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Winds of change: tracking air quality patterns across Romania's urban and metropolitan areas

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Abstract: Urban air quality has undergone significant change over the past two decades in Romania, yet the spatial dynamics of this transformation remain poorly understood at the national scale, particularly across the urban core-to-peri-urban gradient. This study tracks the space-time evolution of $PM_{2.5}$ and NO_2, as retrieved from the European Environmental Agency, across the 319 cities in Romania. A multi-step methodology is used, comprising a population-weighted air quality index anchored to residential population and built-up surface density, agglomerative hierarchical clustering, and an interaction regression model. The results document a general decline in both pollutants while revealing fundamentally different spatial regimes. NO_2 concentrations are driven by population density in metropolitan centres, and by built-up surface density and commuting pressure in peri-urban environments, whereas $PM_{2.5}$ follows built-up surface patterns only at the peri-urban scale. The core-periphery predictors point to the need for differentiated, metropolitan-scale governance in air quality planning. Policy recommendations comprise low-emission zones, public transport modernisation, fiscal instruments targeting traffic, and regional air quality planning frameworks where pollution exposure extends well beyond municipal boundaries.

Keywords: air pollution policies, cities, metropolitan areas, spatio-temporal analysis, Romania

Introduction

Air quality is a growing concern in cities worldwide, though recent years have shown localised encouraging improvements. Air pollution surpassed other chronic illness risk factors, such as obesity, high cholesterol, and malnutrition, to become the fourth most important worldwide risk factor for death in 2019 (Health Effects Institute, 2020). At the first World Health Organisation (WHO) global conference on air pollution and health in 2018, air pollution was described as a "silent public health emergency". The quality of human life on Earth is strongly correlated with and influenced by air quality (Năstase et al., 2018). Air pollution is a problem,

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particularly in urban areas, where pollutant concentrations are high (Kravchuk et al., 2019; Mavroidis & Ilia, 2012). Particulate matter less than 2.5 microns ($PM_{2.5}$) and NO_2 are two of the main pollutants responsible for deaths in cities and metropolitan areas (Alikhani Faradonbeh et al., 2021; Khomenko et al., 2021).

Cities document air quality improvements worldwide (Shi & Brasseur, 2020), including multiple examples in Europe (Maranzano, 2022) and Romania (Chiritescu et al., 2024). Iorga (2016) documents a general declining trend in gaseous emissions across major Romanian cities, with a focus on Bucharest. The capital city reduced its particulate emissions by nearly half between 2000 and 2013, consistent with reductions in SO2 and NOx across the EU. The role of traffic as a primary driver is underscored by Burghelea et al. (2024), who recorded significant PM10 decreases in Bucharest, Brașov, and Iași during the COVID-19 lockdown, when workplace mobility dropped by up to 60%. Local conditions can, however, override broader trends. Bodor et al. (2023) found that the enclosed topography of the Ciuc basin produces winter particulate concentrations several orders of magnitude above summer levels, while Nica & Manoiu (2024) identify port activity and seasonal tourism as drivers of localised NO2 and particulate matter spikes in Constanța. Drăgoi et al. (2025) identify distinct trends, warning that Iași and Suceava risk exceeding 2030 EU limit values for PM10 and PM22.5 unless additional measures are taken. The authors propose composite indicators that capture exceedance magnitude and toxicological load beyond what standard annual averages reveal.

The European Green Deal, adopted in December 2019, aims to reduce health issues and premature deaths from $PM_{2.5}$ by at least 55% by 2030 (compared to 2005 levels) and to bring air pollution below WHO guideline levels, as part of its Zero Pollution Action Plan. It revised the 2013 Clean Air Policy Package, making it more comprehensive. The Green Deal's integrated approach links air quality improvements with climate action, sustainable mobility, and energy transition. Romania's actions involve expanding low-emission zones, modernising public transport fleets, and integrating air quality considerations into urban planning. This commitment translates into stricter legally binding limits: the revised Ambient Air Quality Directive (2024) lowers the annual $PM_{2.5}$ limit from 25 µg/m³ to 10 µg/m³ and the NO_2 limit from 40 µg/m³ to 20 µg/m³, both to be achieved by 2030. Romania's trajectory aligns with broader European patterns where deindustrialisation, EU regulatory frameworks, and technological transitions have counterbalanced urbanisation pressures.

This study aims to identify characteristics of the space-time evolution of air pollution across Romanian cities and their peri-urban areas, focusing on PM2.5 (2007-2024) and NO2 (2014-2024), in relation to the population's exposure to these pollutants. Research consistently documents declining pollutant concentrations within cities, which, given concurrent urban growth, may be counterintuitive. We seek to determine whether these patterns hold across Romania's 319 cities, where urban development has been shaped by post-socialist transition policies, delayed implementation of environmental regulations, and persistent automobile dependence. We examine this question within the context of accelerated urban expansion and the need to understand its environmental consequences. For this purpose, we calculate pollution exposure by weighting annual mean values of PM2.5 and NO2 with the Global Human Settlement Layer's residential population and built-up surfaces, acknowledging the dynamics within the above-mentioned time frames. By including all municipalities with city status, we analyse a complete sample that reveals both similarities and differences among cities of varying sizes, topographies, and areas of influence. This analysis is complemented by a comparison between urban cores and adjacent peri-urban communes, particularly for larger cities experiencing intense peri-urbanisation and urban sprawl.

Despite growing interest in urban air quality across Europe, national-scale analyses that simultaneously address urban cores and their peri-urban surroundings remain scarce for post-socialist contexts, and, to our knowledge, Romania has received particularly limited attention. Most existing studies focus on individual cities or rely on administrative aggregations that may fail to depict metropolitan-scale dynamics. The present core-periphery distinction is not merely methodological. After 1989, Romanian cities experienced rapid and largely unplanned peri-urbanisation alongside the deindustrialisation of urban cores, leading to spatial patterns of pollution that diverge between the two zones and follow different trajectories. Capturing this divergence requires a sufficiently long period and an exposure metric anchored to the residential population distribution. The present study addresses this gap through a population-weighted air quality index for PM2.5 and NO2 across Romania's metropolitan areas. Agglomerative hierarchical clustering and OLS regression are applied at multiple spatial scales, with the analytical contribution lying in their combination. Despite nationally consistent evolution patterns, pollutant levels may be explained differently in urban cores and peri-urban communes.

1. Literature review

$PM_{2.}5$ is a key indicator of air quality (Velea et al., 2023), referring to suspended fine particulate matter with diameters less than 2.5 μm, small enough to penetrate deep into the lungs and enter the bloodstream. Therefore, it causes major health problems, such as cancer, cardiovascular or neurodegenerative diseases, as well as playing a role in viral infections (Tanasa et al., 2023; Thangavel et al., 2022). This particulate matter primarily originates in vehicle exhaust, residential heating (especially wood and coal), industrial emissions, and agricultural activities. NO_2 is mainly produced by combustion processes in heating systems, motor vehicle traffic, power plants, and industrial activities (Maranzano, 2022). Nitrogen oxides (NO_x) are directly associated with impacting the respiratory system (Dix et al., 2019). In this category, NO_2 is primarily a traffic-related pollutant, generated by combustion processes in vehicle engines (Höhne et al., 2023) while industrial facilities and power generation also contribute significantly (Dix et al., 2019). Moreover, NO_2 drives photochemical smog formation by absorbing sunlight, providing the energy for smog reactions. NO_2 forms ozone through specific chemical reactions and absorbs infrared radiation, creating a feedback loop that further enhances the greenhouse effect and global warming (Moomaw, 2002). Through mandated emission controls, heating, and vehicle fleet modernisation, and reduced heavy industrial activity, improvements can be clearly observed.

