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Spatiotemporal trends of ambient air CO in Urmia city

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ABSTRACT

Introduction: This descriptive-ecological study investigated the seasonal, diurnal, and spatial variations of Carbon monoxide (CO) concentration in Urmia's (Northwest of Iran) ambient air over a six-month period, spanning Winter and Spring.

Materials and methods: Sampling was conducted at 20 stations selected from various urban locations. At each station, a portable environmental gas analyzer was used to measure CO concentration during both morning and evening peak traffic hours.

Results: The results revealed a significant seasonal and diurnal pattern. The highest CO means were observed in the cold months (January and February), peaking at an average of 6.19 ppm in January evenings. This increase is strongly linked to temperature inversion and heightened heating system usage. Statistical analysis confirmed a highly significant difference ($P<0.001$) in CO means across months and between morning and evening hours, with concentrations being significantly higher in the evening. Although monthly averages are generally below the 8-h national standard (9 ppm), their proximity to the limit and the registration of high peaks (up to 15.10 ppm) indicate a potential health risk during winter. Spatially, zoning maps showed the central, high-traffic area acts as the main pollution hotspot.

Conclusion: The study highlights that even short-term peak CO exposure can be significant, potentially causing headache and behavioral effects. Additionally, the river and surrounding open spaces help reduce pollution, emphasizing the need for integrated air quality management strategies that account for both seasonal and diurnal variations. These findings underscore the critical need for integrated management strategies sensitive to both the time of day and the season.

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Introduction

In recent decades, accelerating urbanization, the increase in motor vehicles, rising consumption of fossil fuels, and unbalanced urban development have emerged as the most significant environmental challenges in metropolitan areas. These factors have led to increased air pollution on local, regional, and global scales, seriously threatening human health and environmental sustainability [1]. The uncontrolled expansion of cities, the growth of industries adjacent to populous areas, and the combination of these factors with natural and climatic conditions have not only exacerbated urban air pollution but have also caused noticeable changes in the global climate—an issue that has recently attracted the special attention of researchers and planners [2]. Air pollutants, including particulate matter, sulfur dioxide, nitrogen oxides, ozone, and especially Carbon monoxide (CO), are among the most critical compounds that have acute and chronic effects on human health and are considered the cause of many premature deaths in urban settings [3]. Numerous studies have reported a direct link between air pollution and cardiovascular diseases, respiratory disorders, neurological impairments, reduced cognitive function in children, miscarriage, low infant birth weight, and increased rates of strokes and heart attacks [4]. Air quality assessment, as a key environmental evaluation indicator, plays an important role in understanding the current state of pollution, analyzing its changing trends, and planning for its control. The urban transport sector, particularly gasoline and diesel light- and heavy-duty vehicles, accounts for a major share of primary pollutant production [5]. Based on pollutant classification, primary pollutants are emitted directly from sources (e.g., CO, SO_2, and Nox), while secondary pollutants are formed as a result of chemical reactions between primary pollutants and environmental factors such as sunlight and humidity [6]. In urban areas, the predominant source of CO is incomplete combustion in mobile sources, particularly gasoline and diesel vehicles, which often contribute over 70–90% of ambient CO emissions in traffic-heavy cities worldwide. Secondary contributions may come from industrial activities and residential fuel burning, but transportation remains the key driver in most metropolitan environments [7, 8]. This gas is colorless, odorless, and tasteless, easily enters the bloodstream via the respiratory system, and combines with hemoglobin with an affinity approximately 200 to 220 times greater than oxygen, leading to reduced oxygen supply to tissues and the onset of tissue hypoxia [9]. This condition is particularly dangerous for patients with cardiovascular and respiratory diseases. Surveys show that the average CO concentration in high-traffic areas of Tehran during peak traffic hours ranges between 5 to 10 mg/m^3, and sometimes exceeds 15 mg/m^3 under temperature inversion conditions, which is higher than the World Health Organization (WHO) permissible limits [10]. According to WHO guidelines, the permissible CO concentration is set at 10 mg/m^3 for an 8-hexposure and 35 mg/m^3 for a 1-h exposure [11]. In comparison, CO concentrations have been reported up to 20 mg/m^3 in cities like Delhi (India), around 8 to 12 mg/m^3 in Shanghai (China), less than 5 mg/m^3 in Los Angeles (USA), and less than 1 mg/m^3 in Stockholm, Sweden [12-15].

