Romanian Reports in Physics **XX**, XYZ (2025)

IS SUBURBAN AIR QUALITY CATCHING UP TO THE CITY? A CASE STUDY FROM BUCHAREST GREATER AREA

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Received July 2025

Abstract. Present research is focused on the analysis of time series of NOx, PM_{10}, and $PM_{2.5}$ in Bucharest Greater Area (BGA) in order to find out if the air pollution in different parts of BGA has similar level. We statistically analyze time series of NOx, PM_{10}, and $PM_{2.5}$ mass concentrations at three types of stations (urban background, urban traffic, and suburban background) over a 5-year period 01.01.2020–31.12.2024, which includes the period of restrictions caused by the COVID-19 pandemic. The present work also checks if the impact on human health could be greater in the suburban area. For estimating the impact on human health, the hazard quotient method was used, considering the exposure to measured levels of pollutants in relation to the pollutant reference concentrations recommended by World Health Organization, in 2021. The findings suggest in both urban and peri-urban area of Bucharest NOx, PM_{10}, and $PM_{2.5}$ mass concentrations and a long-term human health risk for residents are relatively similar. However, some differences exist, and they were emphasized. The improvement in air quality during the pandemic restriction was just a transient situation, with no lasting effect, as it was found in other worldwide metropolitan areas.

Key words: air pollution, urban, suburban, health risk, hazard quotient.

1. INTRODUCTION

The investigation of air quality/air pollution over a metropolitan area has crucial importance in both scientific and policy terms, due to substantial impacts that air pollutants have on climate [1] and human health [2]. *In situ* surface or remote measurements of air pollutants are very often complemented by modelling approaches and many types of statistical analyses are used to get in-depth results about their sources, variability, dynamics, their underlying drives, temporal trends etc. [3-6]. Computational methods involved in modelling and forecasting of physical and chemical processes have their challenges [7], as well, but using the combination of above approaches represents the best research way when potential mitigation strategies must be developed, especially in areas with multiple pollutant sources. Urban areas typically present higher pollutant concentrations than their peri-urban areas [8,9]. In 2020, this gap narrowed as a result of the lockdown restrictive measures when urban emissions dropped sharply [10]. After the restrictions during lockdown were lifted, in many urban areas, pollutant levels gradually returned to previous levels within a year or less [11]. On the other hand, while urban zones have recorded gradual improvements due to use of cleaner technologies and implementation of stricter regulations, the suburban and peri-urban areas have experienced more variable changes with less consistent trends [9,12]. This is in part linked to their rapid, enhanced development, increased vehicular movement and industrial activity that promote higher local emissions; atmospheric conditions and urban sprawl also might play a role. Few scientific publications [9, 13] mention that the gap between the air pollution within the core urban area and the suburban area has narrowed, in the last years. However, there are many urban areas for which this has not been quantified and it is difficult to draw a general conclusion. Therefore, a need arises to analyze the time series of the main pollutants in as many areas as possible. On the other hand, if this observation turns out to be valid, at least for large cities, it means that it is possible that pollution in the peri-urban areas of larger cities may be sufficiently high to have a greater than before impact on people communities living there. PM_{10}, $PM_{2.5}$, and NOx are well-known air pollutants having substantial impacts on human health [2,14,15,16]. They result from a variety of sources like industrial and construction sites, vehicular traffic, fossil fuel burning for domestic heating in various types of stoves, agricultural practices, wildfires, fugitive sources as wind-blown dust, cooking, various non-exhaust emissions, among other [17,18]. Studies considering the population exposure to air pollutants, in Romania and especially in Bucharest are still very scarce [19-22]. Bodor et al. [19-21] used a different methodology than in present study. Burghelea et al. [22] used a close one, but the impact on public health considered only PM_{10} levels at traffic stations in three urban areas in Romania (Bucharest, Brasov, Iasi) in comparison with PM_{10} regional background during 2017-2022. Major air pollutants in Bucharest Greater Area were in depth analyzed by Iorga et al. (2015) during an earlier period, 2005-2010, at all eight air quality monitoring stations [23]. This study will be used to compare present levels of NOx, PM_{10} and $PM_{2.5}$ with those registered two decades ago. The objective of this paper is therefore twofold. First, we aimed to assess the pollution level by NOx, PM_{10} and $PM_{2.5}$ in different zones in Bucharest Greater Area during 2020-2024, and second, to evaluate the non-carcinogenic risk of population due to exposure to air pollution. The questions to answer are: 1. Is the gap between urban and suburban pollution reduced for the BGA in the period 2020-2024, in comparison to its values during the earlier period 2005-2010? 2. Does the pollution in suburban areas, surrounding larger cities, determine a similar or a different influence on human health than within the core city?

The Section 2 of the paper includes a description of the study area, followed by the data and the methodology used, then Section 3 presents and discusses the results. The conclusion section summarizes the findings.

2. DATA AND METHODS

2.1. BUCHAREST GREATER AREA SHORT DESCRIPTION

The Greater Area of Bucharest (BGA) had undergone the most rapid development in Romania in the last decades, as it is indicated by the city socio-economic statistical indicators (http://statistici.insse.ro:8077/tempo-online/). Main pollution sources that exist in BGA include numerous construction sites for residential and commercial use, very diverse industrial facilities and some power plants for energy production.

