

ECONOMIC DIMENSIONS OF AIR POLLUTION MANAGEMENT IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT: A COMPARATIVE ASSESSMENT OF SELECTED EU COUNTRIES

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ABSTRACT

This study explores the economic dimensions of air pollution management within the broader context of sustainable development, focusing on a comparative analysis of six European Union member states – Austria, Bulgaria, Hungary, Italy, Poland and Romania. Drawing on data from the World Development Indicators, the analysis brings together four interrelated dimensions: exposure to fine particulate matter (PM_{2.5}), carbon intensity of GDP, patterns of economic growth and convergence, and mortality associated with household and ambient air pollution. The results reveal that, although reductions in carbon intensity represent an important component of environmental progress, they do not automatically translate into proportional improvements in air quality or public health outcomes. This finding suggests that aggregate efficiency gains must be complemented by targeted, sector-specific interventions addressing the main sources of particulate emissions. Building on these insights, the study develops a conceptual cluster framework that captures distinct development–pollution–health trajectories across countries. The analysis highlights the need for differentiated, context-sensitive policy approaches that align economic modernization with air quality management and public health objectives. By integrating economic, environmental and health dimensions, the paper offers a more nuanced perspective on the challenges of sustainable air pollution management in heterogeneous European settings.

Keywords: air pollution management, economic dimensions, health, sustainable development, EU.

1 INTRODUCTION

Air pollution continues to represent one of the most significant environmental risks within the European Union, with far-reaching economic and social consequences [1]. Its effects extend well beyond immediate health impacts, influencing labour productivity, increasing public healthcare expenditures, shaping human capital formation, and ultimately affecting long-term economic resilience [2]–[4]. In this context, air pollution management should be understood not merely as an environmental concern, but as an integral component of sustainable economic development [5], [6].

Despite a substantial body of literature examining economic growth, carbon intensity and air pollution as separate phenomena, relatively few studies bring these dimensions together in a unified framework that also incorporates health outcomes, particularly in a comparative and cluster-based EU context [7], [8]. Addressing this gap, the present study integrates economic convergence, structural efficiency, air pollution exposure and mortality outcomes into a multidimensional analytical perspective. The approach is grounded in four interrelated strands of literature: the growth–environment nexus, decarbonization and structural



efficiency, the health impacts of air pollution, and the role of policy instruments and governance mechanisms.

A central issue in environmental economics concerns the nature of the relationship between economic development and environmental degradation [9]. The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental pressures tend to increase during early stages of development, before declining once higher income levels are reached [10], [11]. However, subsequent empirical research has produced mixed evidence, particularly in the case of air pollutants, where the inverted-U relationship appears less robust and more context-dependent [12]. In this regard, the OECD emphasizes that structural transformation, technological progress and policy stringency play a decisive role in shaping environmental outcomes, often outweighing the effect of income levels alone [13].

Reductions in carbon intensity are commonly interpreted as indicators of improved energy efficiency and technological modernization, reflecting shifts toward less carbon-intensive production structures [14], [15]. Nevertheless, existing research highlights an important limitation: improvements in carbon efficiency do not necessarily lead to proportional reductions in local air pollutants such as PM_{2.5} [16]. This distinction is particularly relevant when assessing the effectiveness of decarbonization strategies in addressing broader environmental and health challenges.

From a policy perspective, the Porter Hypothesis suggests that well-designed environmental regulation can stimulate innovation and enhance economic competitiveness [17]. Empirical studies support the idea that regulatory pressure may foster technological upgrading and structural efficiency improvements [18]. At the same time, the health consequences of air pollution remain substantial. Exposure to fine particulate matter has been consistently associated with increased mortality risks, as demonstrated in recent empirical studies [19]. These health effects carry significant economic implications, including productivity losses, rising healthcare costs and broader welfare impacts [20].

Evidence from the European Environment Agency (EEA) further indicates that, despite overall improvements at the EU level, substantial disparities in mortality attributable to air pollution persist across Member States [21]. In this context, climate mitigation policies can generate important co-benefits for public health, as reductions in fossil fuel use are associated with lower pollution-related mortality [22], [23]. Policy instruments such as environmental taxation and emissions trading schemes are designed to internalize environmental externalities and improve cost-effectiveness [24], [25]. However, their effectiveness depends critically on governance quality, administrative capacity and the degree to which public health considerations are integrated into policy design [26].

Taken together, these insights suggest that economic convergence alone does not ensure convergence in environmental performance or health outcomes [27]–[29]. This observation provides the starting point for the present analysis, which seeks to examine how development trajectories, structural efficiency and institutional context interact in shaping air pollution outcomes across European economies.

