Analysis of carbon monoxide concentration in the atmosphere of towns in the Moldova-Romania region

Analyse de la concentration de monoxyde de carbone dans l'atmosphère des villes de la région Moldova-Roumanie

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ABSTRACT: Between 2009 and 2022, at 21 stations in Moldova, the average annual values of carbon monoxide concentration were reduced (0.07–0.62 mg/m³). In winter, carbon monoxide concentrations were higher (0.14–0.91 mg/m³), while in summer they were lower (0.04–0.45 mg/m³). The maximum daily value of carbon monoxide emissions into the atmosphere (7.5 mg/m³ – SV-2 / 21.12.2009) was determined during the cold season and was the result of incomplete combustion of fossil fuels in household appliances, road traffic, weather conditions, and the configuration of the relief, which favored the accumulation of this gas. The limit values according to Law No. 104/June 15, 2011 (10 mg/m³) were not exceeded and the health of the population was not endangered. The monthly, daily, and hourly average values of carbon monoxide fell within the specific quality indices of excellent and average throughout the entire study period. Monitoring the atmospheric concentration of carbon monoxide remains essential for air quality surveillance and the management of potential pollution episodes.

Keywords: carbon monoxide, emissions, Moldova Region.

RÉSUMÉ: Entre 2009 et 2022, dans 21 stations de mesure en Moldavie, les concentrations annuelles moyennes de monoxyde de carbone ont diminué (0,07–0,62 mg/m³). En hiver, les concentrations étaient plus élevées (0,14–0,91 mg/m³), tandis qu'en été, elles étaient plus faibles (0,04–0,45 mg/m³). Le pic journalier d'émissions de monoxyde de carbone dans l'atmosphère (7,5 mg/m³ – SV-2 / 21.12.2009) a été enregistré pendant la saison froide et résultait d'une combustion incomplète des combustibles fossiles dans les appareils ménagers, du trafic routier, des conditions météorologiques et de la configuration du relief, qui favorisait l'accumulation de ce gaz. Les valeurs limites fixées par la loi n° 104 du 15 juin 2011 (10 mg/m³) n'ont pas été dépassées et la santé de la population n'a pas été mise en danger. Les valeurs moyennes mensuelles, journalières et horaires du monoxyde de carbone se sont situées dans les limites des indices de qualité « excellente » et « moyenne » durant toute la période d'étude. La surveillance de la concentration atmosphérique de monoxyde de carbone demeure essentielle pour le suivi de la qualité de l'air et la gestion des épisodes de pollution potentiels.

KEYWORDS: monoxyde de carbone, émissions, région de Moldavie.

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Introduction

Carbon monoxide emissions are generated by anthropogenic sources such as the use of household appliances (stoves, boilers, fireplaces), industrial activities (steel and iron production, oil refining), road traffic, incomplete combustion of fossil fuels (oil, gas, wood, coal), fires, and natural processes (volcanic or post-volcanic emissions). When it accumulates in enclosed spaces, carbon monoxide, a toxic, colorless, odorless, and tasteless gas, is very dangerous to health. In high concentrations (approximately 100 mg/m^3), it becomes lethal by reducing the oxygen-carrying capacity of the blood, with serious consequences for the respiratory and cardiovascular systems.

Scientific studies on this gas have had several objectives, such as analyzing the correlations between its concentration variation and emission sources represented by Airbus commercial aircraft (Nedelec et al., 2003) or its level trend in the northern and southern hemispheres based on satellite observations (Worden et al., 2013; Rajab et al., 2018). A network of sensors located in the Paris region was used to investigate regional anthropogenic carbon monoxide emissions (Té Yao et al., 2012). Specialists have investigated the seasonal variability of carbon monoxide at the Jungfraujoch high-altitude station (3,471 m) in the Bernese Alps (Té Yao et al., 2016). Studies have been conducted on carbon monoxide emissions from the Rotterdam urban-industrial complex and its surroundings (Super et al., 2017), from Madrid, based on data recorded by the MOPITT satellite (Dekker et al., 2017), from above London (Helfter et al., 2016; Pitt et al., 2019) and in the atmosphere of Monte Carlo (Super et al., 2020).

The pandemic period, through the restriction of human activities (with the population isolated and social, cultural, industrial, and economic activities forced to shut down temporarily) led to a significant improvement in air quality (with pollution levels falling by 40-50% in the early stages of quarantine). This aspect was investigated after 2020 in studies aimed at analyzing the effects of restrictive measures on air quality during the COVID-19 pandemic. The reduction in carbon monoxide emissions led to improved air quality (Schumann et al., 2021; Matthias et al., 2021; Levelt et al., 2022; Stloukal et al., 2025; Ulusoy et al., 2025). The results of a comparative analysis of carbon monoxide levels before and after the COVID-19 quarantine period confirmed a decrease in the presence of this gas in the atmosphere in many places: Alexandria - decreases of approximately 10% compared to the emission values recorded in 2019 (Kaamoush et al., 2025), Ecuador - decreases of approximately 13% in the first days of quarantine (González et al., 2022), Port Harcourt (Sowaboma et al., 2022), the Suez Canal (Gamil et al., 2023) or Iraq (Abdulfattah et al., 2025).

Compared to research conducted in other countries, carbon monoxide as an atmospheric pollutant has been less analyzed in Romania or in the Moldova Region. For the main cities in Suceava County, research has been conducted on carbon monoxide (and other gas) emissions resulting from the anaerobic decomposition of organic waste in municipal solid waste landfills (Mihăilă et al., 2014) or produced by the SC Mondeco SRL incinerator (Mihăilă et al., 2015). The studies analyzed carbon monoxide levels alongside other chemical pollutants, in correlation with meteorological elements in the localities of Cluj Napoca, Poiana Stampei, Iași, and Miercurea Ciuc between 2006 and 2013 (Iorga, 2016). In the last decade (for the period 2009-2020/2022), several studies have been conducted in the North-East Region, the municipality of Suceava, and the metropolitan area of the same name. These studies analyzed air quality, carbon monoxide levels, and other chemical pollutants in correlation with meteorological factors, relief configuration, and emission sources (Mihăilă et al., 2020; Mihăilă et al., 2021; Prisăcariu, 2023). Studies on the Suceava metropolitan area also focused on analyzing the health status of the population during episodes of severe pollution (number of cases of illness) (Țiculeanu, 2024). Other research has looked at chemical pollutants in Piatra Neamț between 2009 and 2019, rating the air quality in this tourist destination as very good (Roșu et al., 2020).