Despite the well-documented health impacts of CO exposure and the high burden of cardiovascular and respiratory diseases in West Azerbaijan Province [16-18], there remains a notable gap in comprehensive, spatiotemporal assessments of ambient CO concentrations specifically in Urmia. Most existing studies in Iran have focused on megacities such as Tehran, Ahvaz, or Isfahan, with limited high-resolution data on CO variations in mid-sized cities like Urmia, which face unique challenges including seasonal temperature inversions, traffic congestion from aging vehicle fleets, proximity to dried Lake Urmia (potentially influencing dust and secondary pollutants), and growing urbanization [19-21]. Real-time or seasonal monitoring of CO in such areas is scarce, hindering the development of localized air quality management strategies and public health interventions. Furthermore, with recent reports indicating fluctuating but occasionally elevated CO levels in northwestern Iran, updated spatiotemporal analyses are essential to identify pollution hotspots, seasonal patterns, and peak-hour risks during morning and evening traffic periods. This knowledge is critical for evidence-based policymaking, especially in a region where air pollution contributes significantly to preventable morbidity and mortality. Although this study measured only instantaneous CO levels during peak hours, any exposure is important due to its potential impact on COHb elevation at any time of day. Therefore, the present study aims to comprehensively investigate the trend of CO concentration in the ambient air of Urmia City (2024–2025), specifically by examining its spatial variations and changes across both cold and warm seasons and during morning and evening peak periods, to provide critical data for developing robust urban air quality management policies.

Materials and methods

Study area

Urmia, the capital of West Azerbaijan Province, is a major metropolis in northwest Iran, housing an estimated 1,000,000 inhabitants within a surface area of approximately 100 km2 (Fig. 1). This leads to a high population density and intense urban activities, establishing it as a key regional center. Geographically, Urmia is situated on the slopes of Mount Sir and near Lake Urmia, giving rise to a unique cold semi-humid climate influenced by Mediterranean and Atlantic air masses, characterized by cold and snowy winters and mild, rainy springs (with average annual precipitation between 300 and 400 mm, peaking in March and April). The city's prevailing winds generally blow from the north and northwest; however, the rapid population growth and heavy traffic concentration within this compact area, combined with these specific climatic conditions, result in increasing environmental challenges, particularly regarding air quality [18, 22, 23].

Sampling and CO measurement

Sampling took place over six consecutive months, covering the winter and spring seasons. Four days were randomly selected each month. Sampling was conducted specifically during winter and spring to evaluate seasonal influences on CO levels. Winter conditions, including temperature inversions and atmospheric stability, often result in higher CO accumulation from traffic emissions in urban areas like Urmia. Spring provides a comparative period with changing meteorology (e.g., increasing winds and reduced inversions) and potential regional dust impacts from the nearby Lake Urmia desiccation, facilitating analysis of spatiotemporal variations and peak exposure risks.

To ensure data accuracy and capture true human exposure, the CO sensor was consistently placed at a fixed height of 1.5 m from the ground. Furthermore, sampling was restricted to local conditions where the wind speed was below

10 km/h to minimize the atmospheric dilution effect. On each selected day, measurements were taken during two peak traffic intervals: 8:00 to 10:00 AM (Morning) and 3:00 to 5:00 PM (Afternoon/Evening). Twenty sampling stations were selected (Fig. 1) based on criteria such as traffic density, land-use diversity (high-traffic vs. low-traffic zones), population exposure potential, and accessibility for portable monitoring. This approach ensured representative coverage of urban CO variations driven primarily by vehicular emissions in Urmia. CO concentrations were continuously monitored with portable electrochemical multi-gas sensors capable of measuring CO within a range of 0–100 ppm and a resolution of 0.1 ppm. The device operated in continuous sampling mode with data averaging at 1-min intervals and were equipped with built-in temperature and humidity compensation.