However, challenges still persist. Most Eastern European countries experience more harmful health effects from air pollution than other Central or Western European countries do (Gu et al., 2023). While Romania has made progress in addressing environmental issues, there is still work to be done to ensure that the country fully complies with the EU's environmental regulations and protects its natural resources and public health (Velea et al., 2023). The study of Tanasa et al. (2023) shows that, among the large cities in Romania, Iași is the most polluted with fine particulate matter, while Mihalache et al. (2023) found a great accumulation of PM10 in times of intense anthropogenic activity, atmospheric stability, and episodes of long-range transport of fine particulate matter coming from desert dust for the case of Ploiești. Although general downward trends were observed in most cases (Velea et al., 2023), the values remain above the international thresholds. Chiritescu et al. (2024) observed a significant decrease in pollution, particularly during the pandemic period, beginning with the 2020 lockdown. Năstase et al. (2018) show that nitrogen oxide emissions decreased by 87% over the last 35 years, and CO_2 emissions by 41% over the last 20 years. Iorga (2016) highlights a period of undetermined trends between 2000 and 2012 for $PM_{2.5}$ and NO_2, with a close look at the meteorological context and influence. The broader Eastern European context helps explain the scale of these reductions. Environmental protection received little institutional attention during the communist period, and the post-1989 decline in heavy industry effectively produced an involuntary improvement in air quality before legislative frameworks were adopted. The health implications of the preceding decades of exposure, however, affect the population over much longer timescales.

The main air quality measurement sources in Romania are the National Air Quality Monitoring Network (RNMCA), the independent uRADMonitor® network that consists of 630 sensors measuring PM_{10} and $PM_{2.5}$ concentration levels and complements the national air quality network with sensors in residential areas, intense traffic zones, and industrial areas (Velea et al., 2023), citizen science initiatives and low-cost sensor networks deployed by municipalities, research institutions conducting air quality campaigns with mobile monitoring units (Popescu et al., 2024), and industrial facilities required to monitor emissions under the EU Industrial Emissions Directive.

The guidelines that have to be followed in the Romanian context are comprised by the Law 104/2011 (Romanian Parliament, 2011) and subsequent amendments of the Romanian air quality standards, the Directive 2024/2881 of the European Union, which sets legally binding limits for all member states and has slightly stricter thresholds than the Romanian standards, and WHO air quality guidelines (2021). The values in Table 1 illustrate a progressive tightening of air quality standards over time, as both the WHO and the European Union have decreased their thresholds. Each institution distinguishes among several types of limits: annual mean values, which capture exposure over a full year; 24-hour averages, which flag short-term concentration peaks; 1-hour values, which identify acute episodes; and alert thresholds, which trigger immediate intervention measures when exceeded.

Table 1. Guidelines directives for $PM_{2.5}$ and NO_2

Institution / directive	$PM_{2.5}$	NO_2
Law 104/2011 (Romanian air quality standards)	20 µg/m³ (annual)	200 µg/m³ (1-hour), 40 µg/m³ (annual)
Directive 2024/2881 (EU)	10 µg/m³ (annual) by 2030	20 µg/m³ (annual) by 2030
Previous Directive 2008/50/EC (EU)	25 µg/m³ (annual limit value)	200 µg/m³ (1-hour, not to exceed >18 times/year), 40 µg/m³ (annual), 400 µg/m³ (alert threshold)
WHO Air Quality Guidelines (2021)	5 µg/m³ (annual), 15 µg/m³ (24-hour)	10 µg/m³ (annual), 25 µg/m³ (24-hour)
Previous WHO Air Quality Guidelines (2005)	10 µg/m³ (annual), 25 µg/m³ (24-hour)	40 µg/m³ (annual), 200 µg/m³ (1-hour)

Source: authors' representation

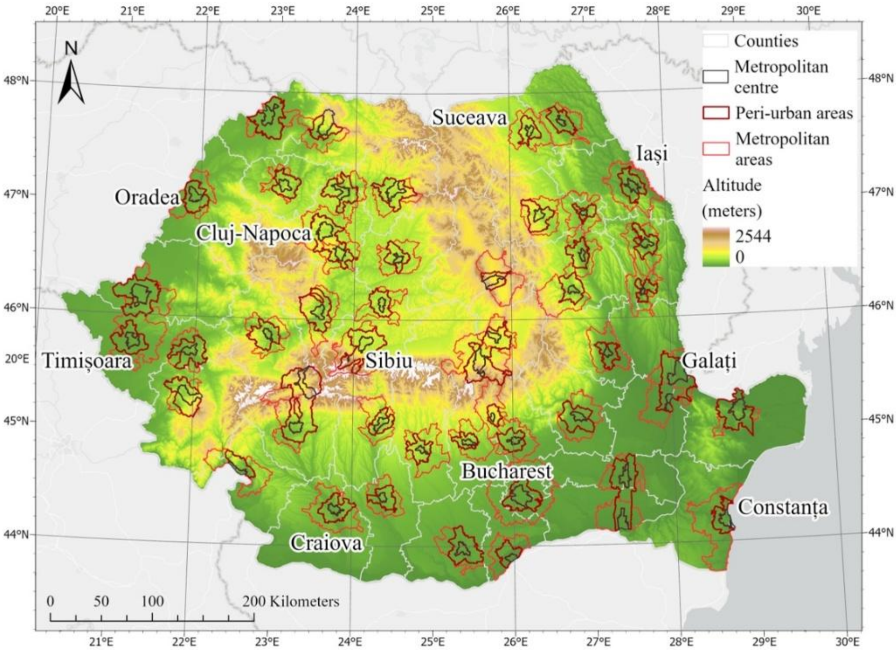
2. Methodology

To achieve the purpose of this research, we employed a multi-step methodology comprising data processing and aggregation, computation of a population-weighted air quality index, statistical regressions and AHC clustering. Firstly, raw air quality data for $PM_{2.5}$ and NO_2 indicators were obtained from the European Environment Agency's gridded concentration estimates at 1 km spatial resolution (European Environmental Agency, 2025). The datasets integrate satellite observations, ground monitoring stations, and atmospheric modelling to provide continuous spatial coverage across Europe. EEA employs a combined methodology of regression and interpolation mapping to generate continuous gridded air quality estimates across Europe. This approach integrates ground-based monitoring station observations, chemical transport model outputs, satellite-derived measurements, meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF), and topographic variables. Regression, interpolation and merging are used to calculate estimates with modelled concentration fields to produce a comprehensive spatial coverage. The methodology used by EEA remains consistent throughout the entire time span, ensuring temporal comparability, though recent datasets increasingly incorporate real-time data streams and refined modelling approaches. While these two pollutants do not cover the whole spectrum of air quality, they are the most consistently monitored and policy-relevant parameters (Evangelopoulos et al., 2020).

PM2.5 covered annual mean concentrations from 2007 to 2024, while NO_2 data covered the period of 2014 to 2024. Spatial aggregation was performed in a GIS environment using ArcGIS Pro 3.4.0. This polygon-based averaging approach accounts for variations in city size and provides representative values for the residential and activity areas within each urban boundary, rather than relying on single-point measurements that may not capture intracity variability. We acknowledge that contemporary urban areas exhibit gradual transitions rather than abrupt boundaries; as a consequence, residential sprawl, peri-urban development, and commuter zones extend beyond administrative limits. While polygons provide standardised units for comparative analysis, they represent administrative rather than functional boundaries (Bănică & Muntele, 2013).

