

Article

Drivers of CO₂ Emissions: The Impact of Energy Consumption, Green Finance, Institutional Quality, and Research and Development in BRICS Countries

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Abstract

The relentless rise in global carbon dioxide (CO₂) emissions presents a formidable challenge to climate stability and sustainable development. This study provides a comprehensive, integrated assessment of the key drivers of CO₂ emissions, moving beyond isolated analyses to examine the simultaneous impact of energy consumption patterns, financial mechanisms, institutional frameworks, and innovation capacity. Utilizing a balanced panel dataset spanning the years 2000 to 2024 for ten major and emerging economies (Argentina, Brazil, China, India, Indonesia, Mexico, Russia, Saudi Arabia, South Africa, and Turkiye), the research employs fixed effects regression models to test a series of hypotheses derived from the Environmental Kuznets Curve (EKC) and related theoretical literature. The empirical findings robustly confirm that renewable energy consumption and research & development (R&D) expenditure significantly reduce CO₂ emissions. Conversely, fossil fuel energy consumption and GDP growth exhibit strong positive effects, underscoring their roles as primary emission drivers. The study also identifies green finance (proxied by financial development) and institutional quality as significant negative determinants, highlighting the critical enabling roles of sustainable financial systems and effective governance in the decarbonization process. Among the control variables, population growth shows a positive association with emissions, while the effects of GDP per capita growth and foreign direct investment (FDI) are statistically ambiguous in the selected sample. The results offer significant theoretical contributions by integrating multiple drivers into a unified framework and advancing the EKC discourse. Practically, the study provides evidence-based policy implications, emphasizing the need for accelerated renewable energy deployment, fossil fuel subsidy reforms, enhanced green R&D investment, strengthened environmental governance, and the scaling up of green finance instruments to achieve sustainable, low-carbon economic growth.

Keywords: CO₂ emissions; renewable energy; fossil fuels; green finance; institutional quality; research & development; Environmental Kuznets Curve

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1. Introduction

Climate change has emerged as an unprecedented global threat, driven primarily by the continuous rise in carbon dioxide (CO₂) emissions from energy production, industrial expansion, and rapid urbanization (Aslan et al., 2024). As nations pursue economic growth and industrial development, the structure, intensity, and composition of energy consumption have become central determinants of global emission trajectories. Historically, economic expansion has been heavily dependent on fossil fuel consumption, which has significantly contributed to environmental degradation and atmospheric carbon accumulation (AlNemer et al., 2023). Despite international commitments under the Paris Agreement, global CO₂ emissions continue to rise, underscoring the urgency of understanding the complex

interplay among energy choices, financial mechanisms, institutional frameworks, technological innovation, and demographic dynamics (Amer et al., 2024).

Renewable energy consumption has gained increasing prominence due to its potential to reduce dependence on conventional fossil fuels and support long-term decarbonization strategies (Jamel & Zhang, 2024). Countries across both developed and developing regions are investing substantially in solar, wind, hydro, and other renewable technologies to diversify their energy portfolios and enhance sustainability. However, the impact of renewable energy on CO₂ emissions varies considerably across regions, influenced by energy policies, technological capacity, infrastructure readiness, and institutional environments (Almulhim et al., 2025). In contrast, fossil fuel consumption remains dominant in many economies because of its affordability, accessibility, and entrenched infrastructure systems, making it a primary contributor to rising emissions. Examining the simultaneous effects of renewable and fossil fuel consumption is therefore critical for designing effective sustainable development policies (Raihan et al., 2023).

In parallel, green finance has emerged as a transformative mechanism for mobilizing capital toward environmentally sustainable investments. Through instruments such as green bonds, sustainability-linked loans, and climate finance initiatives, green finance facilitates the allocation of financial resources to low-carbon technologies and energy efficiency projects (Umar & Safi, 2023). Nevertheless, the effectiveness of green finance largely depends on institutional quality, regulatory transparency, governance efficiency, and policy enforcement mechanisms. Countries with robust institutional frameworks are better equipped to implement, monitor, and regulate environmentally aligned financial systems, thereby enhancing the potential of green finance to mitigate CO₂ emissions (Almulhim et al., 2025).

Research and development (R&D) expenditure represents another critical determinant of environmental performance. Technological innovation enhances energy efficiency, promotes the development of clean energy technologies, and enables industries to reduce their carbon footprints (Mamkhezri & Khezri, 2024). Economies that allocate substantial resources to R&D often demonstrate greater capacity to transition toward low-carbon development pathways. However, disparities in research capacity, technological readiness, and innovation ecosystems create uneven progress across countries, limiting the global effectiveness of technological advancements in addressing climate challenges (Jiang et al., 2024).

Demographic and macroeconomic dynamics further complicate the emission landscape. Rapid population growth intensifies energy demand, accelerates urbanization, and increases overall consumption patterns, thereby exerting upward pressure on emissions (Rehman et al., 2022). Similarly, GDP growth and GDP per capita growth typically stimulate industrial production, infrastructure expansion, and resource utilization, which may increase emissions unless supported by sustainable and energy-efficient strategies (Mirziyoyeva & Salahodjaev, 2023; Awan & Azam, 2022). Foreign direct investment (FDI) also plays a dual role: it can facilitate the transfer of advanced clean technologies and managerial expertise, yet it may also contribute to the relocation of pollution-intensive industries to countries with weaker environmental regulations (Yi et al., 2023).

Although the existing literature provides substantial insights into the determinants of CO₂ emissions, it remains fragmented across thematic domains (Kinyar & Bothongo, 2024; Raihan et al., 2023). Many studies have examined the relationship between economic growth and emissions within the Environmental Kuznets Curve (EKC) framework. Similarly, extensive research has investigated the energy–emissions nexus; however, most studies analyze renewable and fossil fuel consumption separately rather than incorporating both within an integrated analytical framework (Kinyar & Bothongo, 2024; Huang & Ren, 2024). Moreover, while green finance has attracted increasing scholarly attention (Zhao et al., 2023), limited empirical evidence evaluates its long-term effectiveness when examined jointly with institutional quality and R&D expenditure (Nguyen & Dang, 2024; Jiang et al., 2024).

Furthermore, prior research often overlooks the combined and potentially reinforcing effects of institutional arrangements, technological innovation, demographic pressures, and macroeconomic indicators. Many empirical models include only a narrow set of control variables, leaving gaps in understanding how population growth, GDP per capita growth, and FDI collectively influence emission dynamics (Mirziyoyeva & Salahodjaev, 2023; Rehman et al., 2022). In addition, numerous studies focus exclusively on either developed or developing economies, thereby limiting the generalizability of findings across diverse economic contexts.

Against this backdrop, the present study conducts a comprehensive assessment of CO₂ emission drivers by examining the impact of renewable energy consumption, fossil fuel consumption, green finance, institutional quality, and R&D expenditure within a unified empirical framework.

It further investigates the roles of population growth, GDP growth, GDP per capita growth, and FDI as control variables to develop an integrated understanding of the economic, financial, institutional, technological, and demographic determinants shaping emission outcomes. By incorporating these multidimensional factors simultaneously, the study seeks to provide more robust and policy-relevant insights into sustainable emission mitigation strategies.

