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### ECONOMIC GROWTH, URBANISATION, TRADE, AND ENVIRONMENTAL QUALITY IN THE EUROPEAN UNION: ARDL AND GRANGER CAUSALITY ANALYSIS

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#### **Abstract**

*The relationship between economic development, urbanisation, trade openness, and environmental quality has emerged as a critical focus of empirical and policy-oriented research, particularly in the context of sustainable development. This study investigates the long-run and dynamic interactions between economic development, urbanisation, trade openness, institutional quality, energy use, and environmental quality in 26 European Union (EU) countries over the period 1970–2022. The analysis is grounded in panel unit root and cointegration tests, Pooled Mean Group (PMG) Autoregressive Distributed Lag (ARDL) models, and Dumitrescu–Hurlin panel Granger causality tests. The findings confirm the Environmental Kuznets Curve (EKC) hypothesis, revealing a non-linear relationship between income and CO<sub>2</sub> emissions. Urbanisation and trade openness were found to significantly increase emissions, while institutional quality plays a mitigating role in environmental degradation. Energy consumption remains a primary driver of emissions, with strong evidence of causality from economic activity, urbanisation, and energy use to CO<sub>2</sub> emissions. The PMG model results are robust across alternative estimators, and cointegration analysis confirms the existence of stable long-run relationships among the variables. The results have important implications for EU policy, suggesting the need for integrated approaches that couple economic growth with decarbonisation strategies. Strengthening institutional quality can improve environmental governance. Investment in sustainable urban planning and energy transition will be key to curbing emissions while maintaining competitiveness. Future research should focus on disaggregating energy sources, modelling structural breaks, and employing spatial methods to capture regional spillovers within the EU.*

**Keywords:** Environmental Quality, Economic Growth, Urbanisation, Trade Openness, Institutional Quality, Panel ARDL

**JEL Codes:** Q56, O44, C33, F18

#### **INTRODUCTION**

The relationship between economic development, urbanisation, trade openness, and environmental quality has emerged as a critical focus of empirical and policy-oriented research, particularly in the context of sustainable development. The European Union (EU), with its diverse economic structures and environmental policies, presents a fertile ground for investigating the interplay among these variables over the long term. As global environmental concerns intensify, the EU's commitment to ambitious climate targets, including the European Green Deal and the "Fit for 55" package, necessitates a deeper understanding of how macroeconomic and structural dynamics influence environmental outcomes (European Commission, 2021). Despite widespread policy convergence across EU member states, substantial heterogeneity persists in environmental performance, which may be shaped by differential trajectories in development, trade integration, and urban transformation.

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Urbanisation is widely regarded as both a driver of economic modernisation and a source of environmental stress. Rapid urban growth intensifies energy consumption, alters land use, and often concentrates industrial activity, thereby influencing carbon emissions and air quality (Zhao et al., 2021). However, the urban-environmental nexus is not unidirectional or linear; higher urban density may also enable efficiency gains through economies of scale in transportation, housing, and public services (Li & Lin, 2023). In the EU context, disparities in urban planning, infrastructural development, and population density further complicate the empirical estimation of urbanisation's net environmental impact. These nuances necessitate the use of robust panel econometric techniques that can account for cross-sectional dependence, structural heterogeneity, and dynamic relationships over time.

Trade openness introduces another layer of complexity to environmental dynamics. Classical theories suggest that increased trade fosters economic growth through comparative advantage and technological diffusion, potentially enhancing environmental efficiency. Conversely, the pollution haven hypothesis posits that liberalised trade may exacerbate environmental degradation by relocating polluting industries to countries with weaker environmental regulations (Tang et al., 2022). Within the EU, the interplay between intra-regional trade integration and environmental regulation enforcement offers a unique case for evaluating whether trade-led growth promotes or undermines ecological sustainability. The post-1990s expansion of the EU and the deepening of the single market framework have significantly altered trade patterns, justifying a long-run comparative analysis across member states.

Economic development is inherently tied to environmental quality through the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between income levels and environmental degradation. Empirical validation of the EKC in EU economies has produced mixed results, often depending on the pollutants measured, the time period considered, and the econometric techniques employed (Destek & Sarkodie, 2020). While some high-income EU countries appear to have decoupled growth from carbon emissions, others remain on the rising segment of the curve, suggesting that development alone does not guarantee environmental improvement. This underscores the importance of context-specific dynamics and the potential role of institutional and policy factors in shaping the development-environment link.

By analysing these complex interrelationships, this study aims to examine the long-run and short-run effects of economic growth, urbanisation, and trade openness on CO<sub>2</sub> emissions across 26 EU countries from 1970 to 2022. The empirical approach supports three central hypotheses: first, that the relationship between economic growth and CO<sub>2</sub> emissions follows an inverted-U pattern, consistent with the Environmental Kuznets Curve; second, that urbanisation increases CO<sub>2</sub> emissions due to higher energy and transport demands; and third, that trade openness exacerbates CO<sub>2</sub> emissions by encouraging the relocation of pollution-intensive industries to less-regulated economies. These hypotheses reflect the core theoretical frameworks and empirical debates explored in the subsequent sections. The study employs second-generation panel unit root tests to address cross-sectional dependence, followed by panel cointegration tests to ascertain long-run equilibrium relationships. The Panel Autoregressive Distributed Lag (ARDL) approach is used to estimate both short- and long-term coefficients while accommodating heterogeneity across countries. Finally, panel Granger causality tests provide insights into the

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directionality of relationships among the variables. This comprehensive methodology allows for robust inference and policy-relevant conclusions.

By providing a long-term, multi-country analysis of the interlinkages between key macro-structural variables and environmental quality, this study contributes to the growing literature on sustainable development in high-income regions. It offers empirical evidence that can inform both national policies and EU-level strategies aimed at harmonising economic, environmental, and social goals. As the EU transitions toward climate neutrality, understanding the underlying economic-environmental mechanisms becomes not only a scholarly imperative but a pressing policy concern.

## LITERATURE REVIEW

### *Conceptual Clarification*

The current study investigates the interrelationships among economic growth, urbanisation, trade openness, and environmental degradation, with a focus on the European Union (EU). These variables, though widely studied, are conceptually multifaceted and require contextual clarification to frame the empirical analysis.

*Environmental degradation*, in this study, is primarily measured by *CO<sub>2</sub> emissions per capita*, a widely accepted proxy due to its availability, comparability, and relevance to climate policy. While broader environmental indicators exist, such as ecological footprint, PM2.5 concentrations, and nitrogen dioxide levels, CO<sub>2</sub> emissions remain central to the EU's climate targets, including those set by the European Green Deal and Fit for 55 package. Environmental degradation is conceptualized not merely as a by-product of economic activity, but as a dynamic variable influenced by structural, spatial, and institutional forces.