Hence, we took into consideration three different spatial scales: urban cores, first ring of communes as a proxy for peri-urban areas, and entire metropolitan areas (Figure 1). The urban cores form a total of 319 cities in Romania (including towns, municipalities, county seat municipalities, and the capital Bucharest). The metropolitan areas employed in this study follow the delineation proposed by Bănică & Muntele (2013), which draws on a multi-criteria framework encompassing accessibility, economic relationships, estimated flows, and spatial morphology. This approach differs from the legal definition introduced by Law No. 246/2022 (Romanian Parliament, 2022), which limits metropolitan boundaries to the first and second rings of communes adjacent to a city. This delineation is theoretical and does not account for road accessibility or the broader patterns of urban influence and territorial polarisation. Although not all these metropolitan areas exist as legal entities in practice as of 2026, the law provides a starting point that could foster metropolitan collaboration and development. We consider the present analysis at both the urban (i.e., local) and metropolitan scales valuable for capturing pollution variations among Romanian cities and between these urban centres and their peri-urban zones. The study is particularly relevant given that peri-urban environments are increasingly exposed to pollution spillovers from urban cores, yet remain underrepresented in national-scale air quality analyses and largely excluded from existing policy frameworks targeting urban areas.

Figure 1. Study area



Source: authors' representation

We considered that the assessment of pollution exposure was a more relevant indicator oriented towards possible further policies than simple pollution average values. Therefore, population-weighted pollution concentrations were calculated for each administrative unit using gridded demographic and built environment data, retrieved from the Global Human Settlement Layer (GHSL) 2025 dataset at 100-meter resolution (Pesaresi et al., 2024). The GHSL products integrate multiple Earth observation sources, census data, and volunteered geographic information to map human presence at high spatial resolution at the global level. For the weighting variable, the raster was reprojected and resampled to match the pollution rasters coordinate system and 1 km resolution for the year 2024. Population-weighted concentration for each administrative unit was calculated following the formula:

$$C_{pw} = \frac{\sum_{i=1}^{N}(C_i * P_i)}{\sum_{i=1}^{N} P_i}$$

where:
C_i = pollutant concentration in area i (µg/m³)
P_i = the population of area i
N = the number of areas (grid cells).

The Cpw (population exposure) result is the average level of exposure to the pollutant for the entire population analysed, not for a specific place, but for people. This approach accounts for the spatial distribution of human exposure within each administrative unit, since we cannot assume uniform pollution distribution across the territory of a municipality. Therefore, the weighted values provide more relevant estimates for health impact assessments and prioritisation of policy intervention areas, particularly in larger cities where population density varies substantially across neighbourhoods.

In order to best reflect the systematic differences in how urban form relates to pollutant concentrations, we estimate OLS regressions on the pooled sample of 410 observations (50 urban cores and 360 peri-urban communes from the first ring of metropolitan areas). The dummy variable (1 for peri-urban communes, 0 for urban cores) interacts with each density predictor, allowing slopes to differ between the two zones, while the interaction coefficients formally test whether these differences are statistically significant. For each pollutant, we estimate a model without interactions and a model with interaction terms, the latter being the focus of the analysis. Standard errors are clustered at the metropolitan area level to account for spatial dependence between communes within the same metropolitan area, which share common topographic, climatic, and economic features. The dependent variables are the spatial mean concentrations of $PM_{2.5}$ and NO_2 for the year 2024.

$$Y_i = \beta_0 + \beta_1 DensPop_i + \beta_2 DensBuilt_i + \beta_3 Periurban_i + \beta_4 (Periurban_i x DensPop_i) + \beta_4 (Periurban_i x DensBuilt_i) + \varepsilon_i$$

Where:

Y_i = pollutant concentration in unit i

Periurban$_i$ = 1 if unit i is a peri-urban commune, 0 if metropolitan core (dummy variable)

ε_i = error term, with standard errors clustered at the metropolitan area level

Built-up volume was initially considered alongside population density and built-up surface density, but was excluded due to multicollinearity with population density. Furthermore, the relationships between air pollutant concentrations and the selected urban indicators are more complex than a linear framework can fully capture. Indeed, spatial autocorrelation between neighbouring units, potential nonlinearities, and unobserved contextual factors, such as wind patterns, heating fuel mix, or traffic infrastructure, are inherent to the urban- pollution system and underline why our analysis identifies conditional associations rather than causal effects.

Finally, spatial clustering was performed using agglomerative hierarchical clustering (AHC) with Ward’s linkage criterion and Euclidean distance as the dissimilarity measure (Ward, 1963). This multivariate approach treats each urban characteristic (population density, built surface density, $PM_{2.5}$ concentration, and NO_2 concentration) as independent dimensions in a feature space, grouping cities that exhibit similar profiles across these variables simultaneously. Prior to clustering, all variables were standardised using z-score normalisation to eliminate scale effects and ensure that clustering patterns emerged from relative similarities. A four-cluster solution was selected based on the favourable silhouette score and interpretability, ensuring that the resulting groups show meaningful patterns in the urban pollution-density relationship across Romania's settlement system.