The purpose of this study is to analyze the spatial and temporal distribution of carbon monoxide concentrations in the Moldova Region, Romania, based on statistical processing of data recorded at 21 stations within the Air Quality Monitoring Network between 2009 and 2022. The objectives of the research are: i) to identify the causal links between carbon monoxide emissions, specific sources of pollution, and geographical factors that can reduce or increase atmospheric carbon monoxide levels; ii) to analyze the multi-annual, annual, and diurnal patterns of carbon monoxide emissions; iii) to assess air quality spatially and temporally based on carbon monoxide-specific quality indices.

2. Study area

The Moldova region is located in the north-east and east of Romania, extending to the border with Ukraine and the Republic of Moldova, and comprises eight counties: Suceava, Botoșani, Neamț, Iași, Vrancea, Bacău, Vaslui, and Galați (Figure 1).

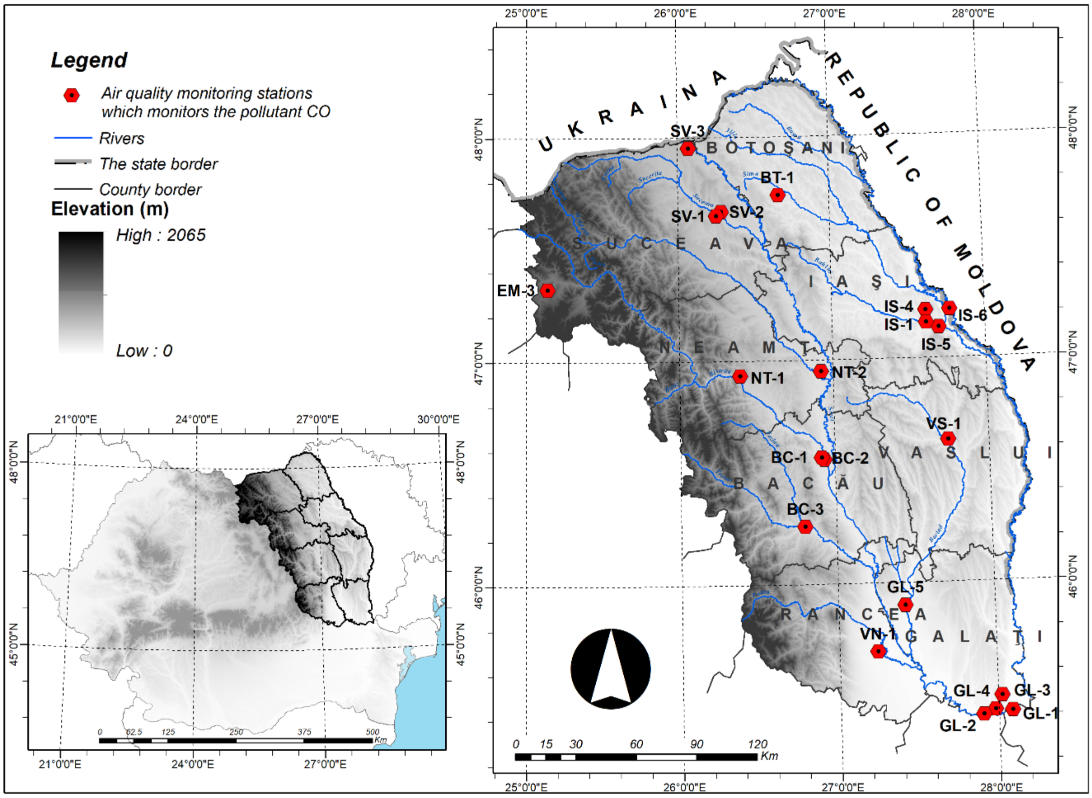


Figure 1 Location of the 21 stations in the Environmental Protection Agency (EPA) network where carbon monoxide was monitored in the Moldova Region (2009–2022).

In the Moldova Region, the air quality monitoring system comprises 25 APM stations, of which 21 monitor carbon monoxide concentrations: one EMEP-type station (EM-3), six industrial-type stations (SV-2, NT-2, BC-2, BC-3, GL-4, GL-5), 6 urban stations (BT-1, SV-1, NT-1, VS-1, BC-1, GL-2), 4 traffic stations (SV-3, IS-1, IS-6, GL-1), 2 suburban stations (IS-5, GL-3), and 2 rural stations (IS-4, VN-1).

Our study analyzes CO emissions based on data recorded at 21 APM stations out of the 25 existing stations in the 8 counties in the Moldova - Romania Region. The research is limited by the small number of stations compared to the surface area of the studied area (46,265 km2), and the radius of the representative area differs from one type of station to another: at traffic stations, 10 - 100 m; at industrial stations, 100 m - 1 km; at urban and suburban stations, 1 - 5 km; at rural stations, 10 m - 5 km; at the EMEP station in a transboundary context, over a longer distance.

3. Methods

In conducting this study, several steps were taken to achieve the proposed objectives: i) studying the legislative framework and specialized literature on carbon monoxide emissions and their impact on air quality in the studied region; ii) direct investigation through field trips to identify the particularities of geographical and anthropogenic factors and to complete observation sheets on the location of monitoring stations; iii) analysis and interpretation of information by processing and systematising bibliographic material and field observations; iv) identification and analysis of sources of carbon monoxide pollution in the study area; v) development of graphic/cartographic support that allowed us to analyze the regime and distribution of carbon monoxide concentrations.

The reference method for measuring carbon monoxide is that provided for in standard SR EN 14626 "Ambient air. Standardized method for measuring carbon monoxide concentration by non-dispersive infrared spectroscopy." According to Law No. 104/June 15, 2011, the limit value for the protection of human health for carbon monoxide is 10 mg/m^3 (maximum daily value of 8-hour averages) (Table 1).

According to Law 104/2011, a specific air quality index has been established for this chemical pollutant. According to Order 1818/2020, with implementation from 2021, carbon monoxide will continue to be monitored, without calculating the specific quality index based on the CO concentration levels recorded at APM stations.

Table 1 Quality indices for carbon monoxide pollutant (Law 104/2011).