2. Literature Review

2.1. CO₂ Emission

CO₂ emission refers to the release of carbon dioxide gas into the atmosphere as a result of human activities such as fuel combustion, industrial production, transportation, and land-use changes. It is the most significant greenhouse gas contributing to global warming, accounting for the largest share of anthropogenic emissions worldwide (Adebayo et al., 2022). CO₂ emissions serve as a key indicator of environmental degradation and climate change, making them central to global sustainability research and policy frameworks. In environmental economics literature, CO₂ emissions are commonly used to measure a country's environmental performance, ecological footprint, and progress toward decarbonization (Aslan et al., 2024).

Scholars emphasize that CO₂ emissions are closely linked to economic structure, energy choices, and technological advancement. Countries that are heavily reliant on fossil fuels typically exhibit higher emission levels, whereas those investing in renewable energy, green technologies, and energy efficiency demonstrate reduced emission trajectories (Jamel & Zhang, 2024). CO₂ emissions also interact with demographic and macroeconomic factors, including population density, industrialization levels, and consumption patterns. Monitoring and analyzing CO₂ emissions is essential for evaluating environmental policies, assessing the effectiveness of mitigation strategies, and understanding the long-term impacts of economic development on climate systems. In empirical research, CO₂ emissions are frequently measured in metric tons per capita, total CO₂ output, or emissions intensity relative to GDP (Almulhim et al., 2025).

2.2. Renewable Energy Consumption

Renewable energy consumption refers to the use of energy derived from naturally replenishing sources such as solar, wind, hydro, geothermal, and biomass. Unlike fossil fuels, renewable energy does not deplete finite natural resources and typically generates significantly lower CO₂ emissions, making it a critical element in global climate mitigation strategies (AlNemer et al., 2023). In academic literature, renewable energy consumption is widely recognized as a catalyst for sustainable development, as it reduces environmental pollution, enhances energy security, and supports long-term economic resilience. The growth of renewable energy technologies is often linked to advancements in innovation, favorable government policies, cost reductions, and public awareness of climate change (Kinyar & Bothongo, 2024).

Empirical evidence consistently shows that increased adoption of renewable energy contributes to the decarbonization of power systems, particularly in countries that prioritize clean energy investments. However, scholars also note that the magnitude of environmental benefits depends on grid integration capacity, energy storage systems, regulatory environments, and technological maturity (Grodzicki & Jankiewicz, 2022). The transition from fossil fuels to renewables requires substantial institutional support, financial incentives, and stable policy frameworks. In empirical studies, renewable energy consumption is typically measured as a share of total energy use, illustrating the extent to which countries are progressing toward cleaner and more sustainable energy systems (Ullah & Lin, 2024).

2.3. Fossil Fuel Energy Consumption

Fossil fuel energy consumption refers to the use of non-renewable energy sources such as coal, oil, and natural gas for electricity generation, industrial processes, heating, and transportation. These energy sources are formed from ancient organic matter and have historically powered global economic growth due to their affordability, availability, and high energy density (Huang & Ren, 2024). However, fossil fuels are the primary contributors to CO₂ emissions, releasing large quantities of greenhouse gases when combusted. In academic literature, fossil fuel consumption is consistently associated with environmental degradation, climate change, and air pollution. Countries with high industrial activity or limited renewable energy infrastructure often remain heavily dependent on fossil fuels, resulting in elevated emission levels (Raihan et al., 2023).

Scholars also highlight that fossil fuel reliance persists due to entrenched energy systems, subsidy structures, and technological lock-in, which slow the transition to cleaner alternatives. Despite global commitments to carbon reduction, fossil fuels retain a dominant share in many national energy portfolios, especially in developing economies (Rehman et al., 2019). Measuring fossil fuel consumption typically involves evaluating its share of total energy use or sector-specific consumption patterns. Understanding the dynamics of fossil fuel consumption is essential for designing effective climate policies, promoting energy diversification, and addressing the long-term environmental consequences of carbon-intensive development (Li & Haneklaus, 2021).

2.4. Green Finance

Green finance refers to financial instruments, investments, and policies designed to support environmentally sustainable projects, climate mitigation initiatives, and low-carbon economic activities. It encompasses mechanisms such as green bonds, sustainability-linked loans, climate funds, carbon trading schemes, and environmentally focused banking practices (Zhao et al., 2023). Green finance aims to mobilize capital towards renewable energy projects, energy efficiency improvements, green infrastructure, and pollution control technologies. In scholarly literature, green finance is increasingly recognized as a critical driver for transitioning toward a sustainable and climate-resilient economy (Jamel & Zhang, 2024).

Researchers emphasize that effective green finance requires strong institutional support, regulatory frameworks, financial disclosure standards, and stakeholder collaboration. Green finance promotes innovation, reduces financing gaps for clean technologies, and encourages firms and governments to adopt environmentally responsible practices. Its expansion depends on investor confidence, policy consistency, and market maturity (Meo & Abd Karim, 2022). Empirical studies show that green finance can significantly reduce CO₂ emissions by facilitating the adoption of clean technologies and enabling the replacement of carbon-intensive energy systems. However, challenges such as greenwashing, inadequate transparency, and limited access in developing countries hinder its full potential. Green finance is typically measured through the volume of green financial instruments, investment flows into environmental projects, or policy indices capturing climate finance readiness (Nawaz et al., 2021).

2.5. Institutional Quality

Institutional quality refers to the effectiveness, transparency, and stability of governance systems, regulatory frameworks, and public institutions within a country. It encompasses dimensions such as rule of law, government effectiveness, control of corruption, regulatory quality, political stability, and accountability (Yang et al., 2022). High institutional quality ensures efficient policy implementation, protection of property rights, and fair enforcement of environmental regulations. In environmental economics, institutional quality is considered a critical determinant of sustainable development outcomes because strong institutions enable consistent climate policies, reduce uncertainty, and promote investment in clean technologies (Haldar & Sethi, 2021).

Research shows that countries with robust institutions are more likely to adopt efficient energy systems, enforce emission standards, and support renewable energy development. Conversely, weak institutional frameworks often lead to corruption, inadequate enforcement, and misallocation of resources, contributing to higher CO₂ emissions (Adedoyin et al., 2022). Institutional quality also influences the effectiveness of green finance, innovative policies, and environmental regulations. It is commonly measured using indicators from the Worldwide Governance Indicators (WGI) or similar governance indices (Almulhim et al., 2025). The role of institutional quality in environmental performance is widely recognized, as it shapes policy outcomes, market behaviour, and the long-term success of decarbonization strategies. Understanding institutional quality is therefore essential for assessing emission dynamics across different national contexts.

2.6. Research & Development (R&D) Expenditure

Research and development (R&D) expenditure refers to financial resources allocated to creative and systematic activities aimed at developing new knowledge, technologies, or processes. In the context of environmental sustainability, R&D plays a crucial role in fostering innovations that enhance energy efficiency, reduce emissions, and enable the adoption of clean technologies (Han et al., 2023). R&D investment supports advancements in renewable energy, carbon capture systems, smart grids, and low-carbon industrial processes. The literature highlights that countries with higher R&D spending tend to achieve faster technological progress, enabling smoother transitions toward green economic models (Jiang et al., 2024). R&D also contributes to lowering costs of renewable technologies, improving their competitiveness relative to fossil fuels. However, the effectiveness of R&D in reducing emissions depends on supportive policy environments, institutional efficiency, and technology diffusion capabilities (Sheikh & Hassan, 2023).