2 MATERIALS AND METHODS

The empirical assessment is based on secondary data extracted from the World Development Indicators database and relies on a set of five indicators selected to capture the economic, environmental and health dimensions of air pollution.

At the environmental level, PM_{2.5} mean annual exposure (µg/m³) is used to approximate population exposure to fine particulate matter and to reflect ambient air quality conditions. This indicator provides a direct measure of environmental pressure. Complementing this dimension, the mortality rate attributed to household and ambient air pollution is employed



as a proxy for the health burden associated with pollution exposure. By linking environmental conditions to human welfare outcomes, this variable allows for an assessment of the broader social costs of air pollution.

From an economic perspective, GDP growth (annual percentage) is included in order to capture short- and medium-term macroeconomic dynamics, while GDP per capita in purchasing power parity (current international dollars) reflects relative levels of economic development and convergence within the European context. In addition, carbon intensity of GDP (kg CO₂e per constant PPP dollar) is used as an indicator of structural and technological efficiency, highlighting the extent to which economic output is associated with greenhouse gas emissions.

The analysis focuses on six European Union member states – Austria, Italy, Romania, Hungary, Bulgaria and Poland – selected to reflect different stages of economic development, energy structure and institutional capacity. This selection allows for meaningful cross-country comparison across heterogeneous development trajectories. Austria is considered a benchmark case, characterized by high income levels and relatively low pollution exposure, while Italy represents a mature economy with distinct structural features. In contrast, Romania, Hungary, Bulgaria and Poland capture the dynamics of Central and Eastern European economies, where rapid economic growth and structural transformation coexist with persistent environmental challenges.

To ensure analytical coherence, the study is structured around four complementary dimensions: air pollution levels and trends, economic growth and convergence, carbon intensity and structural efficiency, and the public health impact of air pollution. This multidimensional approach facilitates an integrated assessment of how economic and environmental processes interact across countries.

Table 1 summarizes average PM_{2.5} exposure levels and their evolution over time. Although a degree of convergence is observable – particularly in the case of Romania, Hungary and Italy – the persistence of higher exposure levels in Bulgaria and Poland points to underlying structural differences, including variations in emission sources, urban development patterns and energy use. When interpreted together with carbon intensity dynamics, the results suggest that improvements in aggregate efficiency do not automatically translate into proportional reductions in particulate pollution. In this sense, the evidence supports the argument that carbon intensity reduction, while necessary, is not sufficient for achieving comprehensive air pollution mitigation.

Table 1: Structural dynamics of PM_{2.5} exposure and carbon intensity.

Country	PM _{2.5} 2000–2014 (µg/m ³)	PM _{2.5} 2015–2024 (µg/m ³)	% change	Carbon intensity 2000–2014	Carbon intensity 2015–2024	Carbon intensity % change
Austria	18.79	12.46	–33.65	0.23	0.17	–25.71
Italy	25.18	16.13	–35.95	0.25	0.18	–26.19
Romania	20.86	16.66	–20.11	0.91	0.41	–54.76
Hungary	21.20	16.68	–21.34	0.61	0.37	–39.36
Bulgaria	25.30	19.61	–22.48	1.50	0.88	–41.06
Poland	26.61	21.42	–19.50	1.05	0.61	–42.07

The representative trend graph (Fig. 1) captures the annual evolution of PM_{2.5} exposure across the selected countries, highlighting both common trends and persistent divergences. When these dynamics are examined alongside changes in the carbon intensity of GDP, a



more nuanced picture emerges, revealing not only elements of convergence but also clear structural mismatches in environmental performance.

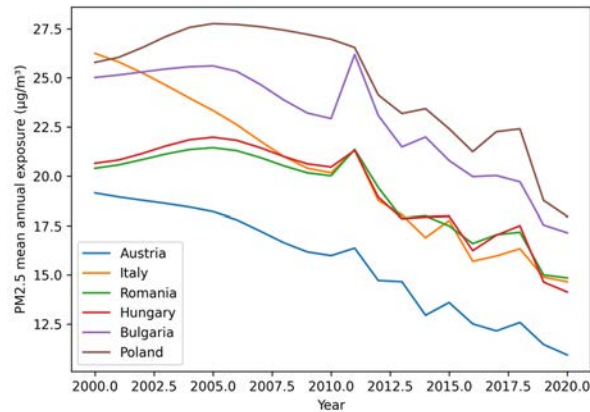


Figure 1: PM_{2.5} exposure trends (2000–2020).