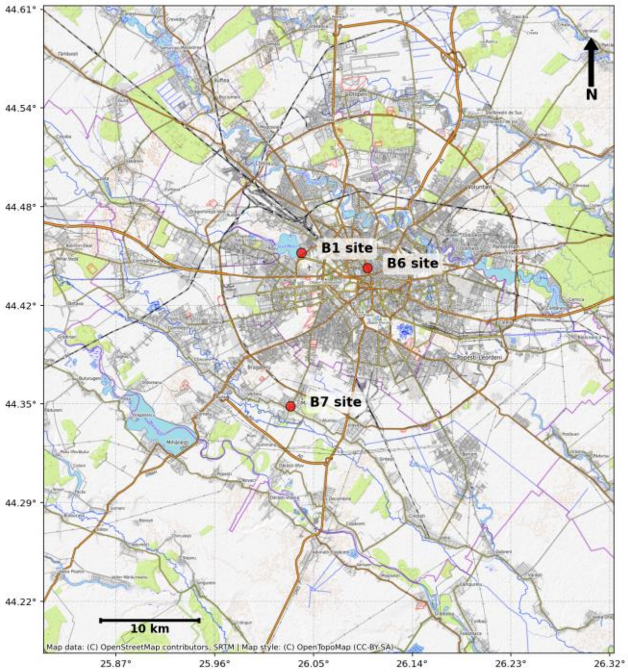

Fig. 1 – Bucharest Greater Area and the location of urban traffic (B6), urban background (B1) and suburban (B7) background AQ monitoring stations. Main roads, the Bucharest ring (the limit between urban core and the suburban/peri-urban area) and the parts of the A1 and A0 highways are also visible.

A very mixed vehicle fleet (new and second hand) increased gradually from 2007 reaching more than 1.6 million registered cars, motorcycles, buses, trams and other commercial vehicles at the end of 2024 (https://www.evmarket.ro/en/Useful/car-fleet-in-Romania-53083-vehicles/). Many heavy-duty trucks are also frequently seen on the roads around Bucharest (the dark orange round route and A0, A1 highways in Figure 1). Other fugitive sources as wind-blown dust, seasonal agricultural practices also exist.

2.2. DATA, STATISTICAL ANALYSIS AND METHODOLOGY

In present analysis, PM_{10}, $PM_{2.5}$, and NOx (=$NO+NO_2$) were selected out of the major air pollutants monitored in Bucharest Greater Area at three stations (urban traffic, B6; urban background, B1, and suburban background, B7). Their hourly mass concentrations were retrieved from the public database of Romanian National Air Quality Monitoring Network between January 1st, 2020 and December 31st, 2024 (www.calitateaer.ro). Present results are based on daily, monthly, and seasonal means, calculated from the pollutant hourly concentrations. NO_2 time series were considered for estimating the impact on public health. PM_{10} and $PM_{2.5}$ reported in the database were measured by both standard gravimetry using low volume samplers LVS and by Tapered Element Oscillating Microbalance (TEOM) techniques for the background stations B1 and B7. We analyzed time series resulted from both measurement techniques.

Urban impact (UI) over the suburban area and traffic impact (TI) were defined using the conceptual model proposed in [24], as differences between mass concentrations of the corresponding pollutant at urban and suburban background stations UI = B1 - B7, and as differences between urban traffic and urban background mass concentrations TI = B6 - B1, respectively. This method is able to indicate if urban core pollutant levels are higher ($UI > 0$) or lower ($UI < 0$) than in the suburban area.

Basic descriptive statistics on PM_{10}, $PM_{2.5}$ ad NOx and on UI and TI time series were complemented by cross-correlation analysis to detect if and how one time series is correlated with another. Cross-correlation analysis is frequently used in both air pollution and its impact on public health studies [25,26]. For long term trend detection Mann-Kendal and Sen’s slope were involved. Statistical analysis for this study was performed by Phyton, at a statistical significance set as $p < 0.05$.

To estimate the human health risk related to exposure by inhalation of nitrogen oxides or particulate matter, the hazard quotient (HQ) method was used [22, 27, 28] with specific assumptions. HQ was calculated according to Equations 1 and 2:

$$HQ = EC / RfC \tag{1}$$

$$EC = CA \times ET \times EF \times ED / AT \tag{2}$$

EC represents the exposure concentration of the considered pollutant. RfC is the threshold value from which, based on toxicological studies, it has been established that health effects may occur. RfC is a reference value (sometimes it is called inhalation toxicity value), specifically attributed by the World Health Organization in 2021 [2] for each pollutant as 10 µg m^{-3} for NO_2, 15 µg m^{-3} for PM_{10}, and 5 µg m^{-3} for $PM_{2.5}$. CA is the monthly mean of the exposure pollutant (µg m^{-3}). The other constants, their measurement units and the values we considered, are as follows: ET is the exposure time in hours/day (8 h/day), EF is the exposure frequency in days/year (220 working days/year), ED is the exposure duration in number of years (5 years), and AT is the averaging time, calculated as 5 years x 365 days/year x 24 h/ day.

HQ assesses the non-carcinogenic risk, i.e. all those adverse health effects in a living organism caused by the corresponding exposure factor, excepting cancer. When $HQ > 1$, the exposure to a selected factor will induce non-carcinogenic chronic effects, while for the $HQ < 1$, this risk is acceptable or not expected.

3. RESULTS AND DISCUSSION

3.1. URBAN-SUBURBAN DIFFERENCES IN LEVELS OF NOx, PM_{10} AND $PM_{2.5}$

The monthly means of NOx, PM_{10} and $PM_{2.5}$ concentrations during the observation period are shown in Figure 2, together with the changes in regional atmospheric boundary height (BLH). BLH synthetizes, from a meteorological perspective, the physical processes like dispersion and removal, and various chemical processes taking place during the studied period. Generally, highest NOx mass concentrations are observed at the traffic station in the very center of Bucharest, while lowest seem to be in the suburban region. However, there are time periods when suburban NOx has the same level as those for the urban background (as in 2022) or even exceed them, as in 2024. This could indicate that NOx sources in the suburban area can be significantly higher than in the urban area. Among possible factors are: local transit traffic using the ring road and A0 highway, the very intense (including heavy-duty) traffic on the Bucharest ring road and the A0 highway to the Southern regions and further on, to the city of Giurgiu and the communes in the area (in intense development, as well) up to the border to Bulgaria. PM mass concentrations seem to have much more close values in both $PM_{2.5}$ and PM_{10} fractions in the entire Bucharest Greater Area. This situation is also revealed by the Figure 3, showing the probability density functions calculated for the entire period 2020-2024. While we observe a wider and right-skewed distribution of NOx at the traffic station B6, areas where B1 and B7 are located present narrower, more peaked distributions. This indicates higher and more variable concentrations in Bucharest central area and lower and more consistent NOx levels at the background stations, both in urban and in suburban areas.