Specific index	Quality index	CO 8h (mg/m^3)
1	Excellent	0
2	Very good	3
3	Good	5
4	Average	7
5	Poor	10
6	Very bad	> 15

The reason why carbon monoxide is no longer considered a specific air quality index in Romania is that the impact of this pollutant on the outdoor atmosphere is considered less relevant compared to other chemical pollutants that frequently exceed the limit values set by Law 104/2011. Carbon monoxide emissions are more important for assessing indoor air quality, where incomplete combustion, poor ventilation, and internal combustion sources can lead to significant concentrations of carbon monoxide that can endanger the health and lives of the population. Other countries that do not consider carbon monoxide emissions as a specific air quality index are: Germany, France, Belgium, the Netherlands, the United Kingdom, the Czech Republic, Spain, Ireland, Sweden, Australia, South Africa, and India.

Maintaining carbon monoxide measurements is important because this chemical pollutant acts as an important precursor in tropospheric oxidation processes, interacting with free radicals (hydroxyl radicals) and thus influencing atmospheric chemical cycles. Through these reactions, carbon monoxide indirectly contributes to the formation of tropospheric ozone, a secondary pollutant with effects on air quality and human health.

4. Results

4.1. Annual CO concentration values

At the APM stations in Moldova, the average annual carbon monoxide concentration values fell within the excellent air quality index (0.07 - 0.62 mg/m^3) (Tables 1 and 4).
The lowest annual average value (0.07 mg/m^3) was calculated for the rural IS-4 station (located in Aroneanu) near Aroneanu International Airport, where there are few sources of carbon monoxide emissions. The highest multi-annual average value of 0.62 mg/m^3 was calculated for the SV-3 traffic station, the main source of carbon monoxide emissions being heavy road traffic (the station is located near the E 85 European road).

Low annual average values of carbon monoxide were also calculated for rural, suburban, and EMEP stations, as a result of lower population density and fewer sources of pollution (IS-4 / 0.07 mg/m^3; IS-5 / 0.12 mg/m^3; EM-3 / 0.15 mg/m^3; VN-1, GL-3 / 0.16 mg/m^3) (Table 4).

At urban stations, the average annual values calculated for carbon monoxide are intermediate (SV-1 - 0.13 mg/m^3; GL-5 - 0.15 mg/m^3; NT-1 - 0.18 mg/m^3; BC-1 - 0.19 mg/m^3; BT-1 - 0.22 mg/m^3; VS-1 - 0.30 mg/m^3), with both road traffic and more intense and concentrated anthropogenic activities in urban areas contributing to emissions of this gas (Table 4).

Slightly higher annual average values for carbon monoxide concentration (calculated for traffic stations located in areas with heavy traffic (busy intersections, main boulevards, European roads - E85, E87, E58), near customs points (road - Siret and Galați; railway – Ungheni), as a result of incomplete combustion of fuel, which produces carbon monoxide in the exhaust gases of old, poorly maintained engines (0.11 mg/m^3 / GL-1; 0.31 mg/m^3 /IS-1; 0.57 mg/m^3 /IS-6; 0.62 mg/m^3 /SV–3) (Table 4).

During the pandemic (2019–2020), the imposition of restrictive measures on anthropogenic activities had the effect of reducing carbon monoxide emissions, a phenomenon that was much more evident at traffic stations. At the SV-3 traffic station, located on European road E85, near the Siret border crossing point, the average annual concentration of carbon monoxide recorded values of 0.82 mg/m^3 (2018), 0.76 mg/m^3 (2019), and 0.50 mg/m^3 (2020). At the other traffic stations (IS-1; IS-6; GL-1), the reduction in carbon monoxide emissions was less significant, as the sources of pollution in their vicinity were more diverse (residential heating systems, railways, road traffic, various anthropogenic activities).

4.2. Seasonal values of CO concentration

The average values calculated for the winter season (ranging from 0.14 to 0.91 mg/m^3) are higher than those calculated for the summer season (0.04–0.40 mg/m^3) due to increased road traffic, in conditions where the average values calculated for the summer season are lower than those calculated for the winter season are higher than those calculated for the summer season (0.04–0.40

mg/m^3), due to increased road traffic, in weather conditions favorable to the accumulation and stagnation of carbon monoxide emissions. During the summer, upward convective movements and precipitation favor the dispersion of carbon monoxide emissions from the atmosphere. In the winter season, the highest average values of carbon monoxide concentration were calculated for SV-3 traffic stations (0.91 mg/m^3) and for the SV-2 industrial station (0.83 mg/m^3), the representative emission sources in their vicinity being road traffic and industrial activities, without, however, having a strong and quantifiable negative effect on the environment and human health.

Table 2 Seasonal average CO concentration values at APM stations in Moldova (2009–2022).

CO - MED	EM-3	SV-1	SV-2	SV-3	BT-1	NT-1	NT-2	BC-1	BC-2	BC-3	IS-1	IS-4	IS-5	IS-6	VS-1	VN-1	GL-1	GL-2	GL-3	GL-4	GL-5
WINTER	0.24	0.24	0.83	0.91	0.40	0.41	0.46	0.39	0.26	0.45	0.6	0.14	0.22	0.73	0.48	0.33	0.20	0.18	0.26	0.23	0.30
SUMMER	0.1	0.06	0.23	0.33	0.12	0.06	0.23	0.07	0.03	0.06	0.11	0.04	0.05	0.4	0.19	0.07	0.07	0.08	0.10	0.19	0.17

Table 3 Maximum seasonal values of CO concentration at APM stations in Moldova (2009–2022)

CO - MAX	EM-3	SV-1	SV-2	SV-3	BT-1	NT-1	NT-2	BC-1	BC-2	BC-3	IS-1	IS-4	IS-5	IS-6	VS-1	VN-1	GL-1	GL-2	GL-3	GL-4	GL-5
WINTER	1.14	2.95	7.46	3.85	3.20	3.73	2.36	3.31	2.49	3.23	2.45	1.23	1.38	2.40	2.19	1.68	3.81	1.72	1.74	2.59	1.92
SUMMER	0.43	1.16	1.18	0.91	1.57	0.43	1.21	0.76	0.32	0.57	0.88	0.26	0.26	1.66	1.5	0.41	0.52	1.07	1.03	3.63	0.40

During the winter season, the maximum concentration of carbon monoxide was recorded at the SV-2 industrial station (7.46 mg/m^3)**,** falling within the limits of the "medium" quality index. The high carbon monoxide values are influenced both by local emission sources (industrial activities on the Suceava industrial platform and heavy traffic on the boulevard crossing the city from north to south) and by the particularities of the relief (the Suceava valley with its depression-like appearance), and weather conditions favorable to the stagnation and accumulation of emissions (thermal inversions, high atmospheric pressure, fog, atmospheric calm) (Tables 2–3).

