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Analysis of nitrogen dioxide levels in the atmosphere of cities in the Moldova Region, Romania

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Abstract

The novelty of this study consists in the spatio-temporal analysis of the annual, seasonal, daily and hourly concentration values of the chemical pollutant NO2 , in the 8 counties of the Moldova - Romania Region (24 stations), over a period of 14 years (2009 - 2022), in close connection with its emission sources and with the geographical factors that can amplify or diminish it. The study is representative through the temporal consistency of the data series, through their number, and by the fact that it integrates three different sub-intervals that influenced the levels of NO_2: two without restrictions, in which human activity was carried out normally (2009 - 2020 and 2021 - 2022) and one pandemic (centered on 2020) in which the population's activity was restricted. The average annual concentrations of the pollutant NO_2 exceeded the limit values only at the IS-1 station (41.5 µg/m^3), due to the intense road traffic on the Red Bridge, the railway traffic and the high degree of urbanization of the indicated perimeter. The effective monthly, daily and hourly average values of NO_2 emissions fell within the specific quality indices of excellent, very good and good throughout the studied interval. The maximum values of the concentration of this gas (127 µg/m^3 – IS-1 / 17.02.2017) were recorded in winter, due to the intensification of road traffic and the production of thermal energy for heating houses. The specific meteorological conditions (thermal inversions, fog, calm atmosphere) and the local configuration of the relief (the Bahlui valley with a depressional corridor appearance), favored the accumulation and stagnation of the pollutant, without it exceeding the limit values according to Law no. 104/15 June 2011 and without endangering the health of the population. The study provides both an overview and a detailed picture of the atmospheric distribution of NO_2 in the eight counties of Moldova and can represent a reporting support for other studies to be carried out in the field of air chemistry at the base of the atmosphere..

Keywords: *quality indices, chemical pollution, traffic, NO_2 concentrations*

Introduction

This study is *necessary* because a detailed, comprehensive analysis of the distribution and regime of NO_2 levels for the Moldova Region has not been carried out to date in such a form and for such a representative time interval. So far, air quality studies have been carried out only in cities such as Suceava, Iași, Galați, Piatra Neamț and Botoșani, over short time intervals and only for certain pollutants. The novelty of this study consists in the analysis in the 8 counties of the Moldova Region, over a period of 14 years, of the spatial and temporality of NO_2, an atmospheric pollutant with a significant impact on the health of the population and the environment, in close connection with its emission sources and with the geographical factors capable of modifying its level.

The purpose of the study is to identify, based on the statistical processing of the data owned (2009 – 2022), places and intervals where increases in NO_2 levels were recorded, with the finding of causal explanations. The objectives of the research are: *i)* identifying the links of the atmospheric pollutant with the concrete sources of pollution and with the environmental factors that can reduce or amplify the pollution process; *ii)* analyzing the multiannual, annual and diurnal regime; *iii)* spatial and temporal assessment of air quality based on specific quality indices of the chemical pollutant NO_2.

Theoretical background

Currently, significant amounts of chemical pollutants are emitted into the air space of cities, which negatively affect human health and the environment. According to the EEA (European Environment Agency) report "Air Quality in Europe – Report 2022", excessive concentrations of chemical atmospheric pollutants caused approximately 357,000 premature deaths, of which approximately 48,000 were directly linked to NO_2 emissions (https://www.stropdeaer.ro/2024/12/12/raport-agentia-europeana-de-mediu-2024-impactul-poluarii-aerului-asupra -sanatatii-umane/).

Nitrogen dioxide is a harmful gas for the environment, human health and animals, with a toxicity level 4 times higher than that of nitrogen monoxide. Exposure to high concentrations can be fatal, and at low concentrations it affects lung tissue and aggravates asthma. Nitrogen oxides are responsible for the formation of smog, acid rain, deterioration of water quality, the greenhouse effect, and reduced visibility in urban areas. In 2019, globally, 1.85 million new cases of pediatric asthma were attributed to nitrogen dioxide, two-thirds of which occurred in urban areas (Anenberg et al., 2022). For this reason, research has been conducted that has considered: the mechanisms of nitrogen dioxide toxicity in humans (Utell et al., 1991; Mayer et al., 2018; Kowalska et al., 2020); long-term nitrogen dioxide concentrations and mortality (Atkinson et al., 2018; Jian Song et al., 2023); increased nitrogen fixation due to human activities and its impact on the environment (Galloway et al., 1995; Mohammed et al., 2024; Pruthviraj et al., 2024).

At *the level of the European continent*, research has been carried out on the modeling of tropospheric NO_2 columns in central Europe (Bruns et al., 2006; Van Noije et al., 2006), south-eastern Europe (Zyrichidou et al., 2009), of hourly NO_2 concentrations recorded by the European monitoring network between 2000 and 2014 (Malley et al., 2018), of emissions generated by land transport in Europe (Kurtenbach et al., 2016). At the regional level, the level of NO_2 concentrations was analyzed in Greece - the city of Thessaloniki (Topaloglou et al., 2005), in Garmisch - Germany (Sussmann et al., 2005), in the coastal area of the Mediterranean Sea (Delgado-Saborit et al., 2006), above the Baltic Sea (Ialongo et al., 2014) and Scandinavia (Riuttanen et al., 2013; Thomas & Devasthale, 2017), in the atmosphere of the city of Paris (Lorente et al., 2019), in the Po Valley (Raffaelli et al., 2020; Veratti et al., 2023).

The pandemic period, by restricting anthropogenic activities, resulted in a significant improvement in air quality, and the global impact of COVID-19 restrictions on surface nitrogen dioxide concentrations was major (Keller et al., 2021). Atmospheric NO_2 and NOx levels decreased by 18% to 28% in most cities in Asia (India), South America and up to 31% in Europe as a result of a 40-50% reduction in urban emissions (Fioletov et al., 2022). Comparison of NO_2 levels recorded between 2017 and 2020 revealed a 73% reduction in NO_2 emissions in 2020 compared to 2017 in central London due to reduced population mobility (Cliff et al., 2023). The reduction in NO_2 levels in the UK was 42% during the COVID-19 lockdown (Lee et al., 2020). Satellite observations during the pandemic have provided clear evidence of air chemistry monitoring related to lockdown-induced changes in NO_2 in Europe (Barré et al., 2021). The observations captured the positive effects of the 2020 pandemic restrictions on air quality due to a 40% to 50% reduction in NO_2 emissions in Mediterranean Europe (Italy, France and Spain) for the period 16 March to 15 June 2020 compared to the average values for the same period in 2018 and 2019 (Petetin et al., 2020; Fioletov, 2022).