A first pattern is observed in the case of Austria and Italy. Both countries combine relatively low carbon intensity levels in the 2015–2019 period with comparatively low PM_{2.5} exposure and substantial long-term reductions. Austria, in particular, exhibits the lowest average exposure in the sample, reflecting a high degree of structural energy efficiency and a relatively consistent environmental policy framework. Italy follows a similar trajectory, where reductions in carbon intensity are closely mirrored by improvements in air quality, suggesting a degree of alignment between decarbonization efforts and particulate emission control.

In contrast, Romania presents a more complex and less linear adjustment process. Although it records the most significant reduction in carbon intensity over the period (–54.8%), the corresponding decline in PM_{2.5} exposure remains comparatively modest (–20.1%). Moreover, recent exposure levels are broadly comparable to those observed in Hungary and only marginally lower than in Italy. This divergence suggests that improvements in aggregate carbon efficiency do not automatically translate into proportional reductions in particulate pollution. A plausible explanation lies in the sectoral composition of emissions, particularly the continued importance of residential heating, urban transport dynamics and local air quality management practices.

A different structural pattern can be identified in Poland and Bulgaria. Despite notable progress in reducing carbon intensity, both countries continue to exhibit the highest PM_{2.5} exposure levels within the sample. This indicates that, although emissions per unit of output have declined, underlying structural factors – such as reliance on solid fuels and the persistence of legacy energy systems – continue to exert a strong influence on air quality outcomes.

Hungary occupies an intermediate position between these trajectories. The country has achieved substantial improvements in carbon efficiency, accompanied by moderate reductions in PM_{2.5} exposure. As a result, it converges toward mid-range levels within the sample, reflecting partial alignment between structural efficiency gains and environmental outcomes.

The economic dimension of the analysis complements this environmental perspective by examining whether improvements in air quality have been accompanied by processes of economic convergence. In this regard, Table 2 summarizes average GDP growth rates across two benchmark periods, providing a basis for assessing the relationship between environmental performance and macroeconomic dynamics.

Table 2: Economic growth and convergence dynamics.

Country	GDP growth avg 2000– 2014 (%)	GDP growth avg 2015– 2024 (%)	GDP per capita PPP avg 2000–2014	GDP per capita PPP avg 2015–2024	GDP per capita growth multiple
Austria	1.94	1.99	31,040	54,562	1.76
Italy	1.54	1.00	28,590	42,012	1.47
Romania	5.23	4.71	7,061	25,354	3.59
Hungary	4.42	4.18	14,267	30,546	2.14
Bulgaria	5.21	3.06	7,592	21,123	2.78
Poland	3.28	4.69	11,896	30,749	2.58

Several structural patterns can be identified when examining the dynamics of economic growth and convergence across the selected countries.

Austria and Italy display relatively modest but stable growth trajectories, reflecting the characteristics of mature economic systems. Over the period considered, Austria's GDP per capita increased by a factor of 1.76, while Italy recorded a more moderate expansion of 1.47. These patterns suggest processes of economic consolidation rather than rapid convergence, with growth driven primarily by incremental efficiency gains rather than structural transformation.

In contrast, Romania, Hungary, Bulgaria and Poland exhibit significantly stronger growth dynamics, particularly in the early 2000s, followed by sustained expansion in the later benchmark period. Romania stands out with the highest convergence multiplier (3.59), indicating a rapid process of structural adjustment and economic catching-up. Poland combines robust recent growth – with an average of 4.69% in the 2015–2019 period – with relatively stable convergence, pointing to a resilient and balanced development trajectory.

However, economic convergence does not translate uniformly into environmental or health outcomes. Romania and Hungary, for instance, have converged toward similar mid-range income levels and display comparable PM_{2.5} exposure values (approximately 16.6 µg/m³). Despite this similarity, Romania records a substantially higher health burden associated with air pollution. A comparable divergence can be observed in the case of Poland and Bulgaria, where significant income gains coexist with persistently elevated levels of particulate exposure. These discrepancies suggest that structural and institutional factors continue to shape environmental and health outcomes beyond what can be explained by income convergence alone.

The temporal dynamics of economic growth are further illustrated in Fig. 2, which highlights three distinct phases. The first phase corresponds to the pre-2008 period of economic expansion, particularly pronounced in Central and Eastern European countries. This is followed by a sharp contraction in 2009, associated with the global financial crisis. The third phase captures the post-2015 stabilization period, interrupted by the economic shock of 2020 linked to the COVID-19 pandemic, and followed by a subsequent recovery. Together, these phases underline the cyclical nature of economic growth, in contrast with the more gradual and structurally driven evolution of environmental indicators.