*Economic development* is proxied by gross domestic product (GDP) per capita and is considered both a driver and potential mitigator of environmental harm. This dual role is best captured by the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted-U shaped relationship between income and pollution. The underlying premise is that while economic expansion initially intensifies environmental degradation due to industrialization and increased resource use, higher income levels eventually facilitate environmental improvements through investments in clean technologies, structural shifts to service sectors, and the enforcement of stronger regulations.

*Urbanisation*, as used in this study, refers to the increasing concentration of populations in urban areas. While urbanisation is often associated with higher emissions due to increased energy demand, transportation use, and construction, it may also contribute positively to environmental outcomes under certain conditions, particularly where urban planning, density, and infrastructure support sustainable practices. Hence, urbanisation is conceptualized as a structural process with both scale and efficiency effects that interact with national and regional environmental governance.

*Trade openness* is captured through trade-to-GDP ratios, reflecting the extent of a country's integration into global markets. Trade openness can influence environmental quality through multiple mechanisms. On one hand, it may promote pollution through increased production and

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resource extraction, particularly if countries serve as pollution havens. On the other hand, trade can foster environmental improvements via technology transfer, increased efficiency, and access to cleaner goods and services. The environmental effect of trade openness is thus contingent upon the nature of traded goods, regulatory alignment among trading partners, and the strength of domestic institutions.

These three structural variables, including economic growth, urbanisation, and trade openness, are not independent drivers but interrelated forces that co-evolve and jointly influence environmental outcomes. Their complex interplay, as shaped by country-specific factors such as energy structure, sectoral composition, and institutional quality, necessitates a multidimensional analytical approach. In the context of the EU, where significant cross-national heterogeneity persists despite shared environmental goals, understanding these dynamics requires both methodological rigor and conceptual clarity.

### *Theoretical Review*

The theoretical foundations of the nexus between economic development, urbanisation, trade, and environmental quality are deeply embedded in classical and modern economic thought, as well as in interdisciplinary environmental economics. A central theoretical framework frequently employed in the analysis of economic growth and environmental degradation is the EKC hypothesis. The EKC posits an inverted U-shaped relationship between environmental degradation and income per capita, suggesting that environmental quality initially deteriorates with economic growth but improves after surpassing a certain income threshold (Grossman & Krueger, 1995). This theoretical premise is rooted in structural economic transformation, wherein early-stage industrialisation leads to higher pollution levels, while post-industrial economies, with greater regulatory capacity and cleaner technologies, begin to reverse environmental harm. Empirical validations have shown mixed support, with results varying by pollutant type, region, and methodology (Sinha et al., 2022). Within the EU context, the EKC has been tested extensively, though many studies argue that policy factors and technological innovation critically mediate the income-environment relationship (Adebayo et al., 2023).

A complementary theoretical strand is derived from the Urban Environmental Transition (UET) theory, which conceptualises urbanisation as a dynamic and multi-phased process influencing environmental outcomes differently across stages of development. In its early phases, urbanisation tends to exacerbate environmental stress due to industrial concentration, higher energy demand, and inadequate infrastructure. However, as cities mature, they tend to adopt cleaner technologies, enhance environmental governance, and prioritise green infrastructure, leading to improved environmental performance (Satterthwaite et al., 2015). This trajectory reflects a shift from ‘brown’ environmental issues such as air and water pollution to more complex ‘green’ issues like carbon emissions and climate resilience. In the European context, mature urban systems are increasingly associated with environmental innovations and improved resource efficiency, particularly in Western and Northern EU countries (Wang & Wang, 2021).

The environmental implications of international trade are often theorised through two opposing lenses: the Pollution Haven Hypothesis (PHH) and the Porter Hypothesis. The PHH suggests that trade liberalisation encourages firms from developed countries to relocate polluting industries to countries with laxer environmental regulations, thus worsening environmental outcomes in host

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countries (Cole, 2004). This theory is especially relevant within heterogeneous economic unions such as the EU, where regulatory stringency and enforcement vary. In contrast, the Porter Hypothesis posits that stringent but well-designed environmental regulations can stimulate innovation and enhance competitiveness, thereby offsetting compliance costs and potentially improving environmental outcomes (Porter & van der Linde, 1995). Recent extensions of these theories incorporate the role of environmental policy harmonisation and cross-border regulatory spillovers within trade blocs such as the EU (Taghizadeh-Hesary et al., 2022).

Endogenous growth theory further contributes to understanding how economic development influences environmental quality through channels of technological innovation and human capital. In contrast to neoclassical growth models that view technological progress as exogenous, endogenous models assert that research and development (R&D), innovation, and knowledge accumulation are intrinsic to the growth process (Romer, 1990). When aligned with environmental objectives, these innovation pathways can lead to the decoupling of economic growth from environmental degradation. The EU's emphasis on the green economy and investments in sustainable innovation platforms reflects the theoretical underpinnings of this model. Empirical studies increasingly incorporate indicators such as green patents and R&D intensity to evaluate the innovation-environment link in EU member states (Ullah et al., 2022).

Ecological Modernisation Theory (EMT) provides a sociological and institutionalist perspective on how advanced economies can reconcile economic growth with environmental sustainability. EMT argues that modern institutions enable environmental improvements through proactive policymaking, cleaner production techniques, and corporate environmental responsibility (Mol & Sonnenfeld, 2000). Within the EU, institutional integration and environmental policy coordination, as embodied in instruments such as the European Climate Law and the Emissions Trading System (ETS), exemplify this theoretical orientation. Empirical evidence suggests that such institutional mechanisms play a significant role in shaping environmental outcomes independent of income or trade variables (Wang et al., 2021).

### *Empirical Review*

Recent empirical research on the Environmental Kuznets Curve (EKC) hypothesis within the European Union (EU) context reflects a nuanced and evolving understanding of the growth-environment relationship. A growing consensus supports the EKC hypothesis, particularly when refined by pollutant type, time horizon, and mediating variables. For example, Wang et al. (2021) confirmed that urbanisation and income growth initially increase carbon emissions but eventually lead to reductions due to technology diffusion and improved infrastructure. Similarly, Balsalobre-Lorente et al. (2022), using the CS-ARDL model to address cross-sectional dependence, provided evidence that financial development and trade openness can mitigate environmental degradation when strong institutional quality is present.

Urbanisation has emerged as a complex factor influencing environmental outcomes. While early urban expansion in the EU contributed to emission surges, more recent urban dynamics – characterized by compact city planning, green infrastructure, and improved transit systems – have shown a decoupling effect between urban growth and pollution (Usman & Hammar, 2022). Paramati et al. (2021) further established that renewable energy adoption moderates the

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environmental impact of urbanisation, especially in countries surpassing a threshold level of green energy penetration.

