016	0.9586
D(lnGDP2)	0.003066	0.060090	0.051024	0.9594
D(lnRE)	-0.016788	0.014440	-1.162580	0.2462
D(lnNRE)	0.690862	0.090829	7.606197	0.0000***
D(lnIVA)	-0.036416	0.039679	-0.917780	0.3597
D(lnFDI)	-0.005377	0.024530	-0.219199	0.8267

Notes: "***", "**" and "*" indicate statistical significance at the 1%, 5% and 10% levels, respectively.

In the long run, the estimation outcomes reveal a negative and statistically significant coefficient for renewable energy consumption. This implies that the adoption of renewable energy sources in the selected emitter countries may contribute to a reduction in CO2 emissions over time. Specifically, a 1% increase in renewable energy consumption is associated with a decrease in CO2 emissions by 0.02%. This discovery aligns with the findings of Farhani and Shahbaz (2014), Al-Mulali *et al.* (2015), and Ben Jebli *et al.* (2016). However, our results diverge from those of Ben Jebli et al. (2015b), who concluded that the consumption of renewable energy in sub-Saharan African countries leads to an increase in CO2 emissions. The decline in CO2 emissions linked to the adoption of renewable energy in the leading emitter countries can be ascribed to several factors. These include the generation of clean energy, advancements in technology, governmental support through policies, strategies for transitioning towards renewable energy sources, and the growing awareness and advocacy among the public for renewable energy adoption and climate-related actions.

The estimated coefficient for non-renewable energy is positive and statistically significant at the 1% level of significance. Additionally, the empirical findings indicate that a 1% increase in non-renewable energy leads to a 0.95% increase in CO2 emissions. These economies heavily rely on fossil fuels for various activities, such as industrial production. The extensive use of polluting energy sources contributes to a notable growth in CO2 emissions rates. Therefore, transitioning from polluting to clean energy sources could be beneficial for these countries. This observation aligns with the conclusions drawn by Karaaslan and Çamkaya (2022) in their study on Turkey, where they employed the ARDL approach.

In the long term, the coefficient associated with financial development exhibits both significance and a negative statistical correlation with CO2 emissions. Specifically, a 1% increase in financial development corresponds to a reduction of 0.05% in CO2 emissions. These findings are congruent with those presented by Zaidi *et al.* (2019), who illustrate that financial advancement within the APEC nations has led to a decrease in CO2 emissions spanning from 1990 to 2016. Moreover, employing the instrumental generalized method of moments (IVGMM) approach, Acheampong *et al.* (2020) conclude that financial progress diminishes CO2 emissions, particularly within 22 developed financial economies and 23 emerging financial economies during the period from 1980 to 2015. Tamazian *et al.* (2009) discovered an inverse relationship between CO2 emissions and financial development during the timeframe spanning 1992 to 2004. In the context of China, Jalil and Feridun (2011) utilized the ARDL method and observed that as financial development progresses, there is a corresponding enhancement in environmental quality, potentially attributable to reduced CO2 emissions. Conversely, contrary to the findings suggested by Pata (2018), who applied a similar methodology to Turkey and found that financial development amplifies carbon emissions under the EKC hypothesis. Furthermore, employing panel data analysis, Zakaria and Bibi (2019) investigated the interplay among financial development, institutional quality, and environmental quality. Their study revealed that while financial development notably diminishes environmental quality, institutional quality exerts a positive influence on it. More recently, Charfeddine and Kahia (2019) utilized the Panel-Vector Autoregressive (PVAR) methodology to analyze twenty-four MENA countries, revealing a positive association between financial development and the acceleration of carbon emissions. Similarly, Saidi and Mbarek (2017) examined this relationship using the generalized method of moments (GMM) technique within emerging economies, highlighting the affirmative role of financial development in enhancing environmental quality. Enhanced financial development plays a pivotal role in facilitating investments in eco-friendly energy technologies and infrastructure. With the evolution and maturation of financial markets, there arises an expanded scope for financing renewable energy projects, energy-efficient innovations, and initiatives focused on carbon capture and storage. These investments act as catalysts for mitigating CO2 emissions by stimulating the adoption of cleaner and sustainable energy alternatives. The estimated parameters obtained through the PMG-ARDL analysis indicate a significant and statistically negative correlation between industrial activity and CO2 emissions in the long term. Specifically, a 1% increase in IVA corresponds to a reduction of 0.05% in CO2 emissions.