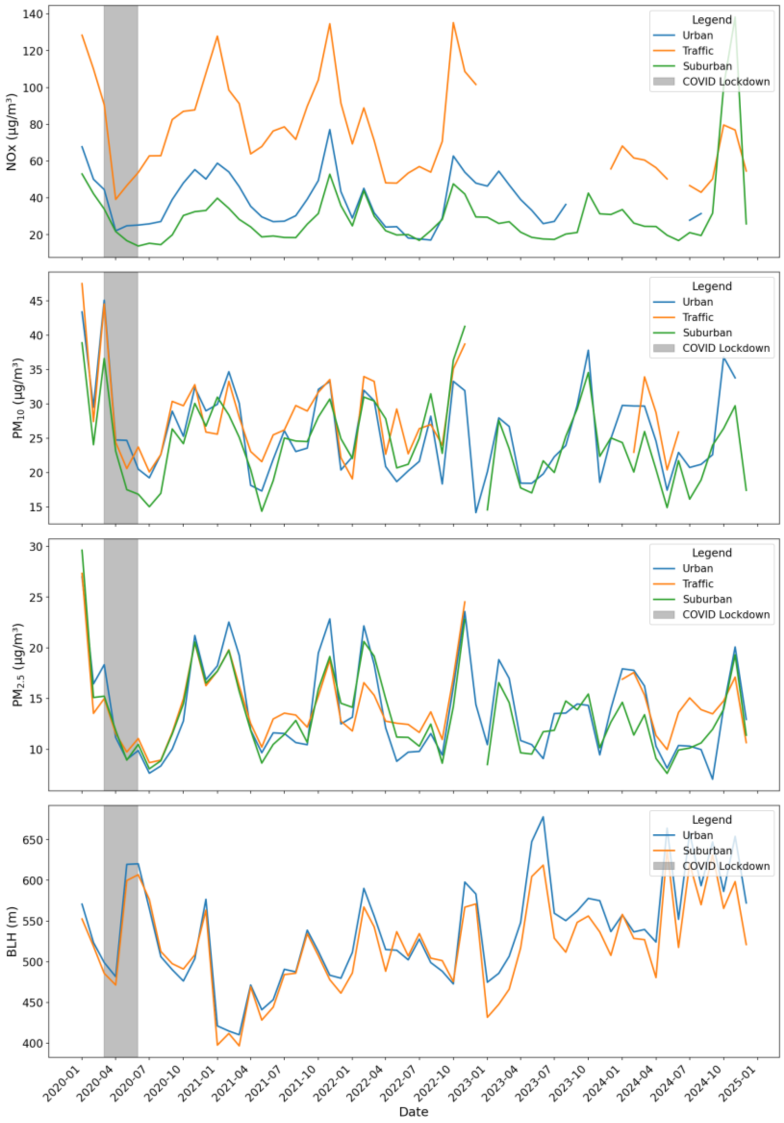

Fig. 2 – Urban traffic (B6), urban background (B1) and suburban background (B7) variations in terms of monthly mean concentrations of NOx, PM$_{10}$ and PM$_{2.5}$, 2020-2024. BLH represents the boundary layer heights. The grey area highlights the lockdown period in 2020 (15th March-15th May).

Particulate matter PM_{10} distributions have right-skewed distributions, with similar central tendencies at all three stations. However, Bucharest central area shows greater variability (B6, a slightly broader spread distribution), and the suburban area presents more consistent concentrations around the mode (B7, a higher peak of the distribution). The fine fraction $PM_{2.5}$ distributions are very similar across all stations.