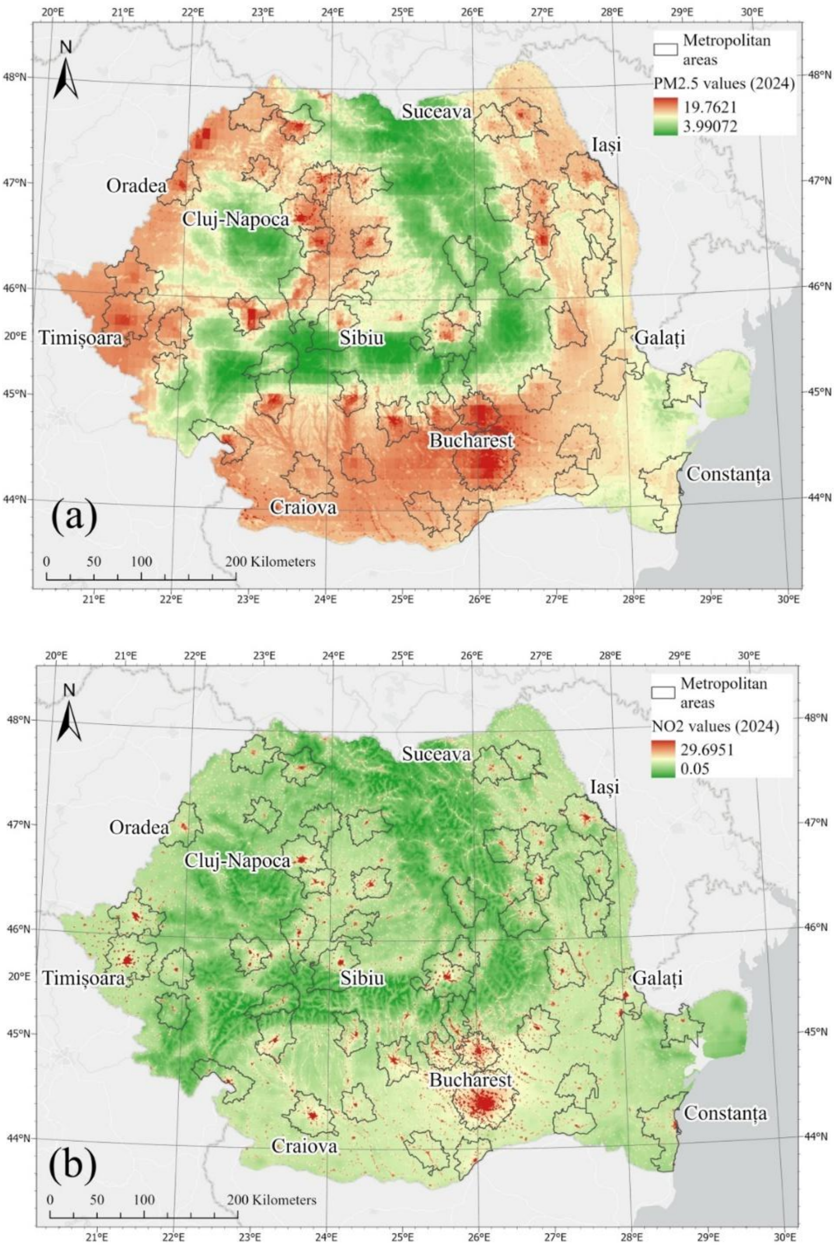
3. Results

3.1. Spatial and temporal evolution of pollution levels

Spatial and temporal variability of urban air pollution reveals both accomplishments and remaining challenges. Air quality measurements are essential for urban planning initiatives, from identifying which areas to prioritise to monitoring the implemented strategies, including those that promote walkability and reduce car dependence. This progress observed across Romania's cities aligns with the country's EU membership since 2007 and the subsequent implementation of air quality directives. While 27.18% of Romanian cities met the WHO Interim Target 4 for $PM_{2.5}$ (10 µg/m^3), according to the 2024 EEA data, the remaining still exceed health-based thresholds. The spatial distribution in Figure 2a and b reveals stark contrasts between mountain-area cities that benefit from natural filtration and ventilation and reduced industrial activity, and Bucharest and other large metropolitan areas that face persistent pollution from traffic and heating emissions. For the NO_2 indicator, the contrast between urban and rural areas is even stronger.

The spatial distribution shows a pronounced urban-rural divide for NO_2, with major metropolitan centres standing out sharply against lower-pollution surroundings. Unlike particulate matter, NO_2 serves as a direct indicator of traffic intensity and combustion efficiency, making it particularly valuable for assessing urban mobility patterns and the effectiveness of transportation policies (Basarić et al., 2014). While stationary NO_x emissions from large combustion plants have decreased, mobile emissions from automobile combustion engines have increased as the number of vehicles grows year by year, both in Romania and in the EU (Năstase et al., 2018). Moreover, large cities exhibit much higher NO_2 levels compared to their medium and small counterparts. This hierarchical gap proves more pronounced for NO_2 than for $PM_{2.5}$, where size-based differences remain relatively modest. During the 2014-2024 decade, $PM_{2.5}$ concentrations across Romanian cities declined by 25%, while NO_2 concentrations decreased by more than 20%.

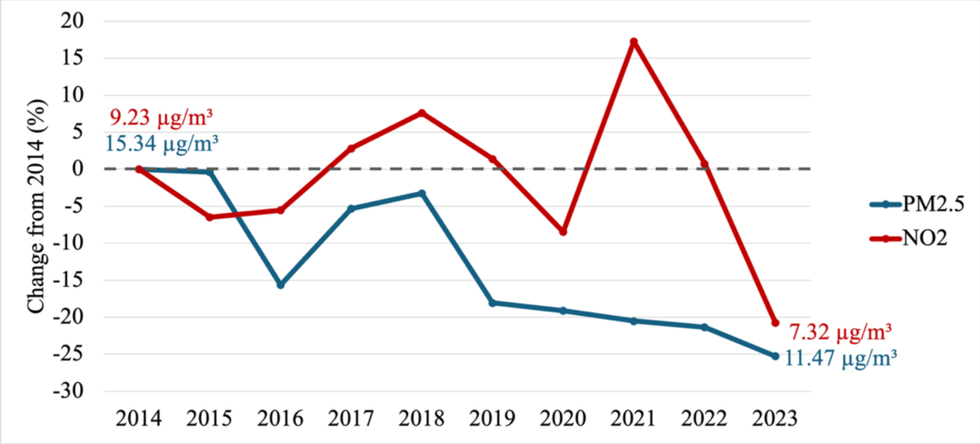
Figure 2. Air quality values for (a) $PM_{2.5}$ and (b) NO_2 across Romania in 2024



Source: authors' representation

The NO_2 series shows the expected pandemic-related drop in 2020, followed by a pronounced rebound in 2021, as economic activity and traffic resumed, before declining sharply over 2022-2023 (Figure 3). This pattern is consistent with the context of continuously growing vehicle numbers, in which even a partial return to pre-pandemic mobility levels generates disproportionate emissions. In 2024, most Romanian cities met the current WHO NO2 guideline (10 µg/m³ annual mean). However, the 13.12% of the cities that still exceeded this threshold account for roughly 46% of the urban population, a disproportion that motivates the population-weighted analysis presented below.

Figure 3. $PM_{2.5}$ and NO_2 temporal evolution in the Romanian urban environment



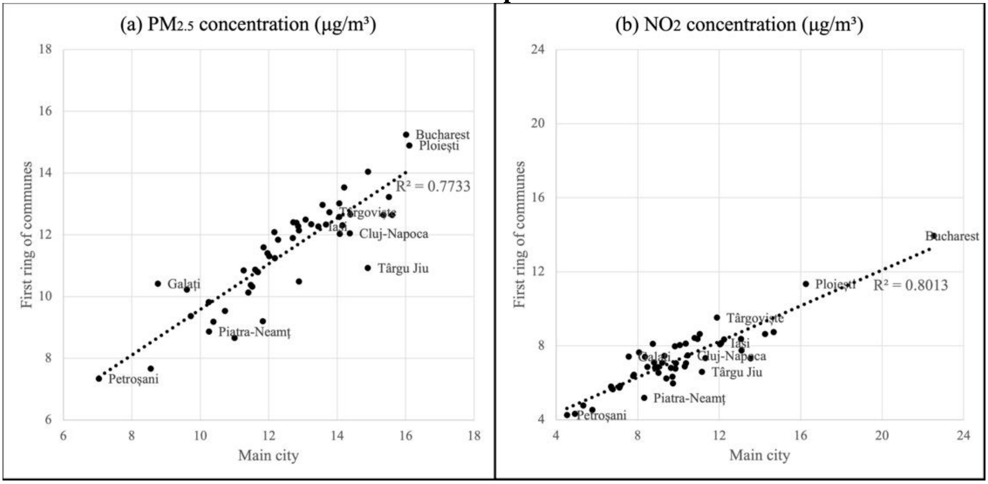
Source: authors' representation

Recent urban mobility initiatives and fleet modernisation have gained traction, with notable examples in Suceava, Constanța, Cluj-Napoca, and cities enrolled in the M100 European project for climate neutrality (M100, 2026). City Index has developed a metric for traffic assessment in Romania's most important cities (Institutul pentru Orașe Vizionare IOV, 2025), confirming that the largest urban agglomerations are the cities where traffic is heaviest and time-consuming (Iași, Cluj-Napoca, Timișoara), with Bucharest standing out.