The cities offer important insights that highlight and underscore the importance of considering the adoption of abatement technologies within industrial operations across the surveyed countries, ultimately aiming to curtail emissions. Industrialized nations, characterized by significant production expansion, often heavily rely on the extraction and consumption of fossil fuels. Despite this growth, the proportion of clean energy generated within these top ten industrial nations remains inadequate in effectively offsetting CO2 emissions. Hence, it becomes crucial for enterprises within these regions to implement requisite measures aimed at reducing pollution levels, with a specific focus on integrating energy efficiency initiatives for the holistic improvement of environmental conditions.

5.5. Granger causality tests

In this section, an analysis of the short- and long-term causal relationships between the variables is conducted using a two-step approach based on the Engle and Granger (1987) methodology. Since the Pedroni cointegration tests indicate the presence of cointegration among the variables with CO2 emissions as the endogenous variable, Granger causality tests were performed to determine the direction of causal relationships, thereby fulfilling the objective of the empirical study. The first step involves estimating the coefficients of the long-term equation outlined in Equation (2) to obtain residuals. The second step focuses on estimating the coefficients for the short-term adjustments. The significance of the short-term causality coefficients is assessed using Fisher statistics (Pairwise Granger causality), while the significance of the long-term causality is determined via t-statistics of the lagged error correction term. The lagged error correction term is statistically significant in all equations.

The equations for Granger causality can be expressed in the following manner:

$$\Delta lnCO_{2it} = \alpha_{1i} + \sum_{j=1}^{q} \alpha_{11ij}\, \Delta lnCO_{2it-j} + \sum_{j=1}^{q} \alpha_{12ij}\, \Delta \mathrm{lnGDP}_{it-j} + \sum_{j=1}^{q} \alpha_{13ij}\, \Delta lnGDP_{it-j}^{2} + \sum_{j=1}^{q} \alpha_{14ij}\, \Delta lnRE_{it-j} + \sum_{j=1}^{q} \alpha_{15ij}\, \Delta lnNRE_{it-j} + \sum_{j=1}^{q} \alpha_{16ij}\, \Delta \mathrm{ln}IVA_{it-j} + \sum_{j=1}^{q} \alpha_{17ij}\, \Delta lnFDI_{it-j} + \theta_{1i} ect_{it-1} + \mu_{1it} \quad (5)$$

$$\Delta lnGDP_{it} = \alpha_{2i} + \sum_{j=1}^{q} \alpha_{11ij}\, \Delta lnCO2_{2it-j} + \sum_{j=1}^{q} \alpha_{22ij}\, \Delta lnGDP_{it-j} + \sum_{j=1}^{q} \alpha_{23ij}\, \Delta lnGDP_{it-j}^{2} + \sum_{j=1}^{q} \alpha_{24ij}\, \Delta lnRE_{it-j} + \sum_{j=1}^{q} \alpha_{25ij}\, \Delta lnNRE_{it-j} +$$

$$\sum_{j=1}^{q} \alpha_{26ij} \Delta lnIVA_{it-j} + \sum_{j=1}^{q} \alpha_{27ij} \Delta \ln FDI_{it-j} + \theta_{2i} ect_{it-1} + \mu_{2it} \quad (6)$$

$$\Delta lnRE_{it} = \alpha_{3i} + \sum_{j=1}^{q} \alpha_{41ij} \Delta lnCO2_{it-j} + \sum_{j=1}^{q} \alpha_{42ij} \Delta lnGDP_{it-j} + \sum_{j=1}^{q} \alpha_{43ij} \Delta lnGDP_{it-j}^{2} + \sum_{j=1}^{q} \alpha_{44ij} \Delta lnRE_{it-j} + \sum_{j=1}^{q} \alpha_{45ij} \Delta lnNRE_{it-j} + \sum_{j=1}^{q} \alpha_{46ij} \Delta \ln IVA_{it-j} + \sum_{j=1}^{q} \alpha_{47ij} \Delta lnFDI_{it-j} + \theta_{4i} ect_{it-1} + \mu_{4it} \quad (7)$$

$$\Delta lnNRE_{it} = \alpha_{5i} + \sum_{j=1}^{q} \alpha_{51ij} \Delta lnCO2_{it-j} + \sum_{j=1}^{q} \alpha_{52ij} \Delta lnGDP_{it-j} + \sum_{j=1}^{q} \alpha_{53ij} \Delta lnGDP_{it-j}^{2} + \sum_{j=1}^{q} \alpha_{54ij} \Delta lnRE_{it-j} + \sum_{j=1}^{q} \alpha_{55ij} \Delta lnNRE_{it-j} + \sum_{j=1}^{q} \alpha_{56ij} \Delta \ln IVA_{it-j} + \sum_{j=1}^{q} \alpha_{57ij} \Delta lnFDI_{it-j} + \theta_{5i} ect_{it-1} + \mu_{5it} \quad (8)$$