For *Romania*, a large study aimed to investigate the temporal and spatial variation of NOx, SO_2 and CO pollutant levels for the cities of Cluj Napoca, Poiana Stampei, Iași, Miercurea Ciuc between January 1, 2006 and December 31, 2013 , and to analyze their relationships with meteorological factors (Iorga, 2016). Until 2010, fewer studies were conducted for the *Moldova Region* (Gugiuman & Cotrău, 1975; Erhan, 1979), but in recent years their number has increased. *The PM_{10}* particulate matter concentration regime during 2015 - 2019 in the same region was investigated by Nistor et al. (2020). The variation of tropospheric ozone concentration in relation to geographical factors in the NE Region of Moldova was the subject addressed by Nistor et al. (2021). In 2023, two complex studies were published on the analysis of five chemical pollutants (PM_{10}, O_3, CO, NO_2, SO_2) in correlation with several climatic elements (air temperature, global radiation, relative moisture, atmospheric pressure and wind speed), both over a period of 12 years (2009 - 2020). The first study was based on hourly data from 4 air quality monitoring stations in Suceava County (EM-3, SV-1, SV-2, SV-3) (Lazurca et al., 2023). The second analyzed hourly data recorded at 19 APM monitoring stations in the NE Region, detailing in the analysis the air quality during the emergency period during the pandemic, when the population of Suceava municipality was quarantined (Mihăilă et al., 2023).

Methodology

Methods

In carrying out this study, several stages were followed in order to achieve the proposed objectives:

i) downloading, checking, organizing hourly NO_2 data from the website http://www.calitateaer.ro/public/monitoring-page/reports-reports-page/?__locale=ro with the calculation of their synthetic indices: averages, frequencies, extraction of extreme values;

ii) field trips during 2020 - 2024 to the 24 APM stations to identify and analyze the particularities of geographical factors (natural and anthropogenic), pollution sources in the representative area of the APM stations and to create rating sheets of the representativeness of the station location: EM-3 Poiana Stampei - EMEP type station (representative area - crossborder area); SV-3 Siret, IS-1 Podu de Piatră, IS-6 Bosia Ungheni, GL-1 Galați - traffic type stations (area 10 - 100 m); SV-2 Suceava, IS-3 Oancea Tătărași, NT-2 Roman, NT-3 Tașca, BC-2 Bacău, BC-3 Onești, GL-4 Galați, GL-5 Tecuci - industrial type stations (area 100 m - 1 km); BT-1 Botoșani, SV-1 Suceava, IS-2 Decebal Cantemir, NT-1 Piatra Neamț, VS-1 Vaslui, BC-1 Bacău, GL-2 Galați – urban stations (area 1 – 5 km); IS-5 Tomești, GL-3 Galați – suburban station (area 1 – 5 km); IS-4 Aroneanu / Copou, VN-1 Focșani – rural station (area 10 m – 5 km) ;

iii) processing, analysis and interpretation of time series of data on atmospheric NO_2 concentration and correlation of the results obtained with field observations;

iv) establishing correlations between maximum NO_2 values recorded at the APM stations and their related synoptic context, downloaded from the website www.wetterzentrale.de ;

v) creating graphic supports using Excel / XLSTAT software, obtaining graphic representations of the regime and cartographic representations of the positioning of the monitoring network of this pollutant.

The reference method for measuring nitrogen dioxide and nitrogen oxides is that provided for in the standard SR EN 14211 «Ambient air. Standardized method for measuring the concentration of nitrogen dioxide and nitrogen monoxide by chemiluminescence ». According to Law no. 104/15 June 2011, different thresholds are established for nitrogen oxides: *i)* limit values: 200 μg/m^3 NO_2 - hourly limit value for the protection of human health and 40 μg/m^3 NO_2 - annual limit value for the protection of human health; *ii)* critical level : 30 μg/m^3 NOx - annual critical level for the protection of vegetation (Table 1). The coding system of the specific quality index corresponding to the pollutant NO_2 has been recently updated, according to Order no. 1818/2020 (Table 2). In this study, we adopted the classification of NO_2 emissions according to the quality indices of Law 104/2011, because the analysis period corresponds mostly to the legislative framework established by this law (except for the last two years, 2021/2022).

Table 1: Quality indices for the pollutant NO_2 (according to Law 104/2011 and Order 1818/2020)

Law 104/2011			Order 1818/2020		
Specific index	Quality index	NO_2 - 1h (μg/m^3)	Specific index	Quality index	NO_2 1h (μg/m^3)
1	excellent	0 - 50	1	good	0-40
2	very good	50 - 100	2	acceptable	40-90
3	good	100 - 140	3	moderate	90-120
4	Medium	140 - 200	4	Bad	120-230
5	Bad	200 - 400	5	very bad	230-340
6	very bad	> 400	6	extremely bad	340-1,000