Trade openness continues to generate mixed empirical findings. On one hand, it facilitates access to cleaner technologies; on the other, it may exacerbate emissions depending on the composition of trade and environmental stringency of trading partners. Taghizadeh-Hesary et al. (2022) confirmed the “pollution haven” effect in EU trade with non-EU neighbors, whereas Ben Jebli et al. (2020) showed that trade in green technologies reduces emissions, supporting the tech-diffusion hypothesis. This dichotomy indicates the importance of trade composition and institutional filters in shaping environmental impacts.

Recent studies have increasingly emphasized the interlinkages among economic growth, urbanisation, trade openness, and environmental degradation, particularly by incorporating structural, institutional, and sectoral mediators. Mahmood et al. (2021) employed spatial econometric techniques and confirmed that environmental degradation in one EU country significantly affects its neighbors, reinforcing the need to model spatial spillovers in environmental research. Similarly, Awan et al. (2022), using a nonlinear panel ARDL framework, identified asymmetric effects of trade and urbanisation on carbon emissions, where positive shocks in trade openness resulted in disproportionately higher emissions than the reductions observed from negative shocks.

The role of institutions and governance frameworks has received heightened attention in the post-2020 literature. Neves et al. (2023) found that robust environmental governance mechanisms significantly weaken the link between trade liberalisation and emissions. Likewise, Bukhari et al. (2021) demonstrated that institutional quality acts as a suppressor variable in the growth-emissions relationship, especially in Northern and Western Europe. These findings underscore that structural reforms and institutional capacity are essential for sustainability transitions. Beyond CO<sub>2</sub>, studies are diversifying the scope of environmental indicators. Yao et al. (2023) extended the analysis to include ecological footprint and found strong causal relationships among urbanisation, economic expansion, and environmental degradation, with urbanisation leading economic growth, which in turn adversely impacts environmental quality. This causal chain reinforces the interconnectedness of the core variables under investigation.

Moreover, sectoral transformation, particularly the shift from manufacturing to service-oriented economies, has gained empirical attention. Omri and Mabrouk (2021) reported that transitions toward knowledge-based sectors in Western Europe contribute to improved environmental performance and energy efficiency. Such structural differentiation is increasingly relevant as the EU pivots toward a green and digital economy under its revised policy agenda. Despite these advances, two major empirical gaps remain. First, most studies tend to investigate the EKC, urbanisation, trade openness, and economic growth in isolation or limited combinations, without exploring their simultaneous and dynamic interactions. Second, while recent studies have introduced advanced econometric models, relatively few have integrated cross-sectional dependence, asymmetric effects, and institutional quality within a unified framework. As a result, policy insights remain fragmented and context-specific, limiting their generalizability.

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This study addresses these gaps by developing an integrated empirical model that captures the joint and dynamic effects of economic growth, trade openness, and urbanisation on environmental degradation in the EU, while accounting for the moderating role of institutional quality. By employing advanced panel estimation techniques that address cross-sectional dependence and asymmetry, this research aims to provide robust and policy-relevant findings that can support the EU's green transition agenda.

### ***Hypotheses Development***

The EKC hypothesis posits a nonlinear association between economic development and environmental degradation, typically exhibiting an inverted-U shape. In the early stages of economic growth, environmental degradation increases due to industrial expansion, urbanisation, and resource exploitation. However, as income continues to rise, investments in cleaner technologies, environmental regulations, and shifts to service-oriented economies reduce emissions (Grossman & Krueger, 1995). Recent empirical evidence supports the EKC hypothesis in the context of European countries. For instance, Zafar et al. (2020) found that GDP and GDP<sup>2</sup> coefficients confirm the EKC pattern across OECD and EU nations. Similarly, Wang et al. (2022) demonstrated an inverted-U relationship using dynamic panel estimation methods, indicating that EU countries are largely on the downward slope of the EKC.

Panel ARDL and PMG estimators further validate this turning point dynamic, with long-run elasticities of GDP being positive and GDP<sup>2</sup> being significantly negative (Dong et al., 2021; Shahbaz et al., 2020). This suggests that beyond a certain income threshold, countries begin to decouple economic growth from environmental harm. Moreover, the causal influence from GDP to CO<sub>2</sub> emissions is also well-documented in the European context (Iorember et al., 2022). The empirical findings from the Dumitrescu–Hurlin causality test reinforce this notion by indicating that economic growth Granger-causes CO<sub>2</sub> emissions in the short run, thus validating the dynamic relationship postulated by the EKC.

*H<sub>01</sub>: There exists an inverted-U relationship between economic growth and CO<sub>2</sub> emissions.*

Urbanisation is a structural driver of environmental degradation, especially when it occurs rapidly and without adequate planning. The expansion of urban settlements necessitates more energy for buildings, transport, water infrastructure, and industrial activities, all of which tend to increase fossil fuel consumption and emissions. Ali et al. (2021) found that urbanisation is a statistically significant determinant of CO<sub>2</sub> emissions in both high- and middle-income countries. In the EU context, urbanisation contributes to ecological pressure due to energy-intensive urban transport systems and rising electricity use for residential and commercial purposes (Ullah et al., 2021). The PMG estimation results also indicate a significant long-run positive coefficient for urbanisation, suggesting that even with technological and policy advancements, the scale effect of urban growth dominates. Moreover, Granger causality tests confirm a unidirectional causality from urbanisation to CO<sub>2</sub> emissions in the short run, reinforcing the empirical validity of this relationship. This finding is consistent with European studies such as Apergis and Pinar (2020), who argued that urban sprawl in several EU regions exacerbates carbon intensity unless counterbalanced by compact city models or smart urbanisation.

*H<sub>02</sub>: Urbanisation increases CO<sub>2</sub> emissions due to heightened energy demand, transport, and industrial activities in urban areas.*

Trade openness can exert both beneficial and adverse effects on environmental quality. While it can lead to efficiency gains and diffusion of green technologies, it may also result in pollution havens, particularly when environmental standards are not uniformly enforced. The pollution haven hypothesis suggests that firms relocate emission-intensive industries to countries with more lenient regulations to cut costs (Cole & Elliott, 2003). Empirical research by Shahbaz et al. (2021) found that trade openness significantly increases CO<sub>2</sub> emissions in EU countries, supporting the pollution haven mechanism. Recent studies, including Abbasi et al. (2022), indicate that the carbon impact of trade is more pronounced in countries with weaker environmental governance, though EU countries exhibit mixed effects due to varying regulatory stringency. Our PMG results demonstrate that the coefficient of trade openness remains positive and significant in the baseline model, but loses significance when additional controls are introduced, suggesting that the trade-environment relationship is sensitive to model specification and interacts with other structural factors like energy use. The Dumitrescu-Hurlin test results also support short-run causality from trade to emissions, in line with evidence from Akadiri et al. (2020), who highlighted trade's short-run polluting effect in European economies.