$$\Delta \ln IVA_{it} = \alpha_{6i} + \sum_{j=1}^{q} \alpha_{61ij} \Delta lnCO2_{it-j} + \sum_{j=1}^{q} \alpha_{62ij} \Delta lnGDP_{it-j} + \sum_{j=1}^{q} \alpha_{63ij} \Delta lnGDP_{it-j}^{2} + \sum_{j=1}^{q} \alpha_{64ij} \Delta lnRE_{it-j} + \sum_{j=1}^{q} \alpha_{65ij} \Delta \ln NRE_{it-j} + \sum_{j=1}^{q} \alpha_{66ij} \Delta \ln IVA_{it-j} + \sum_{j=1}^{q} \alpha_{67ij} \Delta \ln FDI_{it-j} + \theta_{6i} ect_{it-1} + \mu_{6it} \quad (9)$$

$$\Delta lnFDI_{it} = \alpha_{7i} + \sum_{j=1}^{q} \alpha_{71ij} \Delta lnCO2_{it-j} + \sum_{j=1}^{q} \alpha_{72ij} \Delta lnGDP_{it-j} + \sum_{j=1}^{q} \alpha_{73ij} \Delta lnGDP_{it-j}^{2} + \sum_{j=1}^{q} \alpha_{74ij} \Delta lnRE_{it-j} + \sum_{j=1}^{q} \alpha_{75ij} \Delta \ln NRE_{it-j} + \sum_{j=1}^{q} \alpha_{76ij} \Delta \ln IVA_{it-j} + \sum_{j=1}^{q} \alpha_{77ij} \Delta lnFDI_{it-j} + \theta_{7i} ect_{it-1} + \mu_{7it} \quad (10)$$

Where $ln(.)$ denotes the logarithmic transformations; q indicates the number of lags; ect denotes the lagged error correction term; and μ_{it} denotes the error terms.

Table 7 summarizes the results concerning the causal relationships among the variables in both the short and long term. The Pairwise Granger causalities are reported in Figure 4. Based on the results of the Granger causality tests, Table 7 indicates that all lagged error correction terms demonstrate statistical significance at varying levels, namely 1% and 5%. This suggests the presence of a long-term relationship among CO2 emissions, economic growth, renewable and non-renewable energy consumption, industrial value added, and financial development within the selected panel dataset. Based on the results presented in Table 7 and Figure 1, Granger causality analysis indicates short and long-run bidirectional causality between CO2 emissions and GDP, CO2 emissions and renewable energy consumption, and CO2 emissions and industrial value-added. However, there exists short-run unidirectional causality from non-renewable energy consumption to CO2 emissions and from CO2 emissions to financial development. These results align with those of Mahmoodi (2017) in a study encompassing 11 developing countries, employing the panel cointegration methodology. Mahmoodi (2017) observed a bidirectional causality among renewable energy, economic growth, and CO2 emissions, mirroring the findings presented here. Nevertheless, these results diverge from those of Qudrat-Ullah and Nevo (2022) in their study of five sub-Saharan African countries. Their findings indicated a lack of evidence for causality between both economic growth and CO2 emissions, as well as renewable energy consumption and CO2 emissions, contrasting with the observed relationships in this analysis. Additionally, our findings contrast with those of Kahia and Ben Jebli (2021) in their examination of the top ten industrial countries, where they identified no causal relationships between CO2 emissions and industrial expansion. Based on our findings, any alteration in the trajectory of economic activity growth, particularly concerning industrial development, will impact the proliferation of pollution levels both in the short and long term. In light of these results, we recommend that these polluting countries adopt policies that promote economic growth, especially for the industrial sector, while reducing long-term emissions. In doing so, these policies can promote development that is sustainable from both environmental and economic perspectives.

Interestingly, Granger causality shows bidirectional short and long-run causality between industry value-added and renewable energy consumption. Thus, any changes in the use of renewable energy lead to the expansion of industrial activity and vice versa. Also, Granger mentioned bidirectional long-run causality between financial development, renewable energy consumption, industrial growth, and CO2 emissions. Hence, it