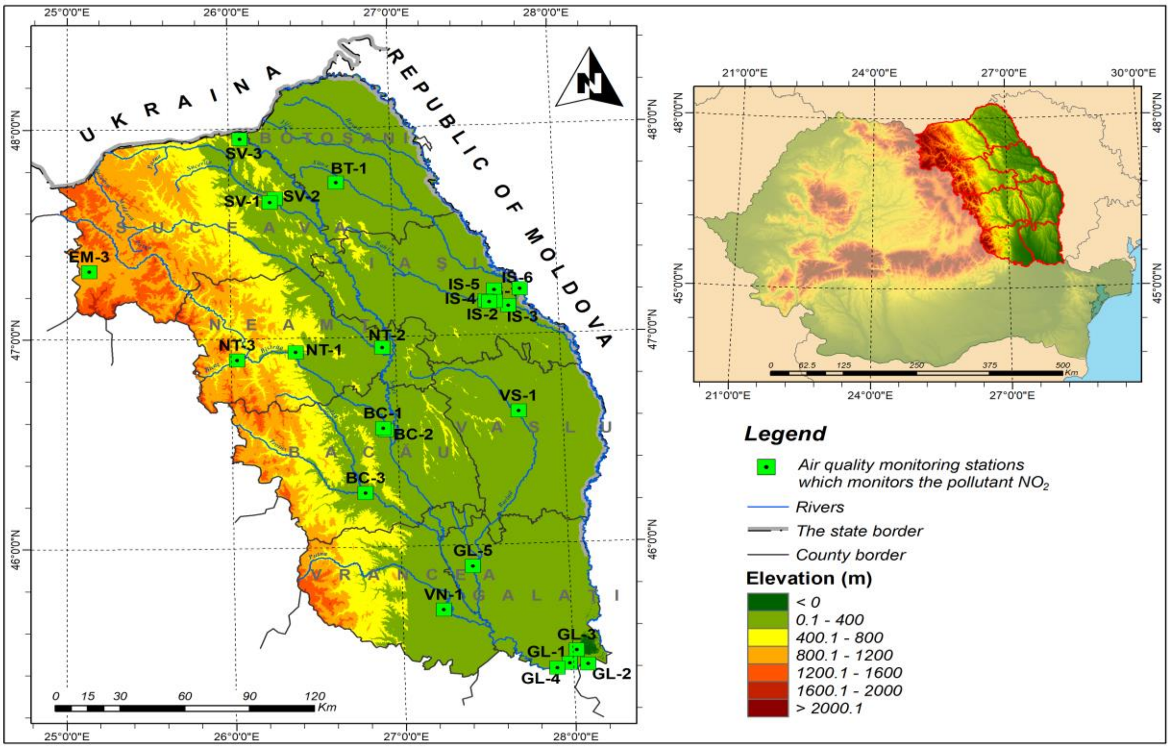


Figure 1: NO_2 monitoring stations in the Moldova - Romania Region

The data were obtained from the County Environmental Protection Agencies of Moldova, for 24 air monitoring stations (APM) in the Moldova - Romania Region, for the time period 2009 - 2022. According to Annex 4 of Law no. 104/2011, the monitoring data quality objective in terms of the minimum data capture over the 1-year averaging period is 90%. Given that the 90% capture requirement does not include data losses due to calibration, verifications and routine maintenance, valid data captures of at least 75% are considered compliant. The data from the Huși station (VS – 2) were not used in this study, due to their discontinuity.

For this study, 2,951,424 hourly values of the pollutant NO_2 from all 24 APM stations were used. For a single APM station, 122,976 hourly data were used for the entire analyzed period (14 years).

Study area

The Moldova region is located in the northeastern and eastern part of Romania, in the vicinity of the border with Ukraine and the Republic of Moldova and extends between 48°15'55.893"N and 45°22'6.52"N northern latitude and between 24°58'16.925"E and 28°17'2.602"E eastern longitude (Fig. 1). It has an area of 46,265 km^2 and includes eight counties: Suceava, Botoșani, Neamț, Iași, Vrancea, Bacău, Vaslui and Galați.

In the Moldova region there is one EMEP type station (EM-3), 8 industrial type stations (SV-2, IS-3, NT-2, NT-3, BC-2, BC-3, GL-4, GL-5), 7 urban type stations (BT-1, SV-1, IS-2, NT-1, VS-1, BC-1, GL-2), 4 traffic type stations (SV-3, IS-1, IS-6, GL-1), 2 suburban type stations (IS-5, GL-3) and 2 rural type stations (IS-4, VN-1). It is possible to put into operation in the near future two urban type APM stations in the cities of Bacău and Onești.

Results

Effective annual NO_2 levels

During the period 2009-2022, annual NO_2 levels, beyond a certain variability, increased from year to year across the entire researched region. An interesting fact was marked by the pandemic period when the decrease in NO_2 levels compared to the previous and subsequent periods was truly statistically representative. Road traffic is the main source of NO_2 emissions originating from the combustion of fossil fuels in vehicle engines, especially diesel ones that emit significant amounts of nitrogen oxides (NOx), which are converted into nitrogen dioxide (NO_2) in the air. The comparative analysis of the annual average values of NO_2 concentrations revealed a downward trend during the pandemic period, compared to the ante-pandemic and post-pandemic periods. For example, at traffic stations SV-3 and GL-1 in 2020, atmospheric NO_2 levels decreased by 25% on average compared to 2019, but increased by 40% in 2021-2022 compared to 2020. Traffic station IS-1 did not operate during the period 16.03.2020 - 31.07.2020 due to faulty analyzers (April, May, June, July), therefore we could not observe the trends of decrease and increase in NO_2 levels, before and after 2020. At industrial stations NT-2, IS-3, NT-3, BC-3 and GL-3 in 2020, atmospheric levels decreased by 10% on average compared to 2019, but increased by 15% in 2021-2022 compared to 2020. After an increase of NO_2 pollution in 2021 due to the resumption of socio-economic activities, the reduction of the average annual concentration of NO_2 in 2022, at most industrial stations was achieved due to the implementation of measures in the Air Quality Plan / local plans, which take into account energy efficiency, reduction of natural gas consumption, improvement and modernization of combustion sources, local industrial modifications.

Seasonal levels of NO_2

In the winter season, the average NO_2 concentrations ranged between 11.3 – 46.5 μg/m^3. The highest average seasonal value was calculated for the IS-1 station (traffic type) of 46.5 μg/m^3, a value that exceeded the annual limit of 40 μg/m^3 for the protection of human health (Table 2) . The main generating factors of these average atmospheric NO_2 levels in the case of IS-1 are road and rail traffic.

In the winter season, the maximum NO_2 concentrations of over 100 μg/m^3 were recorded at stations IS-1, IS-2, IS-3, IS-5 and IS-6, due to meteorological (synoptic) conditions and anthropogenic sources (road traffic, industrial activities, high degree of urbanization). In the summer, the maximum value of NO_2 concentrations (97.4 μg/m^3) was recorded at station GL-5, this level being favored by the configuration of the local relief, the anticyclonic meteorological-synoptic conditions and the more intense industrial activities (Table 3).

