

Spatial and temporal variability of urban air quality across functional land-use zones in Eskişehir, Türkiye

Aylin Cicek^{1*}, Ilknur Zeren Cetin²

¹Ondokuz Mayıs University, Institute of Graduate Studies, Samsun, Türkiye; aylincicek.omu@yahoo.com

²Ondokuz Mayıs University, Samsun, Türkiye; ilknur.cetin@omu.edu.tr

*Correspondence: aylincicek.omu@yahoo.com

Abstract. Urban air quality is spatially heterogeneous because emission intensity, land-use function, daily activity, seasonal energy demand, and atmospheric dispersion vary across the urban fabric. This study quantified the short-term spatial and temporal variability of PM_{2.5}, PM₁₀, and CO₂ across ten functionally contrasting locations in Eskişehir, Türkiye. Field observations were conducted during four weeks in February and four weeks in May, with measurements collected on Mondays, Wednesdays, and Fridays during morning (08:30–10:30) and evening (17:00–19:00) periods. PM_{2.5} and PM₁₀ were measured using a CEM DT-9880 portable particle counter, while CO₂ was measured using an EXTECH EasyView 80 analyzer. Descriptive comparisons were combined with GIS-based Kriging interpolation to visualize broad concentration gradients. The results showed persistent spatial contrasts among industrial, residential, commercial, transportation, and vegetated environments. The Industrial Zone recorded the highest PM_{2.5} concentrations, reaching 543 µg/m³ in winter morning observations and 640 µg/m³ in winter evening observations. Winter CO₂ reached 803 ppm at the Industrial Zone. Residential Area II also showed elevated particulate concentrations, whereas Urban Park and Urban Green Space generally exhibited lower values. Concentrations were generally higher in winter than in summer, and PM_{2.5} commonly increased from morning to evening. These patterns identify functional urban environments that warrant intensified monitoring and targeted management. The study does not establish source-specific causality because source apportionment and simultaneous site-level meteorological measurements were not available. Accordingly, the findings are interpreted as spatial and temporal contrasts within the monitored network rather than as regulatory compliance estimates or quantitative source contributions.

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1. Introduction

Urbanization is one of the principal processes reshaping contemporary human settlements. The concentration of population, employment, infrastructure, production, and services within urban areas has generated substantial economic and social benefits while simultaneously increasing pressure on environmental systems. Global

urban population growth has been accompanied by expanding transportation networks, greater energy demand, industrial intensification, and increasing consumption of natural resources. These processes can alter atmospheric conditions and contribute to the accumulation of pollutants within densely occupied urban environments. The environmental consequences are particularly important because exposure to polluted air occurs across large populations and may persist over long periods (URL1, URL2, URL3, URL4; Cetin 2013; Cetin 2015; Cetin 2016; Cetin et al., 2017; Cetin et al., 2019).

Air pollution is now recognized as a major environmental determinant of human health. Fine particulate matter is particularly important because particles with aerodynamic diameters of 2.5 μm or less can penetrate deeply into the respiratory system and may reach systemic circulation. Epidemiological evidence has linked exposure to particulate matter with cardiovascular and respiratory outcomes, including ischemic heart disease, stroke, chronic obstructive pulmonary disease, asthma, and premature mortality. The World Health Organization (WHO) consequently established substantially more stringent air-quality guideline levels in 2021, reflecting the accumulation of evidence concerning health effects at relatively low exposure concentrations (WHO, 2021). The guideline values include annual and 24-h reference levels for PM_{2.5} and PM₁₀ and provide an internationally recognized framework for interpreting air-quality risks.

The atmospheric behavior of particulate matter is strongly influenced by emission sources and meteorological conditions. Industrial combustion and production processes can release primary particles and precursor substances, while road traffic contributes directly through exhaust emissions, brake and tire wear, and resuspension of road dust. Residential heating is another important source, particularly during cold seasons when solid fuels and other combustion-based heating systems may increase local particle emissions. The relative contribution of these sources differs spatially according to urban morphology, land use, traffic intensity, building density, vegetation structure, and atmospheric dispersion. (Lelieveld et al., 2015; Han et al., 2016; Beelen et al., 2008; Nowak et al., 2006; Powe & Willis 2002; Tallis et al., 2011; Tiwary et al., 2009; Nowak et al., 2014; Kumar et al., 2015; Snyder et al., 2013; Rai et al., 2017; Janhäll 2015; Leung et al., 2011; Abhijith et al., 2017; Jayasooriya et al., 2017; Pugh et al., 2012; Hewitt et al., 2020; Yao et al., 2022).

PM_{2.5} and PM₁₀ are not spatially uniform within cities. Concentrations can vary considerably over relatively short distances because emission sources and atmospheric dispersion processes are spatially heterogeneous. Dense traffic corridors, industrial facilities, commercial centers, and residential districts with high combustion demand may produce local concentration peaks. Conversely, parks and vegetated areas can influence particle deposition, atmospheric mixing, shading, and local microclimatic conditions. However, the relationship between vegetation and air pollution is complex and depends on species characteristics, canopy structure, street geometry, wind conditions, pollutant source strength, and spatial configuration of green infrastructure (Abhijith et al., 2017; Janhäll, 2015; Rao et al., 2014).