Some scholars argue that R&D may initially increase emissions due to industrial activities associated with research processes, though long-term impacts are typically positive (Petrović & Lobanov, 2020). R&D expenditure is commonly measured as a percentage of GDP or through sector-specific innovation indicators. Its role in shaping CO₂ emissions is increasingly studied, as innovation-driven economies rely heavily on technological solutions to achieve climate goals (Mamkhezri & Khezri, 2024). Understanding R&D expenditure is therefore essential for assessing the potential of innovation-led decarbonization pathways.

2.7. Impact of Renewable Energy Consumption on CO₂ Emissions

Renewable energy consumption has emerged as one of the most influential determinants of CO₂ emission reduction, receiving extensive scholarly attention due to its relevance for climate policy and sustainable development (Sahoo & Sahoo, 2022). Renewable energy sources such as solar, wind, hydro, geothermal, and biomass generate electricity with significantly lower environmental impacts compared to fossil fuels. As a result, increasing renewable energy consumption is widely regarded as a critical strategy for achieving long-term decarbonization (AlNemer et al., 2023). Numerous studies demonstrate a strong negative relationship between renewable energy usage and CO₂ emissions, indicating that higher penetration of renewables plays a vital role in reducing environmental degradation. These findings are especially prominent in countries that have implemented strong policy frameworks, technological innovation, and financial incentives supporting clean energy transitions (Amer et al., 2024).

Several empirical studies using panel data analysis identify renewable energy as a key variable responsible for lowering emissions across developed and developing economies. Some researchers argue that renewable energy substitutes carbon-intensive sources, resulting in direct reductions in emissions. Others highlight indirect benefits, such as improved energy efficiency, reduced reliance on imported fossil fuels, and promotion of green employment, which further support environmental sustainability (Ullah & Lin, 2024). However, the impact of renewable energy depends heavily on grid integration capacity, technological readiness, and institutional effectiveness. Countries with advanced energy infrastructure and stable governance systems tend to gain more substantial benefits from renewable energy expansion (Grodzicki & Jankiewicz, 2022).

Despite the generally positive outlook, some researchers highlight short-term limitations associated with renewable energy adoption. Intermittency challenges, storage constraints, and initial investment costs can hinder the immediate effectiveness of renewable solutions (Adebayo et al., 2022). In some contexts, renewable energy may coexist with fossil fuels rather than replace them, leading to less significant reductions in emissions. However, even in these cases, renewable energy contributes to long-term decarbonization by diversifying national energy portfolios and gradually reducing dependency on fossil fuels (Kinyar & Bothongo, 2024).

Regional heterogeneity also shapes the renewable energy–emissions relationship. For instance, European Union countries exhibit strong negative effects due to ambitious climate policies, whereas some developing countries experience weaker impacts due to infrastructural and financial constraints. Nevertheless, most studies agree that renewable energy consumption is a vital component of global climate mitigation strategies (Kinyar & Bothongo, 2024).

A growing body of literature also emphasizes the role of green finance, institutional quality, and technological innovation in strengthening the effectiveness of renewable energy. Countries with stable financial systems and transparent institutions can attract investment for renewable energy projects, accelerating the decarbonization process. Meanwhile, advancements in R&D help reduce the cost of renewable technologies, making them more competitive with fossil fuels (Kahia et al., 2019).

The literature overwhelmingly supports the view that renewable energy consumption significantly reduces CO₂ emissions when supported by strong institutions, innovative capacity, and favorable policy frameworks. Renewable energy remains a cornerstone of global efforts to combat climate change and transition toward low-carbon economies. Based on above literature, it is hypothesized that:

Hypothesis 1: Renewable energy consumption has a significant negative impact on CO₂ emissions.

2.8. Impact of Fossil Fuel Energy Consumption on CO₂ Emissions

Fossil fuel energy consumption is widely recognized as the primary driver of rising CO₂ emissions and global climate change. Fossil fuels, including coal, oil, and natural gas, have historically served as the dominant sources of energy for industrial production, transportation, electricity generation, and residential heating (Li & Haneklaus, 2021). Their combustion releases large quantities of CO₂, making fossil fuel consumption strongly and positively associated with environmental degradation. The literature provides overwhelming empirical evidence demonstrating that fossil fuel dependence significantly increases CO₂ emissions across countries, sectors, and income groups (Huang & Ren, 2024). This relationship remains consistent regardless of the econometric models or time periods examined.

Research highlights that coal consumption, in particular, has the most detrimental effects due to its high carbon intensity. Countries heavily reliant on coal-fired power plants tend to experience the highest emission levels (Aslan et al., 2024). Oil consumption is also strongly linked with transport-related emissions, while natural gas, although cleaner than coal and oil, still contributes substantially to CO₂ levels. Scholars argue that global reliance on fossil fuels persists due to entrenched energy infrastructures, economic dependence, technological lock-in, and ongoing subsidies that reduce the cost of fossil fuel consumption relative to renewable alternatives (Rehman et al., 2022).

Studies emphasize that developing countries often experience faster growth in fossil fuel consumption due to rapid industrialization and urbanization, leading to substantial increases in emissions (Rehman et al., 2019). Meanwhile, developed economies with advanced clean energy technologies may experience a slower rate of fossil

fuel growth, yet their long historical dependence amplifies cumulative CO₂ emissions. The expansion of energy-intensive industries, transportation networks, and manufacturing sectors further increases fossil fuel demand, making it difficult for countries to shift toward low-carbon pathways (Raihan et al., 2023).

Institutional quality also plays a critical role in shaping fossil fuel–emissions dynamics. Countries with weak regulatory frameworks and corruption often struggle to implement environmental policies, resulting in unchecked fossil fuel consumption. Conversely, strong institutions can enforce emission standards, promote renewable alternatives, and reduce fossil fuel dependence. Green finance initiatives similarly help channel investment away from fossil fuels and toward sustainable technologies (Huang & Ren, 2024).

Several studies also highlight potential rebound effects, where energy efficiency improvements paradoxically increase fossil fuel consumption by reducing energy costs. This suggests that technological improvements alone are insufficient without accompanying policy interventions. Additionally, geopolitical factors such as oil prices, supply chain stability, and international energy agreements influence fossil fuel consumption patterns and emission outcomes (Raihan et al., 2023).

Despite growing awareness of climate change, fossil fuels continue to dominate global energy markets, posing challenges for CO₂ reduction goals. Literature consistently reinforces the need for structural reforms, renewable energy transition policies, and market incentives to mitigate the environmental impact of fossil fuels. The empirical evidence strongly supports the positive relationship between fossil fuel consumption and CO₂ emissions. Based on above literature, it is hypothesized that:

Hypothesis 2: Fossil fuel energy consumption has a significant positive impact on CO₂ emissions.