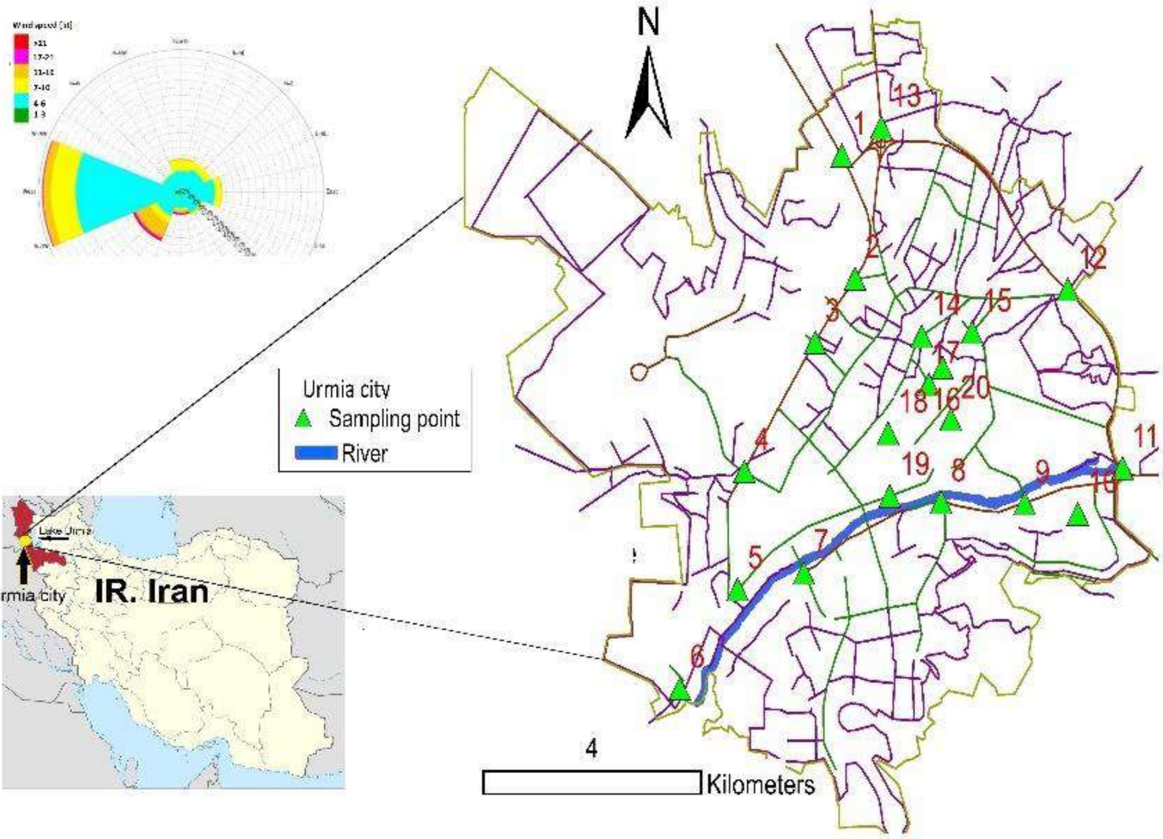

Fig. 1. Map of study area

QA/QC

Prior to deployment, the instruments were calibrated using certified standard CO gas mixtures, followed by post-campaign recalibration. Daily zero and span checks were performed throughout the study period. While these sensors are not certified as regulatory-grade monitors (such as US EPA Federal Reference or Equivalent Methods), quality assurance/quality control (QA/QC) procedures were rigorously followed to ensure acceptable accuracy and reliability for the spatiotemporal analysis of ambient CO levels in Urmia.

Data analysis

The collected data were processed and analyzed using SPSS v20 software. Descriptive statistics, including the mean, standard deviation, minimum, and maximum values, were calculated for each month and season to summarize the pollution characteristics. For inferential testing, the paired samples t-Test was employed to statistically assess the difference in mean CO concentration between the morning and afternoon/evening periods, while a One-Way Analysis of Variance (ANOVA) was used to determine the statistical difference in the mean CO concentration between the spring and winter seasons. For graphical representation, box plot diagrams were generated using Stata software to visually compare data distribution and dispersion across seasons, and time series charts were plotted using Microsoft excel to illustrate temporal variations. Finally, spatial variations were analyzed by creating zoning maps within the GIS software environment (ArcGIS v10.1).

Results and discussion

Based on the data presented in Table 1, CO concentrations in Urmia show a clear seasonal and diurnal cycle, with the highest values occurring during winter. Evening concentrations peak at 6.19 ppm in January, primarily due to increased emissions from domestic heating systems and frequent temperature inversions that trap pollutants near the surface [11]. While morning traffic contributes to elevated CO levels, the most critical short-term peaks 15.10 ppm in January evenings and 12.30 ppm in February evenings occur during evening hours, signaling severe pollution episodes that pose acute risks to sensitive populations. These peaks, particularly in the cold season, pose serious risks for sensitive individuals ([children, the elderly, and those with cardio-respiratory illnesses) and can adversely affect blood Carboxyhemoglobin (COHb) levels during short-term exposure [24]. A comparison with national and WHO guidelines shows that monthly average CO concentrations remain below the 8-h limit of 9 ppm (National Standard and WHO guideline) [11]. However, winter and early spring averages (4.82–6.19 ppm) lie close to this threshold, indicating potential chronic health risks. Although maximum recorded CO values remain below the 1-h limits of 35 ppm (Iran Standard) and 28 ppm (WHO) [25, 26], their large deviation from mean values highlights the presence of acute pollution events requiring urgent mitigation.