Monthly and annual NO_2 levels

The monthly average concentrations from which the annual NO_2 concentrations were calculated were within the legal values allowed at all APM stations in the Moldova Region, except for the IS-1 station, where the highest multi-annual average (2009 - 2022) was calculated, of 41.5 μg/m^3, which exceeds the threshold of 40 μg/m^3, which represents the annual limit value for the protection of human health. The reason is the intense road traffic on the Red Bridge, the railway traffic and the high degree of urbanization of the site surroundings (Table 3, Fig. 2).

During the summer months and in the warm season in general, atmospheric NO_2 levels are visibly lower at all types of monitoring stations, compared to the winter months (and cold season) (Fig. 2, Table 4).

Table 2: Annual average and maximum concentrations of NO_2 at APM stations in the Moldova Region (2009 – 2022)

NO_2		EM -3	SV - 1	SV - 2	SV - 3	BT-1	NT-1	NT-2	NT-3	BC-1	BC-2	BC-3	IS-1	SI-2	SI-3	SI-4	IS-5	IS-6	VS-1	VN-	GL-1	GL-2	GL-3	GL-4	GL-5
Winter	MED	11.7	21.8	28.8	27.1	27.9	18.5	24.4	15.1	27.8	23.2	18.9	46.5	34.5	26.9	11.3	25.1	13.4	21.3	14.4	17.1	21.7	16.1	16.0	20.5
	MAX	40.2	80.6	93.9	88.1	103.1	62.2	94.2	55.5	67.9	96.1	59.1	127.0	108.7	106.1	44.0	117.3	101.9	76.6	66.4	82.5	58.6	59.5	43.3	60.0
Summer	MED	7.7	11.9	14.3	17.0	19.0	10.2	14.7	12.7	15.9	12.9	10.2	36.0	19.9	15.4	7.3	12.6	7.2	14.1	9.4	15.5	12.8	11.2	13.1	21.5
	MAX	29.3	56.3	52.4	46.8	62.8	42.5	34.8	41.1	29.2	59.6	31.7	77.1	43.5	42.2	17.7	29.7	14.6	32.6	39.5	42.1	47.0	42.7	33.0	97.4

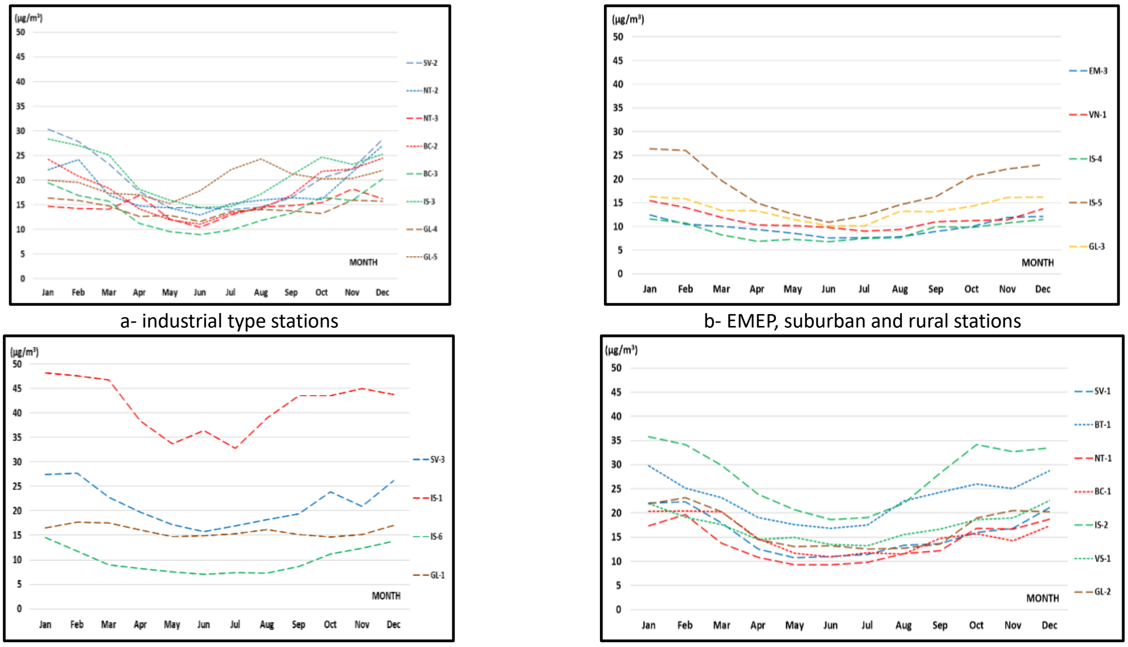
Table 3: Average monthly and annual concentrations for the pollutant NO_2 at APM stations in the Moldova Region (2009 – 2022)