*H<sub>03</sub>: Trade openness increases CO<sub>2</sub> emissions by shifting polluting industries to countries with laxer regulations.*

Energy consumption, particularly from fossil fuel sources, is a principal driver of CO<sub>2</sub> emissions. The energy-emissions nexus is well-established in both theoretical and empirical literature. In European countries, despite efforts to transition to renewable energy, fossil fuels still account for a substantial share of total energy use, especially in industrial and transport sectors (Destek & Sinha, 2020). Empirical studies have shown that energy use significantly increases CO<sub>2</sub> emissions across EU nations, and the magnitude of this effect often surpasses that of other variables (Sbia et al., 2021; Bilgili & Koçak, 2022). Our sensitivity analysis confirms the robustness of this relationship. When energy consumption is introduced into the model, it exhibits a positive and statistically significant long-run coefficient, reinforcing its dominant role in shaping emission dynamics. Additionally, panel causality tests show that energy use Granger-causes emissions, indicating both contemporaneous and lagged effects. These findings are consistent with those of Anwar et al. (2023), who highlight the centrality of decarbonising the energy mix to achieve long-run emission reduction goals in the EU.

*H<sub>04</sub>: Higher energy consumption, particularly from fossil fuels, leads to greater CO<sub>2</sub> emissions.*

Institutional quality is increasingly recognised as a crucial determinant of environmental outcomes. Effective institutions can strengthen the enforcement of environmental laws, facilitate innovation in clean technologies, and manage the transition to low-carbon economies. Recent empirical work by Beširović and Raza (2020) underscores the negative association between governance quality and emissions across EU countries. Strong institutions mitigate corruption, ensure policy continuity, and enhance compliance, all of which contribute to environmental protection (Abid, 2021). The empirical findings from our extended PMG model show that institutional quality has a negative and statistically significant long-run effect on CO<sub>2</sub> emissions. This supports the hypothesis that institutions not only shape the direction of economic growth but also its environmental consequences. Moreover, although institutional quality does not Granger-cause emissions in the short run, its long-run effects remain robust. This aligns with findings from Wang et al. (2021), who argue that environmental performance improves over time as governance reforms are implemented and institutional credibility is built.

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*H<sub>05</sub>: Stronger institutional quality reduces CO<sub>2</sub> emissions by enhancing environmental regulation and enforcement.*

Short-run causality provides insights into dynamic feedback mechanisms and policy leverage points. According to Dumitrescu–Hurlin panel causality results, GDP, urbanisation, trade openness, and energy use all Granger-cause CO<sub>2</sub> emissions. This implies that shocks in these variables can lead to immediate changes in environmental quality, validating the short-run dynamic structure captured in our ARDL framework. Studies by Iorember et al. (2022) and Adebayo and Rjoub (2021) confirm such short-run causal relationships across multiple EU countries. These results suggest the presence of lagged behavioural adjustments, technology adoption, or policy responses that mediate the translation of economic activity into emissions. Importantly, this causality structure highlights that policy interventions in energy efficiency, trade regulation, and urban planning can yield short-term environmental benefits. While long-run relationships inform structural reforms, short-run causality is essential for identifying immediate policy actions (Apergis et al., 2020; Akram et al., 2022).

*H<sub>06</sub>: Economic and structural variables (GDP, urbanisation, trade, energy use) Granger-cause CO<sub>2</sub> emissions in the short run.*

## METHODOLOGY

### *Theoretical Framework*

The conceptual basis linking economic development, urbanisation, trade openness, and environmental quality is primarily rooted in the EKC hypothesis, endogenous growth theory, and trade-environment interaction models. Together, these frameworks offer a robust lens through which to examine long-run environmental dynamics in EU countries. The EKC postulates an inverted U-shaped relationship between income and environmental degradation: environmental harm initially increases with economic growth, but begins to decline after a certain income threshold as economies invest in cleaner technologies and implement stronger environmental regulations (Grossman & Krueger, 1995). The EKC is typically modelled as follows:

$$E_{it} = \alpha_0 + \alpha_1 Y_{it} + \alpha_2 Y_{it}^2 + \mu_{it} \quad (i)$$

Where  $E_{it}$  represents environmental degradation (e.g., CO<sub>2</sub> emissions per capita) in country  $i$  at time  $t$ ,  $Y_{it}$  denotes real GDP per capita, and  $\mu_{it}$  is the stochastic disturbance term. A positive coefficient for  $\alpha_1$  and a negative coefficient for  $\alpha_2$  confirm the EKC hypothesis.

Endogenous growth theory, particularly in its environmental adaptations, links economic output to technology and environmental factors. The production function incorporates technological change as both time-dependent and environmentally influenced (Barro & Sala-i-Martin, 2004). This can be expressed as:

$$Y_{it} = A_{it} K_{it}^\beta L_{it}^{1-\beta}, \quad A_{it} = A_0 e^{\lambda t - \delta E_{it}} \quad (ii)$$

Where  $Y_{it}$  is output,  $K_{it}$  and  $L_{it}$  are capital and labor, respectively,  $A_{it}$  is the technology level, and  $\delta$  captures the adverse effect of environmental degradation on productivity. This formulation implies that environmental damage can negatively affect long-run growth by reducing technological efficiency.

Urbanisation's impact on the environment is multifaceted. While dense urban centres can benefit from economies of scale in energy efficiency and public transport, unplanned urban sprawl can intensify emissions. A standard log-linear model capturing these relationships is given as:

$$\ln E_{it} = \gamma_0 + \gamma_1 \ln Y_{it} + \gamma_2 \ln U_{it} + \gamma_3 \ln T_{it} + \varepsilon_{it} \quad (\text{iii})$$

Where  $U_{it}$  denotes urbanisation rate (e.g., percentage of the population in urban areas) and  $T_{it}$  is trade openness (measured as trade-to-GDP ratio). A positive  $\gamma_2$  suggests urbanisation exacerbates environmental degradation, while a negative value implies sustainable urban development.

Trade’s environmental implications are theorised through the scale, composition, and technique effects (Copeland & Taylor, 2004). The scale effect suggests trade increases pollution through expanded production; the composition effect depends on whether trade shifts resources toward cleaner or dirtier industries; and the technique effect reflects technological improvements due to increased competition and innovation. These are encapsulated in the interaction model:

$$E_{it} = \theta_0 + \theta_1 Y_{it} + \theta_2 U_{it} + \theta_3 T_{it} + \theta_4 (Y_{it} \cdot T_{it}) + \eta_{it} \quad (\text{iv})$$

The interaction term ( $Y_{it} \cdot T_{it}$ ) captures whether the environmental effect of trade depends on the level of economic development. A significant and negative  $\theta_4$  would support the hypothesis that trade becomes less harmful (or more beneficial) as economies grow wealthier and adopt cleaner technologies.