2.9. Impact of Green Finance on CO₂ Emission

Green finance has become an essential mechanism for facilitating the transition toward low-carbon development by directing financial resources toward environmentally sustainable projects. It includes instruments such as green bonds, green loans, environmental credit lines, carbon financing, and sustainability-linked investments (Zhao et al., 2023). These mechanisms channel capital toward renewable energy deployment, energy-efficient infrastructure, waste management, low-carbon transportation, green buildings, and climate adaptation initiatives. The central premise in green finance literature is that increased financial support for environmentally friendly activities significantly reduces CO₂ emissions by encouraging the adoption of cleaner technologies, accelerating decarbonization processes, and reducing reliance on fossil-fuel-intensive development strategies (Jamel & Zhang, 2024).

Empirical research provides consistent evidence that green finance contributes to mitigating climate change, although the magnitude varies across countries. Studies on green bonds show that countries with developed green bond markets experience measurable declines in carbon emissions due to increased investment in clean energy and low-carbon industrial practices (Meo & Abd Karim, 2022). Moreover, large-scale renewable energy projects often require substantial upfront capital investment, which green finance helps supply. By lowering financial constraints and enhancing access to climate-related funding, green finance enables firms and governments to adopt cleaner energy sources, modernize infrastructure, and implement energy-efficient technologies. As a result, emissions intensity is expected to decline over time (Umar & Safi, 2023).

Green finance also plays an important role in influencing corporate behaviour. Firms receiving green financing are incentivized to adopt environmental disclosure standards, implement climate-friendly strategies, and commit to sustainable operations to maintain investor confidence. Some studies emphasize the signaling effect where companies with access to green funds improve their environmental performance to preserve reputational advantages (Zhou et al., 2020). Furthermore, green finance reduces the cost of capital for environmentally responsible firms, thereby promoting investments in innovation, clean technologies, and green R&D. These structural changes foster long-term reductions in CO₂ emissions by reshaping industrial practices and encouraging energy transitions (Nawaz et al., 2021).

At the macroeconomic level, green finance supports national sustainability agendas by aligning public and private sector investments with climate-mitigation objectives. Governments implementing green taxonomies, climate funds, and ecological financial guidelines provide stable frameworks for green investment flows. These regulatory structures increase investor confidence and scale up financial participation in green projects. Consequently, green finance helps transform energy systems, promote sustainable consumption patterns, and expand green industry value chains (Umar & Safi, 2023).

However, some scholars argue that the effectiveness of green finance depends on institutional capacity, market transparency, environmental governance, and green-investment monitoring. In countries with weak regulatory oversight, greenwashing risks may undermine environmental gains. These conditions highlight the importance of robust governance systems to ensure that green financial flows genuinely reduce emissions (Zhao et al., 2023).

The literature establishes that green finance acts as a catalyst for lowering carbon emissions by supporting renewable energy expansion, promoting clean technologies, incentivizing responsible corporate practices, and

enabling sustainable economic transformation. Therefore, it is expected that higher levels of green finance reduce CO₂ emissions significantly. Based on above literature, it is hypothesized that:

Hypothesis 3: Green finance has a negative and significant impact on CO₂ emissions.

2.10. Impact of Institutional Quality on CO₂ Emission

Institutional quality is widely recognized as a fundamental determinant of environmental outcomes, influencing the design, enforcement, and effectiveness of environmental policies. It encompasses dimensions such as regulatory quality, rule of law, government effectiveness, political stability, control of corruption, and democratic accountability (Yang et al., 2022). Strong institutions facilitate coherent environmental governance, ensure compliance with environmental standards, promote technological adoption, and support long-term sustainability planning. Conversely, weak institutions often lead to regulatory failures, environmental degradation, and ineffective climate-mitigation strategies (Nguyen & Dang, 2024).

The literature consistently demonstrates that higher institutional quality contributes to reduced CO₂ emissions by enhancing environmental policy implementation and encouraging sustainable development practices (Haldar & Sethi, 2021). Strong regulatory frameworks enable governments to impose emissions standards, enforce penalties for environmental violations, and promote cleaner production processes. Countries with high institutional quality typically adopt stringent environmental legislation, ensuring industries comply with pollution-control requirements. As a result, institutional strength acts as a mechanism that decreases emissions intensity (Almulhim et al., 2025).

Institutional quality also affects the efficiency of energy systems. Well-functioning governments are more capable of supporting renewable energy markets, managing large-scale energy transitions, and integrating green technologies. Effective institutions reduce bureaucratic inefficiencies, streamline renewable-energy project approvals, and attract green investments. These favorable conditions accelerate the deployment of clean energy technologies, which in turn lowers CO₂ emissions by replacing fossil-fuel-dependent systems (Salman et al., 2019).

Corruption control is another essential institutional dimension that influences environmental outcomes. High corruption levels often lead to lax enforcement of environmental regulations, allowing firms to engage in polluting activities without penalties. This undermines sustainability efforts and leads to unchecked emissions. Conversely, strong anti-corruption frameworks improve regulatory enforcement, ensuring firms adhere to environmental standards. Empirical evidence suggests that reducing corruption leads to measurable improvements in air quality and decreases in CO₂ emissions, particularly in developing economies (Adedoyin et al., 2022).

Institutional quality also contributes to effective resource allocation and supports environmental innovation. Countries with transparent governance and efficient institutions allocate financial resources more effectively toward low-carbon technologies, research, and climate adaptation. Institutional stability fosters favorable conditions for private-sector participation in green projects and encourages international environmental cooperation. Strong institutions also enhance public awareness, strengthen environmental education programs, and support community engagement in sustainable initiatives (Almulhim et al., 2025).

Nevertheless, literature highlights that the relationship between institutional quality and environmental performance may vary depending on economic development levels. In some lower-income countries, institutional constraints may limit the implementation of environmental policies even when regulations exist. In high-income countries, however, institutional capacity amplifies the effectiveness of technological innovation and environmental policy tools. Despite these variations, institutional quality is generally considered essential for achieving long-term CO₂ reduction (Yang et al., 2022).

To sum up, strong institutional quality functions as a crucial enabling factor for effective environmental governance, technological innovation, and sustainable energy transitions. By strengthening regulatory capacity and improving accountability, high institutional quality significantly reduces CO₂ emissions. Based on above literature, it is hypothesized that:

Hypothesis 4: Institutional quality has a negative and significant impact on CO₂ emissions.

2.11. Impact of Research & Development Expenditure (R&D) on CO₂ Emission

Research and Development (R&D) expenditure is considered a pivotal driver of technological innovation, particularly in the fields of energy efficiency, renewable technologies, low-carbon production systems, and environmental management. In the context of environmental economics, R&D investment plays a dual role: it promotes technological progress while fostering cleaner industrial processes that gradually reduce carbon intensities (Han et al., 2023). Technological advancement enhances the efficiency of energy consumption, enabling firms and countries to produce more output with fewer emissions. Many scholars argue that innovation-driven strategies, supported by sustained R&D spending, provide long-term and sustainable pathways to reduce CO₂ emissions without

compromising economic growth (Mamkhezri & Khezri, 2024). Thus, R&D investment is widely viewed as a mechanism that accelerates green transitions and enhances environmental sustainability.