Table 1. Descriptive statistics of CO in sampling points in different times

Month	morning				evening			
	mean	SD	max	min	mean	SD	max	min
December	2.80	1.08	5.32	1.10	1.97	0.86	4.25	0.46
January	4.82	1.51	8.40	2.40	6.19	2.30	15.10	2.00
February	4.62	1.43	7.81	2.10	5.97	1.82	12.30	3.12
March	3.84	1.62	7.50	0.58	3.68	1.57	7.86	0.81
April	3.66	1.44	7.16	0.48	4.30	1.64	8.91	0.54
May	4.94	2.11	11.91	0.23	4.77	2.00	10.25	0.26

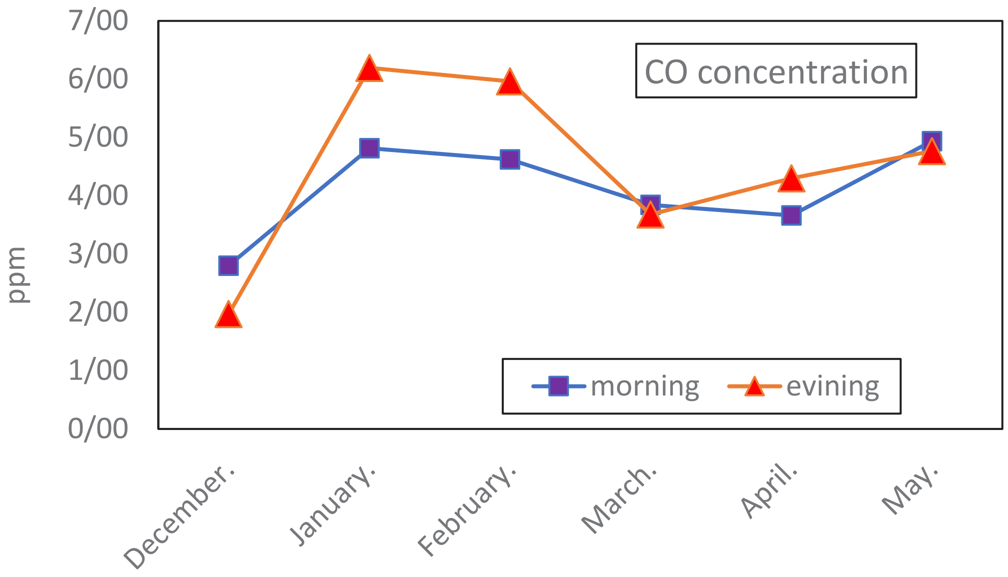

Fig. 2. Monthly average diurnal variation of CO concentration in Urmia city

The time series shown in Fig. 2 confirms a pronounced seasonal pattern, with peak concentrations during the evenings of January and February due to intensified emissions and strong inversion layers. CO levels decline sharply in March as atmospheric mixing improves and then rise again in April and May (around 5 ppm), likely driven by traffic emissions and moderate dispersion conditions. The proximity of these 8-h mean values to the national standard underscores the need for continuous monitoring and stricter pollution control during winter.

One-Way ANOVA indicates significant differences in monthly mean CO concentrations for both morning and evening hours (P<0.001), with a stronger seasonal influence in the evening (F=73.114) compared to morning (F=22.40). A Paired Samples T-Test also confirms consistently higher evening concentrations across the study period (t = −4.723, P<0.001), driven by late-day traffic, atmospheric stability, and reduced nighttime dispersion.

The significant seasonal differences (One-Way ANOVA, P<0.001)are largely driven by meteorological variations: winter's low temperatures and high stability promote inversion layers that enhance CO trapping, while spring's transitional conditions (higher temperatures and variable humidity) facilitate better dilution. The inverse relationship between wind speed and CO concentration, as previously noted, is amplified in winter due to calmer conditions, reinforcing the dominant role of temperature-driven atmospheric stability over humidity in modulating CO levels in this urban setting.

CO concentration in Urmia shows a clear seasonal and diurnal pattern similar to findings from major cities such as Tehran [27], with peak pollution occurring in winter months due to temperature inversion and increased emissions from heating systems and vehicles, while the lowest levels appear in early spring as dispersion improves. Unlike Tehran, where both morning and evening rush hours create pollution peaks, Urmia exhibits higher evening concentrations, reflecting the city’s distinct traffic patterns and topography. The inverse relationship between wind speed and CO concentration—also reported in Tehran [27] highlights the critical role of meteorological conditions in reducing pollution levels in Urmia. Despite generally lower averages than Tehran, the similarity in seasonal patterns and the proximity of winter values to permissible limits underscore the need for integrated, spatio-temporal pollution management in urban environments. Additionally, while Aghdasi et al. [2017] reported an annual mean of 2.5 ppm and a summer peak of 2.8 ppm in Urmia [28], differences from the present study where winter shows the highest seasonal mean likely result from variations in study year, sampling distribution, and analytical methods.

Box Plot diagrams (Fig. 3) reveal a clear temporal pattern in CO concentrations, with morning hours (8–10 AM) showing strong seasonal variability higher medians and greater dispersion in winter due to temperature inversion, increased traffic, and higher fuel consumption—while evening hours (3–5 PM) display a more uniform distribution with weaker seasonal influence, likely because of more stable atmospheric conditions and fewer inversion events. These patterns indicate that both season and time of day significantly shape pollution levels, underscoring the need for air quality management strategies that account for diurnal and seasonal fluctuations. Additionally, this study found higher evening CO levels compared to morning values, differing from Tehran’s dual morning–evening peaks reported by Arab and Mirkarimi, a discrepancy attributable to Urmia’s distinct traffic dynamics and topography [27]. The inverse relationship between wind speed and CO concentration—supported by previous studies—helps explain elevated CO levels on cold, calm days in Urmia, reinforcing the critical role of meteorological factors in understanding and predicting air pollution.