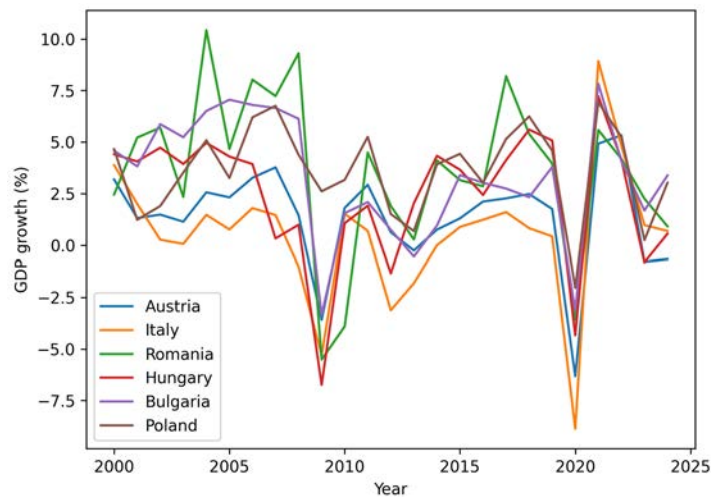


Figure 2: GDP growth trends (2000–2024).

These cyclical fluctuations stand in contrast to the more gradual and structurally driven decline observed in $PM_{2.5}$ exposure. This divergence suggests that improvements in air quality are less responsive to short-term macroeconomic volatility and are instead more closely linked to long-term policy frameworks, technological progress and structural adjustments within the economy.

From this perspective, the results indicate that economic convergence does not automatically lead to proportional environmental convergence. While Austria and Italy combine relatively high-income levels with sustained reductions in $PM_{2.5}$ exposure, the trajectories of Romania and Bulgaria highlight a different pattern, in which rapid GDP growth coexists with persistent air quality challenges. Poland, in turn, reflects an intermediate case: despite strong economic performance, reductions in particulate exposure appear more gradual relative to income gains.

To further explore these structural dynamics, carbon intensity of GDP is introduced as a complementary indicator of environmental efficiency. This measure captures the extent to which economic output is associated with greenhouse gas emissions and provides insight into broader processes of energy use, technological modernization and structural transformation. Although carbon intensity does not directly reflect particulate pollution, it offers a useful proxy for assessing the efficiency of economic systems in environmental terms.

Table 3 presents average carbon intensity levels for the periods 2000–2004 and 2015–2019, together with the corresponding percentage changes. This comparison allows for a more detailed examination of how improvements in structural efficiency relate to observed patterns in air quality and economic development.

A closer examination of carbon intensity dynamics reveals several distinct structural patterns across the selected countries. Austria and Italy maintain consistently low levels of carbon intensity throughout the entire period. Although their reductions are relatively moderate in percentage terms (around -26%), both countries start from comparatively efficient structural positions. This pattern is indicative of mature energy systems and long-standing decarbonization strategies, where improvements tend to be incremental rather than transformative.

Table 3: Carbon intensity of GDP: structural evolution.

Country	Carbon intensity avg 2000–2014	Carbon intensity avg 2015–2024	% change
Austria	0.232	0.172	–25.71
Italy	0.247	0.182	–26.19
Romania	0.914	0.413	–54.76
Hungary	0.610	0.370	–39.36
Bulgaria	1.501	0.885	–41.06
Poland	1.053	0.610	–42.07

In contrast, Romania records the most substantial proportional decline (–54.76%), pointing to a significant process of structural adjustment. This evolution likely reflects a combination of energy sector restructuring, technological upgrading and efficiency gains associated with broader economic transformation. Hungary, Poland and Bulgaria also exhibit considerable reductions, ranging between approximately –39% and –42%, which are consistent with modernization dynamics typically observed in post-transition economies.

However, despite these improvements, important differences persist in absolute terms. Bulgaria and Poland continue to display higher levels of carbon intensity in the 2015–2019 period compared to Austria and Italy. This suggests that structural factors – such as energy dependence on fossil fuels and the legacy of carbon-intensive industrial configurations – continue to shape emission profiles, even in the presence of ongoing efficiency gains.

The time-series evidence presented in Fig. 3 further supports these observations, illustrating a steady downward trajectory in carbon intensity across all countries. The decline is particularly pronounced in Central and Eastern Europe during the mid-2000s and early 2010s, reflecting periods of accelerated structural adjustment. Unlike GDP growth, which exhibits clear cyclical fluctuations, carbon intensity follows a more gradual and persistent downward trend. This pattern underscores the role of long-term technological change and structural transformation, rather than short-term macroeconomic dynamics, in driving improvements in environmental efficiency.