Carbon dioxide provides a complementary indicator of urban atmospheric conditions. Although CO₂ is naturally present in the atmosphere and is not conventionally treated as a primary toxic air pollutant at ordinary ambient concentrations, its spatial distribution can provide information about combustion activity, traffic, building occupancy, ventilation, and local atmospheric mixing. In urban environments, elevated CO₂ concentrations may occur near intense transportation activity, industrial combustion, and areas with substantial fossil-fuel consumption. Seasonal variations can also reflect changes in domestic heating demand and atmospheric stability (Abualqumboz et al., 2017; Adar et al., 2014; Anderson et al., 2012; Begum et al., 2008; Cetin, 2013; Cetin, 2015; Cetin, 2016; Cetin et al., 2017; Cetin et al., 2019).

The interaction between urban form and air quality has received increasing attention within environmental planning research. Buildings, road networks, industrial areas, open spaces, vegetation, and transportation corridors create a heterogeneous urban surface that influences both pollutant generation and dispersion. Street-canyon geometry can restrict ventilation, while open spaces and strategically positioned vegetation may alter local airflow and particle deposition. Therefore, air-quality assessment should not be limited to isolated monitoring stations. Spatial approaches capable

of representing geographic variation can provide additional information for urban planning and environmental management. (Deary et al., 2016; Mukherjee and Agrawal, 2017; Sevik et al., 2019; Turkyilmaz et al., 2018; Yucedag et al., 2018).

Geographic Information Systems (GIS) provide a useful framework for integrating field measurements with spatial information. GIS-based interpolation can estimate pollutant concentrations between observation points and generate continuous spatial surfaces. Kriging is particularly relevant because it incorporates spatial dependence among observations and provides a geostatistical framework for estimating values at unsampled locations. Previous research has demonstrated the application of Kriging and other interpolation procedures to urban particulate-matter mapping and environmental exposure assessment (Lelieveld et al., 2015; Han et al., 2016; Beelen et al., 2008; Nowak et al., 2006; Powe & Willis 2002; Tallis et al., 2011; Tiwary et al., 2009; Nowak et al., 2014; Kumar et al., 2015; Snyder et al., 2013; Rai et al., 2017; Janhäll 2015; Leung et al., 2011; Abhijith et al., 2017; Jayasooriya et al. 2017; Pugh et al., 2012; Hewitt et al., 2020; Yao et al., 2022).

The spatial representation of air pollution is particularly valuable for cities experiencing simultaneous industrial development and urban expansion. Eskişehir provides a relevant case because its metropolitan structure includes industrial districts, organized industrial areas, residential neighborhoods, commercial functions, transportation corridors, university environments, and substantial urban green spaces. These functions generate contrasting activity and emission environments and create a strong basis for examining fine-scale spatial differences in measured air quality.

Previous investigations in Eskişehir have already demonstrated the importance of spatial and seasonal variability in urban air pollution. Gaga et al. (2012) assessed multiple pollutants, including PM_{2.5} and PM₁₀, using passive and active sampling and GIS-based exposure analysis across the city. More recently, Balcılar (2024) examined PM₁₀, PM_{2.5}, and SO₂ at three fixed monitoring stations and evaluated temporal variation and source-related characteristics, while Ari et al. (2025) applied chemical characterization and positive matrix factorization to quantify PM_{2.5} source contributions at an urban-background location. These studies provide important station-based, pollutant-specific, and source-apportionment evidence. The present study addresses a complementary gap by using the same portable measurement framework across ten functionally distinct urban environments and explicitly comparing winter/summer and morning/evening conditions for PM_{2.5}, PM₁₀, and CO₂. Thus, the contribution is empirical and spatial-planning oriented rather than methodological: it provides a functional land-use comparison of short-duration, neighborhood-scale concentration contrasts that cannot be obtained directly from a small number of fixed regulatory stations or from source-apportionment data alone.

Accordingly, the principal objective of this study is to characterize the spatial and temporal variability of PM_{2.5}, PM₁₀, and CO₂ concentrations across ten representative urban locations in Eskişehir. The specific objectives are to: (i) quantify pollutant concentrations during winter and summer; (ii) compare morning and evening conditions; (iii) identify locations with persistently elevated or relatively low concentrations; (iv) examine how observed concentration patterns correspond to dominant urban land-use functions; (v) visualize broad spatial gradients using Kriging interpolation within a GIS environment; and (vi) translate the observed spatial contrasts into planning-relevant recommendations while explicitly recognizing the limitations of short-duration field monitoring.