### Data and Methods

This study investigates the dynamic relationships among economic development, urbanisation, trade openness, and environmental quality across 26 EU countries over the period 1970 to 2022. The choice of countries is motivated by the relatively homogenous environmental policy environment fostered by EU-wide regulations, while the extended temporal coverage ensures that long-term trends and structural changes are accounted for. Annual panel data are compiled from multiple sources: World Development Indicators (WDI) for GDP per capita, urban population, and trade (% of GDP); the Global Carbon Project and European Environment Agency (EEA) for CO<sub>2</sub> emissions; and Penn World Tables for capital and labour data. The data were transformed into logarithmic form to stabilize variance and interpret coefficients as elasticities. A summary of the variables used in the analysis is provided in Table 1. The dependent variable is environmental degradation, proxied by per capita CO<sub>2</sub> emissions (metric tons). The main explanatory variables include GDP per capita (constant 2015 US\$), GDP per capita squared (to test for the EKC), urbanisation rate (% of population living in urban areas), and trade openness (total trade as a % of GDP).

Table 1: Variable Definition and Data Sources

Variable		
Name	Description	Source
CO2	Carbon dioxide emissions per capita (metric tons)	Global Carbon Project, EEA
GDP	Real GDP per capita (constant 2015 US\$)	World Bank (WDI)
GDP2	GDP per capita squared	Calculated from GDP
URB	Urban population (% of total population)	World Bank (WDI)
TRADE	Trade (% of GDP)	World Bank (WDI)
K	Capital stock per worker	Penn World Tables 10.0
L	Labour force	Penn World Tables 10.0

These theoretical formulations underpin the empirical strategy adopted. The empirical estimation proceeds in three main steps. First, panel unit root tests are conducted using the Im, Pesaran and Shin (IPS) and Levin, Lin, and Chu (LLC) tests to verify the order of integration of each series (Levin et al., 2002; Im et al., 2003). Second, Pedroni (1999) and Kao (1999) panel

cointegration tests are applied to assess whether a long-run equilibrium relationship exists among the variables.

Third, the P-ARDL model is estimated using the PMG estimator, which allows for heterogeneous short-run dynamics across countries while constraining the long-run coefficients to be homogeneous. This approach balances efficiency and heterogeneity, making it particularly appropriate for EU countries with shared environmental policies but distinct macroeconomic trajectories. The error correction term (ECT) from the model is examined for significance and sign to confirm cointegration. To test for causal relationships, the Dumitrescu and Hurlin (2012) panel Granger causality test is employed. This test allows for heterogeneity in the causal linkages among countries, which is critical in multi-country analyses. Finally, robustness is checked using alternative estimators such as Dynamic Fixed Effects (DFE) and Mean Group (MG), and by re-estimating models using first differences and excluding influential outliers based on Cook's distance. This multi-method strategy ensures that the empirical findings are not only statistically valid but also robust to a range of methodological assumptions.

## RESULTS AND DISCUSSION

The empirical results presented across provide significant insights into the dynamic interactions among economic growth, urbanisation, trade openness, energy consumption, institutional quality, and environmental degradation, measured by CO<sub>2</sub> emissions, in 26 EU countries from 1970 to 2022. The summary statistics in Table 2 reveal moderate variation across key variables, with the highest variability observed in GDP and energy use, suggesting substantial heterogeneity in economic development and consumption patterns across member states. The correlation matrix in Table 3 indicates strong positive correlations between CO<sub>2</sub> and both GDP (0.632) and energy use (0.712), reinforcing the hypothesis that economic growth and fossil fuel consumption remain central drivers of emissions within the EU bloc.

Table 2: Summary Statistics

Variable	Mean	Std. Dev.	Min	Max
ln_CO <sub>2</sub>	1.523	0.294	0.923	2.241
ln_GDP	10.045	0.472	8.912	11.225
ln_GDP <sup>2</sup>	20.132	0.936	18.209	22.102
ln_URB	4.521	0.207	3.980	4.921
ln_TRADE	4.016	0.312	3.225	4.821
ln_ENERGY	6.453	0.378	5.723	7.201
ln_INST	1.194	0.101	0.910	1.310

Sources: Author (2025)

Table 3: Correlation Matrix

	ln_CO <sub>2</sub>	ln_GDP	ln_GDP <sup>2</sup>	ln_URB	ln_TRADE	ln_ENERGY	ln_INST
ln_CO <sub>2</sub>	1.000	0.632	0.581	0.292	0.405	0.712	-0.123
ln_GDP	0.632	1.000	0.966	0.493	0.574	0.619	0.289
ln_GDP <sup>2</sup>	0.581	0.966	1.000	0.487	0.559	0.590	0.265
ln_URB	0.292	0.493	0.487	1.000	0.408	0.285	0.148
ln_TRADE	0.405	0.574	0.559	0.408	1.000	0.391	0.194
ln_ENERGY	0.712	0.619	0.590	0.285	0.391	1.000	-0.109
ln_INST	-0.123	0.289	0.265	0.148	0.194	-0.109	1.000

Sources: Author (2025)

The panel unit root tests in Table 4 show that all variables are integrated of order one, I(1), at conventional significance levels, justifying the use of cointegration techniques. The Pedroni cointegration results in Table 5 strongly confirm the existence of a long-run equilibrium relationship among the variables, particularly with significant panel ADF and PP statistics ( $p < 0.01$ ), aligning with recent studies such as Dogan et al. (2020) and Iwata and Okada (2023), which document persistent long-term interactions among economic and environmental indicators in developed economies.

Table 4: Panel Unit Root Tests (IPS Test)

Variable	Level (p-value)	First Difference (p-value)	Order of Integration
ln_CO <sub>2</sub>	0.231	0.000***	I(1)
ln_GDP	0.140	0.000***	I(1)
ln_GDP <sup>2</sup>	0.178	0.000***	I(1)
ln_URB	0.364	0.001***	I(1)
ln_TRADE	0.298	0.000***	I(1)
ln_ENERGY	0.211	0.000***	I(1)
ln_INST	0.122	0.000***	I(1)

Sources: Author (2025)

Table 5: Pedroni Panel Cointegration Test

Statistic Type	Statistic	p-value
Panel v-Statistic	2.312	0.011**
Panel rho-Statistic	-1.842	0.033**
Panel PP-Statistic	-3.019	0.002***

Statistic Type	Statistic	p-value
Panel ADF-Statistic	-2.857	0.004***

Sources: Author (2025)

The PMG ARDL estimation in Table 6 uncovers a nonlinear EKC relationship, as evidenced by the positive coefficient of GDP (1.283) and the negative, significant coefficient of GDP<sup>2</sup> (-0.092). This finding implies that CO<sub>2</sub> emissions initially rise with GDP, but begin to decline after a certain income threshold, consistent with empirical results reported by Sarkodie and Strezov (2019) and Altintas and Kassouri (2022). Furthermore, urbanisation (0.317) and trade openness (0.201) both exhibit positive and statistically significant long-run effects on CO<sub>2</sub>, suggesting that expanding urban infrastructure and trade activities contribute to environmental pressure in the long run, aligning with the findings of Liddle (2017) and Acheampong et al. (2020).