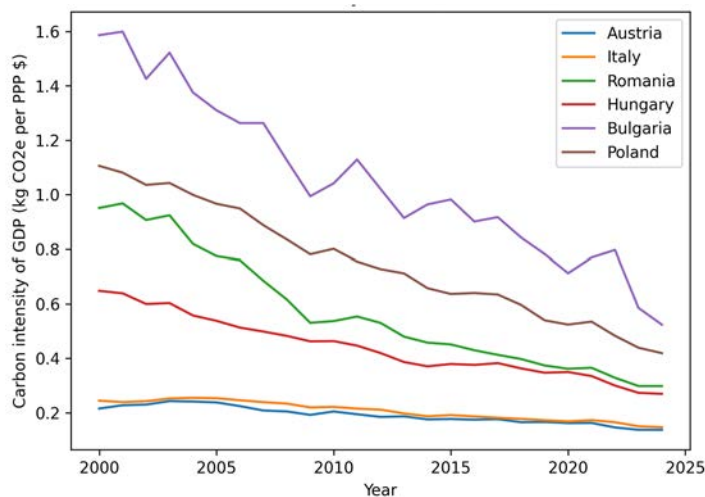


Figure 3: Carbon intensity trends (2000–2024).



Austria and Italy exhibit relatively stable trajectories, characterized by low volatility in carbon intensity over time. In contrast, Romania and Bulgaria display more pronounced declines, particularly in the period following 2008. These sharper adjustments are consistent with broader structural transformations associated with EU integration processes and energy market reforms, which have accelerated changes in energy use and production efficiency.

When carbon intensity trends are considered alongside PM_{2.5} exposure patterns, a more nuanced analytical distinction becomes evident. Austria and Italy combine low levels of carbon intensity with substantial reductions in particulate exposure, suggesting a relatively coherent pathway of structural modernization in which decarbonization efforts are closely aligned with improvements in air quality.

By contrast, Romania illustrates a more uneven trajectory. Despite achieving the most significant reduction in carbon intensity, improvements in PM_{2.5} exposure remain comparatively modest. This divergence points to the fact that gains in aggregate energy efficiency do not necessarily translate into equivalent reductions in particulate pollution. A plausible explanation lies in the continued importance of sector-specific emission sources, including residential heating, transport-related emissions and localized industrial activities, which are not fully captured by aggregate efficiency indicators.

A similar pattern can be observed in Poland and Bulgaria. Although both countries have made notable progress in reducing carbon intensity, they continue to exhibit relatively high levels of PM_{2.5} exposure. This suggests that improvements in macro-level efficiency are insufficient, on their own, to generate proportional gains in urban air quality.

Taken together, these findings indicate that carbon intensity reduction should be viewed as a necessary, but not sufficient, condition for effective air pollution mitigation. Structural efficiency at the aggregate level must be complemented by targeted interventions addressing key emission sources if meaningful improvements in particulate exposure and associated health outcomes are to be achieved.

While PM_{2.5} concentrations provide a measure of environmental pressure, the mortality rate attributed to household and ambient air pollution captures the ultimate social cost of this exposure in terms of premature deaths. As such, this indicator establishes a direct link between environmental performance and human welfare, making it essential for evaluating sustainable development trajectories.

Table 4 presents the mortality rates attributable to air pollution for 2019 (per 100,000 population), which represents the most recent year for which harmonized data are available across the selected countries.

Table 4: Mortality rate attributed to household and ambient air pollution.

Country	Total	Female	Male
Austria	–	–	–
Italy	15.0	11.6	19.2
Poland	40.9	30.9	53.9
Hungary	42.3	33.0	55.0
Bulgaria	62.9	48.1	81.3
Romania	67.8	52.1	87.3

Note: Data for Austria were not available.

The cross-country differences in mortality associated with air pollution are considerable. Romania and Bulgaria record the highest burden, with mortality rates exceeding those observed in Italy by more than fourfold. Hungary and Poland occupy an intermediate



position, while Italy exhibits comparatively low mortality levels. A consistent pattern across all countries is the higher mortality rate among men, which may be attributed both to biological factors and to differences in occupational exposure and behavioural patterns.

When these outcomes are considered alongside PM_{2.5} exposure trends, several important structural insights emerge. Although Romania and Hungary display similar levels of particulate exposure in recent years (approximately 16.6 µg/m³), Romania's mortality burden is substantially higher. This discrepancy suggests that particulate concentration alone does not fully account for observed health outcomes. Instead, factors such as cumulative exposure over time, the capacity and accessibility of healthcare systems, demographic characteristics and urban density appear to play a mediating role.

