ENVIRONMENTAL DRIVERS OF $PM_{2.5}$ CONCENTRATIONS IN THE EUROPEAN E5 NATIONS: THE ROLES OF INDUSTRIAL GROWTH, TRANSPORT SECTOR, URBAN EXPANSION, AND ENERGY USE

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Abstract. Rising concerns over urban air pollution and the inefficiencies of industrial and transport systems have intensified the need for integrated technological and policy solutions in densely populated European economies. This study examines the environmental effects of clean transportation, innovation, and governance in the European E5 nations (France, Germany, Italy, Poland, and the United Kingdom) from 1996 to 2023. Using the Method of Moments Quantile Regression (MMQR), supported by Feasible Generalized Least Squares (FGLS) and Fixed Effects (FE) models, environmental degradation is measured through $PM_{2.5}$ concentrations. The results show that industrial growth consistently aggravates pollution, whereas environmental innovations and governance quality significantly reduce it. Moreover, governance moderates the adverse environmental impacts of transport emissions, indicating that stronger institutions enhance the effectiveness of technological advances. The study contributes by integrating governance, innovation interactions within a quantile framework, revealing heterogeneous effects across pollution levels, an aspect often neglected in prior research. The findings provide evidence-based insights for policymakers, emphasizing the synergistic role of technological progress and institutional strength in achieving sustainable environmental outcomes and supporting the European Green Deal and the UN Sustainable Development Goals (SDGs).

Keywords: *environmental degradation, urban growth, innovations, transportation, governance*

Introduction

European nations have made considerable progress in environmental regulation, however acceptable urban air quality is still a critical challenge across the continent (EEA, 2025; Pouikli and Tsoukala, 2023). Despite stringent EU-level directives and national efforts under frameworks such as the European Green Deal and the Ambient Air Quality Directive (2008/50/EC), most urban populations remain exposed to pollutant concentrations above the World Health Organization's recommended thresholds (Pisoni et al., 2022; Ulpiani et al., 2025). It must be noted that the concentration of $PM_{2.5}$ and other air pollutants locally and temporally exceeds the recommended thresholds, particularly within large metropolitan and industrialized areas (Wu et al., 2024). This spatial and temporal variability reflects the uneven distribution of pollution sources, with industrial hubs and densely populated urban centers experiencing recurrent exceedances despite national and EU-level regulatory efforts (EEA, 2025).

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In particular, $PM_{2.5}$ pollution poses severe risks to public health, with recent studies linking long-term exposure to increased incidence of cardiovascular, respiratory, and neurological disorders, including dementia (Grande et al., 2023; Huang et al., 2025; Wan Mahiyuddin et al., 2023). This persistent exposure highlights structural inefficiencies in existing environmental governance and demands renewed focus on the interaction of economic, technological, and institutional variables shaping air quality outcomes (Ahmad et al., 2023; Çitil et al., 2023; Hashmi et al., 2024; Le and Huynh, 2025; Li et al., 2022a; Steinebach, 2022).

While this study focuses on $PM_{2.5}$ concentrations as a dynamic indicator of environmental degradation, it is acknowledged that soil and water quality parameters offer more stable and representative measures of long-term environmental impacts (Ding et al., 2025). Unlike air pollutants, whose concentrations fluctuate rapidly due to meteorological and seasonal influences, contamination levels in soil and water evolve gradually and can thus reflect the cumulative effects of environmental policies over extended periods. Future extensions of this research could incorporate such indicators to capture broader and more persistent ecological dimensions of policy effectiveness (Jiang et al., 2025).

Industrial growth (IG) continues to drive significant energy demand and emission loads in urban regions. While vital for economic competitiveness, the expansion of industry, particularly in the construction and manufacturing sectors, often outpaces technological upgrades needed to reduce emission intensities (Crawford, 2022; Huang et al., 2020; Jiang et al., 2023; Khan and Khan, 2023). Similarly, urbanization, though a marker of modernization, intensifies transportation (TR) demands and concentrates emission sources, exacerbating pollution in already dense metropolitan zones (Malik et al., 2024; Mills and Li, 2024). Concurrently, innovation (INN) in environmental technologies, such as clean transport systems and energy-efficient solutions, has emerged as a key pathway for decarbonization (Das et al., 2025; Mallouppas and Yfantis, 2021; Sahoo et al., 2022). However, the diffusion and effectiveness of these innovations are not uniform and often hinge on institutional capacity and regulatory enforcement (Olawole and Adeniran, 2025; Sultan et al., 2025).

Governance quality, encompassing the rule of law, regulatory effectiveness, and political stability, plays a pivotal role in determining how policies are implemented and how innovations translate into environmental gains (Dincă et al., 2022; Gök and Sodhi, 2021; Mahmood et al., 2021). The presence of strong institutions can catalyze green technology adoption and ensure compliance with environmental norms, while institutional weaknesses may dilute the intended impact of even the most ambitious environmental policies (Karayalcin and Onder, 2024; Ofoeda et al., 2024; Shapiro, 2025).

This study focuses on the European E5 nations (France, Germany, Italy, Poland, and the United Kingdom) chosen for their economic scale, industrial diversity, and varying levels of institutional strength (Zhelyazkova et al., 2024). These countries also provide a meaningful sample for examining the joint influence of EU policy harmonization and national governance variability (Filip and Momferatou, 2025; Improta, 2025). Using data spanning 1996–2023, which aligns with the availability of comprehensive governance indicators, the research investigates the complex interrelations among industrial growth, energy intensity, urbanization, innovation, transport emissions, and governance quality in shaping air pollution outcomes.

By applying the Method of Moments Quantile Regression, complemented with FGLS and Fixed Effects models, this study enhances existing literature by capturing how these relationships behave across different levels of pollution rather than relying solely on average effects. The novelty of this research lies in its application to the European E5 economies, whose individual and collective policy architectures have not been previously assessed about the selected parameters. This offers a critical benchmark for developing and emerging economies seeking to understand how institutional strength, innovation, and economic growth can be integrated to address environmental degradation more effectively.

Accordingly, the main aim of this study is to examine how industrial growth, energy intensity, urban expansion, innovation, and governance quality collectively influence environmental degradation, measured by $PM_{2.5}$ concentrations in the European E5 nations (France, Germany, Italy, Poland, and the United Kingdom) over the period 1996–2023.

Specifically, the study seeks to:

i. Assess the individual effects of these economic, technological, and institutional factors on air quality.
ii. Evaluate how governance moderates the relationship between transportation-related emissions and environmental degradation.
iii. Provide evidence-based insights for policy frameworks that promote sustainable industrialization and innovation-led emission reduction.

These objectives align with the European Green Deal and the UN Sustainable Development Goals (SDGs), reinforcing the study's relevance for advancing sustainable environmental governance (*Fig. 1*).

Review of the related literature

This section presents a review of the literature exploring the connections between energy intensity, governance, transportation, technological advancement, and environmental health.