4.3. Monthly CO

Based on monthly average values, all types of stations show a decrease in carbon monoxide emissions during the summer months (May–August) as a result of the increase in air temperature, which reduces the use of heating systems. Thermoconvective processes push the pollutant towards the higher layers of the atmosphere.

Table 4 Monthly (and annual) average CO concentrations at APM stations in Moldova (2009–2022).

CO	JAN	FEB	MAR	APR	MA	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
EM-3	0.26	0.22	0.16	0.13	0.09	0.09	0.09	0.12	0.09	0.14	0.20	0.24	0.15
SV-1	0.26	0.23	0.13	0.1	0.06	0.05	0.06	0.07	0.08	0.10	0.15	0.22	0.13
SV-2	0.86	0.68	0.52	0.3	0.18	0.2	0.24	0.27	0.34	0.49	0.64	0.94	0.47
SV-3	0.86	0.90	0.88	0.53	0.35	0.28	0.33	0.39	0.42	0.62	0.87	0.96	0.62
BT-1	0.5	0.31	0.25	0.18	0.13	0.09	0.12	0.15	0.14	0.18	0.25	0.38	0.22
NT-1	0.45	0.36	0.19	0.09	0.05	0.06	0.06	0.07	0.05	0.13	0.23	0.42	0.18
NT-2	0.53	0.41	0.31	0.20	0.19	0.21	0.26	0.2	0.22	0.32	0.34	0.43	0.30
BC-1	0.45	0.33	0.21	0.1	0.06	0.06	0.07	0.08	0.10	0.17	0.25	0.38	0.19
BC-2	0.3	0.20	0.11	0.04	0.03	0.03	0.03	0.04	0.05	0.09	0.14	0.27	0.11
BC-3	0.52	0.34	0.19	0.1	0.06	0.05	0.05	0.06	0.07	0.14	0.25	0.5	0.19
IS-1	0.71	0.45	0.37	0.22	0.14	0.1	0.11	0.13	0.19	0.32	0.39	0.62	0.31
IS-4	0.16	0.1	0.08	0.06	0.04	0.03	0.04	0.04	0.04	0.05	0.08	0.13	0.07
IS-5	0.25	0.19	0.15	0.07	0.05	0.04	0.05	0.06	0.06	0.11	0.15	0.22	0.12
IS-6	0.79	0.71	0.75	0.64	0.41	0.37	0.47	0.37	0.43	0.56	0.66	0.71	0.57
VS-1	0.53	0.41	0.32	0.21	0.15	0.15	0.21	0.22	0.20	0.29	0.37	0.51	0.30
VN-1	0.38	0.26	0.14	0.08	0.05	0.07	0.07	0.08	0.08	0.12	0.19	0.34	0.16
GL-1	0.22	0.23	0.1	0.08	0.07	0.07	0.07	0.07	0.08	0.09	0.11	0.16	0.11
GL-2	0.2	0.16	0.13	0.08	0.08	0.08	0.07	0.08	0.07	0.10	0.15	0.18	0.12
GL-3	0.3	0.24	0.15	0.1	0.08	0.11	0.1	0.10	0.11	0.14	0.20	0.24	0.16
GL-4	0.25	0.21	0.15	0.11	0.1	0.16	0.17	0.23	0.19	0.18	0.18	0.22	0.18
GL-5	0.33	0.29	0.21	0.09	0.06	0.06	0.06	0.09	0.07	0.12	0.17	0.28	0.15

Starting in September, there is a gradual increase in carbon monoxide concentration due to atmospheric cooling and the commissioning of heating systems. In January and February, the atmospheric concentration of this gas reaches its annual maximum.

Analysis of the data recorded and processed at industrial stations shows that the highest monthly average values for carbon monoxide are specific to station SV-2, due to numerous sources of pollution (heavy traffic on the E58 European road connecting the cities of Suceava and Botoșani; shopping centers that attract a significant number of customers, resulting in constant road traffic, especially on weekends; industrial activities, incineration of technological waste Ambro SA), the configuration of the relief (the Suceava river valley) which favors the accumulation and stagnation of carbon monoxide, mainly in the cold season months, against the background of decreasing temperatures, thermal inversions, and fog (Table 4 Figure 2a).

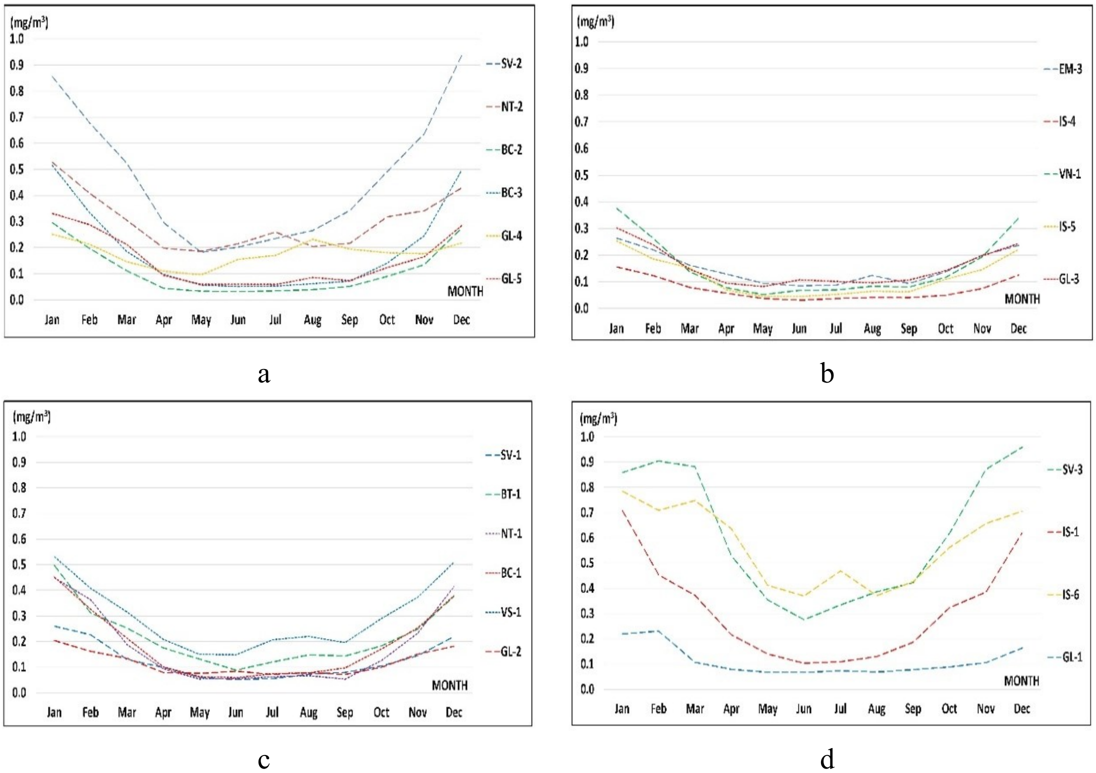


Figure 2 Annual regime based on monthly average CO values at APM stations in Moldova (2009–2022) – a) at the six industrial stations; b) one EMEP station, two rural stations, two suburban stations; c) six urban stations; d) four traffic stations.