A related pattern can be observed in Bulgaria and Poland. Both countries maintain relatively high levels of PM_{2.5} exposure and also report elevated mortality rates, consistent with the expected relationship between environmental pressure and health impact. However, their mortality levels remain below those recorded in Romania, despite comparable or even higher exposure in certain periods. This further highlights the importance of contextual socio-economic conditions and healthcare infrastructure in shaping health outcomes.

Italy provides a contrasting example, combining the lowest mortality rate in the sample with relatively low levels of particulate exposure and a more developed healthcare system. This alignment suggests that sustained environmental management, supported by strong institutional capacity, can effectively reduce vulnerability to pollution-related health risks.

Taken together, these findings indicate that improvements in structural efficiency – such as reductions in carbon intensity – and even measurable declines in particulate exposure do not translate uniformly into proportional health gains. Health outcomes reflect a more complex interaction between environmental conditions, economic development, healthcare capacity and demographic structure, underscoring the need for integrated policy approaches.

3 RESULTS AND DISCUSSION

The development–pollution–health trajectories identified in this study bring together the four analytical dimensions – air pollution exposure, economic convergence, carbon intensity and health impact – into a coherent conceptual typology. The objective is not to perform a formal statistical clustering exercise, but rather to construct an interpretable and policy-relevant classification of countries, grounded in consistent structural patterns observed across the selected indicators.

The proposed typology is organized around three complementary analytical axes. The first axis captures the level of economic development and the dynamics of convergence, measured through GDP per capita in purchasing power parity (average for 2015–2019) and the corresponding convergence multiple relative to the early 2000s (2000–2004). This dimension reflects the extent to which countries have progressed in terms of income levels and structural economic transformation.

The second axis focuses on environmental pressure and structural efficiency. It combines indicators of PM_{2.5} exposure – both in terms of recent levels (2015–2019 average) and long-term reductions – with measures of carbon intensity, again considering both current levels and changes over time. This dual perspective allows for a more comprehensive assessment of how environmental pressures evolve alongside improvements in energy efficiency and production structures.

The third axis addresses health vulnerability, operationalized through the mortality rate attributed to household and ambient air pollution for 2019. This indicator captures the ultimate social consequences of environmental exposure, linking pollution levels to human welfare outcomes. It should be noted that, for Austria, comparable mortality data were not



available in the dataset used. As a result, Austria is positioned primarily along the first two axes and serves as a benchmark case within the typology.

Taken together, these three axes provide a structured framework for interpreting cross-country differences, enabling the identification of distinct development–pollution–health pathways that extend beyond simple comparisons of individual indicators.

Table 5 synthesizes the multidimensional evidence into a structured and policy-relevant typology, allowing for a more integrated interpretation of the relationships between economic development, environmental performance and health outcomes. Three distinct clusters emerge from this framework, each reflecting a specific development–pollution–health trajectory.

Table 5: Conceptual clusters of development–pollution–health trajectories.

Country	Cluster membership	GDP per capita PPP (2015–2024 avg)	PM _{2.5} (2015–2019 avg µg/m ³)	PM _{2.5} % change (2000–2014 → 2015–2024)	Carbon intensity (2015–2024 avg)	Carbon intensity % change (2000–2014 → 2015–2024)	Mortality rate (2019, per 100 k)
Austria	Cluster 1	54,562	12.46	–33.65	0.172	–25.71	–
Italy	Cluster 1	42,012	16.13	–35.95	0.182	–26.19	15.0
Romania	Cluster 2	25,354	16.66	–20.11	0.413	–54.76	67.8
Bulgaria	Cluster 2	21,123	19.61	–22.48	0.885	–41.06	62.9
Poland	Cluster 3	30,749	21.42	–19.50	0.610	–42.07	40.9
Hungary	Cluster 3	30,546	16.68	–21.34	0.370	–39.36	42.3

The first cluster, comprising Austria and Italy, is characterized by high income levels, relatively low carbon intensity and substantial reductions in PM_{2.5} exposure. These countries also display comparatively low health burdens associated with air pollution, with Italy recording the lowest mortality rate in the sample (15 per 100,000 in 2019). Taken together, these features point to a high degree of structural alignment between economic development and environmental performance. This cluster can be interpreted as representing a mature sustainability pathway, where long-term policy consistency, technological advancement and institutional capacity support both decarbonization and sustained improvements in air quality. In this context, economic growth plays a secondary role, while governance quality and regulatory effectiveness become the key drivers of environmental and health outcomes.