Table 7
Granger causality results

	ΔlnCO2	ΔlnGDP/ΔlnGDP2	ΔlnRE	ΔlnNRE	ΔlnIVA	ΔlnFDI	ECT
ΔlnCO2	-	5.16720 (0.0062)***	4.41592 (0.0129)**	6.74253 (0.0014)***	4.07720 (0.0179)**	1.57086 (0.2096)	-0.005153 [-2.48789]***
ΔlnGDP/ΔlnGDP2	7.88701 (0.0005)***	-	6.70310 (0.0014)***	10.7693 (0.0000)***	4.64075 (0.0104)**	4.62650 (0.0105)**	-0.000147 [-2.50479]***
ΔlnRE	3.95416 (0.0202)**	2.39286 (0.0931)*	-	3.76838 (0.0242)**	0.89951 (0.4079)	0.79846 (0.4510)	-0.007272 [-2.15137]***
ΔlnNRE	1.83954 (0.1607)	3.09352 (0.0468)*	3.18955 (0.0426)**	-	1.88744 (0.1533)	1.58367 (0.2070)	-0.054549 [-3.97997]***
ΔlnIVA	6.92838 (0.0011)***	0.87116 (0.4195)	7.52793 (0.0006)***	9.00232 (0.0002)***	-	2.83037 (0.0606)*	-0.004722 [-3.58107]***
ΔlnFDI	15.7327 (0.0000)***	4.55229 (0.0113)**	0.67514 (0.5099)	15.1837 (0.0000)***	2.74922 (0.0656)*	-	-0.015361 [-1.91562]**

Notes: **« *** », « ** », and « * »** indicate statistical significance at the 1% level.

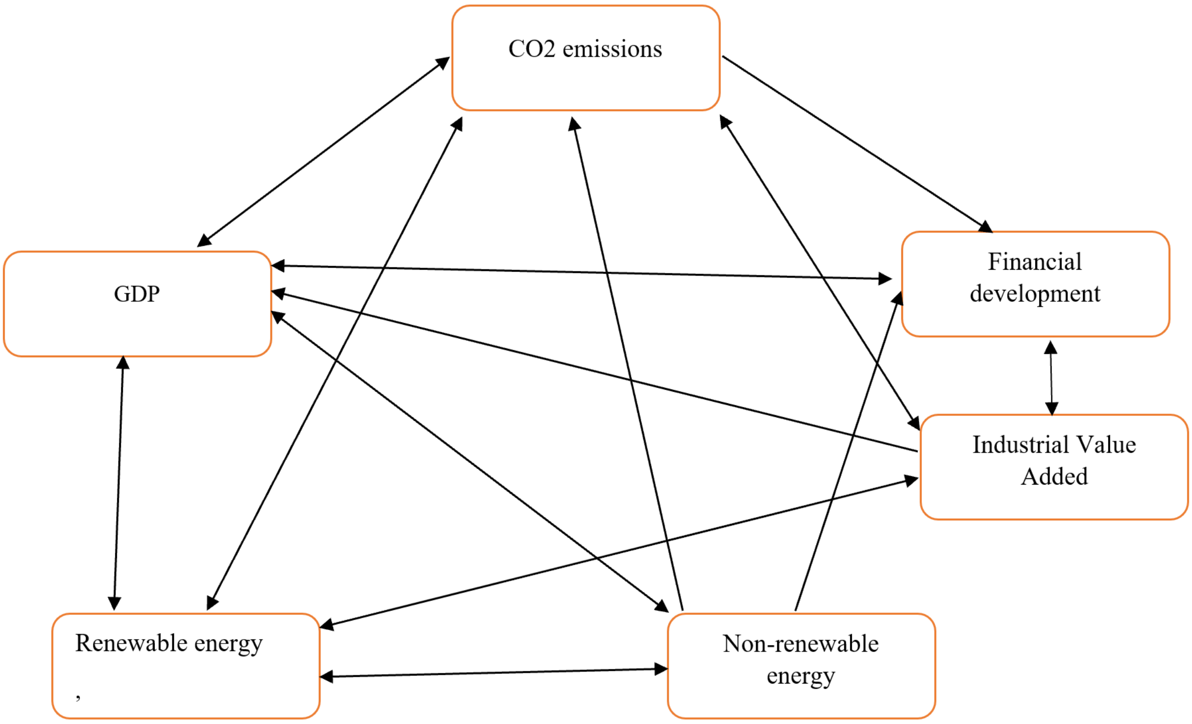

Figure 4. Pairwise Granger causality results

can be inferred that industries within these nations are progressively acknowledging the economic and environmental advantages associated with the adoption of renewable energy sources. Consequently, they are engaging in active investment activities toward renewable energy technologies to fulfill their energy supplies, simultaneously diminishing their dependence on conventional fossil fuels.
A robust financial sector plays a central role in facilitating capital provision and investment paths essential for the advancement and utilization of renewable energy technologies. This financial support can help industries allocate resources towards the development and implementation of renewable energy infrastructure and the urge for industrial expansion.