NO_2	January	February	March	April	May	June	July	August	September	October	Nov	December	YEAR
EM-3	12.5	10.5	10.1	9.4	8.6	7.6	7.7	7.8	8.9	9.9	11.9	12.1	**9.7**
CS-1	22.0	22.3	18.0	12.6	10.8	11.0	11.4	13.3	13.7	16.0	16.8	21.1	**15.8**
SV-2	30.3	27.8	23.3	17.7	14.4	14.4	14.0	14.6	16.5	20.4	22.3	28.3	**20.3**
SV-3	27.4	27.7	22.8	19.8	17.2	15.8	17.0	18.2	19.4	23.9	20.9	26.1	**21.4**
BT-1	29.8	25.1	23.1	19.1	17.6	16.8	17.5	22.5	24.3	26.0	25.1	28.8	**23.0**
NT-1	17.3	19.7	13.8	10.8	9.2	9.2	9.8	11.6	12.2	16.8	16.6	18.7	**13.8**
NT-2	22.1	24.2	17.0	14.7	14.4	13.0	15.2	15.9	16.4	16.0	21.6	27.1	**18.1**
NT-3	14.7	14.3	14.1	16.9	12.1	10.4	12.9	14.5	14.8	15.4	18.2	16.2	**14.6**
BC-1	31.1	29.3	25.4	20.1	15.8	16.1	16.1	15.5	27.7	22.6	17.9	23.2	**21.7**
BC-2	24.2	20.8	18.3	14.2	12.0	11.1	13.3	14.2	17.0	21.8	22.3	24.5	**17.8**
BC-3	19.5	16.9	15.7	11.2	9.5	9.0	9.8	11.8	13.3	16.5	15.9	20.2	**14.1**
SI-1	48.2	47.6	46.7	38.3	33.7	36.4	32.8	39.0	43.5	43.5	44.9	43.8	**41.5**
SI-2	35.8	34.2	29.8	23.9	20.7	18.7	19.0	22.0	28.3	34.1	32.7	33.5	**27.7**
SI-3	28.3	27.0	25.1	18.1	16.0	14.5	14.6	17.2	21.0	24.7	23.2	25.3	**21.2**
SI-4	11.6	10.7	8.3	6.9	7.3	6.8	7.5	7.7	10.0	9.8	10.8	11.5	**9.1**
IS-5	26.4	26.1	19.8	14.9	12.6	10.9	12.3	14.6	16.3	20.6	22.1	23.1	**18.3**
IS-6	14.6	11.8	9.0	8.2	7.6	7.0	7.4	7.3	8.6	11.2	12.4	13.8	**9.9**
VS-1	22.0	19.1	17.6	14.5	14.9	13.5	13.2	15.6	16.7	18.7	18.9	22.5	**17.3**
VN-1	15.4	14.0	11.9	10.3	10.2	9.8	9.1	9.3	11.0	11.2	11.4	13.7	**11.4**
GL-1	16.5	17.7	17.6	16.1	14.7	14.9	15.4	16.2	15.2	14.6	15.2	17.1	**15.9**
GL-2	21.9	23.2	20.3	14.5	13.0	13.2	12.5	12.7	13.6	19.0	20.5	20.3	**17.0**
GL-3	16.3	15.9	13.3	13.3	11.5	10.1	10.1	13.2	13.1	14.2	16.1	16.2	**13.6**
GL-4	16.4	15.9	14.7	12.6	12.8	11.6	13.7	14.0	13.8	13.2	16.0	15.7	**14.2**
GL-5	20.0	19.5	17.3	17.0	15.3	17.8	22.1	24.3	21.3	20.3	20.3	22.0	**19.8**

Daily NO_2 levels

From the analysis of the daily average values of NO_2 concentrations, it emerges that they are directly influenced by anthropogenic activities. At the first three types of stations analyzed (EMEP, rural and suburban), the highest NO_2 levels were recorded at the suburban ones, because human activities are diverse and much more intense, they are located in close proximity to cities, the suburban space constituting the transition between urban and rural.

Of the other three types of stations analyzed (urban, industrial and traffic), those of the traffic type had the highest daily average values, because road traffic is the main source of NO_2 pollution (car traffic transits the central sectors of cities, on the main traffic arteries, and outside them, it takes place along national roads and in localities located on their routes). Considering the daily levels of NO_2, the next ones are urban and then industrial stations. An increase in daily average values is observed in the cold season, due to the intensification of the activities of the electricity and thermal energy industry and road traffic (the population traveling more often by car, because the weather conditions are more unfavorable than those in the warm season) (Fig. 3-4).



a- industrial type stations

b- EMEP, suburban and rural stations

c- traffic type stations

d- urban stations

Figure 2: Annual regime based on monthly average values of NO_2 levels at APM stations in Moldova (2009 - 2022)

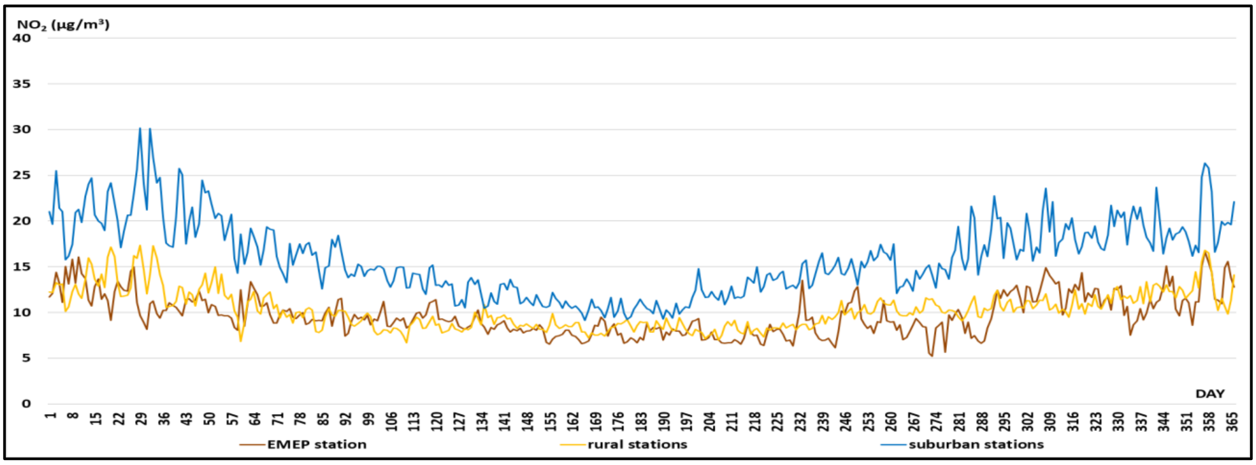


Figure 3: Interdiurnal regime of NO_2 at APM stations in Moldova (daily averages calculated for all stations: EMEP type – one station, rural – two stations and suburban – two stations) (2009 - 2022)