The monthly values of this pollutant concentration are lowest at EMEP, rural, and suburban stations (Figure 2b). Urban stations follow (Figure 2c). Industrial and traffic stations usually have higher monthly values for carbon monoxide concentration (compared to the previous ones) and annual maximums (winter months) and minimums (summer months) that are more evident in the regime typology (Figures 2a and 2d).

4.4. Daily CO concentration values

The lowest average daily values of carbon monoxide concentrations were calculated for the following station types: rural – 0.11 mg/m^3 (IS-4, VN-1), suburban – 0.14 mg/m^3 (IS-5, GL-3) and

EMEP – 0.15 mg/m^3 (EM-3), because road traffic and industrial activities have lower parameters than in urban areas.

Intermediate daily average values of carbon monoxide for the period 2009–2022 were calculated for urban (0.26 mg/m³) and industrial (0.23 mg/m³) stations, where the emission sources are represented by the heating system (incomplete combustion of wood, coal, gas, or other fuels in stoves, power plants, or fireplaces), industrial activities (thermal and thermoelectric power plants, steel, metallurgy, chemical industry, refineries, and petrochemicals), with road transport as a secondary source.

The highest daily average (0.40 mg/m^3) was calculated for traffic stations (SV-3, IS-1, IS-6, GL-1), the main source of pollution being means of transport that emit carbon monoxide as a result of incomplete combustion (Table 5, Figures 3-4).

Table 5 Daily average CO concentration by station type in the Moldova Region (2009–2022).

	EMEP station	Rural station	Suburban station	Urban station	Industrial station	Traffic station
MED	0.15	0.11	0.14	0.26	0.23	0.40

The daily average values of carbon monoxide concentration were above the annual daily averages at all station types between October 10-15 and March 15-April 5. The intensification of heating activities in homes and industrial spaces (stoves, central heating systems, wood, coal, or gas boilers) generates additional carbon monoxide emissions on colder days of the year compared to warmer days (Figures 3 and 4).

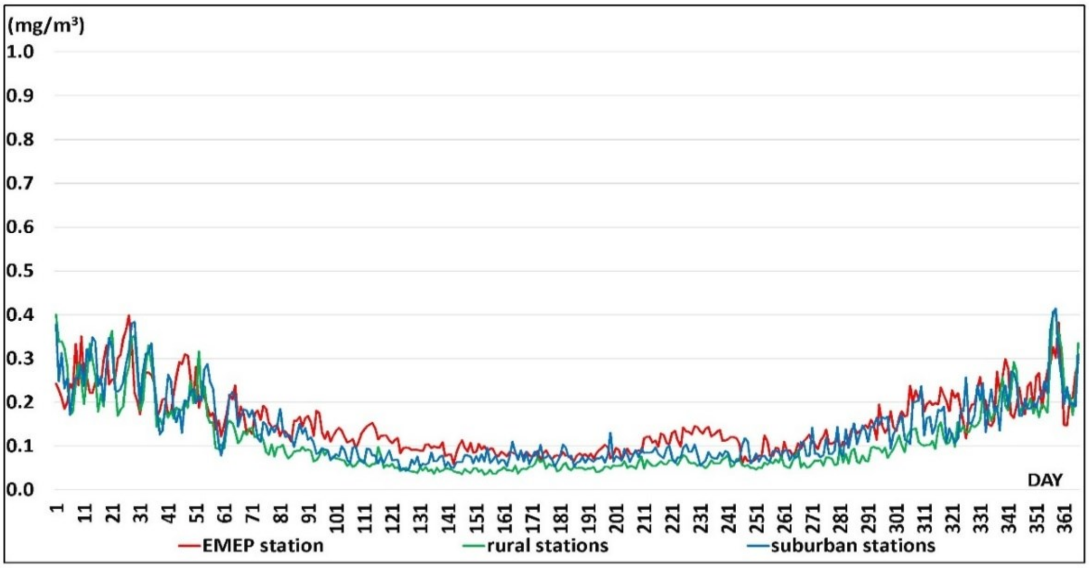


Figure 3 Interdiurnal CO regime at APM stations (one EMEP-type station, two rural background stations, two suburban background stations) in Moldova (average by station type) (2009–2022)

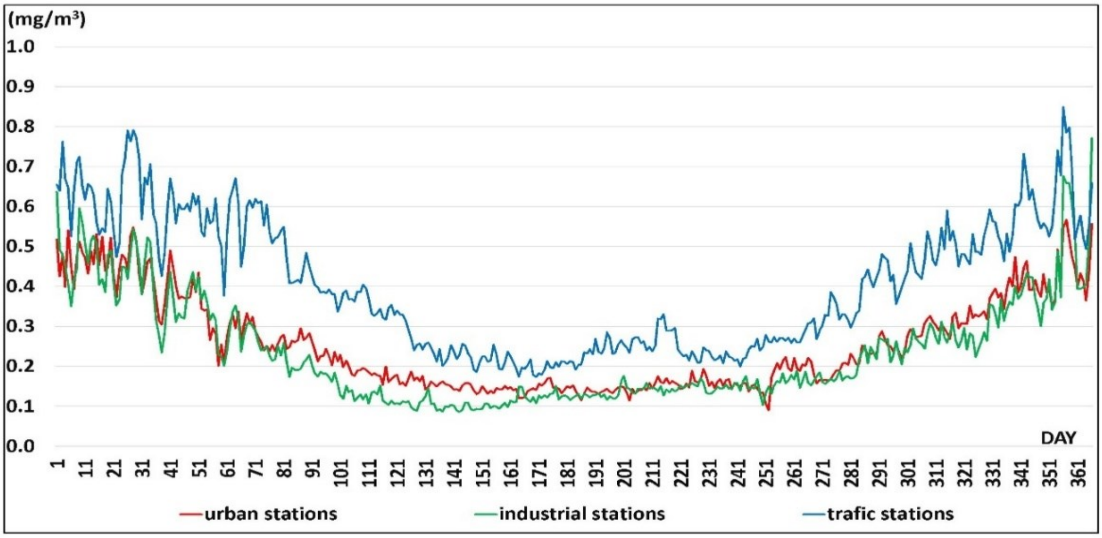


Figure 4 Interdiurnal CO regime at APM stations (six urban background stations, six industrial stations, and four traffic stations) in Moldova (average by station type) (2009–2022)

Table 6 Maximum daily CO concentration by station type in the Moldova Region of Romania (2009–2022).