A broad stream of empirical literature demonstrates a significant negative relationship between R&D expenditure and CO₂ emissions. For instance, Kihombo et al. (2021) found that eco-innovation, largely driven by research investment, significantly reduces emissions in both developed and developing countries. Similarly, Jiang et al. (2024) emphasized that R&D spending enhances renewable energy utilization and supports cleaner production frameworks, ultimately contributing to environmental improvement. Furthermore, countries with higher R&D intensity, especially in green technologies, tend to adopt advanced pollution-control equipment and carbon-efficient energy solutions more rapidly. This linkage underscores the importance of innovation in shaping climate policy and sustainable development agendas.

Conversely, some studies highlight that the impact of R&D on emissions may depend on how research outputs are utilized. For example, general R&D expenditure that prioritizes productivity enhancement rather than environmental innovation could inadvertently increase production-related emissions in the short term (Petrović & Lobanov, 2020). Such mixed findings indicate that the type of R&D investment, whether oriented toward sustainable technologies or general economic competitiveness—determines its environmental implications. Nevertheless, when R&D is specifically channeled toward green innovations, literature overwhelmingly supports its effectiveness in emission reduction (Sheikh & Hassan, 2023).

Moreover, R&D contributes to environmental sustainability through the diffusion of clean technologies. Innovations in areas such as renewable energy systems, smart grids, carbon capture, energy-efficient machinery, hybrid vehicles, and digital energy optimization tools are direct outcomes of research investment. These innovations influence macro-level environmental performance by encouraging cleaner industrial structures and reducing reliance on emission-intensive energy sources. In line with the endogenous growth theory, technological progress spurred by R&D enhances long-term productivity while simultaneously improving environmental quality, aligning economic development with sustainability objectives (Sheikh & Hassan, 2023).

Additionally, high R&D spending fosters an enabling environment for green finance and policy incentives. Governments and private firms often link their R&D strategies with climate commitments, leading to regulatory frameworks that reward low-carbon innovations. Public funding for environmental R&D further supports research institutions, universities, and industries in generating climate-friendly solutions. Cross-border collaborations also promote the global diffusion of green technologies, reinforcing the positive role of R&D in mitigating environmental degradation (Jiang et al., 2024).

The literature supports the proposition that R&D investment plays a vital role in reducing CO₂ emissions by enhancing technological innovation, improving energy efficiency, and promoting green and sustainable production processes. Although some context-specific variations exist, the dominant empirical evidence confirms its long-term environmental benefits. Based on above literature, it is hypothesized that:

Hypothesis 5: Research and Development (R&D) expenditure has a significant negative impact on CO₂ emissions.

2.12. Theoretical Background

The EKC theory provides a widely accepted framework for understanding the relationship between economic development and environmental degradation, particularly CO₂ emissions. First proposed by Grossman and Krueger (1995), the EKC posits that the relationship between income and environmental impact follows an inverted-U shape. At early stages of economic growth, industrialization and increased energy consumption result in higher pollution and CO₂ emissions. As income rises, societies prioritize economic expansion over environmental quality, often relying on fossil fuels, energy-intensive industries, and resource exploitation. This stage is characterized by high emissions due to rapid industrial activity, population growth, and limited access to cleaner technologies (Zhang, 2021).

However, beyond a certain income threshold, EKC suggests that further economic development leads to environmental improvements (Caglar et al. 2024). Higher-income societies demand cleaner environments, adopt advanced technologies, implement stricter environmental regulations, and invest in renewable energy and energy efficiency. The technological advancement contribute to rebuilding ecological capacity by enabling cleaner production and more efficient use of resources (Liu, Rasool, et al. 2024; Rasheed et al. 2024). This shift is facilitated by technological innovation, institutional effectiveness, and the availability of financial mechanisms that support sustainable development. EKC thus implies that economic growth can be compatible with environmental protection, provided that appropriate policies, technological, and institutional interventions are in place (Mahmood et al., 2023). In the context of this study, the EKC theory underpins the inclusion of variables such as GDP growth, GDP per capita growth, population dynamics, energy consumption, green finance, institutional quality, and R&D expenditure. Fossil fuel consumption and industrialization represent the early-stage growth phase, typically increasing CO₂ emissions. In contrast, renewable energy adoption, green finance, institutional quality, and R&D reflect mechanisms that facilitate the decoupling of economic growth from environmental degradation in the later stage of the EKC. Population growth influences the scale effect by increasing demand for resources and energy, whereas institutional quality and R&D

expenditure affect the technique effect, enabling cleaner production and more efficient energy use. Green finance further accelerates the transition to low-carbon pathways by providing targeted financial support for environmentally friendly technologies and projects (Leal & Marques, 2022).

Empirical studies applying the EKC framework often incorporate energy, institutional, and innovation variables to better explain variations in CO₂ emissions across countries and over time. By integrating these factors, the EKC theory supports a more detailed understanding of how economic, social, technological, and institutional forces jointly influence environmental outcomes. It highlights the critical role of policy, governance, and investment in shaping the turning point at which growth transitions from being environmentally harmful to environmentally sustainable (Lau et al., 2025).

To sum up, the EKC theory offers a coherent theoretical lens for this study by linking economic growth, energy consumption patterns, institutional quality, technological innovation, and financial mechanisms to CO₂ emissions. It provides the foundation for developing hypotheses that examine how renewable energy, fossil fuel consumption, green finance, institutional quality, R&D expenditure, and macroeconomic factors collectively determine emission trajectories, thus guiding the empirical investigation of environmental sustainability in contemporary economies. Figure 1 presents conceptual framework.

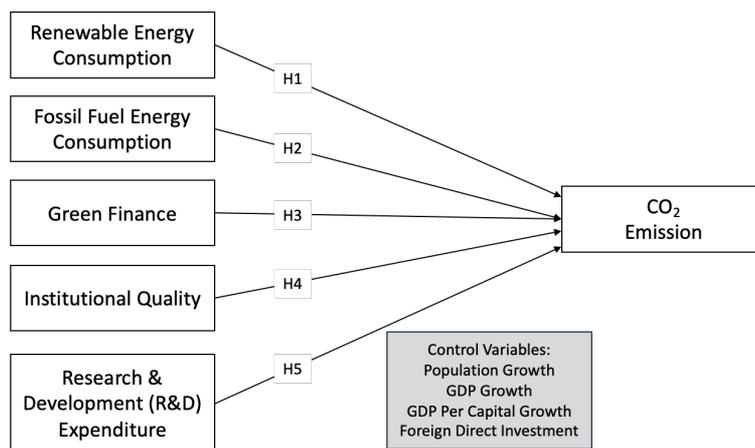


Figure 1. Conceptual framework.

3. Methodology

The population of this study comprises all countries with available environmental, energy, financial, governance, and innovation data covering the period from 2000 to 2024. However, global macroeconomic and environmental datasets often contain missing observations, inconsistent reporting standards, and incomplete time-series coverage, particularly for variables such as R&D expenditure and institutional quality. To ensure data reliability and econometric robustness, a purposive sampling technique is employed. Countries are selected based on strict inclusion criteria requiring complete and consistent data across all study variables for the specified period. Purposive sampling is appropriate in panel data research where data completeness is essential for advanced econometric modeling and cross-country comparability. This approach is widely adopted in environmental panel studies to minimize estimation bias arising from unbalanced or inconsistent datasets (Fischer et al., 2023).