3.2. Urban and peri-urban contrasts

Because NO_2 is more directly linked to urban activities such as traffic and heating systems, the contrast between main urban agglomerations and their outskirts is much sharper than for $PM_{2.5}$. Figure 4 shows the relationship for the year 2024, with the administrative territories of the cities (urban cores) on the X-axis, and the first ring of communes, which represents the space where peri-urban development occurs, on the Y-axis. Urban centres from 50 metropolitan areas are represented on both charts, as they have the strongest influence on their surroundings through urban sprawl, commuting, economic activities, metropolitan cooperation, and joint development projects.

Figure 4. $PM_{2.5}$ (a) and NO_2 (b) concentration in 2024 in urban cores and peri-urban areas for cities that have a theoretical metropolitan area



Source: authors' representation

The results highlight the cities with the highest and most persistent pollution levels. The Bucharest-Ploiești axis experiences heavy traffic and industry (petrochemicals, thermal combustion), being part of the extended influence area of Romania's capital city, alongside the use of solid fuels for residential heating. Topographic factors amplify these conditions by frequently trapping pollutants in the Romanian and Western Plains, while Bacău and Iași experience similar stagnation in the Siret and Bahlui valleys, respectively. Timișoara also struggles with high vehicle ownership and cross-border transit traffic. These cities also serve as regional employment centres, generating commuter traffic from surrounding communes, which concentrates pollution during peak hours.

The functional and economic influence of Bucharest extends across a particularly large area, where differences in pollution values between the city itself and its outskirts are not substantial. The satellite cities in Ilfov function as bedroom communities with their own heating emissions and traffic, creating a regional pollution dome rather than a concentrated urban peak. A similar pattern emerges in Constanța, strongly influenced by its coastal location and its harbour activities that distribute pollution across both urban and peri-urban zones, with sea breezes mixing air masses homogeneously rather than creating sharp gradients. Solid fuel use remains prevalent within the peri-urban communes regardless of settlement size, and occasional agricultural burning in surrounding areas, combined with diffuse residential development, blurs the traditional urban-rural pollution divide in these cities, creating more homogeneous regional pollution patterns.

Unlike $PM_{2.5}$, all cities show a marked shift toward higher urban NO_2 concentrations in the city core compared to peri-urban levels. This is a direct consequence of NO_2 being produced primarily by vehicular traffic and concentrated combustion processes. Bucharest and Ploiești remain the most polluted overall, but cities like Bacău, Brăila, Sibiu, and Piatra Neamț exhibit the sharpest urban - peri-urban gradients. These cities function as centralised employment and administrative hubs within their counties, attracting daily commuter flows that converge on compact historic cores with limited road capacity, generating traffic bottlenecks and elevated NO_2 hotspots. Their surrounding areas remain predominantly agricultural or mountainous, with minimal traffic. Conversely, Vaslui and Baia Mare show nearly equivalent urban and peri-urban NO_2 levels, suggesting more dispersed activity patterns.

3.3. Regression analysis: pollution and urban form

The OLS analysis examining the relationship between pollution concentrations and urban form indicators reveals distinct dynamics between urban cores and peri-urban rings (Table 2). For each pollutant, we report a model without interactions and a model with interaction terms that allow slopes to differ between zones, with the analysis focusing on the latter. The models without interactions assume a uniform relationship across the full sample, a specification that fails to accommodate the structural differences between dense urban cores and predominantly low-density peri-urban communes, as evidenced in our previous analysis. The interaction models relax this restriction by allowing zone-specific slopes, with the interaction coefficients providing a formal test of whether these slopes differ significantly.

For $PM_{2.5}$, the interaction model explains 26.8% of the variance. Within urban cores, neither population density nor built-up surface density significantly predicts $PM_{2.5}$ concentrations, suggesting that intra-urban variation is dominated by factors beyond urban form, such as regional pollution background, topography, and heating systems. Built-up surface density shows a significantly stronger association with $PM_{2.5}$ in peri-urban communes than in urban cores (interaction $\beta = 3.45\times10^{-5}$, $p < 0.05$).

For NO_2, the interaction model explains 72.4% of the variance. In urban cores, NO_2 concentrations rise with population density ($\beta = 1.29\times10^{-3}$, $p < 0.01$), reflecting the role of human concentration in generating traffic and combustion activities, while the interaction with the peri-urban indicator is not significant. In contrast, built-up surface density becomes the dominant predictor of NO_2 in peri-urban areas, with a significantly stronger association than in cores (interaction $\beta = 4.5\times10^{-5}$, $p < 0.01$), where it remains non-significant.

Table 2. Interaction regression model results

Variables	(1) $PM_{2.5}$ (baseline)	(2) $PM_{2.5}$ (interactions)	(3) NO_2 (baseline)	(4) NO_2 (interactions)
Population density	-0.000694** (0.000319)	0.000200 (0.000388)	-0.000407 (0.000348)	0.001294*** (0.000417)
Built-up surface density	0.000040*** (0.000007)	0.000014 (0.000013)	0.000070*** (0.000005)	0.000019 (0.000012)
Peri-urban (vs. urban cores)	0.909701*** (0.272382)	0.028093 (0.581453)	1.627285*** (0.498128)	-0.259008 (0.429867)
Peri-urban × Population density		-0.001941 (0.001595)		0.000498 (0.001118)
Peri-urban × Built-up surface density		0.000034** (0.000016)		0.000045*** (0.000013)
Constant	10.205555*** (0.386004)	11.022564*** (0.643492)	4.666497*** (0.492041)	6.436543*** (0.476190)
Observations	410	410	410	410
R-squared	0.257173	0.267765	0.695950	0.723574
Cluster	Metropolitan area	Metropolitan area	Metropolitan area	Metropolitan area

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Source: authors' representation

3.4. Cluster analysis: typology of local contexts

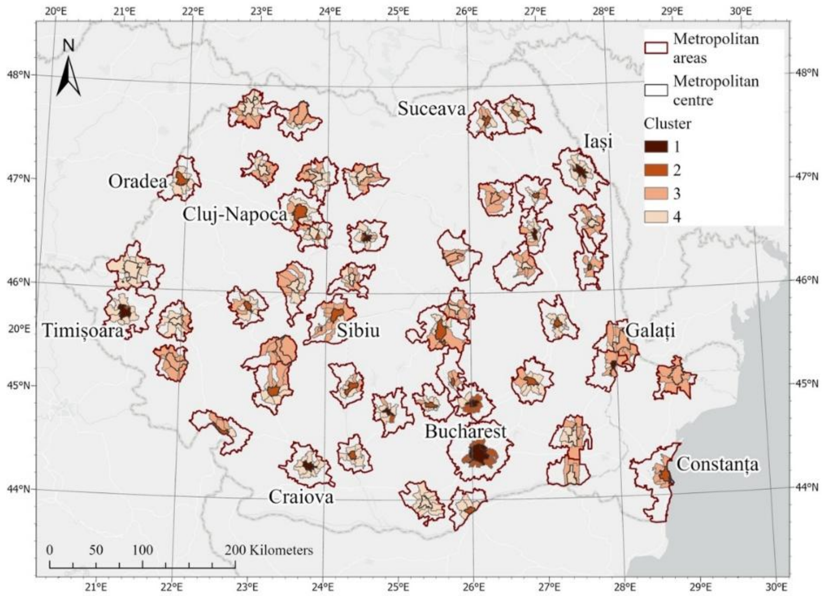
The cluster analysis yielded four groups, whose spatial patterns are shown in Figure 5. Inter-cluster differences and intra-cluster similarities are presented in Table 3 and Figure 6 a-b. The analysis encompasses all Romanian cities along with the first ring of communes surrounding the 50 cities designated as metropolitan areas under Law No. 246/2022.