The second cluster, including Romania and Bulgaria, reflects a markedly different trajectory. These countries have experienced rapid economic convergence, accompanied by substantial reductions in carbon intensity – particularly pronounced in the case of Romania. However, these improvements coexist with persistently high levels of health vulnerability, as reflected in mortality rates of 67.8 and 62.9 per 100,000 population, respectively. At the same time, reductions in PM_{2.5} exposure remain moderate, rather than transformative. This combination highlights a fundamental tension within the sustainable development process: macroeconomic modernization and improvements in aggregate efficiency do not automatically translate into proportional gains in public health. The observed pattern is consistent with the continued influence of sector-specific emission sources, including residential heating, urban transport and localized industrial activity, as well as the persistence of cumulative exposure effects.

The third cluster, represented by Poland and Hungary, occupies an intermediate position between these two trajectories. Both countries have achieved sustained economic growth and significant reductions in carbon intensity, yet they continue to exhibit relatively higher levels

of PM_{2.5} exposure compared to the first cluster. Health impacts are also elevated, although not to the extent observed in Romania and Bulgaria. This suggests that, despite progress in structural efficiency, particulate pollution remains a persistent constraint. The pattern can be interpreted as reflecting an incomplete sectoral transition, where changes in the energy mix, industrial structure and transport systems have not yet fully translated into consistent improvements in air quality.

Overall, Table 5 provides a compact synthesis of the empirical findings and establishes a clear analytical foundation for the subsequent discussion. By grouping countries according to shared structural characteristics rather than treating them in isolation, the cluster framework enables a more nuanced understanding of the interplay between development, pollution and health outcomes.

Building on this typology, the analysis proceeds with a structured SWOT assessment at the cluster level (Table 6). Organizing the discussion around development–pollution–health trajectories, rather than individual country cases, enhances conceptual coherence and allows for the formulation of differentiated policy insights aligned with underlying structural conditions.

The cluster-based SWOT framework outlined above offers a differentiated policy roadmap that is closely aligned with the empirical evidence presented in the analysis. By linking structural characteristics to specific policy challenges and opportunities, it allows for a more targeted and context-sensitive approach to air pollution management within the broader agenda of sustainable development.

In this sense, the framework reinforces the central argument of the study: sustainable development cannot be effectively pursued through isolated policy measures. Instead, it requires a coordinated approach that integrates economic modernization, environmental regulation and public health protection, while accounting for the structural conditions specific to each group of countries. Such an approach recognizes that similar policy instruments may generate different outcomes depending on institutional capacity, energy structures and socio-economic context, thereby underscoring the importance of differentiated strategies.

4 DISCUSSION AND CONCLUSIONS

The comparative and cluster-based analysis highlights that effective air pollution management, when framed within a sustainable development perspective, requires differentiated policy strategies that are closely aligned with underlying structural conditions. Rather than applying uniform solutions, policy design must reflect the specific economic, environmental and institutional configurations identified across the three conceptual clusters.

For the first cluster, encompassing Austria and Italy, the main policy challenge is not structural transformation but rather the consolidation and refinement of an already advanced sustainability trajectory. These countries exhibit a relatively strong alignment between economic development, carbon efficiency and air quality outcomes. In this context, policy priorities should focus on targeted interventions aimed at remaining sources of exposure, particularly in urban environments where pollution hotspots persist. Measures such as low-emission zones, congestion pricing and optimized urban mobility systems can generate incremental yet meaningful improvements. At the same time, the growing impact of climate-related phenomena – such as heatwaves, wildfire smoke and transboundary pollution – calls for a more integrated approach linking climate adaptation and air quality management. Preventing rebound effects associated with economic recovery and increased mobility is equally important, requiring sustained regulatory attention and continued technological



Table 6: Structured SWOT assessment Cluster 1, Cluster 2 and Cluster 3.