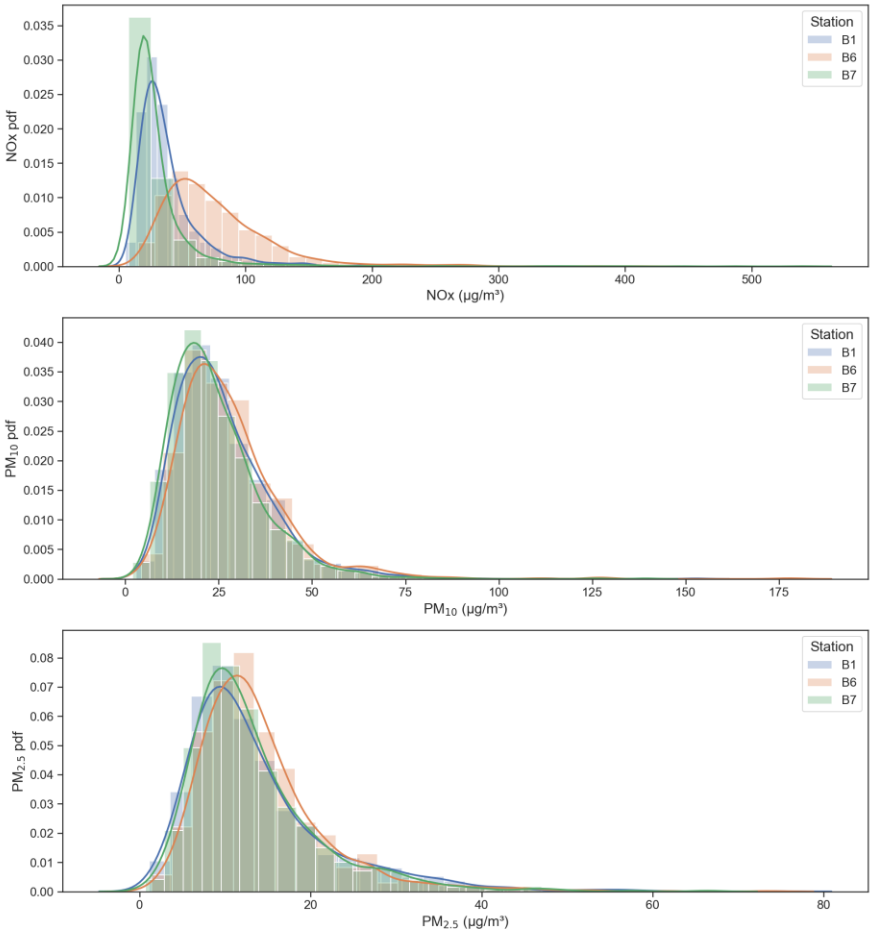

Fig. 3 – Probability density functions of NOx, PM_{10} and $PM_{2.5}$ concentrations across B1, B6, B7 monitoring stations, 2020-2024**.**

The mass concentrations in Figure 2 also show the temporary effect of the improvement of the air quality in BGA in spring of 2020. The decrease in the levels of $PM_{2.5}$ up to about 10 µg m^{-3} (B1, B6, B7), of PM_{10} to 15 µg m^{-3} (B7) and to about 20 µg m^{-3} (B1, B6) during the hard lockdown and shortly after it in 2020 appears as a short-time effect. NOx levels presented sharpest decrease at the traffic station (from about 95 µg m^{-3} at the start of the lockdown to 40 µg m^{-3} at its end) and a moderate decrease (from about 50/40 µg m^{-3} to 20/17 µg m^{-3} at B1 and B7 station, respectively).

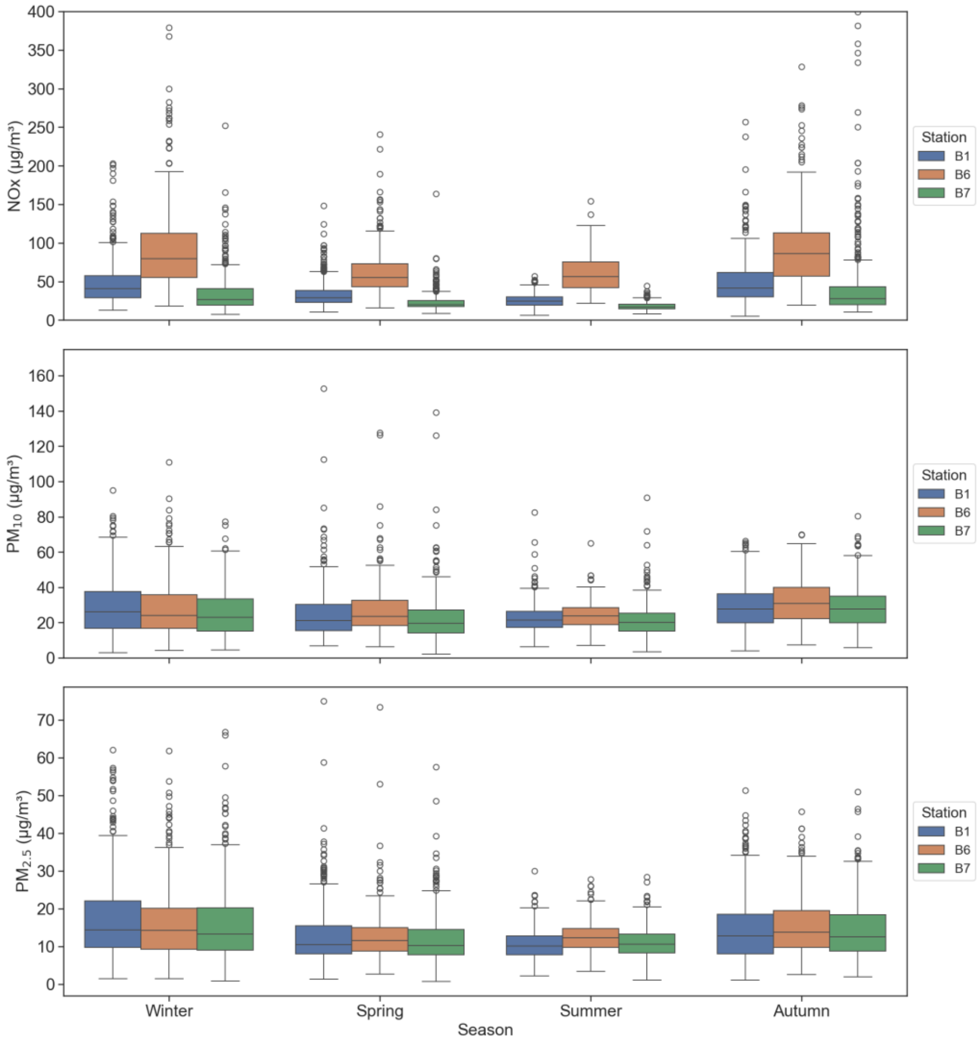

Fig. 4 – Seasonal variation of NOx, PM$_{10}$ and PM$_{2.5}$ at traffic (B6), urban (B1) and suburban (B7) background stations, 2020-2024.

The more or less abrupt reduction in pollutant concentrations and the actual improvement in air quality in urban areas worldwide appear to be more limited than it was reported in earlier studies [29,39]. The lockdown positive effect during the first wave of COVID-19 had no lasting effects in subsequent years. Similar conclusions were also drawn by Turek et al. (2021) and Shi et al. (2021) in other regions on other continents [31,32].