Governance-environmental sustainability link

Recent literature underscores the pivotal role of governance in shaping environmental sustainability outcomes across both emerging and developed nations. In emerging economies, studies such as Akinyele et al. (2025) reveal that institutional structures significantly moderate the relationship between technological expansion, particularly ICT and environmental degradation, with weak governance exacerbating CO_2 emissions through lax enforcement and inefficient regulatory mechanisms. Similarly, Zhang et al. (2025) demonstrate that China's Environmental Protection Law has catalyzed green technology innovation and improved corporate sustainability performance, validating the Porter Hypothesis in the context of emerging markets2. These findings suggest that governance innovation not only enforces compliance but also stimulates eco-efficient transformations in polluting industries. In sub-Saharan Africa, Abaidoo and Agyapong (2023) argue that effective governance, measured through corruption control and regulatory quality, can mitigate the adverse environmental impacts of development, while political instability tends to amplify sustainability risks. Developed nations, on the other hand, exhibit more mature ESG frameworks, as highlighted by Singhania et al. (2024), who categorize countries into distinct stages of ESG policy evolution, revealing that robust governance structures facilitate strategic sustainability reporting and resilient environmental practices4. Moreover, Kvasničková Stanislavská et al. (2023) identify nuanced differences in sustainability disclosures between developed and developing countries, with the former emphasizing supply chain emissions and sustainable production, while the latter focus more on education and human rights, reflecting divergent governance priorities and stakeholder expectations. Collectively, these studies affirm that governance quality, whether through legal enforcement, institutional capacity, or policy coherence, is a critical determinant of environmental sustainability, influencing both the trajectory and effectiveness of ecological interventions across diverse national contexts.

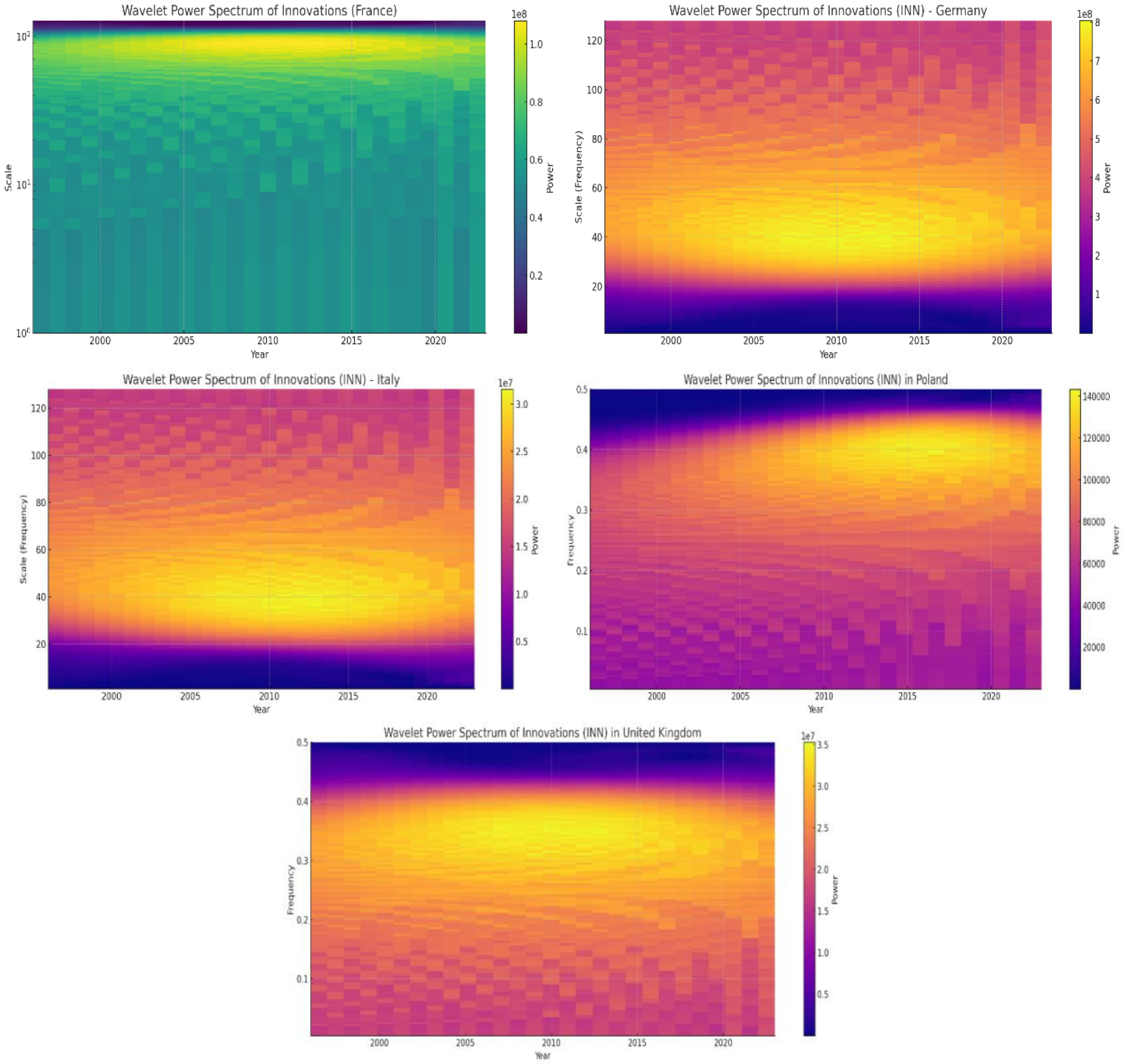


Figure 1. *Wavelet plots for innovations across E5 nations during the study span. (Source: Authors' drawing)*

Energy intensity–environmental impacts nexus

The relationship between energy intensity and environmental impacts has drawn increasing attention in recent empirical research, particularly as nations grapple with the dual challenge of sustaining economic growth while mitigating ecological degradation. In emerging economies, rising energy intensity is often linked to industrial expansion and urbanization, which tend to rely heavily on fossil fuel-based energy systems. This reliance contributes to elevated carbon emissions and deteriorating air quality, as highlighted by Hasan and Adnan (2025), who found that improvements in food security and economic output in developing regions were accompanied by significant increases in CO_2 emissions and energy intensity. Their findings underscore the complexity of balancing developmental goals with environmental stewardship, especially in contexts where institutional capacity and technological infrastructure remain uneven.

In contrast, developed nations have made strides in decoupling energy use from environmental harm through efficiency gains and cleaner energy transitions. Aboulajras et al. (2025) demonstrate that in higher-income economies, energy efficiency and renewable energy adoption play a critical role in reducing carbon footprints, particularly at higher pollution quantiles. Their quantile regression analysis reveals that energy intensity has a nonlinear impact on environmental outcomes, with diminishing returns in emission reductions beyond certain thresholds. This suggests that while technological upgrades are essential, their effectiveness depends on broader systemic factors such as governance quality, financial development, and resource management.

Moreover, regional studies in the MENA and European contexts show that energy intensity interacts with other variables, like foreign direct investment and economic structure, to shape environmental trajectories. For instance, Baffour Gyau et al. (2024) found bidirectional causal links between energy intensity and environmental quality, indicating that policy interventions must address both energy demand and supply-side dynamics. These insights reinforce the need for integrated approaches that combine energy efficiency policies with institutional reforms and innovation strategies.

Overall, the literature points to a nuanced and context-dependent nexus between energy intensity and environmental impacts. While developed nations offer models of low-carbon growth through technological and regulatory sophistication, emerging economies face structural constraints that complicate the path to sustainability. Bridging this gap requires tailored policy frameworks that account for economic diversity, institutional readiness, and the evolving nature of energy systems.