	EMEP station	Rural station	Suburban station	Urban station	Industrial station	Traffic station
MAX	0.40	0.41	0.41	0.57	0.77	**0.85**
Date	Jan	22.XII	23.XII	22.XII	31.XII	21.XII

The daily averages with the highest carbon monoxide concentrations occur in December and January, due to the burning of larger quantities of fuel and favorable weather conditions. The maximum daily value was calculated at traffic stations (0.85 mg/m³). Internal combustion engines (cars, trucks, vans, motorcycles) emit carbon monoxide when fuel combustion is incomplete. Poor fuel quality, old and poorly maintained vehicles — faulty injection or exhaust systems, heavy traffic, traffic jams (frequent starts/stops) — also contribute to incomplete combustion, which reduces combustion efficiency and increases carbon monoxide concentrations (Table 6).

Table 7 Minimum daily CO concentration by station type in the Moldova Romania Region (2009–2022).

	EMEP station	Rural station	Suburban station	Urban station	Industrial station	Traffic station
MIN	0.06	**0.04**	**0.04**	0.09	0.09	0.17
Date	May 25	May 9; May 15; May 25; May 28 2 - 6.VI; 14.VI	May 5	8 Sep	6 – 7 May; 14 – 16 May; May 21–23; May 26–30	12 Jun; 18 Jun

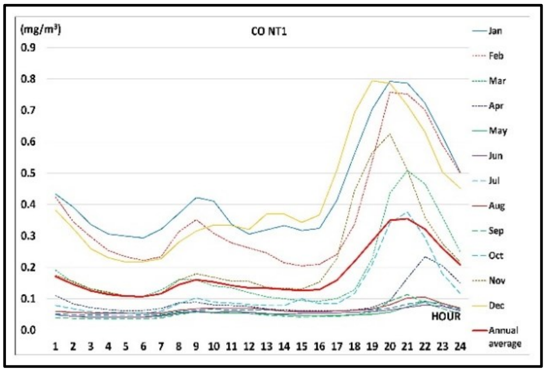
The daily averages with the lowest carbon monoxide concentrations ranged between 0.04 mg/m³ (at rural and suburban stations) and 0.17 mg/m³ (at traffic stations). They occur during the warm season, mainly in May and June, when atmospheric pressure is lower and wind and precipitation disperse and "wash" carbon monoxide from the atmosphere, thus contributing to air purification (Table 7).

Carbon monoxide can accumulate to dangerous levels, especially during periods of calm weather in winter and spring when fossil fuel combustion reaches its peak. This gas is much more chemically stable at low temperatures. Throughout the entire period analyzed, in Moldova, the average daily values of carbon monoxide did not exceed the limit value of 10 mg/m³, corresponding to the maximum daily value of 8-hour averages, established by Law No. 104/2011 on ambient air quality. These results indicate that the level of carbon monoxide concentrations in the open atmosphere did not pose a significant risk to public health and did not have a major negative impact on the components of the natural environment.

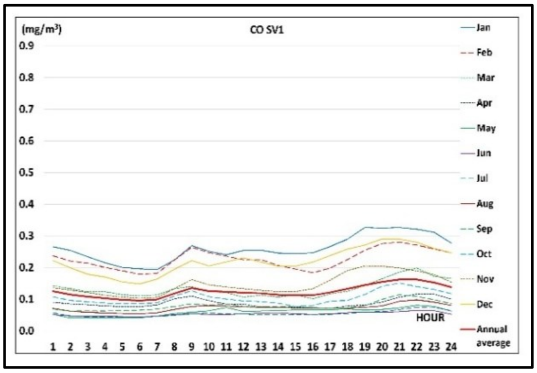
4.5. Hourly CO concentration values

The daytime interval in which the highest hourly average values were recorded is between 7:00 p.m. and 11:00 p.m. (increased road traffic and heating processes) at all stations analyzed, with the exception of the GL-1 traffic station, which recorded high hourly average values in the morning, between 9:00 a.m. and 11:00 a.m. (corresponding to the morning traffic peak generated by daily commutes to work and educational institutions). The lowest hourly average values were calculated for the interval $4^{00} – 7^{00}$, when anthropogenic activity and road traffic are reduced.

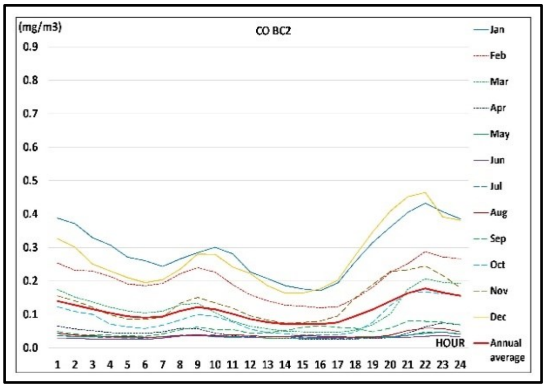
According to the legislation in force, at the six APM stations analyzed (NT-1, SV-1, BC-2, GL-4, IS-4, GL-1), between 2009 and 2022, the average hourly values of carbon monoxide concentration did not exceed the threshold of 3 mg/m³ and fell within the specific index 1 (Excellent). The highest hourly average value was calculated at the urban station NT-1, of 0.79 mg/m³ (January – 8 p.m. – 9 p.m. and December – 7 p.m. – 8 p.m.). These values can be explained in a specific local context, in which the intensification of traffic and heating processes at the end of the day, when the population returns home, fuel consumption is higher, and road traffic is more intense, most likely played an important role.