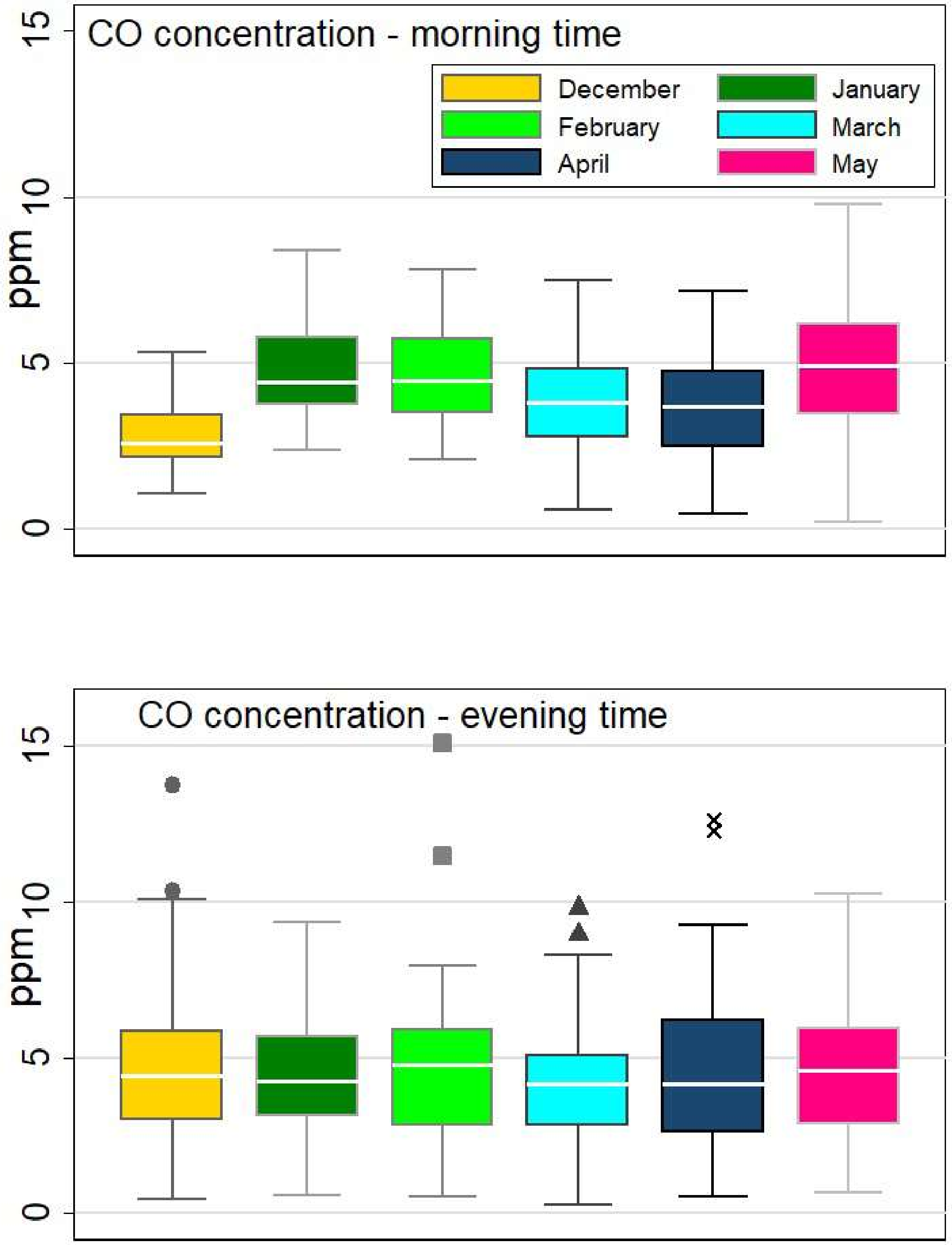

Fig. 3. Box plot of monthly CO level distribution during morning and evening hours in Urmia city

A study in Ardabil by Fazizadeh et al. (2016) showed that outdoor CO levels (2.18 ppm) were significantly higher than indoor levels (0.57 ppm), producing an Indoor/Outdoor ratio below 1, a pattern also observed in the present study, indicating that outdoor air remains the primary pollution source while indoor factors such as heating systems and smoking can still affect indoor concentrations [29]. Although Urmia's average CO levels are lower, the similarity of its seasonal trends to Tehran and its proximity to permissible limits highlight a shared warning for urban managers. These findings underscore the need for integrated control strategies targeting vehicle emissions, heating sources, and meteorological influences especially the inverse wind CO relationship while also addressing Urmia's distinct temporal and spatial characteristics, including its consistently higher evening CO concentrations.