Innovations–environmental health connection

Recent scholarship underscores the transformative role of technological innovation in enhancing environmental health outcomes, particularly through mechanisms that reduce pollution, improve resource efficiency, and enable real-time environmental monitoring. Innovations in green technologies, artificial intelligence (AI), and biotechnology have emerged as pivotal tools in mitigating environmental degradation and its associated health risks.

In the context of emerging economies, Shabir et al. (2023) highlight that environmental-related technological innovation significantly reduces CO_2 emissions when coupled with strong institutional frameworks. Their panel data analysis across APEC countries reveals that innovation not only curbs emissions but also fosters sustainable development by improving air quality and reducing exposure to harmful pollutants.

Similarly, Wu and Mariano Junior (2023) provide bibliometric evidence that emerging technologies such as remote sensing, IoT, and AI are reshaping global health paradigms. Their study emphasizes that innovation quality, measured through dynamic interactions among key elements, is central to managing environmental health challenges in both developed and developing nations.

From a public health perspective, Li et al. (2022) argue that environmental-related technological innovation enhances regional competitiveness and supports green economic systems. Their findings suggest that innovation facilitates the integration of environmental resources, thereby improving population health through reduced pollutant exposure and better ecosystem management.

Moreover, Ugah et al. (2025) explore how innovations like bioremediation, phytoremediation, and AI-driven pollution control are redefining environmental health strategies. Their interdisciplinary review stresses the importance of adaptive technologies in addressing emerging contaminants such as microplastics and e-waste, which pose novel risks to human health.

Collectively, the literature affirms that innovation is not merely a technical upgrade but a strategic imperative for environmental health governance. It enables proactive responses to climate-induced health threats, supports equitable access to clean resources, and fosters resilience in vulnerable communities. However, the effectiveness of these innovations is contingent upon institutional quality, policy coherence, and inclusive stakeholder engagement.

Transportation-ecological degradation relationship

The relationship between transportation and ecological degradation has drawn substantial scholarly attention, particularly as global mobility intensifies and sustainability imperatives sharpen. Transportation systems, while foundational to economic growth and social integration, are among the primary contributors to environmental degradation. The heavy reliance on fossil fuel-based infrastructure has led to increased emissions of greenhouse gases (GHGs) such as CO_2, alongside other pollutants like nitrogen oxides and particulate matter, which pose significant risks to both ecological integrity and public health. Urban transportation, in particular, has been implicated in exacerbating air quality deterioration, contributing to the formation of urban heat islands, and facilitating land-use changes that disrupt natural habitats and biodiversity.

Empirical studies have adopted diverse econometric and analytical frameworks to investigate this nexus. Ouni et al. (2023), through a systematic review of 52 articles, underscore the predominance of multivariate co-integration and GMM approaches in capturing long-run dynamics between transport activity and environmental indicators. Meanwhile, Listiono (2018), using a Three-Stage Least Squares (3SLS) methodology across 90 countries, reveals a bi-directional causality between freight transport and CO_2 emissions, particularly pronounced in middle-income economies where regulatory oversight remains limited. These findings are echoed in research by Li et al. (2020), who argue that while urban transport policies often aim to reduce environmental harm, they may inadvertently aggravate it due to misaligned implementation strategies and infrastructural inertia.

The cumulative evidence points to a consistent positive correlation between transportation intensity and ecological degradation, with developing nations experiencing disproportionate impacts due to rapid urbanization, weak governance structures, and limited adoption of cleaner technologies. Emissions from road transport alone are estimated to account for 30%–50% of urban air pollution in OECD regions, a figure that underscores the urgency of systemic policy reform. Beyond air pollution, transportation also contributes to ecological stress through noise, soil erosion, and heavy metal contamination, threatening terrestrial and aquatic ecosystems alike.

Despite growing literature, notable gaps persist. Few studies fully integrate governance and institutional quality variables into transport–ecology models, leaving a critical dimension of policy efficacy underexplored. Similarly, comparative analyses across income groups remain underdeveloped, restricting insights into differentiated vulnerabilities and adaptive capacities. Emerging research trajectories now emphasize green logistics, electrified transit networks, and intermodal transport systems as feasible pathways toward decoupling mobility from environmental harm. In this context, the transportation–ecological degradation link represents not only a challenge but an opportunity for holistic policy innovation and interdisciplinary collaboration.

Research gaps and contributions

This study advances existing literature in several meaningful ways by addressing clear gaps and making substantive scholarly contributions.

First, prior research has robustly examined individual links, such as governance-sustainability, energy intensity, innovation, and transport emissions, but rarely within a unified, cross-country European framework. This research fills that gap by focusing specifically on the European E5 nations, whose shared EU policy architecture and yet diverse national trajectories have not been previously analyzed for this combination of environmental, economic, technological, and institutional variables. Secondly, while many quantitative studies apply average-effect regression or panel models, the present work enhances literature by integrating quantile regression with interaction effects specifically between transport emissions and governance quality allowing for a layered understanding of how these relationships shift across low, median, and high pollution contexts.

Third, this study addresses the recognized multicollinearity between innovation and transport emissions not by variable suppression or dimensional reduction (e.g., PCA), but by retaining these variables through robust estimators such as MMQR, FGLS, and fixed effects. This approach allows for preserving policy-relevant interpretability while offering a methodological contribution for handling collinear yet theoretically significant variables.

Additionally, unlike most studies that treat governance as a static control variable, this work operationalizes governance as an interaction moderator, revealing how institutional strength can attenuate the adverse effects of transport emissions and amplify the gains from green innovation. This approach has not been extensively explored in the European context.

Finally, because the European E5 sample combines both institutional maturity and variation, the findings also offer transferable insights for emerging and developing economies seeking to align innovation, energy efficiency, industrial growth, and governance to address urban air pollution. By using a mixed-method estimation strategy and explicitly modeling heterogeneity and interaction effects across pollution regimes, the study provides a novel and policy-relevant contribution to the literature on environmental sustainability, innovation governance, and urban air quality in high-income settings and beyond.

Data and methodology

Data and variables

This study uses annual data for the European E5 nations (France, Germany, Italy, Poland, United Kingdom) for 1996–2023. *Table 1* lists the variables and data sources.

The dependent variable is environmental degradation measured by annual mean $PM_{2.5}$ concentration (µg/m^3).

Explanatory variables include industrial growth (value added, % of GDP), urban growth (annual urban population growth rate, %), environmental innovation (environment-related patents per capita), energy intensity (energy use per capita), transport emissions (CO_2 from transport), and a Policy Governance Index constructed via principal component analysis of World Governance Indicators. Missing observations were addressed by linear interpolation where required. All data sources are indicated in *Table 1.*

Table 1. *Data source and variables*

Parameters	Acronym	Proxy & measurement (with units)	Type of variable	Origin of data
Environmental degradation	ED	$PM_{2.5}$ air pollution, mean annual exposure (µg/m^3)	Dependent	WDI (2025)
Industrial growth	IG	Industry (including construction), value added (% of GDP)	Control	WDI (2025)
Urban growth	UG	Urban population growth (annual %)	Independent	WDI (2025)
Innovation	INN	Total environment-related technologies (inventions per million people)	Independent	OECD (2025)
Energy intensity	EI	Energy use (kg of oil equivalent per capita)	Independent	WDI (2025)
Transport emissions	TR	CO_2 emissions from transport sector (Mt CO_2e)	Independent	WDI (2025)
Policy governance index	PGI	Composite index from six WGI dimensions (unitless, standardized PCA score)	Independent	WGI (2025)

Source: Authors' compilation

Econometric strategy and rationale

The Method of Moments Quantile Regression (MMQR) developed by Machado and Santos Silva (2019) is particularly suited for panel data with heterogeneous conditional distributions, as it captures variations in covariate effects across different quantiles of the dependent variable. This technique has been successfully applied in recent environmental studies to explore distributional heterogeneity and tail-sensitive behavior (Li et al., 2025).