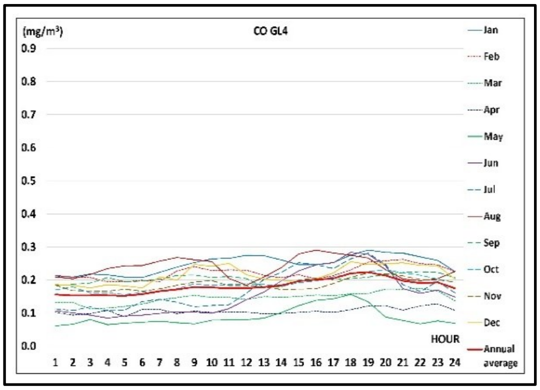


a

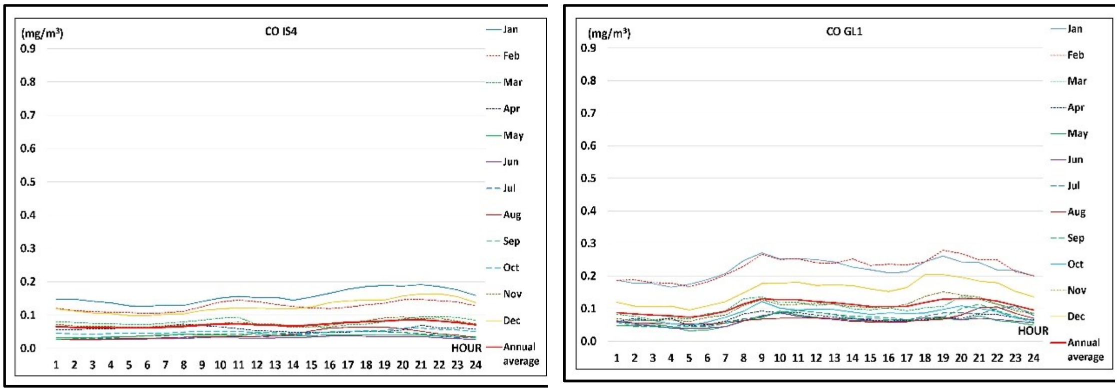


b





c d



e f

Figure 5 a-f Diurnal regime of CO concentrations at stations APM NT-1 and SV-1 (urban), BC-2 and GL-4 (industrial), IS-4 (rural) and GL-1 (traffic) (2009–2022).

At urban stations (SV-1, NT-1), traffic stations (GL-1), and industrial stations (BC-2, GL-4), two distinct peaks in hourly carbon monoxide concentration were observed, at 9:00 a.m. and 8:00 p.m. The first peak (9:00 a.m.) corresponds to the increase in road traffic in the morning, associated with people traveling to work, educational institutions, and urban centers, as well as the resumption of industrial activities (the start-up of industrial machinery and installations, which can emit high concentrations of carbon monoxide through incomplete fuel combustion). The second peak (8:00 p.m.) can be correlated with the return home of the population and employees from industrial areas, which results in increased traffic and the start-up of domestic heating and cooking systems (Figures 5 a - d, f).

The fluctuations in hourly carbon monoxide concentrations recorded between the two daily peaks correlate with the dynamics of urban activities. Thus, the increase in carbon monoxide levels is associated with the intensification of commercial and administrative activities and road traffic in central urban areas, as well as with the accumulation of emissions in conditions of insufficient atmospheric ventilation. Conversely, a reduction in the hourly values of the pollutant analyzed is recorded when anthropogenic activity decreases and when favorable weather conditions allow for more efficient dispersion of emissions.

At the IS-4 rural station, during the daytime regime of this pollutant, hourly maximums and minimums are observed in the morning and evening, but to a lesser extent, due to the proximity of emission sources that are low in number and emission power for this gas (Figure 5e).

Table 8 Hourly maximum values (day/month/year) of CO concentration at stations in Moldova (2009–2022).

No.	APM station	Max	Date	No	APM station	Maximum	Date
1	SV-2	7.5	21.12.2009	12	IS-6	2.4	03.01.2013
2	GL-1	3.8	30.01.2015	13	VS-1	2.2	27.12.2012
3	GL-4	3.6	12.06.2014	14	VS-2	2.2	06.01.2015
4	BC-1	3.3	05.01.2017	15	NT-2	2.0	22.04.2011
5	SV-3	3.2	02.12.2008	16	GL-5	1.9	31.12.2022
6	BC-3	3.2	29.12.2017	17	GL-3	1.7	13.11.2010 / 04.02.2011
7	BT-1	3.2	27.03.2021	18	GL-2	1.7	16.01.2017

8	SV-1	3.0	10.02.2009	19	VN-1	1.7	04.12.2011
9	NT-1	2.9	09.01.2011	20	IS-5	1.4	23.12.2016
10	BC-2	2.5	21.12.2010	21	IS-4	1.2	26.01.2010
11	IS-1	2.5	13.01.2009 / 21.12.2010	22	EM-3	1.1	22.12.2016

The highest effective values of atmospheric carbon monoxide concentration in the ambient air (7.5 mg/m³) were recorded at station SV-2 on December 21, 2009 (Table 8). These high hourly values of carbon monoxide concentration were associated with synoptically unusual weather conditions in the, which favored the accumulation of pollutants in the lower atmosphere. However, the levels recorded did not pose a substantial risk to public health, as they did not exceed the limit value of 10 mg/m³ (maximum daily 8-hour average), according to Law No. 104 of June 15, 2011, on ambient air quality.

5. Discussions

The study provides a detailed analysis of atmospheric carbon monoxide concentrations in the Moldova region of Romania for the period 2009–2022 and provides relevant statistical and graphical information on the daily and annual patterns of this gas. Even though the daily and hourly average values of carbon monoxide concentration in the study area did not exceed the maximum daily value of 8-hour averages legally established by Law No. 104/2011, the study is relevant from several perspectives. Monitoring the atmospheric concentration of this pollutant over a period of 14 years helps to assess the effectiveness of air protection policies and detect potential risks due to pollution, identify sources of pollution, and correlate maximum daily and annual values with road traffic, industrial activities, and heating processes. Even if the atmospheric concentration of carbon monoxide remains below legal limits, the information obtained can be useful for urban planning and traffic management, preventing the dangerous accumulation of carbon monoxide during critical periods of thermal inversions, atmospheric calm, and reduced ventilation, which can favor the accumulation of this pollutant. The research results can be used as a reference in the comparative analysis between Moldova and other regions/cities in Romania and for assessing the impact of changes in the atmospheric concentration of this gas due to changes in the vehicle fleet, the urbanization process of some cities, or regional parameters of extreme weather events.