The study is designed as a spatially explicit field assessment rather than a long-term regulatory monitoring program. Therefore, the results are interpreted primarily as relative spatial and temporal variability within the monitored network. Comparisons with WHO guideline values are used only as health-oriented context because the observations are short-duration measurements and cannot be treated as standardized 24-h averages. Likewise, relationships between concentration patterns and land-use functions are interpreted as associations rather than quantified source contributions.

2. Materials and methods

The study was conducted within the metropolitan area of Eskişehir, Türkiye. Eskişehir is located in Central Anatolia and functions as an important urban, industrial, educational, and transportation center. The city has a continental climate characterized by cold winters and warm summers. Seasonal differences in temperature, atmospheric stability, heating demand, and air-mass movement can affect pollutant dispersion. During colder periods, increased residential heating demand may increase combustion-related emissions, while stable atmospheric conditions can reduce vertical mixing and favor near-surface accumulation. The metropolitan landscape is heterogeneous, with industrial and organized industrial districts occurring alongside residential neighborhoods, commercial centers, university areas, transportation corridors, parks, and other urban green spaces. This functional diversity makes Eskişehir suitable for a comparative assessment of neighborhood-scale air-quality conditions.

The study area contains several potential emission environments. Industrial and organized industrial locations may be affected by stationary combustion, production processes, material handling, and industrial traffic; transportation and commercial environments may be influenced by vehicle activity and resuspended road dust; and residential environments may be affected by domestic energy use, particularly during winter. Vegetated locations provide contrasting settings with generally lower direct emission intensity, although their effects on pollutant concentrations may also depend on canopy structure, airflow, and surrounding urban geometry. These source descriptions are used to define functional contexts rather than to infer quantitative source contributions from the measured concentrations.

Ten representative monitoring locations were selected according to dominant land-use characteristics and potential emission environments. The network was intentionally designed to capture contrasting urban functions rather than to form a statistically uniform sampling grid. The selected environments were: University District; Urban Park; Residential Area I; Commercial Center; Industrial Zone; Urban Green Space; Residential Area II; Organized Industrial District; Transportation Corridor; and Residential Area III. Collectively, these locations represent educational, vegetated, residential, commercial, industrial, and transportation-dominated settings. The design therefore supports comparative analysis of functional urban environments while acknowledging that the ten sites do not represent the full spatial variability of the metropolitan area.

Measurements were undertaken during winter and summer observation periods. The winter campaign covered four weeks in February, and the summer campaign covered four weeks in May. Measurements were performed three days per week (Monday, Wednesday, and Friday) during two daily periods: morning (08:30–10:30) and evening (17:00–19:00). The temporal design was selected to represent contrasting phases of daily urban activity and to enable seasonal comparison. Because observations were collected during defined time windows rather than continuously, the resulting values represent conditions during the measurement periods and should not be interpreted as full-day or long-term averages.

Particulate matter was measured using a CEM DT-9880 six-channel portable particle counter, and CO₂ was measured using an EXTECH EasyView 80 CO₂ Analyzer. CO₂ concentrations were recorded in parts per million (ppm), while PM_{2.5} and PM₁₀ were recorded in µg/m³. The same instrument types were used across the monitoring network to maintain methodological consistency among locations and observation periods. The available study record does not provide additional co-located reference-monitor calibration data; therefore, the measurements are treated as field observations suitable for relative spatial comparison rather than as a substitute for certified regulatory monitoring.

Measurements were organized by location, season, time of day, and pollutant. Descriptive comparisons were used to identify concentration ranges and differences among functional environments. The analysis focused on spatial and temporal contrasts rather than predictive modelling or source apportionment. The principal comparisons were winter versus summer, morning versus evening, industrial versus residential environments, transportation-oriented versus commercial

environments, and built-up versus vegetated environments. No statistical source-apportionment model was applied, and no causal contribution of a particular emission source was estimated.

QGIS was used for spatial data processing and visualization. Geographic coordinates of the monitoring locations were associated with the corresponding pollutant observations, and Kriging interpolation was applied to generate continuous surfaces between measured points. Kriging estimates values at unsampled locations using spatial dependence among observations (Cressie, 1993; Goovaerts, 1997). The manuscript does not specify a validated source-specific semivariogram model or cross-validation procedure; accordingly, the interpolated surfaces are used as exploratory representations of broad spatial gradients rather than as high-resolution predictive exposure fields.

Separate spatial representations were generated for winter morning, winter evening, summer morning, and summer evening conditions. This design enables comparison of concentration gradients across both seasons and daily periods. Given the limited network of ten locations, interpolation uncertainty is expected to increase where sampling points are widely separated or where strong local sources occur between measurement sites. The maps should therefore be interpreted in conjunction with the measured values in Tables 1 and 2. Future monitoring should incorporate denser spatial coverage, meteorological observations, and independent validation of interpolation performance.