Cluster 1 exhibits the highest standardised values across all four variables: population density, built surface density, NO_2 concentration, and $PM_{2.5}$ concentration. This cluster comprises Bucharest and many of its satellites, primarily marking the capital's territorial expansion beyond administrative boundaries, sustained by the transformation of neighbouring localities over time. Major cities such as Iași, Timișoara, and Craiova, are also included, alongside medium-sized centres like Brăila, Bacău, and Ploiești.

Cluster 2 also contains Bucharest satellites alongside major cities with lower pollution levels and superior maintenance (Cluj-Napoca, Brașov, Constanța) and several medium-sized centres. This cluster's defining characteristic is built-up surface density exceeding population density, indicating zones with predominantly individual housing or low-rise apartment buildings.

Clusters 3 and 4 occur predominantly in areas where natural environments remain largely preserved, with comparable population and built-up surface densities at low values, yet pollution concentrations differ. Cluster 3 records significantly lower pollution, typically located further from cities in areas with better atmospheric circulation, mountain regions or the Danube Delta. Cluster 4 is distinctive, showing lower NO_2 than $PM_{2.5}$ values, contrary to other clusters.

Figure 5. Cluster analysis based on population density, built-up surface density, NO_2 and $PM_{2.5}$ values



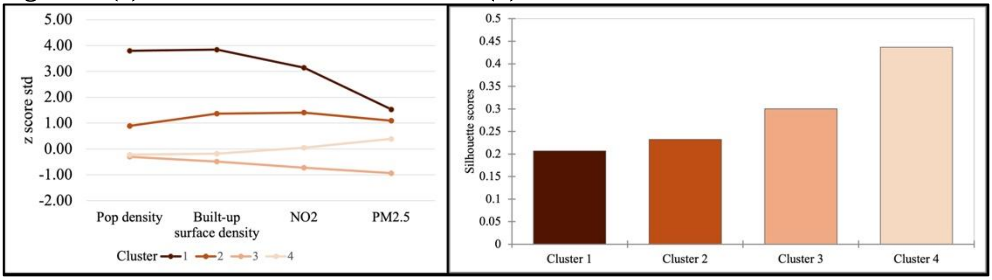
Source: authors' representation

Table 3. Results by cluster

Cluster	1	2	3	4
No. of objects	14	42	155	199
Within-cluster variance	10.295	2.841	0.896	0.555
Min. dist. to centroid	1.211	0.672	0.103	0.087
Avg. dist. to centroid	2.569	1.539	0.822	0.676
Max. dist. to centroid	8.247	3.831	2.725	1.816

Source: authors' representation

Figure 6. (a) - Profiles of the four clusters; (b) - Silhouette scores for the four clusters



Source: authors' representation

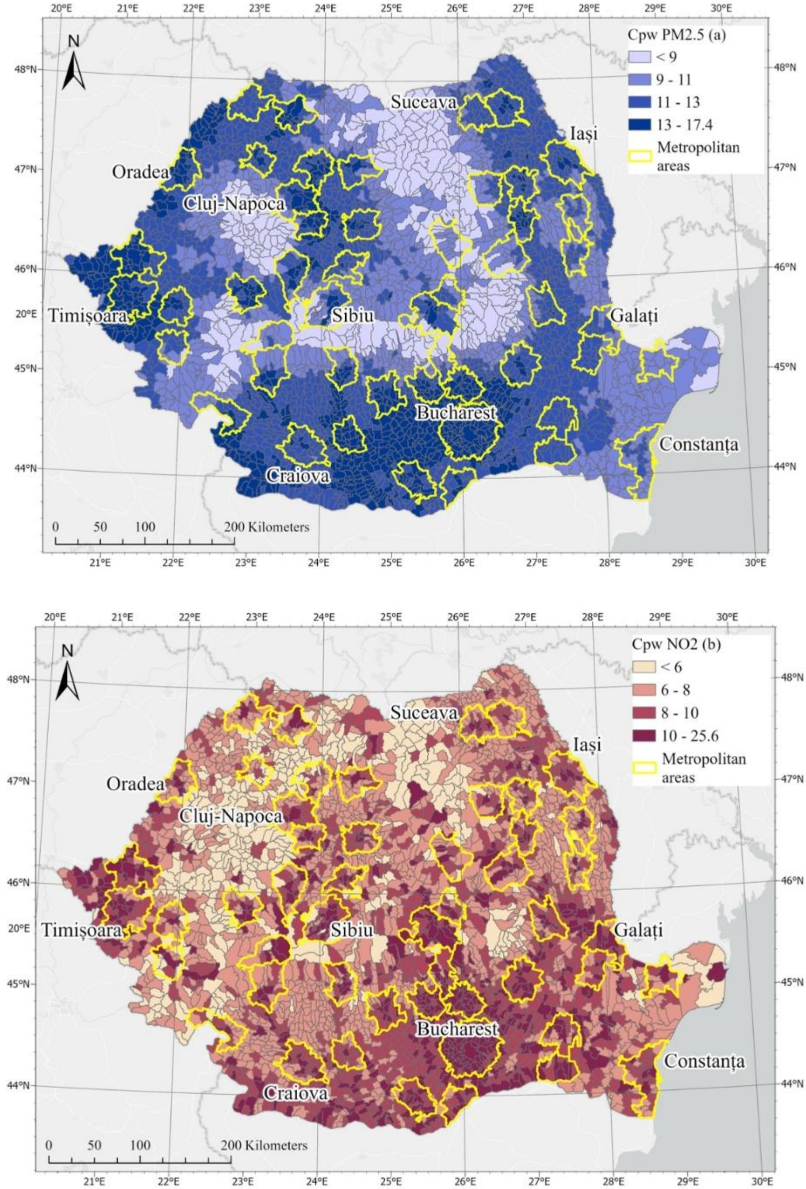
The progression of within-cluster variance from Cluster 1 to Cluster 4, together with the parallel decrease in average distance to centroid, indicates increasing internal homogeneity from the most urbanised and polluted cluster to the least. This pattern suggests that high-pollution urban contexts in Romania form a more heterogenous group, shaped by diverse combinations of historical, morphological, and topographic factors, while low-pollution rural-peripheral contexts converge toward a more uniform profile. The silhouette analysis (Figure 6b) supports the four-cluster solution.

3.5. Population-weighted exposure (Cpw)

The population-weighted pollution index provides a fundamentally different and more relevant metric than simple spatial averages (Figure 7a-b). The standard mean pollution approach systematically underestimates exposure in cities where populations concentrate in high-pollution neighbourhoods and overweighs sparsely populated rural areas in regional assessments. The Cpw metric corrects this by weighting pollution concentrations by the actual number of people experiencing them, yielding exposure estimates directly relevant for health impact assessments and policy prioritisation.

Population-weighted $PM_{2.5}$ concentrations display small urban-rural contrast, but more regionally consistent exposure. Values range from below 9 µg/m³ in northern and mountainous counties to over 13 µg/m³ in southern and western plains. Unlike NO_2, $PM_{2.5}$ shows broader regional zones of elevated exposure rather than point-source hotspots. The Bucharest metropolitan area again records the highest and most consistent population-weighted concentrations.