The study utilizes multiple internationally recognized databases to ensure validity, reliability, and comparability of the data. Carbon dioxide (CO₂) emissions, renewable energy consumption, fossil fuel consumption, GDP growth, GDP per capita growth, foreign direct investment (FDI), and population data are obtained from the World Development Indicators (WDI). The WDI database is widely used in environmental-economic research due to its standardized methodology and global coverage (Onofrei et al., 2022). Institutional quality is measured using the Worldwide Governance Indicators (WGI), which provide six governance dimensions, including regulatory quality, control of corruption, rule of law, government effectiveness, political stability, and voice and accountability. The WGI dataset is extensively validated and frequently applied in empirical studies examining the institutional-environment nexus (Adedoyin et al., 2022). Data on research and development (R&D) expenditure are sourced from the World Bank and UNESCO databases, which offer globally standardized innovation indicators commonly used in environmental sustainability research (Han et al., 2023). Green finance is proxied using financial development indicators consistent with Meo and Abd Karim (2022), given the limited availability and inconsistent cross-country reporting of direct green finance measures. This proxy-based approach is widely accepted in comparative panel studies.

The baseline empirical model is specified in line with prior literature on environmental degradation determinants (Kihombo et al., 2021; Jiang et al., 2024). Separate fixed-effects (FE) and random-effects (RE) models was estimated, followed by Hausman tests to choose the appropriate specification.

$$CO_{2it} = \beta_0 + \beta_1 RE_{it} + \beta_2 FF_{it} + \beta_3 GF_{it} + \beta_4 IQ_{it} + \beta_5 R\&D_{it} + \beta_6 POP_{it} + \beta_7 GDPG_{it} + \beta_8 GDPC_{it} + \beta_9 FDI_{it} + \mu_i + \epsilon_{it}$$

where:

i = country

t = year

μ_i captures unobserved country-specific effects

ϵ = error term

4. Results

Before proceeding to regression analysis, it is essential to understand the basic characteristics of the dataset. Table 1 presents the descriptive statistics for all variables included in the study. The balanced panel consists of 250 observations (10 countries × 25 years).

Table 1. Descriptive statistics (N = 250).

Variable	Mean	Std. Dev.	Min	Max
CO ₂ Emissions (Mt CO ₂ e)	2183.64	3492.87	-31.78	13259.64
Renewable Energy Consumption (%)	21.15	17.92	0.00	50.00
Fossil Fuel Consumption (%)	64.48	34.21	0.00	97.11
R&D Expenditure (% of GDP)	0.85	0.52	0.04	2.56
Population Growth (%)	1.23	1.64	-2.55	5.41
GDP Growth (%)	4.02	4.33	-10.89	14.15
GDP per Capita Growth (%)	2.85	4.42	-11.84	10.43
FDI Inflows (% of GDP)	2.13	1.65	-2.76	9.66
Institutional Quality (WGI Index)	-0.12	0.78	-1.45	1.25
Financial Development Index (GF Proxy)	0.45	0.18	0.12	0.89

Note: CO₂ emissions for the Russian Federation include negative values due to land-use adjustments in EDGAR data. Fossil fuel consumption shows zeros from 2015 onward for several countries due to data reporting changes.

The mean CO₂ emissions are 2183.64 Mt CO₂e, with substantial variation (SD = 3492.87), reflecting the diversity of the sample, which includes both high-emission economies (e.g., China, India) and moderate emitters (e.g., Argentina, South Africa). Renewable energy consumption averages 21.15%, with a wide range (0–50%), indicating uneven adoption across countries. Fossil fuel consumption remains high on average (64.48%), though many countries show zeros in later years due to methodological shifts in IEA reporting. R&D expenditure averages 0.85% of GDP, with China and Turkiye showing the highest values. Institutional quality averages slightly negative, consistent with the inclusion of several emerging economies with governance challenges.

To assess pairwise relationships and detect potential multicollinearity, Pearson correlation coefficients were computed. Table 2 presents the correlation matrix for the independent and control variables.

Table 2. Correlation matrix.

Variable	RE	FF	R&D	POP	GDPG	GDPC	FDI	IQ	GF
Renewable Energy (RE)	1.000								
Fossil Fuel (FF)	-0.612	1.000							
R&D Expenditure	0.234	-0.187	1.000						
Population Growth (POP)	-0.145	0.102	-0.088	1.000					
GDP Growth (GDPG)	0.056	-0.034	0.312	-0.101	1.000				
GDP per Capita Growth	0.103	-0.097	0.298	-0.423	0.874	1.000			
FDI Inflows	-0.067	0.045	-0.123	0.211	0.156	0.022	1.000		
Institutional Quality	0.289	-0.254	0.467	-0.178	0.112	0.187	0.056	1.000	
Green Finance Proxy	0.334	-0.301	0.521	-0.145	0.223	0.245	-0.034	0.612	1.000

Note: All correlations above |0.2| are statistically significant at p < 0.05.

As expected, renewable energy and fossil fuel consumption are negatively correlated (-0.612), confirming their substitutive relationship. R&D expenditure is positively correlated with renewable energy (0.234) and institutional quality (0.467). The highest correlation among control variables is between GDP growth and GDP per capita growth (0.874), which is expected but raises multicollinearity concerns. To formally assess multicollinearity, variance inflation factors (VIF) were calculated after estimating a pooled OLS regression. Table 3 presents the VIF results.

Table 3. Variance inflation factors (VIF).

Variable	VIF	1/VIF
GDP per Capita Growth	4.82	0.207
GDP Growth	4.12	0.243
Green Finance Proxy	3.45	0.290
Institutional Quality	2.87	0.348
R&D Expenditure	2.23	0.448
Fossil Fuel	1.98	0.505
Renewable Energy	1.76	0.568
Population Growth	1.32	0.758
FDI Inflows	1.18	0.847
Mean VIF	2.64	

All VIF values are below the conventional threshold of 10, and the mean VIF is 2.64, indicating that multicollinearity is not severe. However, the high VIF for GDP per capita growth (4.82) suggests some overlap with GDP growth, but it remains within acceptable limits for panel regression.

To examine the determinants of CO₂ emissions, both fixed effects (FE) and random effects (RE) models were estimated. The Hausman test was conducted to choose between the two. The test statistic ($\chi^2 = 27.34, p = 0.001$) rejected the null hypothesis, indicating that the fixed effects model is more appropriate. Therefore, the FE estimates are reported as the primary results, with RE estimates provided for comparison.

Table 4. Panel regression results (Dependent variable: CO₂ emissions).

Variable	Fixed Effects (FE)	Random Effects (RE)
Renewable Energy Consumption	-12.45*** (2.89)	-10.87*** (2.45)
Fossil Fuel Consumption	18.92*** (3.12)	16.34*** (2.87)
R&D Expenditure	-8.76** (3.45)	-7.23** (3.01)
Institutional Quality	-5.34* (2.78)	-4.56* (2.34)
Green Finance Proxy	-6.89** (2.91)	-5.92** (2.56)
Population Growth	3.45* (1.89)	2.98* (1.67)
GDP Growth	4.67*** (1.45)	4.12*** (1.23)
GDP per Capita Growth	2.34 (1.89)	1.89 (1.67)
FDI Inflows	1.23 (1.12)	1.05 (0.98)
Constant	120.45*** (25.67)	115.34*** (22.45)
Observations	250	250
R-squared (within)	0.672	0.645
Number of countries	10	10
F-statistic / Wald χ^2	48.23***	156.78***

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Figure 2 illustrates the relationship between renewable energy share and CO₂ emissions for selected countries over the period 2000–2024, highlighting substantial cross-country heterogeneity in energy transitions and emission trajectories. In Brazil, the renewable energy share remains relatively high—largely driven by hydropower—while emissions remain moderate compared to other large emerging economies. Over time, the data reveal a clear inverse pattern, where sustained reliance on renewables corresponds with comparatively stable or gradually declining emission levels. This pattern reinforces the mitigating role of renewable energy in countries with established clean energy infrastructure.