The main sources of carbon monoxide emissions identified in the study area were road traffic, the burning of fossil fuels in individual and centralized heating systems, and industrial activities. Over the last ten years, numerous studies have been conducted on air quality in the municipality of Suceava and its metropolitan area. One of the studies highlighted the negative impact of household waste on air quality in the areas surrounding waste management platforms, identifying other sources of carbon monoxide emissions: landfills, uncontrolled waste burning, incomplete oxidation processes in storage areas, fires, or related processes at the local level. By processing data from 2007 to 2012, it was demonstrated that biological decomposition processes (especially in the warm season) and uncontrolled burning have the effect of increasing local atmospheric carbon monoxide levels (Mihăilă et al., 2014). The incineration of hazardous waste (petroleum residues, pesticides, varnishes, dyes, adhesives, organic solvents, hospital and food industry residues) by S.C. Mondeco S.R.L. Suceava involved intense and variable thermal processes, which favored episodes of incomplete combustion and higher temporary emissions of carbon monoxide into the urban atmosphere. By processing and analyzing the data recorded in 2013 at the air quality monitoring station located near the incinerator, the study showed that during the periods when the incinerator was in operation, there were increases in carbon monoxide concentrations, with the maximum carbon monoxide emission values being associated with the heating stages of the plant and episodes of incomplete combustion of hazardous materials (Mihăilă et al., 2015).

To assess air quality in the cities of Piatra Neamț and Suceava, studies were conducted on the annual and diurnal regime of carbon monoxide (Roșu et al., 2020; Mihăilă et al., 2020; Mihăilă et al., 2021; Prisăcariu, 2023; Țiculeanu, 2024). Even though the areas covered by these studies were more limited than those covered by the present study, they showed excellent air quality indices for Suceava and Piatra Neamț in 99.78% of the observation hours at stations SV-1 and NT-1 and in 97.32% of the observation hours at station SV-2. This study reinforces and integrates the results of previous research.

To date, research has been conducted on the impact of restrictive measures during the pandemic, which led to a reduction in road traffic primarily and economic activities secondarily, with the effect of reducing carbon monoxide emissions in the North-East Region of Romania (Mihăilă et al., 2023). This study confirms for an area that we have extended to the counties of Vrancea and Galați that the pandemic period was one of improved air quality.

In-depth investigations have identified complex correlations between periods of pollution, severe weather conditions, and the deterioration of the population's health in the Suceava metropolitan area. An increase in the number of patients with respiratory diseases was recorded during the cold season, when temperatures drop below 0°C and high atmospheric pressure favors the accumulation and stagnation of chemical pollutants with negative effects on human health (Țiculeanu et al., 2024). On frosty nights during the cold season, the accumulation of carbon monoxide in the open atmosphere at the level of the respiratory tract is influenced by intense fuel combustion and favorable weather conditions.

Maintaining CO measurements allows for a more complex and comprehensive chemical analysis of atmospheric composition, contributing to the modeling of oxidation processes in the troposphere and the estimation of tropospheric ozone formation, a process in which carbon monoxide plays an intermediate role.

6. Conclusion

In the Moldova Region, the average annual values of carbon monoxide concentration ranged between 0.07–0.62 mg/m^3 and fell within quality index 1 (Excellent) at all 21 stations included in the study, indicating that the air in the study area contains very low levels of carbon monoxide and that this gas does not pose a significant risk to human health or the environment. During the pandemic, restrictive measures led to a significant reduction in carbon monoxide emissions, especially at traffic stations. The decrease in atmospheric carbon monoxide concentration was more pronounced at station SV-3, located on European road E85, near the Siret border crossing point, which shows that the reduction in road traffic had a direct impact on this gas in the atmosphere.
The average values of the atmospheric concentration of carbon monoxide show seasonal variations, being higher in the winter months (0.14–0.91 mg/m^3) compared to those in the summer (0.04–0.40 mg/m^3). The increase in concentration during the cold season is due to increased road traffic, industrial activities, and home heating, combined with weather conditions favorable to the accumulation of pollutants (thermal inversions, fog, atmospheric calm) and the configuration of the relief. In the warm season, higher temperatures, vertical air movement, and precipitation favor the dispersion and "cleaning" of carbon monoxide from the air. The highest monthly average values of atmospheric carbon monoxide concentration are specific to the cold season and fell within the Excellent quality index (0–3 mg/m^3), without having a significant impact on ecosystems and public health.

Throughout the entire period analyzed, the average daily values of carbon monoxide concentration did not exceed the legal threshold of 10 mg/m³, posing no significant risk to public health and having no major impact on the environment. Analysis of the average daily values shows that they were influenced by the type of station, road traffic, and industrial activities. The lowest average daily carbon monoxide concentrations were recorded at EMEP, rural, and suburban stations, as road traffic in their vicinity is much lower than in urban areas. The highest daily average values were also recorded at traffic stations, the main mobile source of pollution being means of transport that emit carbon monoxide. The average daily values of carbon monoxide concentration were higher in the cold season, influenced by heating activities and weather conditions that prevent the dispersion of the pollutant, and lower in the warm season, when wind and precipitation favor the dispersion of emissions.

At all stations analyzed, hourly values of atmospheric carbon monoxide concentration fell within quality index 1 (Excellent), with no exceedances of the 3 mg/m³ threshold. The highest hourly average rose to 0.79 mg/m³ at station NT-1. At urban, industrial, and traffic stations, two daily peaks are evident (around 9:00 a.m and 8:00 p.m.), associated with heavy traffic and the resumption and end of economic and industrial activities, respectively. The hourly trend in carbon monoxide concentration values between these peaks reflects the pace of urban socio-economic activities and atmospheric dispersion conditions. A closer analysis of the hourly carbon monoxide concentration values shows that it is higher in the evening between 7:00 p.m.and 11:00 p.m., due to increased road traffic and the use of heating systems. At the GL-1 traffic station, we identify a maximum in the morning (09:00–11:00), similar in value to that in the evening, due to increased traffic. The minimum daily values are recorded between 04:00and 07:00,when anthropogenic activity is low. At the IS-4 rural station, no significant daytime fluctuations were observed, in the absence of significant local sources of emissions of this gas. The daytime pattern of atmospheric carbon monoxide concentration at this station remains the same, but is much flatter. The highest hourly value of carbon monoxide concentration (7.5 mg/m³ - SV-2, December 2009) was determined by meteorological conditions that favored the accumulation of pollutants.

The carbon monoxide concentration values recorded in the atmosphere of the Moldova region between 2009 and 2022 did not exceed the limit values set by Law 104/2011. Monitoring this pollutant remains important for maintaining air quality and preventing possible pollution episodes that may occur as a result of human activities (transport, industry).

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