The choice of the MMQR estimator is also motivated by the structural and economic heterogeneity within the E5 group. The sample combines advanced economies (France, Germany, and the United Kingdom) with a post-socialist transition economy (Poland) and a Southern European industrial economy (Italy). These countries differ in technological maturity, governance effectiveness, and industrial structure, which naturally generate diverse environmental responses to similar policy and innovation shocks. Hence, an estimator that captures country-specific slope heterogeneity and distributional asymmetry, such as MMQR, is most appropriate for this context.

The approach provides more robust inference than traditional mean regressions by accounting for non-normality, heteroscedasticity, and country-specific fixed effects (Chen, 2023). Thus, the MMQR estimator is appropriate for analyzing the heterogeneous effects of clean transportation, innovation, and governance on environmental degradation across the E5 economies.

Diagnostic and pre-tests

Prior to estimation we conduct a battery of diagnostic tests to inform model specification:

- Cross-sectional dependence (CD) test (Pesaran, 2007): To test whether residuals are correlated across countries.
- Slope homogeneity test (Pesaran and Yamagata, 2008): To assess whether slope coefficients can be assumed equal across countries.
- Panel unit root tests (CIPS/CADF): To determine integration orders of series in presence of cross-section dependence.
- Panel cointegration (Westerlund, 2007): To test for long-run relationships among non-stationary series.
- Multicollinearity Assessment: Before conducting the regression analysis, multicollinearity among the explanatory variables was examined using the Variance Inflation Factor (VIF) approach. VIF values were computed by regressing each explanatory variable on all other independent variables and calculating the reciprocal of the tolerance statistic:

$$VIF_i = \frac{1}{1-R_i^2}$$

where R_i^2 is the coefficient of determination from the auxiliary regression for variable *i*. The test helps identify whether predictor variables are highly correlated, which can distort coefficient estimates. Following conventional econometric guidelines (Alnahdi, 2024), a VIF value above 10 indicates serious multicollinearity concerns, while values below this threshold are considered acceptable. The calculated VIF values for all variables are reported in *Table 4*.

Estimation details and interaction term

The MMQR specification estimates conditional quantiles of $PM_{2.5}$ as functions of the logged covariates (where applicable). We include an interaction term between transport emissions and the Policy Governance Index (TR × PGI) to test whether governance quality moderates transport's impact on pollution (Shahbaz et al., 2024). Coefficients in log–log specifications are interpreted approximately as elasticities. Standard errors for MMQR are calculated using the recommended bootstrap procedure. For robustness, we also present FE and FGLS estimates.

Two model specifications were estimated to examine how clean transportation, innovation, and governance jointly influence environmental degradation.

- Model 1 (Baseline Model) includes the core explanatory variables only industrial growth (IG), innovation (INN), transport emissions (TR), energy intensity (EI), and policy governance index (PGI).
- Model 2 (Extended Model) augments the baseline specification by introducing an interaction term between transport emissions and governance (TR × PGI), allowing the analysis to capture whether stronger governance mitigates the environmental impact of transport activities.

Comparing the two models reveals the moderating role of governance in shaping the transport–pollution relationship. Both models were estimated using the MMQR framework across multiple quantiles ($\tau = 0.25, 0.50, 0.75, 0.90$).

Results and discussion

Descriptive statistics and correlations

In *Figure 2,* the line chart shows $PM_{2.5}$ annual mean concentrations (µg/m³) for five countries (France, Germany, Italy, Poland, United Kingdom) from 1996 through 2023. The X-axis is labeled “Years (1996–2023)” and the Y-axis is labeled “$PM_{2.5}$ concentrations (µg/m³)”. All five national series decline over time; Germany starts highest (~34 µg/m³ in 1996) and shows a steady decline to ~13 µg/m³ by 2023, Italy and Poland show intermediate starting levels and steady declines, and France and the UK start lower and decline to values below 10 µg/m³ by 2023. The legend identifies each colored line. The data source is World Development Indicators (WDI)/Authors’ calculations.

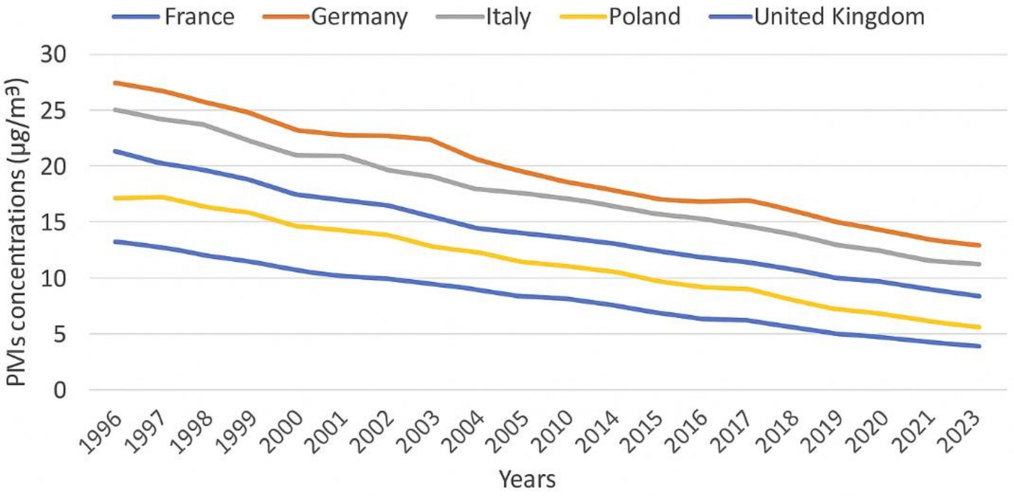


Figure 2. *Temporal variations and levels of environmental degradation ($PM_{2.5}$ concentrations, µg/m³) across European E5 nations (1996–2023). (Source: Authors’ drawing)*

Urban growth (UG) exhibits both positive and negative values, underscoring contrasting demographic dynamics, such as urban shrinkage in some areas versus expansion in others. The mean innovation index (INN) of 7.718, measured in log form, indicates a generally high level of environment-related technological activity, with a right-skewed distribution as seen in the difference between mean and median. The wavelet power spectra for innovations across E5 nations in *Figure 3* reveal distinct temporal variations, with France and Germany showing sustained high-frequency bursts post-2000, while Italy, Poland, and the UK exhibit intermittent but intensifying innovation cycles, particularly around 2010–2015. These patterns reflect heterogeneous policy responsiveness and innovation diffusion timelines across the European economies.