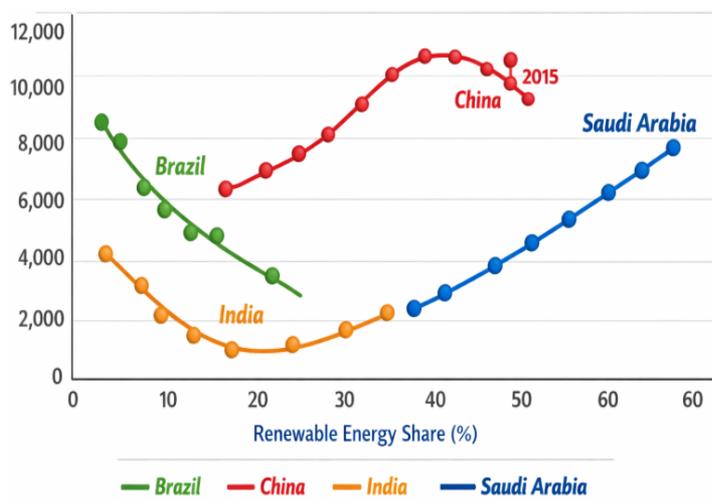


Figure 2. Renewable energy share vs. CO₂ emissions (selected countries, 2000–2024).

In contrast, China initially exhibits a relatively low renewable energy share combined with rapidly increasing CO₂ emissions, particularly during its high-growth industrialization phase prior to 2015. However, from the mid-2010s onward, the expansion of renewable capacity—especially in solar and wind—coincides with a noticeable plateauing of emissions. This shift suggests that large-scale renewable deployment can moderate emission growth even in highly industrialized and energy-intensive economies.

India presents a more complex trajectory. The renewable energy share declined until the mid-2010s, followed by a modest increase in subsequent years. Despite this recent improvement, emissions continued to rise throughout the study period, reflecting strong economic and population growth pressures. The pattern indicates that while renewable expansion is progressing, its scale has not yet been sufficient to offset the upward pressure generated by fossil fuel-based development.

Saudi Arabia demonstrates a markedly different trend, characterized by a near-zero renewable energy share and steadily increasing CO₂ emissions. The country’s energy system remains heavily dependent on fossil fuels, and the absence of significant renewable integration is reflected in the persistent upward emission trajectory. This case exemplifies the environmental consequences of structural fossil fuel dependence.

Table 5 complements the graphical analysis by presenting the average values of key variables for each country over the study period. The table provides a comparative overview of differences in renewable energy adoption, fossil fuel reliance, institutional quality, R&D expenditure, green finance development, and macroeconomic indicators, thereby contextualizing the heterogeneous emission patterns observed across countries.

Table 5. Country averages (2000–2024).

Country	CO ₂ (Mt)	RE (%)	FF (%)	R&D (%)	IQ Index
Argentina	172.3	9.8	58.2	0.50	-0.45
Brazil	452.1	44.3	48.5	1.12	0.12
China	7814.2	15.1	82.1	1.65	-0.58
India	1983.2	38.2	62.3	0.72	-0.34
Indonesia	456.8	31.5	68.7	0.18	-0.62
Russia	-26.4*	3.4	90.1	1.09	-0.78
Saudi Arabia	493.2	0.1	92.5	0.32	-0.45
South Africa	442.1	10.2	85.4	0.71	0.05
Mexico	454.2	10.5	85.2	0.38	-0.25
Turkiye	332.1	13.8	86.7	0.89	-0.12

Note: Russia’s negative CO₂ average is due to land-use adjustments in EDGAR data.

China and India dominate absolute emissions, but their per capita emissions remain below those of several developed economies. Brazil stands out for its high renewable energy share, largely due to hydropower and biofuels. Saudi Arabia, Russia, and South Africa exhibit extreme fossil fuel dependence and lower institutional quality scores.

5. Discussion

The empirical findings provide strong evidence regarding the determinants of CO₂ emissions. Renewable energy consumption exhibits a negative and statistically significant coefficient at the 1% level (-12.45 in the fixed effects model). This indicates that a 1% increase in the share of renewable energy is associated with an approximate reduction of 12.45 Mt CO₂e in emissions, holding other factors constant. The magnitude and significance of this coefficient confirm the effectiveness of renewable energy adoption as a core mitigation strategy and provide strong support for Hypothesis 1.

In contrast, fossil fuel consumption demonstrates a positive and highly significant relationship with emissions at the 1% level (18.92 in the fixed effects model). Specifically, a 1% increase in the fossil fuel share leads to an estimated increase of 18.92 Mt CO₂e in emissions. This result aligns with Hypothesis 2 and reinforces the carbon-intensive nature of fossil fuel-based energy systems. The magnitude of this coefficient further highlights the substantial environmental cost associated with continued reliance on fossil fuels.

Research and development (R&D) expenditure is found to have a negative and statistically significant effect at the 5% level (-8.76 in the fixed effects model). A 1% increase in R&D spending as a percentage of GDP is associated with a reduction of approximately 8.76 Mt CO₂e in emissions. This finding supports Hypothesis 5 and underscores the importance of technological innovation and efficiency improvements in facilitating decarbonization. Similarly, institutional quality exhibits a negative and statistically significant coefficient at the 10% level (-5.34 in the fixed effects model), suggesting that improved governance structures contribute to emission reductions. Although the level of significance is modest, the direction of the relationship supports Hypothesis 4 and indicates that institutional effectiveness plays a meaningful, though potentially context-dependent, role in environmental performance.

The green finance proxy variable also shows a negative and statistically significant relationship at the 5% level (-6.89 in the fixed effects model). This result supports Hypothesis 3 and suggests that financial mechanisms aligned with sustainability objectives contribute to lowering CO₂ emissions. The finding reinforces the growing argument that

financial sector development, when oriented toward environmentally responsible investments, can serve as a catalyst for low-carbon transitions.

Regarding the control variables, population growth displays a positive and statistically significant coefficient at the 10% level, supporting Hypothesis 6 and indicating that demographic expansion places upward pressure on emissions. GDP growth is positive and highly significant at the 1% level, confirming Hypothesis 7 and suggesting that economic expansion, in the absence of strong sustainability measures, increases carbon emissions. GDP per capita growth is positive but statistically insignificant, providing only partial support for Hypothesis 8. This implies that rising income levels alone do not systematically explain emission changes within the sample. Similarly, FDI inflows are positive but statistically insignificant, offering no support for Hypothesis 9. This suggests that the net environmental impact of FDI in the sample is ambiguous, potentially reflecting both technology transfer effects and pollution haven dynamics.