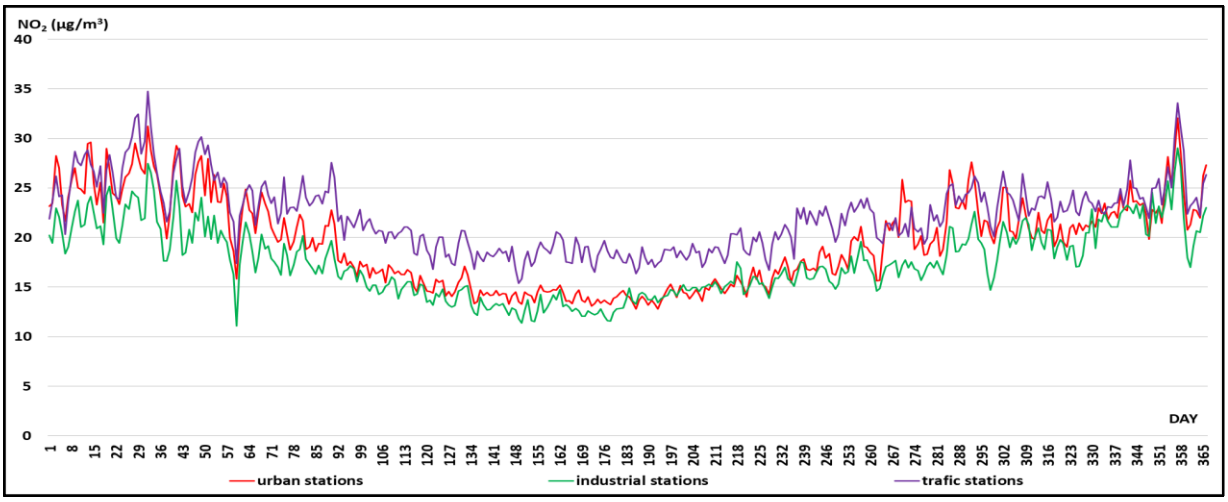


Figure 4: Interdiurnal regime of NO2 at APM stations in Moldova (daily averages calculated for all stations: urban type – seven stations, industrial – eight stations and traffic – four stations) (2009 - 2022)

Hourly levels of NO_2

According to the legislation in force, the hourly average values of NO_2 concentrations fell into the specific class of index 1 (Excellent). These hourly averages did not exceed the threshold of 50 µg/m^3 during the period 2009 - 2022 at the 5 APM stations analyzed (IS-3, IS-2, SV-3, GL-3, IS-4), where the validity of the data captures was over 75% (Fig. 5 a-e).

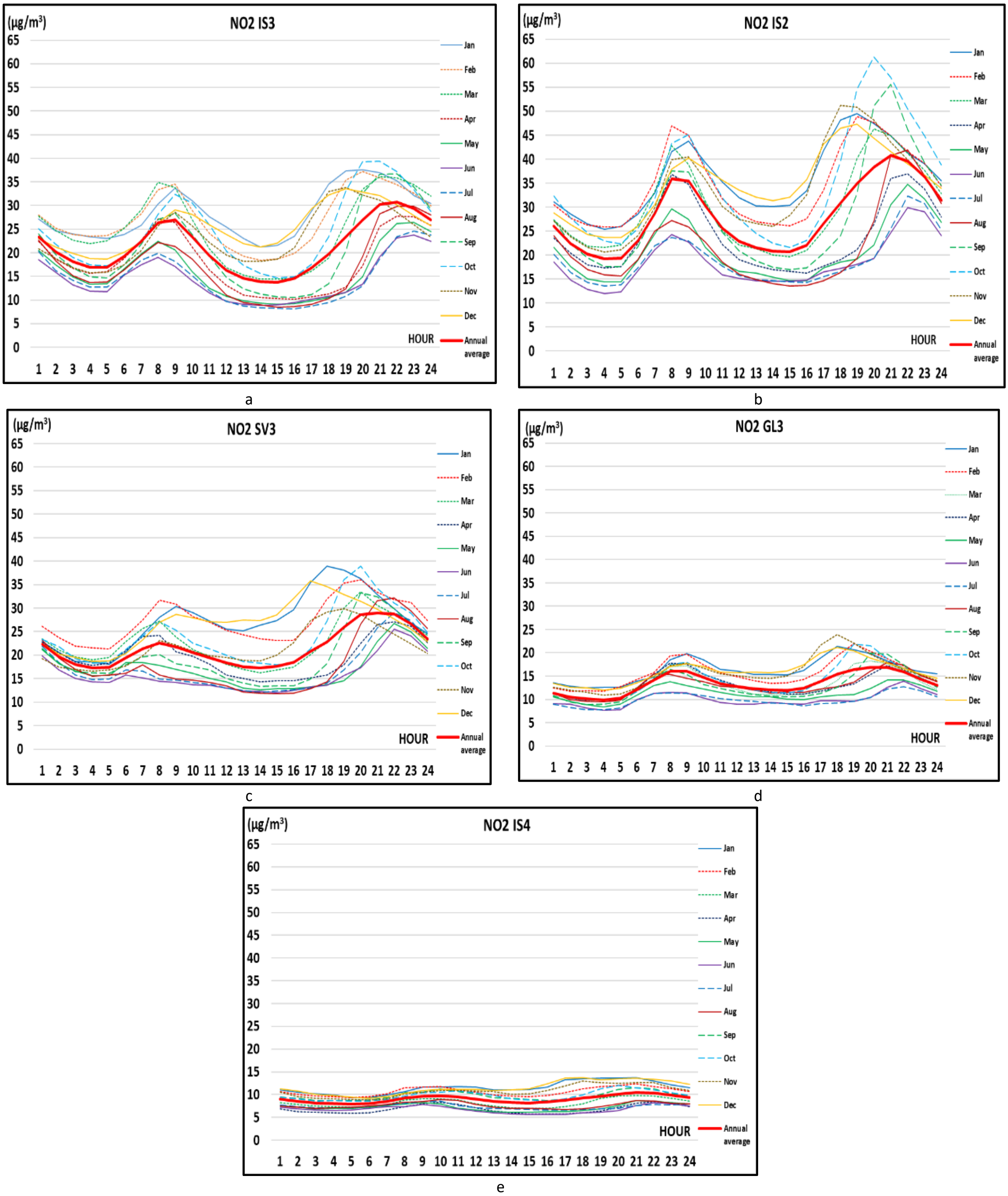


Figure 5a-e. Histograms of the diurnal regime of NO2 concentrations at different APM stations in the Moldova - Romania Region (2009 - 2022)

The hourly average values of NO_2 concentrations did not exceed the limit of 200 µg/m³ at any of the APM stations analyzed during the period 2009 - 2022. The highest values exceeded 60 µg/m³ only at the urban station IS-2 (61.3 µg/m³ - 8 pm - October), without presenting a danger to the health of the population. For the rural station IS-4, the lowest hourly average values were calculated, up to 20 µg/m³ because there is no intense road traffic and the only source of pollution is the Iași International Airport located at a distance of 3 km.