Figure 7. Population-weighted exposure index for $PM_{2.5}$ (a) and NO_2 (b)



Source: authors' representation

Western metropolitan areas (Timișoara, Oradea) and eastern regions (Iași, Galați) show moderate population-weighted PM2.5 (11-13 µg/m³), while the Carpathian regions maintain the lowest exposure levels even in urbanised areas. A more pronounced urban-centred pattern is revealed by the population-weighted NO_2 concentrations, with values ranging from below 6 µg/m³ in rural and mountainous areas to 25.6 µg/m³ in major metropolitan cores. Significant hotspots include Bucharest, Iași, Cluj-Napoca, and Timișoara, where metropolitan areas show consistently high values (10-25.6 µg/m³). Notably, NO_2 pollution exhibits sharp gradients at metropolitan boundaries, with population-weighted concentrations dropping in non-metropolitan communes immediately adjacent to these urban zones.

4. Discussions and policy implications

The present study provides a general framework for designing differentiated air quality policies in urban areas and their spheres of influence, aligned with EU pollution thresholds. By tracking the long-term evolution of two major pollutants over at least 10 years in relation to built-up area expansion and population density dynamics, the analysis yields evidence relevant not only at the local level but also for regional and national planning. It does not examine momentary threshold exceedances, the intensity or duration of pollution episodes, or toxicological indicators, as addressed in more specialised recent work (Drăgoi et al., 2025); rather, the contribution of this study lies in the dimensions outlined above. As such, this section is organised around two themes: differentiated policy responses across urban contexts (4.1), and the implications of urban form for pollutant-specific dynamics (4.2).

4.1. Differentiated policy responses across urban contexts

Major cities like Iași, Cluj-Napoca, and Timișoara offer the most promising scenarios for integrated urban development. Their improving air quality should align with walkability initiatives, creating a favourable environment in which reduced car dependence leads to cleaner air, encouraging more walking. Effective policy interventions should prioritise air filtration and emission reduction through strategic green infrastructure. Urban forests and green corridors function as emission sinks, absorbing pollutants while simultaneously providing cooling effects that reduce energy consumption and create inviting recreational spaces. Integrated approaches demonstrate that green infrastructure delivers multiple co-benefits: improved air quality, temperature regulation, opportunities for physical activity, and social gathering spaces (Haq et al., 2021). Traffic management must complement greening efforts, combining pedestrian zones, cycling infrastructure, and prioritising public transport. At the national level, maintaining EU policy alignment is important (Rakutiene, 2025), as improvement trends directly coincide with membership requirements and funding mechanisms. The metropolitan regions require accelerated intervention as a national priority, and improvements here would rapidly benefit the broader influential area surrounding the main city. In fact, Bucharest has historically ranked among the most polluted European capitals, recording the highest composite air quality index across the cities compared by Alpopi & Colesca (2010), surpassing Rome, Paris and Prague for suspended dusts. While the present results indicate some improvement since that period, Bucharest and several large Romanian metropolitan areas continue to exhibit pollution profiles more characteristic of Central and Eastern European cities than of their Western counterparts, reinforcing the need for targeted local and regional policies beyond generic EU-level measures.

The clustering analysis indicates urban and peri-urban contexts with different properties. The cities that were heavily systematised during the communist period have a high population and built-up density, went through intensive industrial activity, or are located in depressionary corridors where polluted air stagnates. They show significantly higher NO_2 than $PM_{2.5}$ values, suggesting predominance of NO_2-characteristic sources including vehicular traffic and concentrated combustion processes. Moderate values of population density and pollution occur in cities with extensive historical cores (cities from Transylvania, Constanța, Târgu Jiu) where socialist housing estate construction was less intensive, and in the surrounding towns of Bucharest, where peri-urban residential development extends outward from former village nuclei that subsequently gained urban status. Lower pollution is typically located further from cities in zones with better atmospheric circulation, mountain regions or the Danube Delta. One distinctive type of settlements shows lower NO_2 than $PM_{2.5}$ values, typically around Iași, Timișoara, Craiova, Târgu Mureș, and Bacău, where the contrast between urban and peri-urban areas is most pronounced, or around Oradea, Cluj-Napoca, Botoșani, and Slatina, where differences exist but to a smaller extent. This reflects the sharper gradient of NO_2 from urban centres toward peripheries compared to $PM_{2.5}$, whose high concentrations extend across greater distances from emission sources.

The population-weighted exposure maps reinforce a distinction that carries direct policy implications. Mountain areas and cities that underwent severe deindustrialisation emerge as low-pollution baselines. This status results from a combination of favourable topography, dispersed settlement patterns, and the natural regrowth of vegetation that followed industrial decline, rather than from deliberate environmental management. For these contexts, the appropriate policy response is protective rather than remedial. Places like Reșița, Petroșani, or Sfântu Gheorghe face the risk of gradual deterioration if development pressures are left unaddressed. These cities were identified as among Romania's cleaner urban environments (Institutul pentru Orașe Vizionare IOV, 2025). Solid fuel adoption, driven by economic distress, increased transit traffic, and uncontrolled expansion of built-up areas, represents the most plausible pathway towards an air quality backslide. Preventing this trajectory calls for early intervention with strict building and heating standards applied before conditions deteriorate, controls on transit corridor development, preservation and extension of peri-urban green infrastructure, comprising green belts, vegetated corridors, and hedgerow buffers that serve as protective barriers.

The air pollution patterns identified in this study suggest that southern Romania requires governance approaches that extend well beyond individual city boundaries. Across Oltenia and Muntenia, millions of people experience elevated exposure even outside formal metropolitan limits, as a result of overlapping pressures: the sprawl of the metropolitan area of Bucharest, oil refining and resource extraction activities, widespread solid fuel heating, agricultural residue burning, and cross-border pollution transport. This combination forms a southern regional $PM_{2.5}$ belt, where population-weighted exposure remains persistently high due to the cumulative effect of metropolitan, agricultural, industrial, and transport pressures operating simultaneously across different spatial scales. National air quality data confirm this picture, with frequent exceedances of particulate matter concentration limits recorded across southern counties, particularly during the cold season and in peri-urban areas (National Air Quality Monitoring Network RNMCA). The national air quality management platform already provides for the development of integrated air quality plans in areas where limit values are exceeded for multiple pollutants, pointing to the type of multi-scalar governance this study advocates. In practical terms, this means coordinating the prohibition and enforcement of agricultural burning across southern counties as a regional measure rather than a local one, aligned with the Common Agricultural Policy (CAP) conditionality. Industrial contributions to the regional $PM_{2.5}$ background include large combustion plants and thermal power stations, and fall under integrated pollution control frameworks such as OUG 152/2005 (Romanian Government, 2005), and their management should be explicitly incorporated into regional air quality planning. Given the longer atmospheric lifetime of $PM_{2.5}$ and its capacity for long-range transport, air quality plans conceived at the municipal scale are insufficient. The development region offers a more appropriate planning unit for addressing this southern pollution belt.