Studies from multiple regions including the central Taiwan Basin, China, and Bursa in turkey show that CO concentrations typically decrease in summer due to favorable atmospheric dispersion and enhanced photochemical removal, a pattern consistent with reductions observed in Urmia and Tehran; however, the mechanisms differ, as Iranian cities experience winter pollution peaks driven by temperature inversion and reduced wind speed rather than sea-breeze effects. The Taiwan study's long-term decline of 0.02 ppm per year and China's substantial annual CO reduction rate of 3.7 driven 80% by anthropogenic emission controls demonstrate the effectiveness of policy-based mitigation, emphasizing the importance of similar integrated strategies in Iran. Bursa's findings further support Urmia's pattern, showing high CO levels in autumn and winter due to increased heating and poor dispersion, confirming the dominant role of domestic and industrial fuel use [30-32]. Additionally, as Fig. 1. wind direction, Urmia's prevailing west to east winds play a crucial role in pollutant dispersion, especially during spring when wind speed increases and significantly enhances dilution and transport of CO, highlighting the seasonal importance of meteorology in shaping pollution levels.

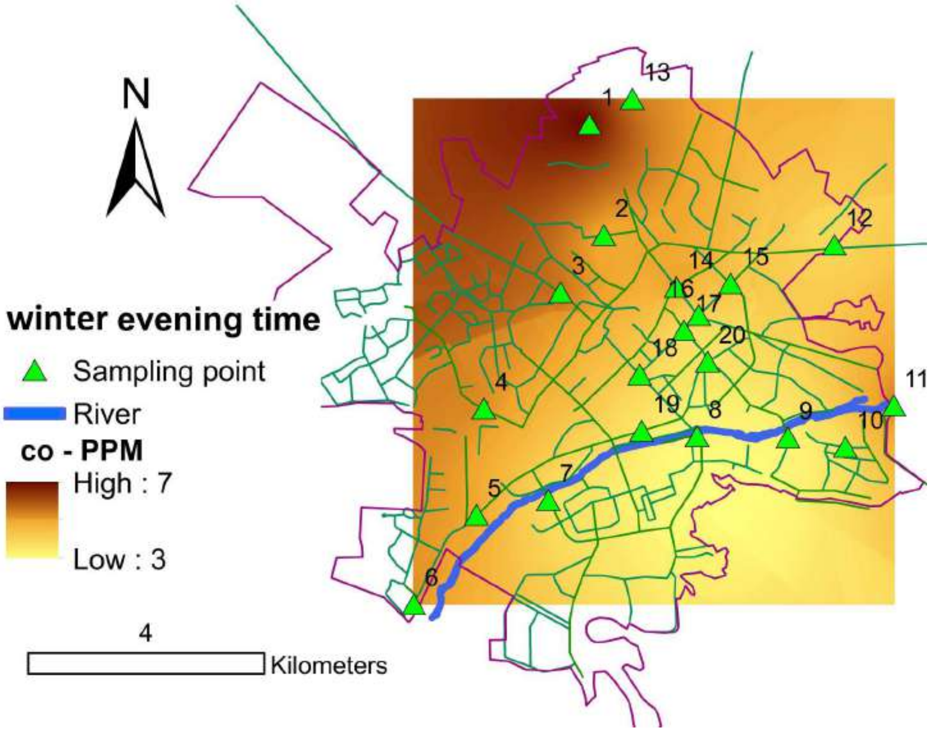

Fig. 4. Distribution map of study area

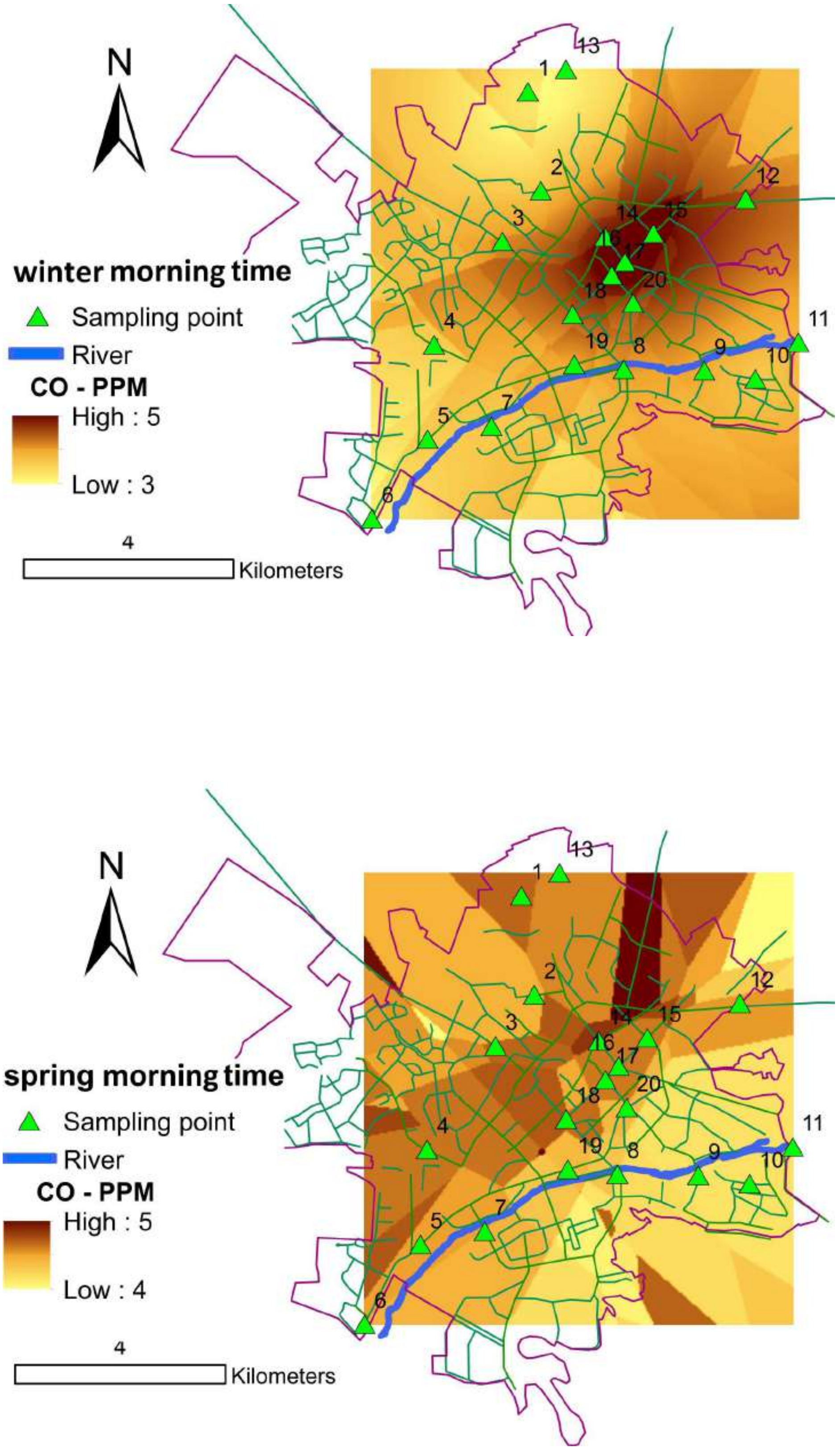

Fig. 4. Distribution map of study area

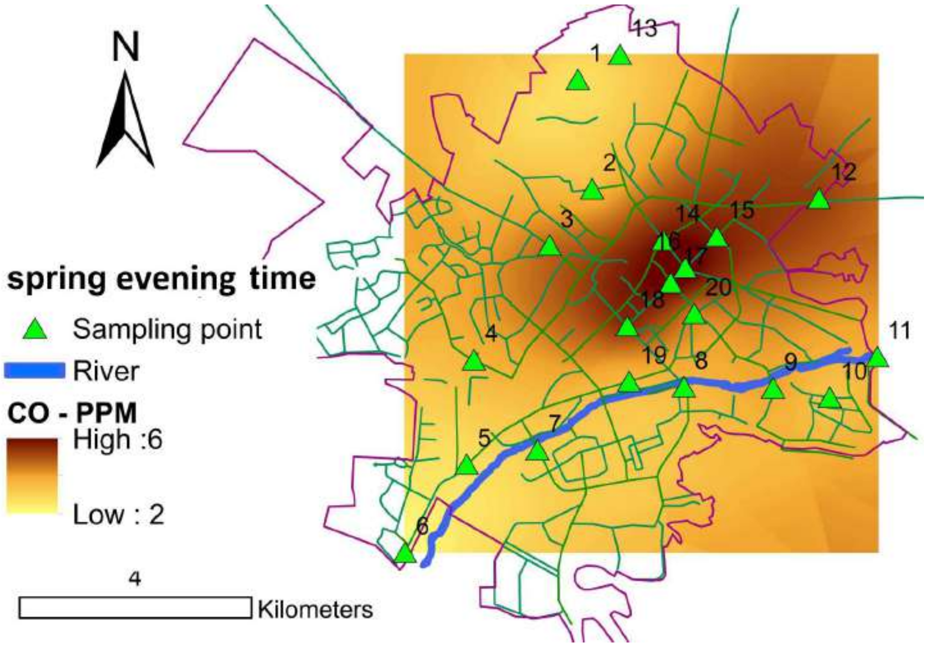

Fig. 4. Distribution map of study area

The zoning maps of CO concentration in Urmia (Fig. 4) reveal a distinct spatial-temporal pattern in the pollutant's distribution. These maps illustrate the distinct spatio-temporal distribution of CO levels in Urmia City across the spring and Wwinter seasons during both morning and evening periods. In all four maps, the main CO pollution hotspot is clearly concentrated in the central and northeastern areas of the city, which confirms that CO concentration is highest in the city core due to high traffic density and commercial/administrative land use. The highest intensity is observed in the winter evening map (peaking at 7 ppm), although the spring period also shows consistently high concentrations. Generally, concentrations are higher in the evening hours, which confirms the influence of evening traffic patterns and stable atmospheric conditions. Importantly, in all maps, CO value is relatively lower in the vicinity of the river, indicating that the river and its surrounding open spaces act as a pollution-reducing factor by facilitating better pollutant dispersion. These results