Seasonal variation of studied pollutants in Figure 4 highlights a clear seasonal and spatial variability, with pollutant levels at station B6 consistently higher - especially in winter and autumn - while B7 remains lowest for NOx concentrations. Particulate matter levels are more stable across stations and seasons, though both PM_{10} and $PM_{2.5}$ peak slightly in winter, suggesting seasonal influence likely due to residential heating and atmospheric conditions. The same conclusion resulted from statistics of NOx, PM_{10} and $PM_{2.5}$ time series performed for weekend versus weekdays (not shown here).

Time series of PM_{10} and $PM_{2.5}$ fractions resulted from both measurement techniques (standard gravimetric PM measurements by low-volume samplers and by Tapered Element Oscillating Microbalance) were compared using scatter plots of the mass concentrations at both B1 and B7 stations. The agreement of the techniques was moderate. TEOM measurements underestimated with about 15-20% the mass concentrations obtained by the gravimetric standard method, and R^2 was about 0.68 for PM_{10} and ranged between 0.49 to 0.62 for $PM_{2.5}$. While 68% of the variability in PM_{10} values obtained by TEOM can be explained by gravimetric PM, more than 30% could be due to other factors not accounted for in the model. Among these, the poor sensitivity of TEOM regarding the semi-volatile chemical species as ammonium nitrate and organic aerosols is widely recognized [33]. In practice, by APHEIS project of European Commission, a conversion factor of 1.3 is recommended to be used for sites in Europe when a local factor is not available [34]. Present outcome indicates that the appropriate factor is 1.15 for urban core and 1.2 for suburban/peri-urban area of Bucharest.

To further explore the delayed impact of ambient air pollutants in Bucharest core area and the peri-urban area, the cross-correlation analysis was performed. The results of cross-correlation analysis at various lags are summarized for background stations urban (B1) and suburban (B7) and for traffic (B6) versus urban background (B1) in Table 1. Based on Table 1, B1 and B7 are characterized by weakly to moderate positive correlations for both NOx and PM_{10}. NOx at B1 precedes NOx at B7 by 1 day, meaning that changes in NOx levels at B1 will be seen in changes in NOx at B7 in the next day. Traffic (B6) and urban background (B1) time series are better correlated and a relatively short time effect is observable for both NOx and PM_{10}. NOx at B1 might also have some influence in future values of NOx at B7 in 7 days but the correlation is weak. Cross-correlation coefficients R_{NOx} (B1, B7) and R_{NOx} (B6, B1) are lower after the 7th-day lag. It could be a long-term relationship or a delayed effect, but other factors like weather conditions or local sources could change this outcome and this relationship is not strong or consistent. This possible delayed effect is not seen for PM_{10}.

Table 1

Cross-correlation coefficients between concentrations of NOx, PM10 over a 7-day lags in BGA (B1 vs B7 in first line per lag and B6 vs B1 in second line per lag); CI = confidence interval; $p < 0.001$.

Lag	R_{NOx}	95% CI		R_{PM10}	95% CI	
0	**0.668**	0.638	0.696	**0.789**	0.768	0.807
	0.855	0.838	0.869	**0.827**	0.803	0.847
1	**0.441**	0.398	0.483	**0.529**	0.490	0.565
	0.516	0.473	0.557	**0.488**	0.434	0.539
2	0.228	0.177	0.277	**0.328**	0.280	0.373
	0.269	0.215	0.321	**0.295**	0.231	0.357
3	0.171	0.119	0.221	0.226	0.176	0.274
	0.217	0.162	0.272	0.214	0.147	0.279
4	0.151	0.099	0.202	0.204	0.154	0.253
	0.246	0.191	0.299	0.175	0.107	0.241
5	0.132	0.080	0.183	0.188	0.137	0.236
	0.214	0.158	0.268	0.162	0.094	0.228
6	0.191	0.140	0.241	0.181	0.130	0.230
	0.255	0.200	0.308	0.154	0.086	0.220
7	**0.235**	0.184	0.283	0.163	0.112	0.212
	0.326	0.274	0.377	0.135	0.067	0.202

All previous investigations during a 5-year period suggest that, most probably, a major difference between the levels of studied pollutants does not exist. Therefore, the Bucharest suburban/peri-urban area seems to suffer from the same level of pollution as in the urban area. A difference is seen only when we compare the levels of nitrogen oxides in the suburban area with their levels in the traffic area; a factor that could determine this difference is the vehicular traffic, although in last years the traffic in peri-urban area has increased significantly.

3.2. STATISTICS OF URBAN IMPACT AND TRAFIC IMPACT IN TIME SERIES

Further on, we compared UI and TI time series in order to see if we obtain similar results. The present approach has the advantage that minimizes the fugitive impact of local sources (like temporary waste burning) and the impact of pollutants coming from medium or long-range distances (like Sahara dust intrusions). Therefore, the results can show a better image on the pattern of regional area pollution. Synthesis of statistics is shown in Tables 2 and 3. The resulted time series of UI and TI showed slightly flat and relatively symmetric distributions by each year, in a very good approximation (skewness ranged from 0.32 to 1.17 for $PM_{2.5}$, from 0.28 to 1.28 for PM_{10} and from 0.76 to 4.5 for NOx, in absolute values, and mean kurtosis was about 9.7 for NOx, 4.3 for PM_{10}, and 4.76 for $PM_{2.5}$).

Table 2

Urban impact descriptive statistics (2020-2024).