4.2. Urban form and pollutant-specific dynamics

The regression results reveal a meaningful divergence in how the two pollutants relate to urban form. For $PM_{2.5}$, at the peri-urban level, built-up surface density was statistically significant, while in the urban core, no variable was significant. This pattern is consistent with the morphological character of many Romanian cities. Historic urban cores, particularly those shaped by Austro-Hungarian planning or by coastal development as in the case of Constanța, tend to have a higher density of built surface relative to population, reflecting limited socialist-era dense block construction. The same logic applies in peri-urban areas, where low-rise housing predominates, and horizontal sprawl generates more sealed surface per capita than vertical residential development would.

The compact morphology of many Romanian city centres may further limit the natural dispersion of pollutants, creating urban canyon effects that trap street-level emissions. PM2.5 concentrations in Romanian cities are influenced by sources that are difficult to isolate at the scale of this analysis, such as biomass burning, construction activity that disregards dust-control regulations, and individual or small-scale combustion installations.

For NO2 in urban cores, population density is the most significant variable, whereas built-up density in peri-urban rings is a significant predictor. In urban cores, NO_2 gradients reflect the density and diversity of traffic flows. Effective intervention points toward the reallocation of street space; dedicated bus lanes, cycling infrastructure, and micromobility networks represent targeted responses to a problem that is, at its core, spatial. Many peri-urban communes act as dormitories, where residential population density translates directly into commuting pressure and peak-hour traffic flows toward urban cores, generating NO_2 concentrations along transport corridors even where the built environment remains relatively sparse. In metropolitan cores, the coexistence of resident traffic, commercial activity, through-traffic, and varied heating systems creates a complex source mix where no single density measure is sufficient to explain pollutant concentrations. Peri-urban areas, by contrast, show a notably better model fit for NO_2 because pollution generation there is dominated by a single, more predictable commuting mechanism. This need for coordinated action is further supported by environmental monitoring reports, which document elevated congestion and pollution specifically in localities bordering major metropolitan areas, a pattern that reinforces the case for air quality planning at the metropolitan rather than the municipal scale (Bănică & Muntele, 2017).

The regression findings inform on a set of policy priorities for Romania's larger metropolitan areas. In contexts where population-weighted exposure is highest, a necessary intervention package would include low-emission zones (LEZ), the electrification of residential heating, public transport modernisation, and fiscal instruments such as congestion charges, parking pricing, subsidies for cleaner vehicles and others. LEZs have already demonstrated measurable reductions in particulate emissions and improvements in public health across numerous European cities. In Eastern and Central Europe, Warsaw, Riga and Sofia have introduced the first such zones in recent years (Eurocities, 2023), placing Romania behind the regional trend despite several cities facing severe traffic-related NO_2 problems. Where traffic pressure is most intense, integrated packages are needed. These may include fleet renewal programmes, bus rapid transit corridors, park-and-ride infrastructure, and restrictions on older diesel vehicles (National Air Quality Monitoring Network RNMCA). The specific composition of these packages should reflect local conditions, as the results show that the relationship between urban morphology and pollutant levels varies considerably across cities and peri-urban/metropolitan areas (Observatorul Român de Sănătate, 2018). A uniform national approach is unlikely to be sufficient. Therefore, a framework that defines common standards while leaving room for city-specific implementation is required.

Conclusions

This study aims to investigate the spatiotemporal evolution of air pollution across 319 cities in Romania, with a focus on $PM_{2.5}$ and NO_2, the two most consequential pollutants for public health. The study provides a particular focus on three spatial scales: urban (local), peri-urban and metropolitan. This is a distinction that, in the Romanian context, carries particular weight given the rapid and largely unplanned peri-urbanisation that followed 1989 and the divergent pollution patterns it produced.

The winds of change have shifted Romania's air quality in the right direction, with results showing a general improvement over the study period. $PM_{2.5}$ concentrations declined by approximately 25% between 2007 and 2023, while NO_2 fell by over 20% between 2014 and 2023, with a sharp drop during the pandemic years and with continued progress thereafter. Yet, a limited number of cities that host nearly half of the Romanian urban population still exceed international limit values, which means that population distribution remains a critical lens through which to interpret aggregate figures.

The spatial patterns of the two pollutants diverge considerably, which is among the key findings of this study. NO_2 concentrations are consistently higher in urban cores than in surrounding peri-urban areas, a gap that reflects the primary association of this pollutant with vehicular traffic and concentrated combustion. Cities that show the sharpest urban-peri-urban gradients function as centralised employment hubs that draw daily commuter flows into compact cores with limited infrastructure. $PM_{2.5}$, by contrast, exhibits broader regional patterns rather than point-source hotspots, with the highest population-weighted exposure concentrated in the southern plains and the lowest in Carpathian regions, where both concentrations and population distribution favour cleaner conditions. The interaction regression analysis indicates that, in urban cores, population density is the significant predictor of NO_2, whereas in peri-urban rings, built-up surface density is the main explanatory variable for both $PM_{2.5}$ and NO_2. This reflects the dormitory character of many peri-urban communes, where residential density translates directly into commuting pressure, and it points to fundamentally different pollution regimes operating on either side of the metropolitan boundary.

The policy implications that follow from these findings are place-specific by nature. For the largest metropolitan areas, where population-weighted exposure is highest and traffic pressure most intense, an effective intervention package would combine low-emission zones, the electrification of residential heating, public transport modernisation, and fiscal instruments such as congestion charges, parking pricing or subsidies for cleaner vehicles. Industrial contributions to the regional $PM_{2.5}$ background, particularly from large combustion plants and thermal power stations, fall under integrated pollution control frameworks, and their management needs to be embedded in regional air quality plans. At the opposite end, mountain cities and those that have benefited from deindustrialisation require a preventive logic, with strict building and heating standards, controls on transit-corridor development, and the preservation and extension of peri-urban green infrastructure, such as green belts and green corridors. These findings carry particular urgency in the context of the European Green Deal and its associated air quality integration, whose targets must be met by 2030. At the current rate of improvement, meeting the new EU annual limit of 10 µg/m³ will require substantial policy acceleration, as in 2024 over 70% of Romanian cities still exceeded this threshold, with the highest values concentrated across Oltenia and Muntenia.

The main limitation of this study concerns the quality and density of the underlying monitoring data. The partial inaccuracies in some results in this study signal a broader concern about the adequacy of Romania's air quality monitoring network. There are 143 official stations, although many are non-functional or characterised by significant measurement gaps, but the network remains too sparse to capture the spatial specificity needed to distinguish the contributions of road traffic, residential heating, and industrial activity at a meaningful local scale. A proposal to supplement this infrastructure with 60 additional stations was put forward in 2020 (Iorga, 2021), but it was not implemented, leaving the coverage largely unchanged. Complementary data sources exist, including ground-based samplers, satellite-derived products, remote sensing instruments, and sun-photometers, but their integration with official network data remains problematic due to the absence of standardised protocols and the need for additional validation (Voinea et al., 2018). Densifying the monitoring network is therefore a technical priority and a precondition for policy-relevant analyses that urban air quality management increasingly demands. A further aspect concerns the number of pollutants considered. While $PM_{2.5}$ and NO_2 are among the most policy-relevant indicators of urban air quality, a more complete picture would require the inclusion of additional parameters such as ozone, particulate matter of coarser fractions, or heavy metals. Reliance on annual mean values represents another analytical constraint. Threshold exceedances, peak concentrations, and the considerable seasonal variability in pollutant levels are parameters that can further explain air quality dynamics. Future research could build on this foundation by incorporating higher-spatial- and higher-temporal-resolution monitoring data and by extending the framework to examine short-term concentration episodes, seasonal variability, and the specific contribution of individual emission source categories.

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