Cluster 1: Mature low-pressure pathway (Austria, Italy)	
Strengths	Weaknesses
High income levels and advanced institutional capacity. Structurally low carbon intensity and sustained decarbonization trajectories. Significant long-term reductions in PM _{2.5} exposure (approximately –34% to –36%). Low mortality burden attributable to air pollution (Italy) and likely similar structural resilience for Austria. Stable regulatory frameworks and strong environmental governance.	Limited macroeconomic growth momentum (particularly Italy), potentially constraining fiscal flexibility. Exposure remains non-negligible in dense urban areas, indicating diminishing marginal returns from general policy measures. Ageing populations may increase health vulnerability even at lower pollution levels.
Opportunities	Threats
Technological leadership in green innovation and advanced urban mobility systems. Further integration of climate neutrality and air quality strategies. Export of environmental governance models and best practices. Deployment of precision-based air quality management in metropolitan regions.	Rebound effects linked to economic recovery and mobility growth. Increasing climate-related shocks (heatwaves, wildfire smoke) affecting air quality. Political fatigue regarding environmental regulation in low-pressure contexts.
Cluster 2: Converging high-vulnerability pathway (Romania, Bulgaria)	
Strengths	Weaknesses
Rapid economic convergence and significant improvements in carbon intensity (Romania strongest reduction in sample). Structural modernization underway, including energy sector adjustments. Access to EU structural and recovery funds supporting green transition.	Persistently high mortality burden attributable to air pollution. Moderate reductions in PM _{2.5} exposure relative to economic and carbon-efficiency gains. Structural dependence on residential solid fuel use and localized pollution sources. Institutional capacity gaps in enforcement and urban planning.
Opportunities	Threats
Targeted investment in residential heating modernization. Urban transport electrification and smart mobility infrastructure. Strengthening environmental health integration in public policy. Leveraging EU funding for structural energy transition and local air quality monitoring systems.	Risk of ‘growth-first’ development strategies sidelining health considerations. Regional disparities in infrastructure and administrative capacity. Vulnerability to energy price shocks affecting low-income households’ heating choices.



Table 6: Continued.

Cluster 3: Intermediate transition pathway (Poland, Hungary)	
Strengths	Weaknesses
Sustained economic growth and structural modernization. Substantial reductions in carbon intensity (~ -39% to -42%). Moderate mortality burden compared to Cluster 2. Industrial and technological integration within EU markets.	Structurally higher PM _{2.5} exposure levels (especially Poland). Continued reliance on fossil fuels and legacy industrial regions. Urban pollution concentration in metropolitan and industrial corridors.
Opportunities	Threats
Accelerated coal phase-out and diversification of energy mix. Strengthening local air quality governance and emission standards. Investment in public transport and urban infrastructure modernization. Regional reindustrialization aligned with clean technology sectors.	Political and social resistance to rapid energy transition. Economic dependence on carbon-intensive sectors. Risk of partial decarbonization without proportional particulate reduction.

innovation. More broadly, these countries are well positioned to act as drivers of innovation, promoting advanced environmental technologies and governance models at the European level. Overall, the strategic orientation for this cluster centres on optimization, resilience and leadership within a mature sustainability framework.

In contrast, the second cluster, represented by Romania and Bulgaria, faces a more fundamental challenge, defined by the disconnect between rapid economic convergence and persistently high health vulnerability. In this case, policy efforts must move beyond aggregate efficiency improvements and focus directly on the main sources of particulate exposure. A priority area is the modernization of residential heating systems, where the continued reliance on solid fuels remains a major contributor to air pollution. This should be supported through targeted subsidies, building retrofitting programs and the expansion of cleaner heating alternatives. At the same time, accelerating the transformation of urban transport systems is essential, particularly in the context of increasing car ownership and urbanization pressures. Strengthening the integration between environmental and public health policies is also critical, including the use of vulnerability mapping and targeted interventions for at-risk populations. These efforts must be underpinned by improvements in institutional capacity, ensuring effective monitoring, enforcement and local governance. In addition, the strategic use of EU recovery and cohesion funds represents a key opportunity to support structural investments in cleaner infrastructure. Taken together, the policy orientation for this cluster should emphasize health-centred interventions aimed at directly reducing particulate exposure and its associated social costs.

The third cluster, including Poland and Hungary, occupies an intermediate position, where significant progress in carbon intensity reduction coexists with persistently higher levels of particulate pollution. In this context, policy priorities should focus on completing the ongoing sectoral transition processes. A central element is the diversification of the energy mix, particularly through the accelerated phase-out of coal and the expansion of renewable energy sources. At the same time, targeted support for industrial modernization is required to address pollution hotspots in traditionally carbon-intensive regions. Strengthening urban air quality



governance, including stricter emission standards and improved spatial planning, is also necessary to reduce the structural persistence of PM_{2.5} exposure. Finally, regional transition strategies must take into account the socio-economic implications of structural change, with just transition mechanisms playing a crucial role in mitigating resistance and ensuring social acceptance. From a strategic perspective, this cluster must avoid stagnation by deepening structural transformation and ensuring that gains in energy efficiency are matched by tangible improvements in air quality.

Taken together, these differentiated policy pathways underline the importance of aligning economic, environmental and health objectives within a coherent and context-sensitive framework. The evidence suggests that sustainable air pollution management cannot rely solely on broad efficiency gains or general policy instruments but must instead address the specific structural drivers of pollution within each development context.

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