	UI, NOx (µg m^{-3})	**UI, PM10 (µg m^{-3})**	**UI, PM2.5 (µg m^{-3})**
Parameter	**2020**		
Mean (95% CI)	13.03 (11.28-14.79)	4.79 (3.28-6.30)	1.10 (-0.07-0.226)
Range (min; max)	(-34.55; 96.32)	(-26.79; 94.98)	(-44.45; 75.03)
	2021		
Mean (95% CI)	14.09 (12.30-15.87)	2.06 (1.07-3.05)	1.42 (0.57-2.27)
Range (min; max)	(-61.60; 128.37)	(-32.34; 52.31)	(-32.91;37.59)
	2022		
Mean (95% CI)	4.25 (2.76-5.74)	-0.24 (-1.13-0.64)	1.86 (1.02-2.71)
Range (min; max)	(-70.06; 69.27)	(-35.26; 33.29)	(-32.26; 33.39)
	2023		
Mean (95% CI)	-2.35 (-5.27-0.58)	0.20 (-0.45-0.85)	1.81 (1.06-2.56)
Range (min; max)	(-148.45; 101.30)	(-35.83; 19.17)	(-18.79; 35.46)
	2024		
Mean (95% CI)	-31.32 (-38.04-(-24.60))	-1.38 (-2.73-(-0.03))	2.11 (1.20-3.02)
Range (min; max)	(-339.78; 53.05)	(-64.59; 27.47)	(-29.48; 42.18)

Regarding the NOx and PM_{10}, we observe $UI > 0$ in 2020. Therefore, urban core shows higher values than suburban. In 2024 it seems that the suburban area is more polluted than the urban background ($UI < 0$). In addition, the urban versus suburban gap is reduced in 2024 compared to 2020 when the temporary effect of better air quality during the restrictions due to COVID-19 pandemic appeared. Combining the long-term analysis (2005-2024) of temporal trends of UI using Mann-Kendal and Sen's slope with values reported in [23] by Iorga et al. (2015) for time period 2005-2020, and in the view of the dispersion characteristics in Bucharest Greater Area [35], we can conclude that the urban impact during 2020-2024 compared with earlier periods is similar for all pollutants considered here. In case of fine particles $PM_{2.5}$, urban area is characterized by relatively the same levels as suburban region on both short and long-term.

Concerning the traffic impact TI within Bucharest urban area over a 5-year (2005-2010 versus 2020-2024), the comparison based on Table 3 and the findings in [23,35], it seems that ambient air within Bucharest urban core presents relatively similar levels, variations being only of local nature. It also seems that more PM_{10} particles are present in the western part of the city, maybe as a result of many construction activities, in the last years. However, the long-term analysis (2005-2024) using Mann-Kendal and Sen's slope method revealed a very significant result ($p < 0.001$) of traffic urban-urban background gap narrowing for nitrogen oxides NOx. The trend slope of TI, NOx is -5.5% per year. The calculated trend for TI (PM_{10}) was significant ($p < 0.05$) but the slope was very low (-0.25% per year), while the calculated trend of TI ($PM_{2.5}$) was not significant.

The present concept of UI and TI does not provide the information that the pollution produced in the urban area, by its emission sources, disperses over the peri-urban area. Consideration of more pollutants and especially an analysis of the differences in the chemical compositions of both fine and coarse PM fractions would give such a result. Meteorology factors should be added to analysis, as well. However, the concept of UI is a good "proxy" to derive information to which extent the pollution levels in various zones in Bucharest Greater Area are similar.

Table 3

Traffic impact descriptive statistics (2020-2024).

	TI, NOx (μg m^{-3})	TI, PM10 (μg m^{-3})	TI, PM2.5 (μg m^{-3})
Parameter		**2020**	
Mean	39.05	1.77	-1.17
95% CI	36.26-41.84	0.14-3.41	-2.13-(-0.22)
Range (min; max)	(-45.65;173.13)	(-59.17;127.67)	(-54.08;37.45)
		2021	
Mean	46.78	-2.75	-0.96
95% CI	43.86-49.70	-4.40-(-1.09)	-1.80-(-0.12)
Range (min; max)	(-45.94;216.92)	(-52.31;85.85)	(-35.78;30.66)
		2022	
Mean	39.59	-5.83	-1.75
95% CI	36.78-42.40	-7.63-(-4.03)	-2.73-(-0.76)
Range (min; max)	(-74.65;180.14)	(-82.42;48.41)	(-58.72;36.24)
		2023	
Mean	-21.15	-20.07	-11.92
95% CI	-24.09-(-18.22)	-21.43-(-18.70)	-12.68-(-11.17)
Range (min; max)	(-147.98;111.62)	(-68.44;0.00)	(-44.07;0.00)
		2024	
Mean	44.35	-11.66	0.16
95% CI	40.53-48.16	-13.36-(-9.97)	-0.70-1.03
Range (min; max)	(-74.81;252.88)	(-75.09;35.44)	(-37.99;24.98)

3.3. HUMAN HEALTH RISK ASSESSMENT

Figure 5 synthetizes the evaluated HQ values associated with the exposure to NO_2, $PM_{2.5}$ and PM_{10} in BGA.

In accordance with WHO (2021) guidelines [2], the hazard quotient HQ values due to exposure to NO_2 were calculated as follows: between 1.61 in December 2024 and 3.62 in January 2021 in the very center of the city, between 0.85 in July 2022 and 2.42 in November 2021 in the urban core, and between 0.63 (June 2020) and 2.88 (November 2024) in suburban area.

The potential non-carcinogenic chronic health risks due to $PM_{2.5}$ exposure, ranged as follows: from 1.20 (July 2020) to 3.30 (January 2020) in the very center of the city, from 0.85 (September 2024) to 3.25 (January 2020) in urban core, and from 0.92 (May 2024) to 3.57 (January 2020) in suburban zone.

The potential non-carcinogenic chronic health risks due to PM_{10} exposure are somehow lower, HQ varies between 0.77 (January 2022) to 1.91 (January 2020) in the Bucharest center, between 0.70 (May 2024) and 1.74 (January 2020) within the urban core and between 0.58 (May 2021) and 1.66 (November 2022) in the suburban area. The value of HQ =1.8 in March 2020 is related to a transient situation (desert dust intrusion in end of the month, [22]) which influenced the PM_{10} monthly mean concentration. In spring and summer 2020, lower HQ values were obtained in BGA, suggesting a potential benefit from the combined effect of traffic restrictions, regional climate and people habits to leave BGA for vacations.