Table 2 reports descriptive statistics for the sample (1996–2023). The mean $PM_{2.5}$ concentration for the sample is 17.245 µg/m³ (Min = 8.330, Max = 29.298). Urban growth, innovation, and governance measures display heterogeneity across countries. The correlation matrix in *Table 3* indicates a strong positive correlation between environmental degradation (ED) and industrial growth (IG) ($r = 0.713$, $p < 0.01$). There are notable correlations among other covariates that motivate multicollinearity diagnostics.

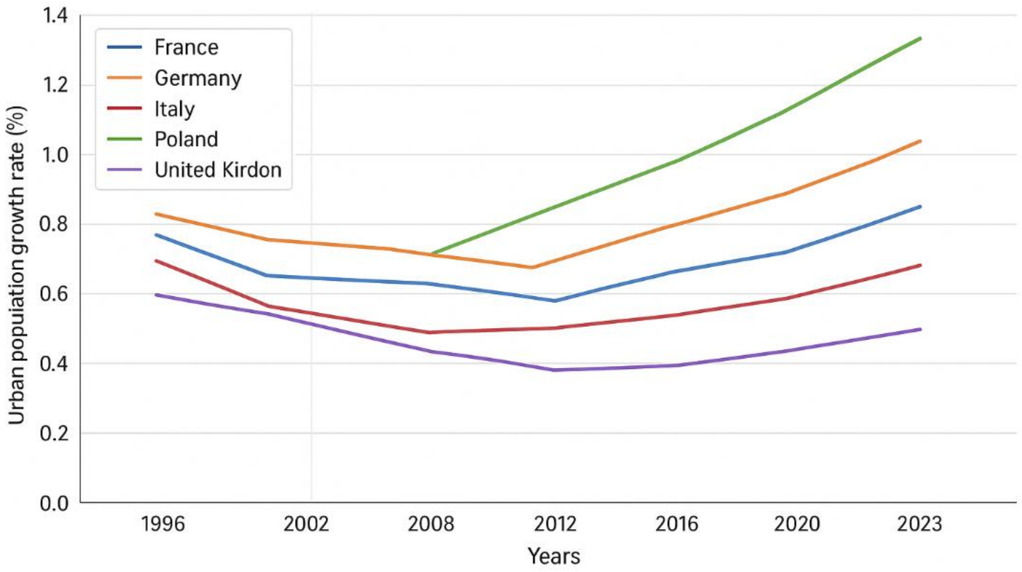


Figure 3. *Demographic changes and urbanization trends across European E5 nations (1996–2023). The X-axis represents years (1996–2023) and the Y-axis shows urban population growth rate (%). The figure illustrates demographic change through annual urbanization trends in France, Germany, Italy, Poland, and the United Kingdom*

Table 2. *Results of descriptive statistics*

	ED	IG[a]	EI[a]	UG	INN[a]	TR[a]	PGI
Mean	17.245	3.13	8.069	0.412	7.718	4.62	1.44E-09
Median	16.306	3.138	8.059	0.436	8.12	4.803	0.436
Maximum	29.298	3.479	8.373	1.594	9.771	5.18	2.856
Minimum	8.33	2.778	7.672	-1.602	2.69	3.23	-3.634
Std. Dev.	5.724	0.191	0.206	0.528	1.729	0.489	2.121
J-B stats	14.900***	40.960***	11.680***	17.950***	23.840***	30.750***	13.400***
Observations	140	140	140	140	140	140	140

[a] is the logarithmic term. The significance at 1% is denoted by ***. Source: Authors' compilation

Table 3 presents the correlation matrix capturing the linear associations among the variables used in the analysis of environmental degradation in European E5 countries. The results show a strong positive correlation between environmental degradation (ED) and industrial growth (IG) ($r = 0.713$, $p < 0.01$), underscoring the significant role of industrial activity in exacerbating urban air pollution. Conversely, ED is negatively correlated with energy intensity (EI), urban growth (UG), innovations (INN), transport emissions (TR), and policy governance index (PGI), all significant at the 1% level. These negative correlations suggest that improvements in energy efficiency, urban planning, technological advancement, and institutional quality are associated with lower PM2.5 levels.

Table 3. *Correlation analysis*

	ED	IG[a]	EI[a]	UG	INN[a]	TR[a]	PGI
ED	1.000						
IG[a]	0.713***	1.000					
EI[a]	-0.346***	-0.181**	1.000				
UG	-0.528***	-0.716***	0.336***	1.000			
INN[a]	-0.691***	-0.465***	0.665***	0.459***	1.000		
TR[a]	-0.661***	-0.487***	0.699***	0.517***	0.962***	1.000	
PGI	-0.613***	-0.295***	0.684***	0.459***	0.631***	0.642***	1.000

[a] is the logarithmic term. *** and ** show the p-value at < 0.01 and < 0.05, respectively. Source: Authors' compilation

Multicollinearity and diagnostics

Table 4 shows Variance Inflation Factors (VIF). The mean VIF is 6.66; INN and TR have high VIF values of 14.09 and 16.10 respectively, indicating potential multicollinearity concerns between innovation and transport variables. Given this, we proceed with robust estimators (MMQR, FGLS, FE) and interaction specifications to preserve interpretability while addressing collinearity.

Table 4. *Multicollinearity check*

Variables	VIF	1/VIF
$IG_{i,t}$	2.238	0.420
$EI_{i,t}$	2.600	0.385
$UG_{i,t}$	2.530	0.396
$INN_{i,t}$	14.090	0.071
$TR_{i,t}$	16.100	0.062
$PGI_{i,t}$	2.260	0.443
Mean VIF	6.660	-

Source: Authors' compilation

The results of the multicollinearity diagnostics using Variance Inflation Factors (VIF). The mean VIF value of 6.66 falls within an acceptable range, though it warrants attention due to the presence of two variables, environmental innovations (INN) and transportation factor (TR), with notably high VIF values of 14.09 and 16.10, respectively. These exceed the conventional threshold of 10, indicating potential multicollinearity concerns. This is consistent with the strong correlation observed between INN and TR in the previous correlation analysis, likely reflecting overlapping variance due to shared technological and environmental dimensions.

The remaining variables, including industrial growth (IG), energy intensity (EI), urban growth (UG), and policy governance index (PGI), exhibit VIFs below 2.6, indicating minimal concern for multicollinearity. However, environmental innovations (INN) and transport emissions (TR) display notably high VIF values, suggesting significant collinearity between these two indicators. To mitigate the potential distortion this could introduce into coefficient estimates, the study employs a robust econometric strategy.

Specifically, Method of Moments Quantile Regression (MMQR) is used to capture distributional heterogeneity in environmental degradation, allowing for a more nuanced understanding of how predictors influence pollution at different quantiles. In addition, Fixed Effects estimation is applied to control for unobserved time-invariant heterogeneity, while Feasible Generalized Least Squares (FGLS) addresses issues of heteroskedasticity and autocorrelation, reinforcing the consistency and reliability of the results.