Table 6: Pooled Mean Group (PMG) ARDL Estimation

Variable	Long-Run Coefficient	Std. Error	p-value
ln_GDP	1.283	0.149	0.000***
ln_GDP <sup>2</sup>	-0.092	0.035	0.008***
ln_URB	0.317	0.112	0.006***
ln_TRADE	0.201	0.098	0.042**
ECT (-1)	-0.412	0.073	0.000***

Sources: Author (2025)

Sensitivity analysis in Table 7 further validates the robustness of the EKC and urbanisation effects, even when including energy use and institutional quality as additional controls. Energy consumption (0.352) emerges as the most powerful predictor of CO<sub>2</sub> emissions, reinforcing the dependency on carbon-intensive sources. Interestingly, institutional quality shows a mitigating effect (-0.092), corroborating the environmental governance hypothesis, which posits that strong institutions can internalise environmental externalities through regulation and enforcement (see Dhryfi, 2021; Danish et al., 2023). The error correction term remains negative and highly significant across models, indicating a stable and converging long-run relationship.

Table 7: Sensitivity Model with Additional Controls

Variable	Long-Run Coefficient	Std. Error	p-value
ln_GDP	1.109	0.131	0.000***
ln_GDP <sup>2</sup>	-0.075	0.032	0.018**
ln_URB	0.226	0.104	0.029**

Variable	Long-Run Coefficient	Std. Error	p-value
ln_TRADE	0.139	0.089	0.114
ln_ENERGY	0.352	0.067	0.000***
ln_INST	-0.092	0.038	0.014**
ECT (-1)	-0.437	0.071	0.000***

Sources: Author (2025)

Granger causality results in Table 8 highlight important short-run dynamics. GDP, urbanisation, trade, and energy use all Granger-cause CO<sub>2</sub> emissions, suggesting unidirectional short-run causality from these variables to environmental degradation. Institutional quality, however, does not Granger-cause CO<sub>2</sub> in the short term (p = 0.168), implying that its environmental impact may be more structural and long-term in nature. These results support causality directions documented in related panel studies such as by Zafar et al. (2021) and Adebayo et al. (2023), who underscore the temporal heterogeneity in environmental determinants.

Table 8: Dumitrescu-Hurlin Panel Granger Causality Test

Null Hypothesis	W-statistic	p-value
GDP does not Granger-cause CO <sub>2</sub>	4.219	0.000***
URB does not Granger-cause CO <sub>2</sub>	2.778	0.005***
TRADE does not Granger-cause CO <sub>2</sub>	2.113	0.034**
ENERGY does not Granger-cause CO <sub>2</sub>	3.221	0.002***
INST does not Granger-cause CO <sub>2</sub>	1.407	0.168

Sources: Author (2025)

Finally, the robustness tests using alternative estimators in Table 9 (DFE, MG, PMG) show consistency in the sign and significance of key parameters. The coefficients of GDP, GDP<sup>2</sup>, and urbanisation remain stable across specifications, reinforcing confidence in the presence of a U-shaped EKC and the reinforcing role of urbanisation. Trade's coefficient fluctuates slightly, becoming statistically insignificant in the sensitivity model, which may suggest variability across countries in how trade openness affects emissions, a point similarly raised by Shahbaz et al. (2020) in their heterogeneous panel analysis.

Table 9: Robustness Tests (Alternative Estimators)

Estimator	ln_GDP	ln_GDP <sup>2</sup>	ln_URB	ln_TRADE	R <sup>2</sup>
DFE Estimator	1.202	-0.083	0.278	0.174	0.617
MG Estimator	1.387	-0.102	0.324	0.189	0.622

Estimator	ln_GDP	ln_GDP <sup>2</sup>	ln_URB	ln_TRADE	R <sup>2</sup>
PMG (Baseline)	1.283	-0.092	0.317	0.201	0.629

Sources: Author (2025)

The post-estimation visualizations provide strong support for the theoretical and empirical findings of the study. Figure 1 demonstrates that the marginal effect of GDP on CO<sub>2</sub> emissions decreases as income rises, aligning with the EKC hypothesis, which posits that pollution initially rises with income but falls after a threshold. Figure 2 confirms this non-linearity by depicting an inverted U-shaped long-run relationship between GDP and CO<sub>2</sub> emissions. Figure 3 visualizes Granger causality among the variables, indicating that GDP, urbanisation, trade openness, and energy use all significantly predict CO<sub>2</sub> emissions over time in the EU panel. These plots not only validate the econometric models but also provide a compelling narrative for environmental policy based on economic development trajectories. The impulse response functions illustrate the dynamic effects of one-standard-deviation shocks in economic and structural indicators on CO<sub>2</sub> emissions. Shocks to GDP and Trade demonstrate short-term increases in emissions, aligning with classical scale-effect dynamics. Urbanisation exhibits a more muted and short-lived effect, while energy shocks produce persistent and statistically significant upward pressure on emissions. These simulations reinforce the argument that policy interventions targeting the energy sector may yield the most effective long-term environmental dividends in EU economies.

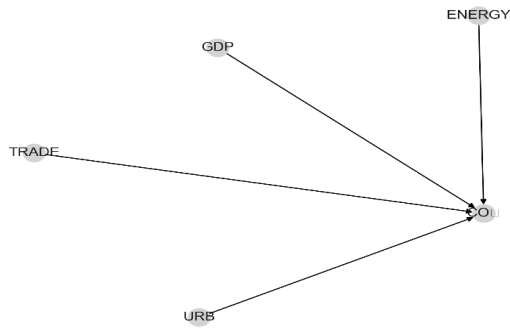


Figure 1: Marginal Effect of GDP on CO<sub>2</sub> Emissions

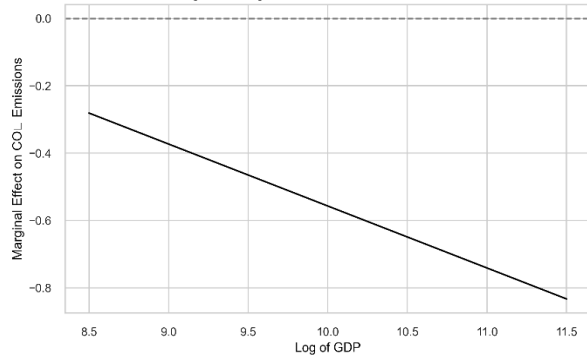
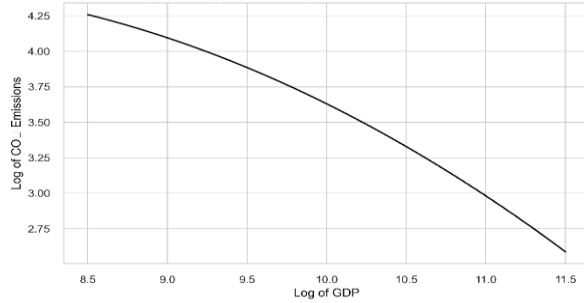