In summary, a serious potential risk for chronic pathologies due to exposure to nitrogen oxides and particulate matter is present in both urban and peri-urban area of BGA. A higher risk is recorded during the cold season, which is associated with an increased concentration of pollutants. The hazard coefficient HQ (due to exposure to NOx, $PM_{2.5}$) has the highest values in the central area of Bucharest, regardless of the season comparing with other urban zones and the suburban area. The risk due to NOx is lower in the suburban area only during the summer due to both climate and behavioral factors (higher BLH favoring dispersion, lower traffic because of the vacations/holidays). The general HQ pattern due to exposure to all studied pollutants shows maximum values in the cold season (when residential heating activity contributes to higher pollutant concentrations) and the lowest values in summer, indicating increased risk of adverse effects in this order: NOx, $PM_{2.5}$, PM_{10}.

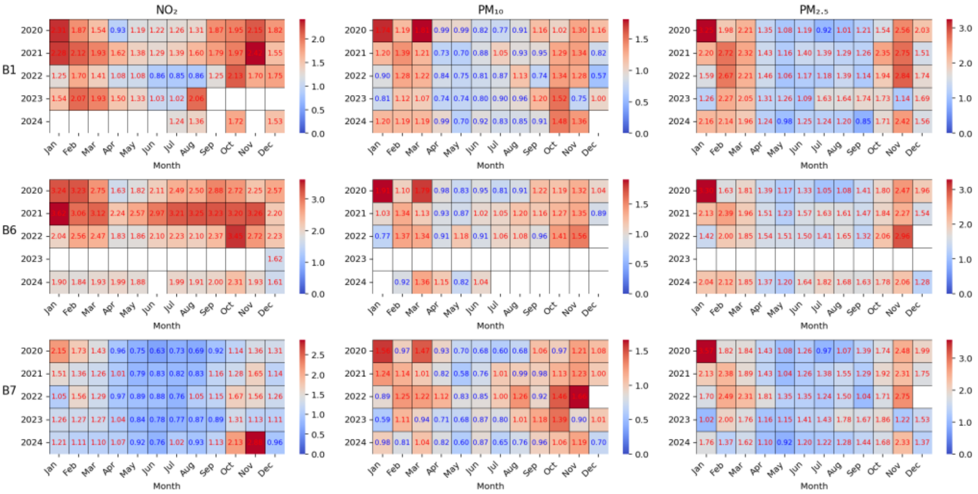

Fig. 5 – Human health risk quantified by hazard quotient (HQ) calculated for NO_2, PM_{10} and $PM_{2.5}$ in Bucharest Greater Area, following WHO (2021) recommendations. Please note the scales are pollutant-specific, from 0 to the corresponding calculated maximum value. Values of HQ > 1 are written in red, Values of HQ < 1 are written in blue.

The population exposure to nitrogen oxides and particulate matter in Bucharest Greater Area and the associated health risks expressed by HQ according to WHO (2021) guidelines still represents a major concern. Present results complement the results for HQ due to PM_{10} exposure in BGA [22] during 2017-2022 and health risk calculated in [19] for all-cause mortality associated with short-term PM_{10} exposure in different Romania regions. Present risks are higher than others identified in some remote European regions [36] but lower than HQ calculated in other cities, with different climates or higher pollutant levels [37,38].

4. CONCLUSIONS

The statistical analysis of particulate matter ($PM_{2.5}$, PM_{10}) and nitrogen oxides (NO_2, NOx) time series at three stations across Bucharest Greater Area and the chronic non-carcinogenic human health risk calculated based on exposure concentrations from 2020 to 2024 in present study generated three major findings.

First, regional changes in ambient concentrations of key air quality species seem to have the same level for $PM_{2.5}$ and PM_{10} in both the urban core area and in suburban/peri-urban area. For NOx the differences between urban and suburban background are only of a few tens of $\mu g\ m^{-3}$. Significant differences exist only between the NOx levels in Bucharest core where the traffic density is highest, relative to the urban background station (up to 50-60 $\mu g\ m^{-3}$ in monthly means). Some seasonal effect can be seen only for nitrogen oxides.

Second, the level of pollution in the urban core and the surroundings is high and is relatively at the same level as in the years before 2020. Long term analysis for traffic impact in urban Bucharest showed a narrowing gap (urban traffic-urban background) has been identified only for NOx. Although the measurement techniques (standard gravimetry versus TEOM) give results of different amplitudes, the pattern is similar.

Third, the present study clearly highlights the high potential non-carcinogenic chronic health risk due to exposure to NOx and fine particles $PM_{2.5}$ for resident population in both urban core and in the suburban/peri-urban region at the relatively same level.

Given the outcomes of this approach, the implications for regional and national environmental policies are significant: suburban/peri-urban areas seem to require pollution control measures similar to those in the urban area around them. Future environmental health programs should be designed considering the specificities of metropolitan/ urban agglomerations where they should be applied in, using also the local health risk estimates. Thus, the residents who are most susceptible to develop the adverse health impacts because of the local poor air quality could be better protected.

Acknowledgment:
The hourly air pollutants and atmospheric boundary layer height datasets were extracted from the National Air Quality Monitoring Network Database for Bucharest, stations B1, B6 and B7, and

ERA5, which are public available at www.calitateaer.ro and https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview, respectively (last accessed January 2025). The authors thank to L. Dumitrache for preparing the working database.