Table 5 reports the results of the cross-sectional dependence (CD) test, which evaluates whether unobserved common factors affect the panel units in a correlated manner. The CD statistics for all core variables (ED, IG, EI, INN, TR, and PGI) are highly significant at the 1% or 5% levels, with test values well above conventional thresholds. This strongly indicates the presence of cross-sectional dependence, implying that shocks or policy changes in one country likely influence others within the European E5 group. UG exhibits marginal dependence at the 10% level, suggesting weaker but non-negligible interdependence in urban expansion trends. The presence of significant cross-sectional dependence across most variables justifies the use of panel econometric techniques such as MMQR and FGLS that can account for such interlinkages and ensure robust inference across countries with interconnected environmental and policy dynamics.

Table 5. *Cross-sectional dependence (CD) test*

Parameters	Value	P-value
$ED_{i,t}$	15.860***	0.000
$IG_{i,t}$	9.160***	0.000
$EI_{i,t}$	4.610***	0.000
$UG_{i,t}$	1.310*	0.078
$INN_{i,t}$	11.280***	0.000
$TR_{i,t}$	2.430**	0.015
$PGI_{i,t}$	5.490***	0.000

The significance at 1%, 5%, and 10% is specified by ***, **, and *. Source: Authors' compilation

Table 6 presents the results of the Slope Homogeneity (SH) test using the standard and adjusted Swamy-type test statistics. Both the $\hat{\Delta}_{S-HT}$ and the adjusted ($\hat{\hat{\Delta}}_{adj.S-HT}$) statistics are highly significant at the 1% level, with values of 4.807 and 5.688, respectively. These findings decisively reject the null hypothesis of slope homogeneity across the panel, confirming that the relationships between the explanatory variables and environmental degradation differ significantly across the E5 countries.

Table 6. *Slope heterogeneity (SH) test*

Test	Value	P-value
$\boldsymbol{\hat{\Delta}_{S-HT}}$	4.807***	0.000
$\boldsymbol{\hat{\hat{\Delta}}_{adj.S-HT}}$	5.688***	0.000

The significance at 1% is denoted by ***. Source: Authors' compilation

This result underscores the presence of structural heterogeneity, where the impact of factors such as innovation, energy use, or governance varies by national context.

Consequently, it supports the application of estimation techniques like Method of Moments Quantile Regression (MMQR) that allow for slope heterogeneity and provide richer insights across different conditional distributions. The rejection of homogeneity further validates the empirical strategy's emphasis on capturing cross-country differences in policy effectiveness and environmental outcomes.

Table 7 displays the results of the Cross-sectionally Augmented IPS (CIPS) unit root test, assessing the stationarity properties of the panel data series. At the level, only environmental degradation (ED) is found to be stationary (I(0)) at the 1% level, with a CIPS statistic of -2.917 surpassing the critical threshold. All other variables, including IG, EI, UG, INN, TR, and PGI, fail to reject the null hypothesis of non-stationarity at the level, as their test statistics fall short of the 10% critical value.

However, after first differencing, all variables become stationary at the 1% level, with CIPS values well below the critical threshold. This confirms that the majority of the variables are integrated of order one, I(1), and that their dynamic behavior is captured more accurately in differences rather than levels. The stationarity structure supports the use of econometric methods that accommodate mixed integration orders and non-stationary behavior, such as MMQR and FGLS, which are robust to panel unit roots and allow for both short-run and long-run dynamics.

Table 7. *CIPS unit root test*

Parameters	**I(0)**		**I(1)**
ED$_{i,t}$	-2.917***		-5.030***
IG$_{i,t}$	-1.771		-4.025***
EI$_{i,t}$	-1.336		-5.159***
UG$_{i,t}$	-2.511		-4.919***
INN$_{i,t}$	-1.613		-4.681***
TR$_{i,t}$	-1.761		-3.275***
PGI$_{i,t}$	-1.589		-4.351***
Critical values at	10%	5%	1%
	-2.73	-2.86	-3.1

*** shows the significance at 1%. Source: Authors' compilation

Table 8 reports the results of Westerlund (2007) panel cointegration test, which evaluates the existence of a long-run equilibrium relationship among the variables. Among the four test statistics, Gt and Pt are highly significant at the 1% level, with Z-values of -6.217 and -5.054, respectively, and corresponding p-values of 0.000. These results reject the null hypothesis of no cointegration, indicating that a stable long-run relationship exists between environmental degradation and its key determinants across the E5 countries.

In contrast, the Ga and Pa statistics are not statistically significant, proposing that panel-wide cointegration cannot be confirmed based solely on these group-mean tests. Nonetheless, the significance of the Gt and Pt statistics both of which are more sensitive to individual cross-sectional units strongly supports the presence of cointegration at the country level. These findings reinforce the empirical model's validity by confirming that the identified relationships are not spurious and persist over time, vindicating the practice of long-run estimators such as MMQR and FGLS in the analysis.

Table 8. *Cointegration test*

Statistic	Value	Z-value	P-value
Gt	-5.508***	-6.217	0.000
Ga	-15.436	0.410	0.659
Pt	-11.203***	-5.054	0.000
Pa	-15.136	-0.452	0.326

Source: Authors' compilation

MMQR main results (distributional effects)

Table 9 presents MMQR estimates at selected quantiles (Q0.25, Q0.50, Q0.75, Q0.90) for two models: (1) baseline and (2) with TR × PGI interaction. The significant slope heterogeneity confirmed by the Pesaran–Yamagata test aligns with the structural diversity of the E5 nations, which combine advanced and post-transition economies.

Key findings:

- Industrial growth (IG) is consistently positive and statistically significant across quantiles, with effect sizes increasing toward upper quantiles (e.g., elasticity rising from ~0.557 at Q0.25 to ~0.848 at Q0.90).
- Innovations (INN) show negative and increasingly significant coefficients at higher quantiles, indicating stronger mitigation effects where pollution is high (e.g., −2.286 at Q0.75 and −3.402 at Q0.90 in the baseline specification).
- Transport (TR) is positive and significant in extended specifications at higher quantiles, while the interaction (TR × PGI) is negative and highly significant across quantiles, indicating governance reduces the pollution impact of transport emissions.

Energy intensity (EI) shows mixed effects across quantiles; its sign and significance vary by quantile and specification.

Table 9. *Results of MMQR*

Variables	Location	Scale	Quantiles			
			$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
$ED = f(IG, EI, UG, INN, TR)$						
$IG_{i,t}$	0.663***	0.098	0.557*	0.630**	0.732***	0.848***
$EI_{i,t}$	0.001	-0.003***	0.004**	0.002	-0.002	-0.006***
$UG_{i,t}$	0.532	0.027	0.502	0.523	0.551	0.584
$INN_{i,t}$	-1.620	-0.943	-0.597	-1.298	-2.286*	-3.402*
$TR_{i,t}$	-0.003*	0.088	-0.098	-0.033*	0.058	0.162**
Constant	12.163	8.411	3.040	9.297	18.100*	28.060*
$ED = f(IG, EI, UG, INN, TR \times PGI)$						
$IG_{i,t}$	0.792***	0.040	0.757***	0.805***	0.828***	0.852***
$EI_{i,t}$	0.002***	-0.001***	0.003***	0.002***	0.001***	0.001*
$UG_{i,t}$	1.368	-1.180**	2.414*	0.964	0.278	-0.418
$INN_{i,t}$	-2.212***	-0.896***	-1.418**	-2.518***	-3.039***	-3.568***
$TR_{i,t}$	0.048*	0.061***	-0.007	0.068**	0.104***	0.140***
$(TR \times PGI)_{i,t}$	-0.012***	-0.002***	-0.010***	-0.013***	-0.014***	-0.016***
Constant	3.479	4.799**	-0.778	5.120	7.911*	10.742**

***, **, and * show the p-value at < 0.01, < 0.05, and < 0.1 respectively. Source: Authors' compilation

The results of the Method of Moments Quantile Regression (MMQR) applied across different conditional quantiles of environmental degradation, offering a detailed understanding of how the impact of each explanatory variable varies across low, median, and high pollution levels. Two model specifications are tested: the baseline model (ED as a function of IG, EI, UG, INN, and TR) and an extended interaction model that incorporates the moderating effect of policy governance (TR × PGI).