collectively emphasize the need for traffic management and green space development in the central area.From a spatial perspective, many reasearchers study, using Kriging analysis, also showed that the northeastern parts of Urmia City are more polluted due to heavy traffic [28]. This aligns with the zoning maps of the current study, which show pollution concentrated in the central and high-traffic areas, underscoring the key role of traffic as the main CO source in Iranian cities. Based on the study by researchers in South Korea, the role of land use in pollutant concentration clearly shows that the highest CO concentration occurs in commercial areas. This finding aligns with the present study in Urmia, which indicates a pollution concentration in the central and high-traffic areas of the city. This consistency affirms the key role of traffic and transportation activities as the primary CO source in both urban contexts. Conversely, the south Korea study demonstrated that green belt areas registered the lowest concentrations for all pollutants except ozone, with total oxidant values closer to background conditions [33]. This finding emphasizes the importance of nature-based strategies, such as the development and preservation of urban green spaces, as an efficient tool for mitigating exposure to pollutants like CO. Therefore, although the nature of emission sources may differ between

Urmia and Korean cities, the common spatial pollution pattern concentration in human activity cores and reduction in green spaces indicates a universal principle. This highlights the necessity of integrating land use planning and vegetation cover management alongside direct emission control as a unified strategy for air quality management in cities like Urmia.

Overall, these maps confirm that the central area of Urmia City acts as the primary CO hotspot across both seasons and both time intervals (morning and evening), likely due to high traffic density, commercial/administrative land use, and the city's physical structure. Additionally, the role of the river and the open space surrounding it is evident as a pollution-reducing factor, particularly in the Spring Evening map. These findings emphasize the necessity of implementing traffic management, green space development, and continuous monitoring. Although this study measured only instantaneous CO levels during peak hours, any exposure is important due to its potential impact on COHb elevation at any time of day. Moreover, the concentrations observed are sufficiently high to potentially cause symptoms such as headache, reduced concentration, and behavioral effects in exposed individuals.