REFERENCES

1. IPCC, 2023: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, Geneva, Switzerland, 184 pp, 2023.
2. WHO, 2021: *WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. Geneva, World Health Organization, 300 pp., 2021.
3. C. Stihi, O. C. Bute, Rom. Rep. Phys. **75**, 706 (2023).
4. A. Ajdour, B. Ydir, J. Chaoufi, R. Leghirib, Rom. J. Phys. **69**, 808 (2024).
5. A. Bărbulescu, Climate **12**, 34 (2024).
6. Y. Saliba, A. Bărbulescu, Canada, Rom. Rep. Phys. **76**, 701 (2024).
7. V. Marascu, M.I. Mihailescu, V. Barna, Rom. Rep. Phys. 75, 907 (2023).
8. W. Han, Z. Li, J. Guo, T. Su, T. Chen, J. Wei, M. Cribb, Remote Sens. **12**, 2320 (2020).
9. D.J. Kilpatrick, P. Hung, E. Crouch, S. Self, J. Cothran, D.E. Porter, J.M. Eberth, GeoHealth **8**, e2023GH000920 (2024).
10. J.D. Berman, K. Ebisu, Sci. Total Environ. **739**, 139864 (2020).
11. R.D. Das, S. Bandopadhyay, S. Ghosh, M. Das, M. Chowdhury, A. Cotrina-Sanchez, C. Kumar, C. Mitra, 2023, Phys. Chem. Earth **132**, 103452 (2023).
12. S. Muhammad, X. Long, M. Salman, Sci. Total Environ. **728**, 138820 (2020).
13. X. Li, F. Zhang, J. Ren, W. Han, B. Zheng, J. Liu, L. Chen, S. Jiang, Environ. Pollut. **304**, 119146, (2022).
14. A.J. Cohen, M. Brauer, R. Burnett, H.R. Anderson, J. Frostad, K. Estep, K. Balakrishnan, B. Brunekreef, L. Dandona, R. Dandona, V. Feigin, G. Freedman, B. Hubbell, A. Jobling, H. Kan, L. Knibbs, Y. Liu, R. Martin, L. Morawska, C.A. Pope III, H. Shin, K. Straif, G. Shaddick, M. Thomas, R. van Dingenen, A. van Donkelaar, T. Vos, C.J.L. Murray, M.H. Forouzanfar, Lancet **389**, 1907-1918 (2018).
15. H.-Y. Liu, D. Dunea, S. Iordache, A. Pohoata, Atmosphere **9**, 150 (2018).
16. Y. Saliba, A. Bărbulescu, Toxics **13**, 52 (2025).
17. W.G. Tucker, Fuel Process. Technol. **65–66**, 379–392 (2000).
18. R.M. Harrison, T.V. Vu, H. Jafar, Z. Shi, Environ. Int. **149**, 106329 (2020).
19. K. Bodor, R. Szép, Z. Bodor, Toxicol. Rep. **9**, 556–562 (2022).
20. K. Bodor, R. Szép, Z. Bodor, Heliyon **9**, e21810 (2023).
21. B. Mahler, D. Băiceanu, T.C. Panciu, R.M. Florea, A.L. Iorga, M. Gnat, C.F. German, S. Pârvu, D. Paraschiv, D. Manea, M. Mihai, E. Ibraim, B. Timar, F.D. Mihaltan, Atmosphere **14**, 867 (2023).
22. G.-B. Burghelea, L. Mărmureanu, G. Iorga, B. Antonescu, Appl. Sci. **14**, 8169 (2024).
23. G. Iorga, C.B. Raicu, S. Stefan, Atmos. Poll. Res. **6**, 824–834 (2015).
24. H. Puxbaum, B. Gomiscek, M. Kalina, H. Bauer, A. Salam, S. Stopper, O. Preining, H. Hauck, Atmos. Environ. **38**, 3949–3958 (2004).
25. H. Wang, C. Tian, W. Wang, X. Luo, Int. J. Environ. Res. Public Health **16**, 1585 (2019).
26. D.M. Vlachogiannis, Y. Xu, L. Jin, M. Gonzalez, Appl. Netw. Sci. **6**, 32 (2021).
27. L. Levei, M.-A. Hoaghia, M. Roman, L. Mărmureanu, C. Moisa, E.A. Levei, A. Ozunu, O. Cadar, Romania, Appl. Sci. **10**, 5331 (2020).

28. M. Van Poppel, J. Peters, E.A. Levei, L. Mărmureanu, A. Moldovan, M.A. Hoaghia, C. Varaticeanu, J. Van Laer, Atmos. Environ. **297**, 119594 (2023).
29. K. Slezakova, M.C. Pereira, 2020, Sci. Rep. **11**, 21336 (2021).
30. R.V. Chiritescu, E. Luca, G. Iorga, Rom. Rep. Phys. **76**, 702 (2024).
31. T. Turek, E. Diakowska, J.A. Kamińska, Poland, Atmosphere **12**, 1549 (2021).
32. Z. Shi, C. Song, B. Liu, G. Lu, J. Xu, T. Van Vu, R.J.R. Elliott, W. Li, W.J. Bloss, R.M. Harrison, Sci. Adv. **7**(3):eabd6696 (2021).
33. C.M. Salvador, C.C.K. Chou, Atmos. Environ. **95**, 288–295 (2014).
34. S. Medina, *Air Pollution and Health : A European Information System (APHEIS)*, 3rd year Report 2002-2023, 135 pp. (2004).
35. G. Iorga, *Air pollution and environmental policies, EU and Romania: Where we stand, what the data reveals, what should be done in the future?* In *Europeanization of Environmental Policies and their Limitations: Capacity Building*; Todor, A., Helepciuc, F.E., Eds.; Springer Nature Switzerland AG, Cham, Switzerland, 23pp. (2021).
36. A. Gruszecka-Kosowska, J. Dajda, E. Adamiec, E. Helios-Rybicka, M. Kisiel-Dorohinicki, R. Klimek, D. Pałka, J. Wąs, Atmosphere **12**, 615 (2021).
37. M. Yunesian, R. Rostami, A. Zarei, M. Fazlzadeh, H. Janjani, Microchem. J. **150**, 104174 (2019).
38. X. Seposo, M. Kondo, K. Ueda, Y. Honda, T. Michikawa, S. Yamazaki, H. Nitta, Environ. Int. **120**, 525–534 (2018).