3. Results

Winter observations demonstrated pronounced spatial variability in all three monitored parameters. The highest CO₂ concentrations occurred at the Industrial Zone (803 ppm in the morning and 762 ppm in the evening), followed by the Organized Industrial District (762 and 712 ppm, respectively) and Residential Area II (682 and 642 ppm). By contrast, Urban Green Space recorded 358 ppm in the morning and 322 ppm in the evening, while Urban Park recorded 382 and 362 ppm. The difference between the highest and lowest winter morning CO₂ observations was 445 ppm. These contrasts indicate strong spatial differentiation within the monitoring network; however, CO₂ concentrations cannot be attributed to industrial or residential sources quantitatively without concurrent meteorological observations and source-specific measurements (Table 1; Figure 1).

Table 1. Winter mean air-quality measurements across the monitored urban environments

Sampling location	Period	CO ₂ (ppm)	PM _{2.5} (µg/m ³)	PM ₁₀ (µg/m ³)
University District	Morning	623	105	13
University District	Evening	572	192	43
Organized Industrial District	Morning	762	238	11
Organized Industrial District	Evening	712	371	63
Commercial Center	Morning	572	216	15
Commercial Center	Evening	557	363	66
Residential Area I	Morning	452	53	7
Residential Area I	Evening	422	61	11
Residential Area II	Morning	682	243	18
Residential Area II	Evening	642	363	78
Industrial Zone	Morning	803	543	21

Industrial Zone	Evening	762	640	11
Transportation Corridor	Morning	498	125	28
Transportation Corridor	Evening	447	147	10
Urban Park	Morning	382	38	12
Urban Park	Evening	362	51	10
Urban Green Space	Morning	358	44	30
Urban Green Space	Evening	322	58	28
Residential Area III	Morning	595	111	53
Residential Area III	Evening	485	137	83

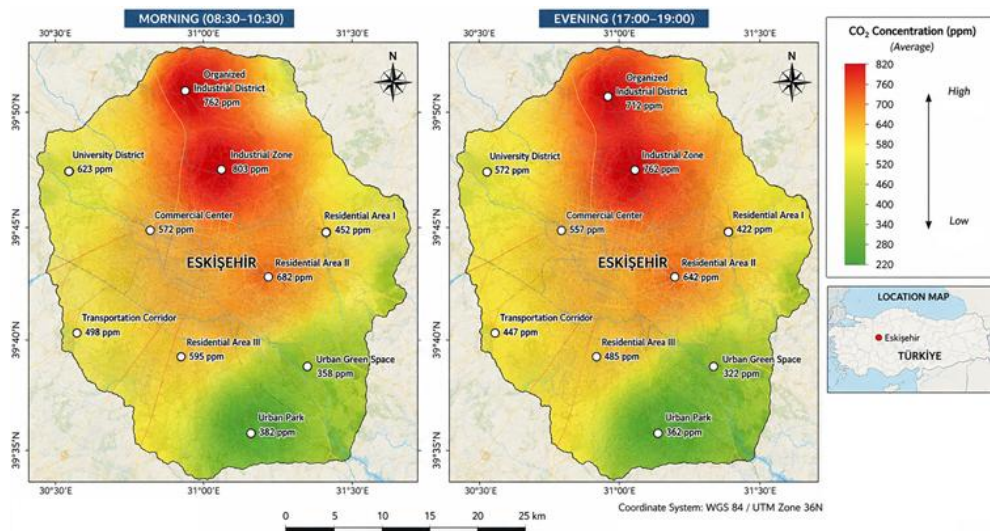


Figure 1. Average CO₂ winter

PM_{2.5} showed particularly strong spatial differentiation during winter. The highest morning concentration was recorded at the Industrial Zone ($543 \mu\text{g}/\text{m}^3$), followed by Residential Area II ($243 \mu\text{g}/\text{m}^3$) and the Organized Industrial District ($238 \mu\text{g}/\text{m}^3$). During evening observations, the Industrial Zone reached $640 \mu\text{g}/\text{m}^3$, while the Organized Industrial District, Residential Area II, and Commercial Center recorded 371, 363, and $363 \mu\text{g}/\text{m}^3$, respectively. Urban Park remained comparatively low at $38 \mu\text{g}/\text{m}^3$ in the morning and $51 \mu\text{g}/\text{m}^3$ in the evening, while Urban Green Space recorded 44 and $58 \mu\text{g}/\text{m}^3$. The repeated concentration contrast between industrial/built-up and vegetated locations is a robust descriptive feature of the monitored network. It should not, however, be interpreted as quantitative evidence of a specific emission source because source apportionment was not performed. The measured values are also not directly comparable with the WHO 24-h guideline as regulatory averages because the present observations represent short-duration field measurements (Figure 2).