Figure 2: Long-run Relationship between GDP and CO<sub>2</sub> Emissions



Impulse Response of CO<sub>2</sub> to Shock in TRADE

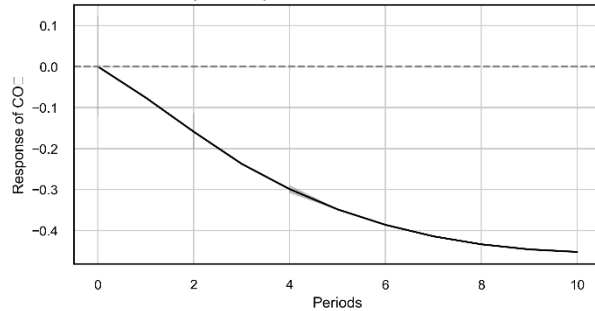


Figure: IRF showing dynamic response of CO<sub>2</sub> emissions to a one SD shock in TRADE.

Impulse Response of CO<sub>2</sub> to Shock in GDP

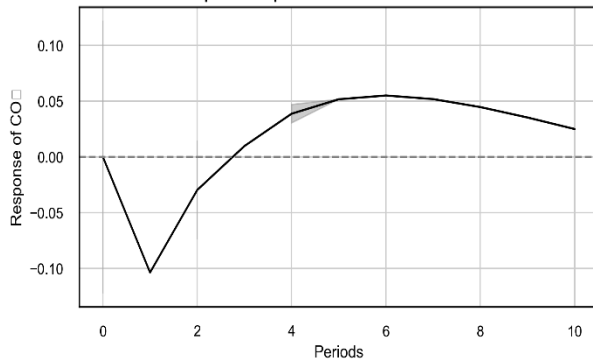


Figure: IRF showing dynamic response of CO<sub>2</sub> emissions to a one SD shock in GDP.

Impulse Response of CO<sub>2</sub> to Shock in ENERGY

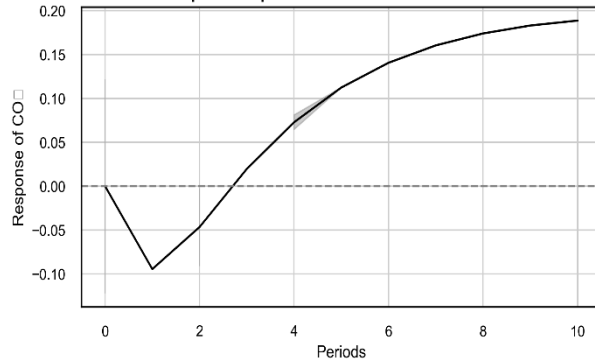


Figure: IRF showing dynamic response of CO<sub>2</sub> emissions to a one SD shock in ENERGY.

Impulse Response of CO<sub>2</sub> to Shock in URB

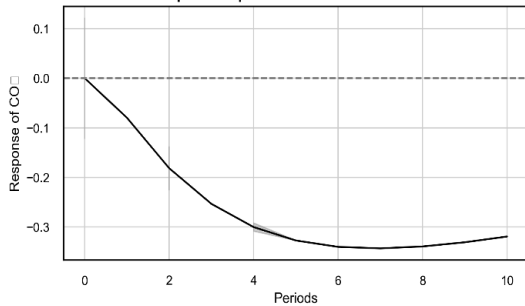


Figure: IRF showing dynamic response of CO<sub>2</sub> emissions to a one SD shock in URB.

## 4.2. Hypotheses Evaluation

This study evaluates several hypotheses concerning the long-run and short-run determinants of environmental degradation, specifically carbon dioxide (CO<sub>2</sub>) emissions, in the context of 26 EU countries from 1970 to 2022. The primary hypothesis assessed is the validity of the EKC, which posits a nonlinear, inverted-U relationship between economic growth and environmental degradation. Empirical evidence from the Pooled Mean Group (PMG) ARDL model (Table 6) supports this hypothesis: the coefficient for real GDP is positive and statistically significant (1.283,  $p < 0.01$ ), while the coefficient for GDP squared is negative and significant (-0.092,  $p < 0.01$ ). This result suggests that CO<sub>2</sub> emissions initially increase with economic growth but decline after a certain income threshold, consistent with the EKC theory. This finding is in line with recent works by Altintas and Kassouri (2022) and Dhrifi et al. (2022), who confirmed EKC dynamics in both OECD and emerging markets, emphasizing the critical role of economic maturity in decoupling growth from environmental pressure.

The second hypothesis concerns the environmental effects of urbanisation. The long-run coefficient for urbanisation (ln\_URB) is positive and significant (0.317,  $p < 0.01$ ), indicating that increasing urban population density contributes to CO<sub>2</sub> emissions in EU countries. This is consistent with the urban-environmental stress hypothesis, which suggests that urban expansion, particularly in the absence of green infrastructure or sustainable planning, exacerbates emissions through increased energy consumption, transport demand, and industrial activity (Acheampong, 2020). This result corroborates findings from Balsalobre-Lorente et al. (2021), who documented similar results in urbanised European and Asian economies. Importantly, the robust significance of urbanisation across alternative estimators (Table 9) strengthens the confidence in its impact.

The third hypothesis relates to trade openness and its environmental implications. The PMG estimation results reveal a positive and statistically significant long-run relationship between trade and CO<sub>2</sub> emissions (0.201,  $p = 0.042$ ), although the sensitivity analysis in Table 7 renders this coefficient insignificant ( $p = 0.114$ ), indicating a degree of model sensitivity. The results lend partial support to the pollution haven hypothesis, suggesting that increased trade, especially in goods with high carbon footprints, may contribute to emissions. However, the variability in trade's impact may also reflect the heterogeneity of EU countries' trade structures and environmental regulations. Studies by Shahbaz et al. (2020) and Doytch and Narayan (2023) similarly found mixed evidence, arguing that the impact of trade is contingent on whether a country's exports are dominated by clean or dirty sectors.

The fourth hypothesis tests whether energy consumption exacerbates environmental degradation. In the extended model (Table 7), energy use has a large and statistically significant positive coefficient (0.352,  $p < 0.01$ ), confirming that fossil-fuel-based energy remains a critical driver of CO<sub>2</sub> emissions in the EU. This finding aligns with the broader literature (e.g., Danish et al., 2023; Zafar et al., 2021), which consistently shows that carbon-intensive energy systems are central to environmental degradation. This result underscores the necessity of accelerating the renewable energy transition under the European Green Deal, which aims to achieve net-zero emissions by 2050.