6. Discussion

6.1 Main Findings of the Present Study

The analysis shows there is a stable, long-term connection between carbon dioxide emissions, economic growth, types of energy use, financial development, and industrial activity in the ten countries responsible for the most emissions between 1990 and 2021. The EKC theory is supported: when economies start to grow, emissions rise, but after a certain point, further economic development helps reduce environmental damage. Renewable energy and a developed financial sector help lower emissions, but the use of fossil fuels and rapid industrial growth tend to increase them.

6.2 Comparison with Other Studies

These results agree with earlier work by Ang (2008), Ben Jebli et al. (2016), and Zaidi et al. (2019), who showed that the mix of energy sources and financial growth plays an important role in environmental quality. The confirmation of the EKC is also in line with studies from both developing and developed countries (such as Shahbaz *et al.*, 2013; Apergis & Payne, 2010). This study goes further by concentrating on the highest-emitting nations and by confirming that renewable and non-renewable energy have different effects, supporting findings by Tran *et al.* (2023) and Nguyen *et al.* (2023).

6.3 Implication and Explanation of Findings

The outcomes of this study suggest that moving toward cleaner energy and improving financial institutions are essential steps for high-emitting countries to cut down carbon dioxide. If industrialization continues without efforts to adopt greener technologies, environmental problems will likely worsen. The EKC theory suggests that while economic growth initially benefits, true sustainability can only be achieved when countries also adopt advanced technology and supportive financial systems.

6.4 Strengths and Limitations

One of the main advantages of this research is its focus on the top ten polluting nations, because their choices have a big impact on global climate change. Using the PMG-ARDL method also enables the analysis of both immediate and long-term effects across countries. However, there are some limitations: for example, the research could not include other possible factors, such as government effectiveness or digitalization, due to missing data. In addition, country-level data may hide important patterns happening within specific sectors.

6.5 Conclusion, Recommendation, and Future Direction

In summary, the study shows that expanding renewable energy and strengthening the financial sector can effectively reduce CO2 emissions in major polluting countries, but ongoing use of fossil fuels and rapid industrialization remain challenges.

Policymakers should focus on investing in clean energy technology, encouraging sustainable financing, and regulating industries that produce high emissions. Future studies should look at how factors like the quality of institutions, city management, and digital innovations affect emissions, or analyze different sectors to better understand where specific actions are needed.

7. Conclusion

This study examined the dynamic relationships among CO_2 emissions, economic growth, renewable and non-renewable energy consumption, financial development, and industrial value-added in the ten highest-emitting countries from 1990 to 2021. Using the PMG-ARDL estimator and Granger causality tests, the results confirmed long-run cointegration among the variables and validated the Environmental Kuznets Curve (EKC) hypothesis. Consistent with earlier findings by Shahbaz *et al.* (2013) and Apergis and Payne (2010), the study revealed that economic growth initially increases CO_2 emissions but eventually promotes environmental improvement. Moreover, in line with Charfeddine and Kahia (2019) and Zaidi *et al.* (2019), renewable energy and financial development were found to mitigate emissions, while non-renewable energy consumption and industrialization heightened environmental degradation.

These findings highlight that the transition toward cleaner energy and stronger financial systems is fundamental for sustainable growth. The results also align with Zafeiriou *et al.* (2023), who emphasize energy–growth linkages as key drivers of environmental degradation in EU economies, and with Michailidis *et al.* (2025), who demonstrate the importance of governance and policy frameworks in advancing renewable energy transitions across developing MENA countries. Collectively, this evidence underscores that sustainable development requires coordinated policy efforts that integrate economic, financial, and environmental dimensions.

From a policy standpoint, governments in major emitting economies should intensify investments in renewable energy infrastructure, promote green finance mechanisms to support low-carbon technologies, and encourage industrial innovation that prioritizes energy efficiency and emission reduction. Establishing transparent governance frameworks and coherent policy environments can further enhance the effectiveness of these measures and foster long-term sustainability.

The study's main strengths lie in its focus on the world's largest emitters and in the application of the PMG-ARDL model, which captures both short- and long-run dynamics while accounting for cross-country heterogeneity. Nevertheless, limitations include the reliance on annual data, which may obscure short-term fluctuations, and the exclusion of variables such as institutional quality and technological innovation due to data constraints. Future research should therefore employ more granular and sectoral data to explore the role of governance, digital transformation, and technological progress in shaping emissions and sustainability outcomes.

Overall, this study contributes to the literature by jointly analyzing financial development, industrial value-added, and the energy mix within the EKC framework. It enhances understanding of the structural drivers of CO_2 emissions in high-emission economies and offers a replicable empirical framework for policymakers and researchers seeking to align economic growth with environmental sustainability.

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