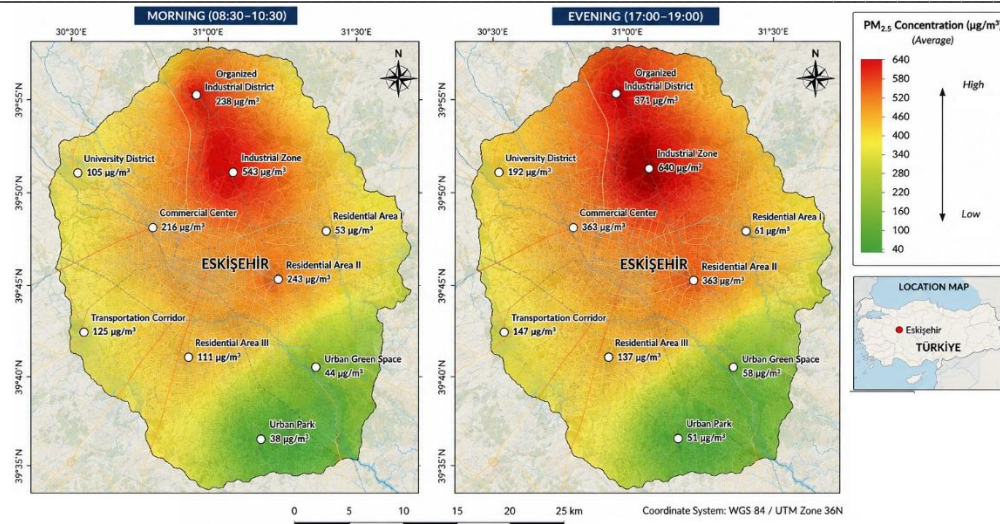


Figure 2. PM2.5 concentrations winter

PM10 displayed a different magnitude pattern from PM2.5 while retaining clear differences among functional environments. Residential Area III recorded the highest winter PM10 concentrations during both morning and evening observations (53 and 83 $\mu\text{g}/\text{m}^3$), followed by Residential Area II in the evening (78 $\mu\text{g}/\text{m}^3$) and the Commercial Center (66 $\mu\text{g}/\text{m}^3$). The Organized Industrial District recorded 63 $\mu\text{g}/\text{m}^3$ in the evening. These relatively high values in residential and commercial settings may be compatible with traffic, domestic activity, road dust, or surface resuspension, but the present dataset does not permit their individual contributions to be separated. Urban Park recorded 12 and 10 $\mu\text{g}/\text{m}^3$, whereas Residential Area I recorded 7 and 11 $\mu\text{g}/\text{m}^3$. The results therefore indicate that PM10 variability is not restricted to industrial environments and may reflect multiple local processes.

Summer observations showed a spatial structure broadly consistent with winter, although concentrations were lower at many locations. The highest summer morning CO₂ concentration occurred at the Industrial Zone (743 ppm), followed by the Organized Industrial District (722 ppm) and Residential Area II (622 ppm). Evening concentrations were 715 ppm at the Industrial Zone, 697 ppm at the Organized Industrial District, and 632 ppm at Residential Area II. Urban Park and Urban Green Space remained among the lowest CO₂ environments (312–322 ppm and 317–327 ppm, respectively). The lower summer values are consistent with reduced heating demand and potentially different atmospheric dispersion conditions, although the absence of simultaneous meteorological measurements prevents these mechanisms from being quantified. Vegetation-related carbon exchange may also contribute locally, but its magnitude cannot be determined from the present measurements (Table 2; Figure 3).

Table 2. Summer mean air-quality measurements across the monitored urban environments

Sampling location	Period	CO ₂ (ppm)	PM2.5 (µg/m ³)	PM10 (µg/m ³)
University District	Morning	562	97	11
University District	Evening	552	162	37
Organized Industrial District	Morning	722	212	9
Organized Industrial District	Evening	697	332	58
Commercial Center	Morning	552	205	12

Commercial Center	Evening	527	308	58
Residential Area I	Morning	432	47	4
Residential Area I	Evening	412	57	8
Residential Area II	Morning	622	237	14
Residential Area II	Evening	632	338	67
Industrial Zone	Morning	743	463	15
Industrial Zone	Evening	715	552	10
Transportation Corridor	Morning	492	108	23
Transportation Corridor	Evening	442	127	8
Urban Park	Morning	322	28	11
Urban Park	Evening	312	47	9
Urban Green Space	Morning	327	38	11
Urban Green Space	Evening	317	50	10
Residential Area III	Morning	512	98	5
Residential Area III	Evening	492	112	8