These representations synthesize the entire statistical spectrum of variability in the 2009-2022 interval of the average hourly concentrations of NO_2, placing the rural monitoring station IS-4 in the position of the station with the cleanest air among those analyzed, with a very low variability of the values of the NO_2 concentration in the atmosphere, and the urban stations IS-2 and industrial station IS-3 in the position of those with the most polluted air and with the highest variability of the monitored pollutant (Fig. 6). Those expressed graphically in Figure 6 are found in detail extracted in Table 4.

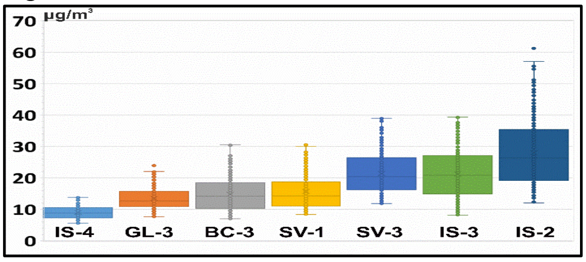


Figure 6: Boxplots of the average hourly NO2 concentrations at seven APM stations in Moldova (2009 - 2022)

Table 4: Relevant statistical parameters of the hourly average concentration of NO_2 in the atmosphere at seven air quality monitoring stations in Moldova (2009 – 2022)

	IS-4	GL-3	BC-3	SV-1	SV-3	IS-3	IS-2
Xmax	13.8	20.1	30.6	30	39	39.4	57.1
Q3	10.6	15.7	18.5	18.7	26.4	27.1	35.4
Median	**8.8**	**12.7**	**14.2**	**14.3**	**20.4**	**20.9**	**26.3**
Q1	7.3	10.9	10.3	11	16.2	14.9	19.2
Xmin	5.6	7.7	7	8.4	11.8	8.2	12
STDEV	**2.0**	**3.4**	**5.4**	**5.5**	**6.3**	**7.9**	**10.4**

(STDEV - standard deviation, Xmin - percentile 0, Q1 - lower quartile, Q3 - upper quartile, Xmax - percentile 100)

Maximum NO_2 levels

In the time interval 2009 - 2022, the maximum hourly values of NO_2 were recorded on days of the cold season, in the interval October - February: 127.0 µg/m³ at the traffic station IS–1 (17.02.2017), 117.3 µg/m³ at the suburban station IS–5 (10.02.2017), 108.7 µg/m³ at the urban station IS–2 (10.02.2014), 106.1 µg/m³ at the industrial station IS–3 (25.01.2020), 103.1 µg/m³ at the urban station BT–1 (03.01.2020), 102.6 µg/m³ at the industrial station GL-5 (21.10.2022) and 101.9 µg/m³ at the IS-6 traffic station (11.01.2013). At the other APM stations in the Moldova Region, the maximum hourly values of NO_2 were below 100 µg/m³.

Most hourly maximum values were recorded on days in the winter months: January – 7 cases (IS-3, BT-1, IS-6, SV-3, VN-1, BC-3, IS-4), December – 6 cases (BC-2, NT-2, GL-1, VS-1, NT-1, NT-1, EM-3), February – 5 cases (IS-1, IS-5, IS-2, SV-2, SV-1). At some stations, hourly maximum values were also recorded on days outside the winter timeframe (at 6 stations – Table 5).

Table 5: Maximum hourly values (day / month / year) at APM stations in Moldova of NO 2 concentration (2009 – 2022)

No. crt	APM Station	Maxim	Date	No. crt	APM Station	Maxim	Date
1	IS-1	**127.0**	17.02.2017	13	GL-1	82.5	23.12.2014
2	IS-5	**117.3**	10.02.2017	14	SV-1	80.6	10.02.2017
3	IS-2	**108.7**	10.02.2014	15	VS-1	76.6	27.12.2012
4	IS-3	**106.1**	25.01.2020	16	VN-1	66.4	22.01.2021
5	BT-1	**103.1**	03.01.2020	17	NT-1	64.4	23.12.2009
6	GL-5	**102.6**	21.10.2022	18	GL-2	62.8	17.10.2009
7	IS-6	**101.9**	11.01.2013	19	GL-3	60.1	24.11.2009
8	BC-2	96.1	21.12.2010	20	BC-3	59.1	09.01.2016
9	NT-2	94.2	14.12.2016	21	NT-3	57.9	30.11.2009
10	SV-2	93.9	10.02.2017	22	IS-4	44.0	26.01.2010
11	SV-3	88.1	08.01.2020	23	GL-4	43.8	01.11.2019
12	BC-1	82.8	28.09.2021	24	EM-3	40.2	12.12.2011

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Discussion

The World Health Organization recommends that the annual average atmospheric level of NO_2 should not exceed 10 µg/m³. EU Member States, including Romania, as well as the United Kingdom, currently apply an annual limit value of 40 µg/m³. There is a legislative proposal from the European Commission, with an agreement finalised in 2024, which will reduce the annual limit to 20 µg/m³ from 2030, aligning more closely with WHO standards (https://www.eea.europa.eu/en/newsroom/news/air-pollution-standards-still-not-fully-met-across-europe).