Limitations

While this study highlights seasonal and diurnal CO patterns in Urmia, limitations include reliance on portable electrochemical sensors (potential sensitivity to environmental interferences despite calibration), restricted sampling to peak hours and two seasons, and a finite number of points, which may limit generalizability to full-year or off-peak exposures.

Future directions

Future efforts should involve continuous, multi-season monitoring, integration of fixed reference instruments, advanced statistical modeling of meteorological influences, and epidemiological linkages to assess health impacts, supporting targeted interventions in Urmia and similar cities.

Conclusion

The study confirms that CO pollution in Urmia City is a significant environmental challenge, exhibiting a pronounced seasonal and spatial pattern highly influenced by local and climatic factors. The high concentrations observed in winter evenings (peaking around 6.2 ppm average and 15.10 ppm maximum) are a direct consequence of the combined effects of traffic, increased heating emissions, and temperature inversion. Although average levels generally comply with the 8-h standard, the proximity to the limit and the occurrence of extreme peaks necessitate urgent attention, especially given the established link between air pollution and elevated rates of cardiovascular and respiratory diseases. The central urban area is consistently identified as the primary pollution hotspot. Therefore, effective air quality management in Urmia must focus on: 1) Implementing stricter traffic control measures during cold seasons, 2) Managing heating source emissions, and 3). Integrating land-use planning and green space development (as suggested by the observed role of the river as a mitigating factor). The similar seasonal patterns observed in comparison with Tehran further stress that pollution management requires sustained, integrated, and spatio-temporally sensitive policies applicable across Iranian cities.

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Competing interests

The authors declare no conflicts of interest.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely ob-served by the authors. The study protocol was approved by the Ethics Committee of Urmia University of Medical Sciences (Approval code: IR.UMSU.REC.1403.371; Grant number: 13447). AI Disclosure: Artificial intelligence tools [ChatGPT and Gemini] were used solely to edit and improve the writing and language of the manuscript.

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