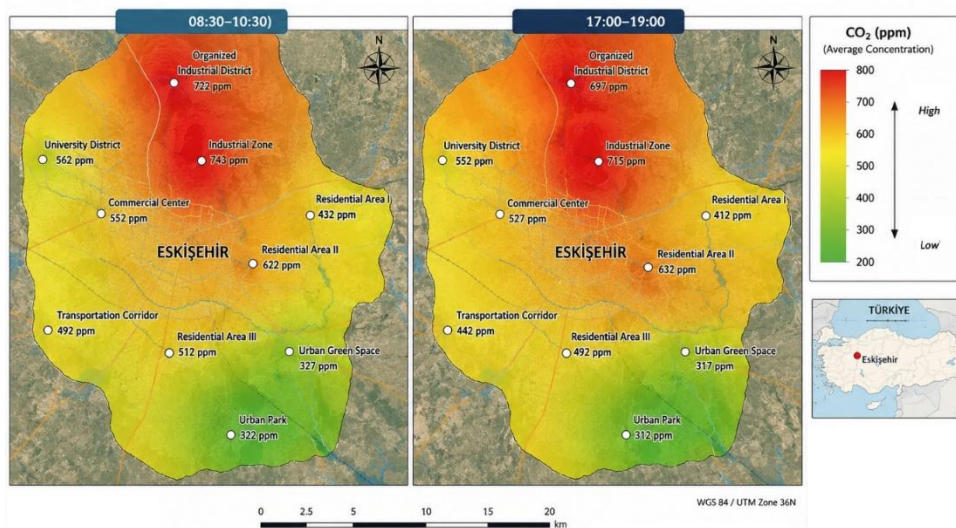


Figure 3. Average CO₂ summer

The Industrial Zone again exhibited the highest summer PM_{2.5} concentrations, with 463 $\mu\text{g}/\text{m}^3$ in the morning and 552 $\mu\text{g}/\text{m}^3$ in the evening. Residential Area II recorded 237 and 338 $\mu\text{g}/\text{m}^3$, the Organized Industrial District 212 and 332 $\mu\text{g}/\text{m}^3$, and the Commercial Center 205 and 308 $\mu\text{g}/\text{m}^3$. Urban Park recorded 28 and 47 $\mu\text{g}/\text{m}^3$, while Urban Green Space recorded 38 and 50 $\mu\text{g}/\text{m}^3$. The persistence of the same broad spatial ordering across seasons indicates that functional differences were stable within the observed network. These results should be interpreted as spatial associations rather than source-specific effects.

Summer PM₁₀ concentrations were generally lower than the corresponding winter values. The highest morning value was recorded at the Transportation Corridor ($23 \mu\text{g}/\text{m}^3$), whereas the highest evening value occurred at Residential Area II ($67 \mu\text{g}/\text{m}^3$). The Organized Industrial District and Commercial Center each reached $58 \mu\text{g}/\text{m}^3$ in the evening. Urban Park and Urban Green Space remained comparatively low. The summer pattern further indicates that coarse-particle concentrations vary among transportation, residential, commercial, industrial, and vegetated environments and are likely influenced by multiple interacting processes (Figure 4).

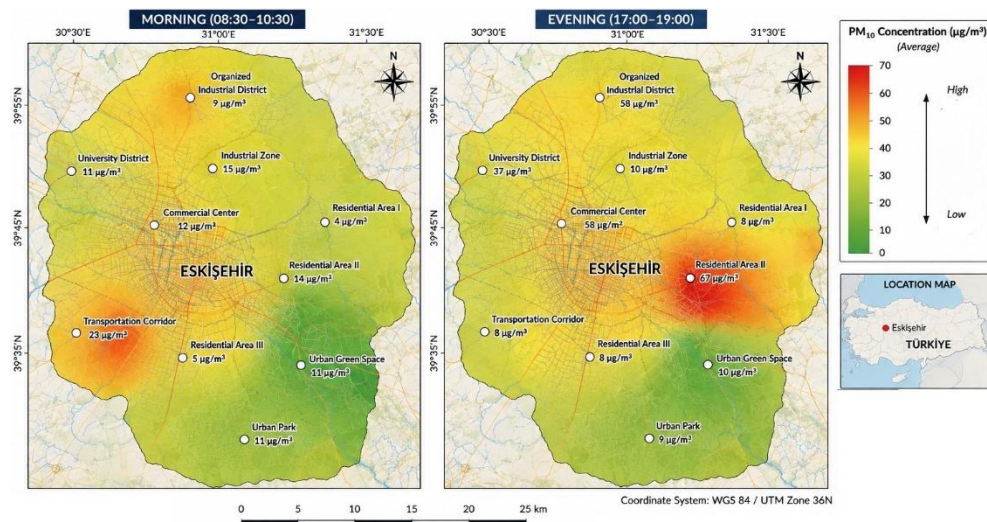


Figure 4. Average PM₁₀ summer

4. Discussion

The principal finding is pronounced spatial heterogeneity in air-quality conditions across Eskişehir. Concentrations differed systematically among the ten monitored functional environments, with the Industrial Zone and Organized Industrial District generally exhibiting the highest CO₂ and PM_{2.5} values. This spatial pattern is compatible with the higher activity and emission intensity expected in industrial settings, but the study design does not permit attribution to individual industrial processes. The result is nevertheless important from a planning perspective because the concentration contrast persisted across seasons and daily periods. Earlier Eskişehir studies have similarly demonstrated spatial and seasonal variability, but they have generally relied on fixed monitoring stations, broader pollutant suites, or chemical source-apportionment approaches (Gaga et al., 2012; Balçılar, 2024; Ari et al., 2025). The present study complements this evidence by explicitly comparing ten functionally distinct urban environments using the same field-monitoring framework.