It is difficult to make a comparison between the average values of NO_2 recorded in different cities around the world and those in Romania, for at least two reasons. The first is that Romanian cities do not have multimillion-dollar demographic dimensions (with the exception of Bucharest, which exceeds 2.1 million inhabitants - https://bucuresti.insse.ro/populatia/). The higher the number of inhabitants - the case of megalopolises with over 10 million inhabitants, the more intense human activity will be and will generate heavy traffic, the main source of NO_2 emissions. The second reason derives from the average limit values established by law, different from one country to another (USA, Brazil - 100 µg/m³; Egypt - 60 µg/m³; South Africa, China - 40 µg/m³; Australia - 28 µg/m³). In some countries (Chile, Argentina) these limit values are not clearly specified (https://deframedia.blog.gov.uk/2021/09/23/who-updates-guideline-levels-for-air-pollutants/). However, for the authors, the interconnection of data, results with finding differences / similarities in the distribution and regime of this pollutant was an accomplished endeavor.

In Romania, the increase in NO_2 concentration levels in the most populated and industrialized urban areas is consistent with trends identified at European and extra-European level (Kurtenbach et al., 2016; Krotkov et al., 2016; Malley et al., 2018) and is due to the increasing number of vehicles, the amplification of industrial activities, especially in meteorological conditions favorable to the accumulation of NO_2 emissions (Qu Z. et al,. 2020; Yu Wang et al., 2021; Rodriguez-Villamizar et al., 2024; Cárdenas et al., 2025).

The present study brings a scientific addition to the analysis of annual, seasonal and diurnal NO_2 levels on the territory of a large Romanian region and representative of its geographical particularities. The study is representative due to the long interval analyzed and the fact that it integrates three different sub-intervals that influenced NO_2 levels: two without restrictions, in which human activity was carried out normally (2009 and 2021 – 2022) and one pandemic (centered on 2020) in which population activity was restricted.

Our study focused on the spatio-temporal analysis of the concentration of a single chemical pollutant - NO_2, in comparison with the research carried out so far in our country, which aimed at the comparative analysis of emissions of several pollutants: PM_{10}, O_3, CO, NOx, SO_2 (Mihăilă et al., 2023). For the analysis of the multiannual, annual and diurnal regime of NO_2, time series of NO_2 recorded over a period of 14 years (2009 - 2022) were used for the first time, at 24 APM stations, to provide both an overview and details of the atmospheric distribution of NO_2 in the eight counties of the Moldova - Romania Region.

Currently, most studies on air pollution at national and international levels have been conducted based on data from urban stations (Topaloglou et al., 2005; Iorga, 2016; Wang N. et al., 2019; Ying Xu et al., 2020; Cárdenas et al., 2025). Our research aimed to process and compare the levels of NO_2 concentrations recorded at all types of stations in the territory (EMEP, industrial, urban, traffic, suburban and rural) located in different environmental conditions.

Among the APM stations where the annual average values of NO_2 concentrations exceeded the limit value established by Law No. 104/2011 (40 µg/m³), we noted only the IS-1 traffic station where the exceedances of the limits of this pollutant were more frequent and relevant.

Since most of the studied interval falls within Law 104/2011 (valid until 2020), the analysis of the quality indices was carried out according to it. The hourly average values of NO_2 up to 100 µg/m³ fell within the *Very good* index according to Law 104/2011 and the *Acceptable* quality index according to Order 1818/2020 (40-90 µg/m³). The hourly average values of NO_2 between 100 and 120 µg/m³ fell within the *Good* index according to Law 104/2011 and the *Moderate* quality index according to Order 1818/2020. The maximum hourly value of 127 µg/m³ fell within the *Good* quality index according to Law 104/2011 and the *Bad* quality index according to Order 1818/2020. We note that after the new legislation, the thresholds established for specific quality indices decreased with the aim of limiting NO_2 emissions by economic agents and raising public awareness of the negative impact of this pollutant on human health.

In the Moldova Region, NO_2 concentrations have a tendency to increase from rural to urban localities (county capitals and municipalities), where the main pollutant source is road traffic, and from the surrounding lands to road transport axes. Although NO_2 emission values are lower than in other regions and intensely urbanized and industrialized perimeters in Europe and other non-European continents, there are cities that have exceeded the annual average limit value (40 µg/m^3) established by Law no. 104/2011 and that have developed and implemented integrated air quality plans according to the legislation in force, in order to reduce the negative impact of NO_2 pollution on the health of the population (Iași, Bacău, Galați).

The study places Moldova, as a region, back on the map of air quality analysis, anchored in a relevant time scale. We are confident that specialists will find in this study benchmarks for their studies and we are convinced that we are contributing to the knowledge of a facet of the air environment on which people's health and quality of life depend.

Conclusions

In the Moldova - Romania Region, the average annual levels of the pollutant NO_2 fell within the specific quality indices of excellent, very good and good at all APM stations in the territory. In the cold season, the average monthly concentrations/levels of NO_2 concentrations had high values due to the intensification of road traffic, industrial activities - the production of thermal and electrical energy for heating housed, on their own or centralized system, meteorological conditions (thermal inversions, fog, calm air) and the configuration of the relief that favored the accumulation and stagnation of pollutants. In the warm season, the average monthly concentrations of NO_2 had lower values, because the air temperature increases, the atmospheric pressure decreases - the warm air masses move vertically upward and the pollutants disperse (no longer stagnate at ground level), and precipitation episodes occur that "clean" the atmosphere of chemical pollutants. The highest monthly average values of NO_2 concentrations were recorded in the cold season, but without a significant negative impact on the environment and the population, as they fell within the excellent specific indices: NO2 (0 – 50 µg/m^3). During the period 2009 – 2022, the maximum hourly values of NO_2 (which rose to 127 µg/m^3) were recorded in the cold season at the IS-1 traffic station on 17.02.2017, the main cause being the intensification of road traffic, due to the unfavorable weather conditions. Monitoring of this pollutant led to the knowledge of its levels for different temporal and spatial entities, and the authorities can include in their plans of measures to improve air quality, the results obtained in this study for different cities.

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Author contribution

All authors contributed to the conceptualization, methodology, design, and writing of this paper. Data collection was performed by NA and NB, analysis was performed by NA, NB, and MD, and graphical representations were prepared by NA, NB, MD, and BPI. The first draft of the manuscript was drafted by MD and written by NA and NB, and all authors discussed and provided input. All authors reviewed the manuscript and ultimately agreed on the version submitted for review and publication.

Conflicts of interest

The authors declare no conflict of interest.

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