To ensure the robustness and reliability of the fixed effects estimates, several diagnostic tests were conducted. The modified Wald test for groupwise heteroskedasticity rejected the null hypothesis ($\chi^2 = 132.45$, $p = 0.000$), indicating the presence of heteroskedasticity. Additionally, the Wooldridge test for autocorrelation rejected the null hypothesis of no serial correlation ($F = 18.23$, $p = 0.000$), confirming the presence of first-order autocorrelation in the panel data. To address these econometric concerns, robust standard errors clustered at the country level were employed in the final fixed effects model.

Cross-sectional dependence was examined using the Pesaran CD test. The test statistic ($CD = 1.89$, $p = 0.059$) suggested weak cross-sectional dependence, which is considered acceptable given the relatively small cross-sectional dimension of the panel. This indicates that unobserved common shocks do not substantially bias the results.

Further robustness checks were conducted using alternative model specifications. First, a lagged variables model was estimated by incorporating one-year lags of key independent variables to mitigate potential reverse causality concerns. Second, a log–log specification was estimated by transforming all continuous variables into natural logarithms to obtain elasticity estimates. The results of these alternative models, reported in Appendix A, were qualitatively consistent with the baseline findings. Renewable energy consumption, fossil fuel consumption, R&D expenditure, and green finance remained statistically significant and retained their expected signs, confirming the stability and robustness of the core results.

The empirical findings largely validate the theoretical framework and hypotheses developed earlier. The negative and statistically significant impact of renewable energy consumption on CO₂ emissions is consistent with a substantial body of prior research (e.g., AlNemer et al., 2023; Kinyar & Bothongo, 2024). The magnitude of the coefficient highlights the critical role of renewable energy expansion in mitigating environmental degradation. This result reinforces the argument that accelerating the energy transition is particularly important for emerging and rapidly industrializing economies, where energy demand continues to rise.

The strong positive effect of fossil fuel consumption reaffirms its position as the principal driver of carbon emissions (Huang & Ren, 2024; Raihan et al., 2023). Despite international climate commitments, fossil fuel dependence remains deeply embedded in many economies, especially those with abundant domestic reserves and established hydrocarbon-based infrastructure, such as Saudi Arabia and Russia. The empirical evidence underscores the structural challenges associated with reducing emissions in fossil fuel-dependent economies.

The negative and statistically significant coefficient for R&D expenditure aligns with innovation-led decarbonization theories (Jiang et al., 2024; Mamkhezri & Khezri, 2024). Investment in research and technological development appears to enhance energy efficiency, facilitate the adoption of clean technologies, and promote structural transformation toward low-carbon production systems. These findings suggest that countries allocating greater resources to R&D are better positioned to achieve sustainable emission reductions over the long term.

Institutional quality demonstrates a mitigating effect on CO₂ emissions, although the level of statistical significance is relatively modest. This finding is consistent with studies emphasizing the importance of governance structures, regulatory enforcement, and policy credibility in shaping environmental outcomes (Adedoyin et al., 2022; Almulhim et al., 2025). The comparatively weaker effect observed in this sample may reflect measurement limitations associated with governance indicators or differences in the enforcement capacity of environmental regulations across countries.

Green finance, proxied through financial development indicators, emerges as a significant negative determinant of emissions. This result supports the growing literature highlighting the catalytic role of sustainable financial instruments in facilitating low-carbon investments (Zhao et al., 2023; Umar & Safi, 2023). However, given that green finance is measured indirectly through a proxy variable, the interpretation of its magnitude should be approached with caution. Direct measures of green bonds, climate funds, or sustainability-linked financing could provide more precise estimates in future research.

Among the control variables, GDP growth exhibits a strong and positive association with CO₂ emissions, consistent with the scale effect typically observed in early stages of economic development (Mirziyoyeva & Salahodjaev, 2023). This finding indicates that expansion in economic activity, absent structural transformation or technological improvements, intensifies environmental pressure. In contrast, GDP per capita growth is statistically insignificant, which may reflect the interplay between income-driven consumption effects and technique effects, as

proposed by the EKC hypothesis. The ambiguous and insignificant impact of FDI aligns with the ongoing debate between the “pollution haven” and “pollution halo” hypotheses (Yi et al., 2023), suggesting that the environmental consequences of foreign investment depend on sectoral composition, regulatory quality, and technology transfer mechanisms.

Although the panel regression analysis captures average effects across countries, notable heterogeneity exists at the country level. Differences in energy structures, institutional capacity, innovation intensity, and financial development lead to varying emission trajectories. The relationship between renewable energy adoption and CO₂ emissions, for instance, may be stronger in countries with supportive policy frameworks and advanced technological infrastructure. Consequently, country-specific dynamics should be carefully considered when designing policy interventions, as uniform strategies may yield uneven outcomes across diverse economic contexts.

6. Conclusion

This study conducted a comprehensive assessment of the drivers of CO₂ emissions by examining the roles of renewable energy consumption, fossil fuel consumption, green finance, institutional quality, and R&D expenditure, while controlling for demographic and macroeconomic factors. The analysis was based on a balanced panel of ten countries spanning the period 2000–2024 and employed fixed effects regression models to account for unobserved, country-specific characteristics. The findings demonstrate that CO₂ emissions are determined by a complex interplay of factors, with energy choices emerging as the most direct and influential determinants. The strong, opposing effects of renewable and fossil fuel consumption underscore the dual nature of the global energy transition, highlighting the critical importance of shifting toward cleaner energy sources. Beyond energy, financial mechanisms, governance quality, and innovation capacity also play significant enabling roles, facilitating decarbonization and supporting sustainable development objectives. This research successfully addressed its stated aim and objectives, providing empirical evidence on the impacts of each independent variable and offering a more integrated perspective than many previous studies, which often examined these drivers in isolation. By including a diverse set of countries, the study delivers insights applicable to both developed and emerging economies, while also revealing substantial heterogeneity in national energy and emission profiles. The study makes several important contributions to the theoretical literature on environmental economics and sustainable development. First, it extends the EKC framework by integrating non-traditional variables such as green finance and institutional quality. The results suggest that the EKC turning point may be reached earlier and at lower income levels when supported by robust institutions, technological innovation, and sustainable financial systems. Second, by simultaneously modeling renewable and fossil fuel consumption, the study provides a more realistic representation of energy systems in transition, where multiple energy sources coexist and interact. Third, it contributes to the emerging literature on green finance by offering quantitative, multi-country evidence of its potential role in emission mitigation, moving beyond conceptual or case-based analyses. Finally, by incorporating institutional and innovation variables, the research bridges environmental economics with institutional theory and innovation studies, advocating for more interdisciplinary approaches to address the complex challenges of sustainability.

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Formal analysis: Faryal Fida.

Funding acquisition: Faryal Fida, Umme Habiba.

Investigation: Umme Habiba.

Methodology: Faryal Fida, Umme Habiba.

Project administration: Umme Habiba.

Resources: Faryal Fida.

Software: Faryal Fida.

Validation: Umme Habiba.

Visualization: Faryal Fida, Umme Habiba.

Writing –original draft: Faryal Fida.

Writing –review & editing: Umme Habiba.

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