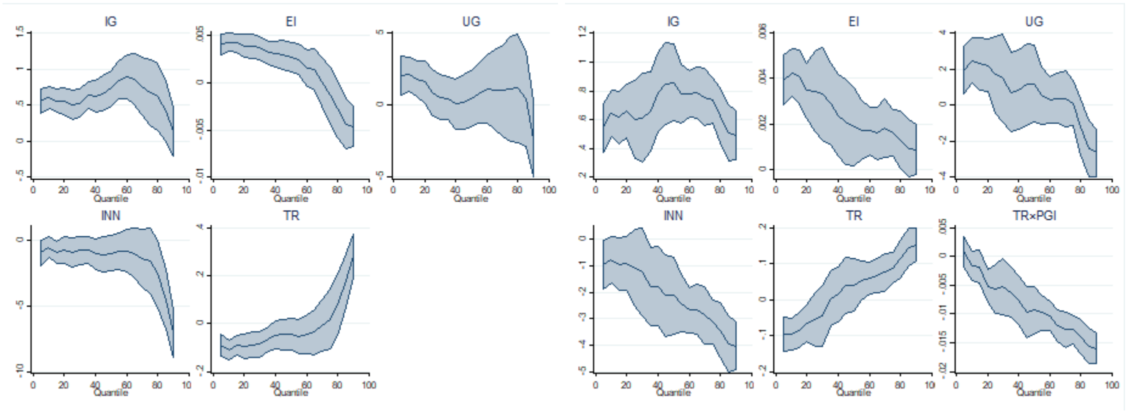
In the baseline model, IG has a consistently positive and statistically significant effect across all quantiles, with the magnitude increasing at higher levels of pollution. A 1% increase in IG is associated with an estimated rise in PM2.5 levels of 0.557% at Q0.25 and up to 0.848% at Q0.90, indicating that industrial activity is a stronger contributor to air pollution in more environmentally stressed contexts. This finding is corroborated by Akram et al. (2024). Energy intensity (EI) shows mixed significance; while statistically insignificant at central quantiles, its impact becomes significantly negative at the upper tail (Q0.90), where a 1% increase in energy use per capita reduces PM2.5 concentrations by approximately 0.006%. This counterintuitive result may reflect technological transitions or cleaner energy sources in highly polluted settings.

UG does not exhibit statistically significant effects across any quantile, suggesting that population dynamics alone are not a strong driver of environmental degradation once other factors are controlled. This finding is corroborated by Quito et al. (2023). INN, on the other hand, shows increasingly negative and significant effects at higher pollution quantiles. At Q0.75 and Q0.90, a 1% increase in green inventions per capita is associated with reductions in PM2.5 of 2.29% and 3.40%, respectively, affirming the critical role of technology in mitigating environmental harm where it is most severe. This outcome is similar to Pata et al. (2023). TR shows weak or marginal effects, with a small but significant negative impact at Q0.50. This finding aligns with Kharlamova et al. (2022).

The extended model, which includes the interaction term between transportation and the Policy Governance Index (TR × PGI), reveals clearer dynamics. IG remains positively and significantly associated with environmental degradation across all quantiles, reinforcing the industrial pollution linkage. EI turns statistically significant and positive across all quantiles, indicating that increased per capita energy use, when combined with weak governance, exacerbates pollution. INN continues to exert a strong negative influence, and its effect intensifies across higher quantiles, highlighting its robust mitigation potential even in high-emission regimes.

Transportation (TR) becomes positively and significantly associated with degradation in the extended model, particularly at Q0.75 and Q0.90. However, the interaction term (TR × PGI) carries a consistently negative and highly significant coefficient across all quantiles. This finding underscores the critical role of governance in moderating the environmental impact of transport emissions. Specifically, a 1% increase in PGI reduces the pollution effect of transport emissions by 0.012% to 0.016%, depending on the pollution level. The governance mechanism thus acts as a dampening force, enhancing regulatory oversight, clean transport incentives, and enforcement capacity.

The significance of the PGI in this study is profound. In the European context, where institutional maturity and policy sophistication vary across countries, governance quality directly influences how transport systems contribute to or mitigate environmental degradation. Stronger governance not only tempers the adverse effects of emissions but also enables more effective integration of innovation and energy policy, reinforcing systemic resilience against environmental pressures. These findings reinforce the call for strengthened institutional frameworks, particularly in high-emission settings, to support the transition toward cleaner, more sustainable urban environments. *Figure 4* shows the graphical results of MMQR findings for both models.



Model 1 Model 2

Figure 4. *Distributional effects of clean transport, innovation, and governance on PM$_{2.5}$ (MMQR estimates across quantiles)*

Robustness checks (FGLS and FE)

Table 10 reports FGLS and Fixed Effects estimations. Main patterns are consistent with MMQR: IG positively contributes to PM$_{2.5}$, INN reduces pollution, and TR × PGI remains negative and significant, confirming the moderating role of governance. EI is positive and significant in robustness models.

Table 10. *Robustness check*

Variables	**FGLS**		**FE**	
	Coefficients	**Standard error**	**Coefficients**	**Standard error**
$ED = f(IG, EI, UG, INN, TR)$				
$IG_{i,t}$	0.663***	0.108	0.613***	0.151
$EI_{i,t}$	0.001**	0.001	0.005***	0.001
$UG_{i,t}$	0.532	0.858	0.670	0.546
$INN_{i,t}$	-1.620***	0.586	-1.902***	0.394
$TR_{i,t}$	-0.003	0.029	-0.034	0.025
Constant	12.163***	4.333	4.560	4.122
Wald test/F-stat.	272.880***	-	47.060***	-
$ED = f(IG, EI, UG, INN, TR \times PGI)$				
$IG_{i,t}$	0.792***	0.086	0.512***	0.154
$EI_{i,t}$	0.002***	0.001	0.004***	0.001
$UG_{i,t}$	1.368**	0.678	0.439	0.545
$INN_{i,t}$	-2.212***	0.464	-1.678***	0.398
$TR_{i,t}$	0.048**	0.023	-0.022	0.025
$(TR \times PGI)_{i,t}$	-0.013***	0.001	-0.009**	0.004
Constant	3.479	3.518	6.000	4.094
Wald test/F-stat.	532.820***	-	41.600***	-

The p-values of < 0.01 and < 0.05 are indicated by *** and **. Source: Authors' compilation

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Robustness checks using FGLS and Fixed Effects (FE) models, largely confirming the MMQR findings. IG consistently shows a positive and significant impact on environmental degradation across all models, reinforcing its role as a key pollution driver. INN also maintains a strong negative association, validating their pollution-mitigating effects observed in MMQR, especially at higher quantiles.