Residential environments also exhibited substantial internal variability. Residential Area II repeatedly showed higher PM_{2.5} and PM₁₀ concentrations than Residential Area I, while Residential Area III recorded relatively high PM₁₀ values, particularly during winter evenings. These contrasts demonstrate that the residential land-use category should not be treated as environmentally homogeneous. Heating technology, fuel type, local traffic, building configuration, surface conditions, and ventilation may all influence measured concentrations, but their relative contributions cannot be separated using the present dataset. The appropriate interpretation is therefore that different residential environments exhibited different observed concentration regimes.

Winter concentrations were generally higher than summer concentrations, particularly for PM_{2.5} and CO₂. Increased heating demand provides a plausible contextual explanation for part of the seasonal contrast, while lower temperatures and atmospheric stability can reduce dispersion. However, the absence of simultaneous site-level meteorological measurements is a major interpretive limitation. Temperature, wind speed, relative humidity, boundary-layer height, and atmospheric stability were not available at the monitoring locations; consequently, emission-related and

meteorological effects cannot be quantitatively separated. This limitation is explicitly incorporated into the interpretation of the seasonal findings rather than treated as evidence of a causal heating effect.

Morning–evening differences were particularly pronounced for PM_{2.5}. At the Industrial Zone, winter PM_{2.5} increased from 543 µg/m³ in the morning to 640 µg/m³ in the evening, while the corresponding summer values increased from 463 to 552 µg/m³. Similar evening increases occurred at several residential and commercial locations. These differences may be associated with accumulated daily emissions, traffic activity, industrial operating schedules, or residential activity, but the available observations do not identify which mechanism dominates. CO₂ exhibited a different temporal response at several locations, with morning concentrations sometimes exceeding evening values. This divergence confirms that CO₂ and particulate matter should not be treated as interchangeable indicators of urban atmospheric conditions.

The contrasting temporal behavior of PM_{2.5}, PM₁₀, and CO₂ supports the use of multi-pollutant monitoring. Combining pollutants with different emission pathways and atmospheric behavior can reveal spatial contrasts that would be obscured by a single indicator. For urban planning, this is particularly relevant because pollutant-specific hotspots may correspond to different intervention priorities.

The maximum PM_{2.5} concentration was observed at the Industrial Zone, reaching 543 µg/m³ in the winter morning period and 640 µg/m³ in the winter evening period. These measurements identify the Industrial Zone as the strongest observed PM_{2.5} hotspot within the monitoring network. They do not, however, establish a direct causal relationship with a particular industrial source because source apportionment was not performed and meteorological conditions were not measured simultaneously at the sites. The appropriate planning implication is therefore prioritization of the area for longer-duration monitoring, industrial emission assessment, and source-specific investigation rather than attribution of the measured concentration to a single source category. Recent source-apportionment work in Eskişehir demonstrates the value of chemical characterization and receptor modelling for resolving this distinction (Ari et al., 2025).

Transportation corridors and commercial centers generally exhibited intermediate particulate concentrations relative to the principal industrial locations. The Transportation Corridor recorded winter PM_{2.5} values of 125 and 147 µg/m³ and summer values of 108 and 127 µg/m³ in the morning and evening, respectively. PM₁₀ also showed elevated values in some transportation- and commercial-oriented settings. Traffic, brake and tire wear, and road-dust resuspension are plausible contextual mechanisms, but their contributions cannot be quantified from the present measurements. The results nevertheless support transportation management, road-dust control, and targeted monitoring along high-activity corridors. Urban parks and green spaces consistently recorded lower concentrations within the monitored network. This pattern is compatible with literature describing pollutant interception and deposition by vegetation, while recognizing that dense vegetation can also restrict airflow under some street-canyon configurations (Janhäll, 2015; Abhijith et al., 2017; Hewitt et al., 2020). Therefore, the planning implication is not simply to maximize vegetation cover, but to place and configure green infrastructure in relation to pollutant sources, street geometry, and ventilation conditions.

The observed PM_{2.5} and PM₁₀ concentrations provide evidence of substantial short-duration concentration episodes at several sites. WHO 2021 guideline values provide a useful health-oriented reference, including 24-h guideline levels of 15 µg/m³ for PM_{2.5} and 45 µg/m³ for PM₁₀ (WHO, 2021). Several measured values exceed these reference levels; however, direct compliance or non-compliance cannot be inferred because the observations are not standardized 24-h averages. The comparison is therefore used only to emphasize the need for longer-duration monitoring at locations where high short-term concentrations were repeatedly observed.

The Kriging maps provide an exploratory spatial framework for visualizing broad pollutant gradients across the monitored urban area. Their main value is to integrate point observations into a geographic planning context and to identify locations where additional monitoring may be warranted.

With only ten monitoring locations, however, interpolation uncertainty may be substantial between points, particularly near localized emission sources. The maps should therefore not be interpreted as validated high-resolution exposure surfaces. A stronger future framework would combine denser measurements with meteorological variables, road and traffic data, land-use indicators, building morphology, and independent interpolation validation.