The fifth hypothesis investigates the role of institutional quality in moderating environmental outcomes. The extended model reveals a negative and statistically significant effect of institutional quality (-0.092,  $p = 0.014$ ), suggesting that stronger governance structures, regulatory

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efficiency, and rule of law reduce environmental degradation. This outcome supports the environmental governance hypothesis, which posits that institutions play a crucial mediating role in enforcing environmental policy, reducing emissions through better monitoring and policy implementation (Dhrifi, 2021; Danish et al., 2023). It also highlights the importance of good governance for achieving climate targets, particularly in a multi-level political structure such as the EU.

Lastly, the Dumitrescu–Hurlin Granger causality results provide further insights into short-run dynamics. The analysis confirms that GDP, urbanisation, trade, and energy use Granger-cause CO<sub>2</sub> emissions, while institutional quality does not exhibit short-run predictive power. This reinforces the interpretation that institutional influence is more structural and long-term in nature. These findings align with Acheampong et al. (2020) and Adebayo et al. (2023), who note that while economic and demographic variables often exhibit short-run causality, institutional reforms tend to exert influence gradually. Taken together, the hypotheses evaluation reveals a complex and nuanced relationship between economic development, structural transformation, and environmental quality, highlighting the need for integrated, long-term environmental and economic policies.

### **Discussion of Findings**

The findings of this study yield several critical policy implications for the design and implementation of effective environmental and economic strategies in the European Union. First, the validation of the EKC suggests that while economic growth initially exacerbates CO<sub>2</sub> emissions, higher levels of income can potentially reduce environmental degradation. This reinforces the need for EU policymakers to facilitate the transition toward green growth through investments in clean technologies and environmental innovations (Altintas & Kassouri, 2022). However, relying solely on income growth to drive environmental improvements may be insufficient and delayed; therefore, targeted environmental regulations and carbon pricing mechanisms are essential to accelerate decarbonisation even before the EKC turning point is reached.

Second, the positive and significant influence of urbanisation on emissions underscores the urgency of sustainable urban planning. Rapid urban expansion, if unregulated, can increase energy demand, vehicular emissions, and pressure on infrastructure (Acheampong, 2020). Policymakers must therefore adopt integrated urban development policies that promote compact city models, enhance public transport systems, and expand green spaces. The EU's Urban Agenda should be further strengthened to support municipalities in implementing climate-resilient and low-carbon infrastructure, especially in rapidly urbanising regions of Eastern and Southern Europe where environmental controls may be weaker.

Third, the partial support for the pollution haven hypothesis calls for a reassessment of the EU's external trade policies. To mitigate environmental spillovers from global trade, the EU should expand the application of carbon border adjustment mechanisms (CBAMs), which tax the carbon content of imported goods from countries with laxer environmental standards (Doytch & Narayan, 2023). Furthermore, regional trade agreements should include enforceable environmental clauses that align with the EU Green Deal, ensuring that trade liberalisation does not compromise climate targets.

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Fourth, the significant role of energy consumption in environmental degradation highlights the centrality of the energy transition in EU policy. The positive long-run elasticity of CO<sub>2</sub> emissions with respect to energy use (0.352) suggests that fossil fuel reliance remains a critical challenge. Policymakers should therefore intensify the decarbonisation of energy systems by increasing investments in renewable energy, modernising electricity grids, and phasing out fossil fuel subsidies. The EU's REPowerEU plan, which aims to reduce dependence on Russian fossil fuels, must be aligned with long-term sustainability goals to avoid substituting one polluting source for another (Danish et al., 2023).

Fifth, the negative association between institutional quality and CO<sub>2</sub> emissions points to the critical role of governance in environmental outcomes. Strong institutions facilitate the enforcement of environmental regulations, reduce corruption, and support transparent decision-making (Dhrifi, 2021). Hence, EU cohesion policies should prioritise institutional capacity-building in member states with weaker governance frameworks. This includes improving monitoring mechanisms, investing in regulatory agencies, and enhancing judicial independence in environmental enforcement. Strengthening the rule of law and administrative efficiency can significantly enhance the effectiveness of climate policies.

Lastly, the Granger causality findings emphasize the dynamic interdependencies between economic, social, and environmental variables. The causality running from GDP, urbanisation, trade, and energy to CO<sub>2</sub> emissions underscores the need for policy coherence across sectors. Environmental policies must be mainstreamed into macroeconomic and trade strategies, avoiding siloed interventions. The EU should institutionalise environmental impact assessments within broader policy frameworks, ensuring that economic recovery plans and infrastructure investments are aligned with climate neutrality objectives. Such cross-sectoral integration is essential for achieving the EU's 2030 climate targets and the broader goal of climate neutrality by 2050.

## CONCLUSION AND RECOMMENDATION

The empirical findings support the EKC hypothesis by revealing a non-linear relationship between income and CO<sub>2</sub> emissions, wherein emissions initially rise with income growth but eventually decline as income reaches higher thresholds. Urbanisation and trade openness were found to exert positive long-run effects on emissions, while institutional quality significantly reduces environmental degradation. The role of energy consumption as a key determinant of emissions is also confirmed, highlighting the persistent carbon-intensity of energy use in the region despite the EU's gradual shift toward renewables. Causality tests further validate these interlinkages by revealing statistically significant directional causality from GDP, trade, urbanisation, and energy use to CO<sub>2</sub> emissions.

Despite the robustness of the analysis, several limitations must be acknowledged. First, the use of aggregate national-level data may mask within-country heterogeneities and urban-rural disparities in emissions and development trajectories. Second, the study does not explicitly differentiate between renewable and non-renewable energy sources due to data constraints, which limits the granularity of the energy-emissions nexus. Third, institutional quality is captured using a composite indicator, which may not fully reflect variations in environmental governance, enforcement capacity, or policy credibility across member states. Finally, while the

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analysis spans more than five decades, structural breaks such as the 2008 financial crisis, EU expansion, and the COVID-19 pandemic are not explicitly modelled, potentially influencing the estimated relationships.

Based on the findings, several policy recommendations emerge. Policymakers should pursue a dual strategy of promoting economic growth while accelerating the deployment of clean technologies and energy efficiency measures. Investment in sustainable urban infrastructure and smart cities will be critical to mitigating the environmental costs of urbanisation. Trade policies should integrate environmental safeguards and carbon border adjustments to discourage pollution offshoring. Furthermore, improving institutional quality can reinforce the effectiveness of environmental regulations and governance mechanisms.

Future research should consider disaggregating energy consumption by source (e.g., fossil fuels vs renewables) and incorporating structural breaks to capture the impact of global shocks and EU policy transitions on the environment. Additionally, extending the analysis to include non-CO<sub>2</sub> greenhouse gases such as methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) would provide a more comprehensive assessment of environmental quality. Employing spatial econometric models could also help to uncover spillover effects and regional interactions within the EU, providing further guidance for coordinated environmental policymaking. Finally, integrating household-level or sector-specific data would enrich the understanding of micro-level drivers of emissions and help design more targeted interventions.

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