EI appears positive and significant in both robustness models, contrasting with MMQR, where its effect was negative at higher quantiles, suggesting that MMQR better captures efficiency improvements in high-pollution contexts. UG remains broadly insignificant, aligning with MMQR, though FGLS hints at marginal relevance in extended models.

TR displays mixed results weak or insignificant in FE, but positive and significant in extended FGLS. Importantly, the interaction term (TR × PGI) is consistently negative and significant across models, affirming the vital moderating role of governance in reducing transport-related environmental harm. These results confirm the robustness of key MMQR findings while highlighting its strength in revealing distributional heterogeneity.

Granger causality

Table 11 summarizes Dumitrescu–Hurlin panel Granger causality tests. Several variables (EI, INN, TR, PGI) Granger-cause ED, indicating predictive relationships from these determinants to $PM_{2.5}$. IG shows marginal unidirectional causality to ED. These causality results complement the regression evidence and suggest leading policy levers.

Table 11. *Granger-causality analysis*

Causality	F-stat.	P-value
$IG_{i,t} \rightarrow ED_{i,t}$	1.004*	0.057
$ED_{i,t} \rightarrow IG_{i,t}$	0.361	0.121
$EI_{i,t} \rightarrow ED_{i,t}$	0.180**	0.041
$ED_{i,t} \rightarrow EI_{i,t}$	0.206	0.178
$UG_{i,t} \rightarrow ED_{i,t}$	0.007***	0.009
$ED_{i,t} \rightarrow UG_{i,t}$	0.314*	0.077
$INN_{i,t} \rightarrow ED_{i,t}$	0.136**	0.015
$ED_{i,t} \rightarrow INN_{i,t}$	0.307	0.234
$TR_{i,t} \rightarrow ED_{i,t}$	0.054**	0.038
$ED_{i,t} \rightarrow TR_{i,t}$	0.351*	0.076
$PGI_{i,t} \rightarrow ED_{i,t}$	0.204***	0.001
$ED_{i,t} \rightarrow PGI_{i,t}$	0.330	0.155

The significance level is indicated as *** < 1%, ** < 5%, and * < 10%. Source: Authors' compilation

The Granger causality results, shedding light on the directional influence between ED and its determinants. The findings indicate unidirectional causality from several predictors to ED, affirming their predictive power.

IG Granger-causes ED at the 10% level ($p = 0.057$), suggesting that industrial expansion precedes environmental degradation, but the reverse is not true, indicating that economic activity drives pollution rather than being reactive to it. EI, INN, and TR all show significant unidirectional causality toward ED at the 5% level, reinforcing their role as leading contributors to environmental degradation, consistent with MMQR results. UG exhibits bidirectional causality at marginal levels ($p < 0.10$), pointing to a feedback loop where urban expansion and pollution may reinforce one another. The most robust causal pathway is from PGI to ED ($p = 0.001$), underscoring the pivotal influence of governance in shaping environmental outcomes, with no evidence of reverse causality.

The observed heterogeneity in the estimated effects across the E5 countries is not unexpected, given their distinct economic and institutional characteristics. France, Germany, and the United Kingdom represent mature industrial and governance systems with advanced clean-technology infrastructure, whereas Poland retains features of a post-socialist transition economy with evolving environmental governance. Italy, meanwhile, bridges these extremes as an industrialized yet institutionally diverse economy. These structural and developmental differences explain the cross-country variation detected in the MMQR results and reinforce the importance of adopting differentiated policy frameworks across the E5 region.

These causality results complement the MMQR findings by confirming that most independent variables, particularly PGI, TR, and INN, are not only correlated with but also precede environmental changes, highlighting their strategic policy importance in the European context.

Conclusion and policy implications

This work explores the environmental implications of technological and policy innovations across the European E5 nations (France, Germany, Italy, Poland, and the United Kingdom) over the period 1996 to 2023. Leveraging advanced econometric methods, including Method of Moments Quantile Regression (MMQR), Fixed Effects models, and Feasible Generalized Least Squares (FGLS), the analysis captures both distributional dynamics and cross-country heterogeneity in environmental degradation, measured via PM2.5 concentrations.

The findings reveal that industrial growth consistently exacerbates environmental degradation, particularly in higher pollution contexts. Conversely, environmental innovations demonstrate a significant mitigating effect, especially at upper quantiles of degradation. Transport emissions are context-sensitive but become more detrimental in the absence of effective governance. Importantly, the Policy Governance Index (PGI) emerges as a critical moderator, reducing the environmental impact of transport emissions and enhancing the effectiveness of green innovations. Granger causality results further validate the predictive direction of these relationships. Overall, the study underscores the complex interplay between industrial activity, technological progress, and governance in shaping urban environmental outcomes across advanced European economies.

Policy recommendations

Based on the empirical findings, several targeted policy interventions are warranted to reinforce environmental sustainability in the European E5 context. Given the significant role of industrial activity in driving PM2.5 pollution, national governments, supported by the European Commission’s Green Deal framework, should incentivize cleaner industrial technologies and enforce stricter emission standards through the EU Emissions Trading System (EU ETS). The pronounced environmental benefits of green innovations observed in the study highlight the need for increased funding toward R&D through platforms such as Horizon Europe, particularly for clean transportation and energy efficiency technologies.

To strengthen governance capacity, institutions like the European Environment Agency (EEA) and national audit offices should enhance transparency, regulatory oversight, and enforcement mechanisms targeting environmental violations. The study's confirmation of governance as a moderator of pollution emphasizes the importance of cross-sectoral coordination, where the European Union Agency for Fundamental Rights (FRA) and the World Governance Indicators (WGI) framework can aid in benchmarking and improving institutional quality.

In alignment with Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 9 (Industry, Innovation, and Infrastructure), European nations must promote integrated urban development strategies that prioritize low-emission public transport, circular economy models, and clean energy transitions. The robust link between innovation and improved air quality suggests that scaling up support for environmental patents through the European Patent Office (EPO) and fostering green entrepreneurship ecosystems can yield long-term benefits.

Lastly, given the differentiated environmental responses across countries and pollution levels, a regionally adaptive policy approach is crucial. Institutions like the Committee of the Regions (CoR) should coordinate subnational actions, ensuring that EU-wide sustainability objectives are effectively localized. These measures, collectively, can fortify Europe's leadership in environmental governance and its commitment to a sustainable, low-carbon future.

Limitations and future research directions

This study, despite its robust methodological design, faces several limitations. The selected indicators, while comprehensive, omit factors like renewable energy use or electric vehicle adoption that could enrich environmental analysis. Although MMQR and FGLS effectively capture distributional dynamics, the absence of dynamic models (e.g., PVAR) limits insights into time-lagged effects. Multicollinearity between innovation and transport emissions, while acknowledged, was not resolved through techniques like PCA or composite index construction, which future studies could explore.

Governance was treated as a unified moderator without dissecting the effects of individual components, such as the rule of law or regulatory quality. Future research may use mediation or structural modeling to assess these pathways. Additionally, potential nonlinear or threshold effects were not examined and could be addressed using advanced methods like machine learning. Lastly, the focus on E5 European nations limits generalizability, suggesting that comparative studies including emerging economies could provide broader insights.

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