The findings have several planning implications. First, industrial and organized industrial areas should receive priority for continuous or repeated monitoring and source-specific emission assessment. Second, residential heating should be considered in seasonal air-quality management, particularly where elevated winter particulate concentrations recur. Third, transportation corridors require integrated measures addressing traffic emissions and road-dust resuspension. Fourth, green infrastructure should be strategically configured rather than increased indiscriminately, with attention to source location, canopy structure, street geometry, and ventilation. Fifth, air-quality information should be incorporated into land-use planning so that sensitive land uses are not unnecessarily exposed to persistent emission environments. Finally, the existing fixed monitoring network can be complemented by mobile or neighborhood-scale measurements to capture local gradients. These recommendations are planning implications derived from observed spatial contrasts, not estimates of the effect size of individual interventions.

5. Conclusion

This study characterized the short-term spatial and temporal variability of CO₂, PM_{2.5}, and PM₁₀ across ten functionally contrasting urban environments in Eskişehir, Türkiye. The monitoring network revealed clear differences among industrial, organized industrial, residential, commercial, transportation, university, park, and urban green-space settings. The Industrial Zone consistently represented the strongest observed PM_{2.5} hotspot, with winter concentrations of 543 µg/m³ in the morning and 640 µg/m³ in the evening; winter CO₂ also reached 803 ppm at this location. Residential Area II showed comparatively elevated particulate concentrations, while Urban Park and Urban Green Space generally recorded lower values. Winter concentrations were generally higher than summer concentrations, and PM_{2.5} commonly increased from morning to evening. These patterns demonstrate that functional land-use context is closely associated with the spatial organization of measured urban air-quality conditions within the monitoring network. Importantly, the revised interpretation does not attribute these differences to specific sources because source apportionment and simultaneous site-level meteorological measurements were unavailable. Kriging interpolation provides a useful exploratory visualization of broad spatial gradients, but the limited number of sampling locations restricts the predictive resolution of the interpolated surfaces. The principal planning value of the study is therefore the identification of priority environments for denser monitoring, industrial emission assessment, residential-heating management, transportation and road-dust control, and strategically designed green infrastructure. Future research should combine continuous measurements with co-located meteorological observations, chemical characterization, source-apportionment modelling, denser spatial sampling, and validated geostatistical or land-use-based models. Such an integrated framework would allow the observed functional contrasts to be linked more rigorously to emission sources, atmospheric processes, and population exposure.

6. Supplementary Materials: No supplementary material.

7. Author Contributions

Conceptualization - A.C., I.Z.C.; methodology - A.C., I.Z.C.; software - A.C., I.Z.C.; validation - A.C., I.Z.C.; formal analysis - A.C., I.Z.C.; investigation - A.C., I.Z.C.; resources - A.C., I.Z.C.; data curation - A.C., I.Z.C.; writing - original draft preparation - A.C., I.Z.C.; writing - review and editing - A.C., I.Z.C.; visualization - A.C., I.Z.C.; supervision - A.C., I.Z.C.; project administration - A.C., I.Z.C.; funding acquisition - A.C., I.Z.C. All authors have read and agreed to the published version of the manuscript.

8. Author Information

Cicek, Aylin - Researcher, Ondokuz Mayıs University, Institute of Graduate Studies, the Master's Program in City and Regional Planning, Samsun, Türkiye, 55200; aylincicek.omu@yahoo.com, <https://orcid.org/0009-0008-3323-6550>

Cetin, Ilknur Zeren – Assoc. Prof. Dr., Advisory, Researcher, Ondokuz Mayıs University, Faculty of Architecture, Department of City and Regional Planning, ilkadim, Samsun, Türkiye, 55200; ilknur.cetin@omu.edu.tr, <https://orcid.org/0000-0003-3908-0370>

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Түркияның Эскишехир қаласы мысалында функционалдық аймақтар бойынша қалалық ауа сапасының кеңістіктік-уақыттық динамикасын бағалау

Aylin Cicek, Ilknur Zeren Cetin

Аңдатпа. Қала ауасының ластануы - өнеркәсіптік қызмет, халық тығыздығы, энергияны пайдалану, тұрмыстық жылыту және көлік өзара әрекеттесіп, атмосфералық жағдайға әсер ететін қарқынды дамып келе жатқан қалалардағы басты экологиялық мәселелердің бірі. Бұл зерттеуде Түркияның Эскишехир қаласындағы жер пайдалану мен қалалық белсенділіктің әртүрлі типтерін көрсететін он бақылау нүктесіндегі PM_{2.5}, PM₁₀ және CO₂ концентрацияларының кеңістіктік және уақыттық сипаттамалары зерделенді. Далалық өлшеулер қысқы және жазғы кезеңдерде таңертеңгі және кешкі уақытта SEM DT-9880 қалқыма бөлшектер анализаторы мен EXTECH Easyview 80 CO₂ анализаторының көмегімен жүргізілді. Алынған мәліметтер өнеркәсіптік, тұрғын үй, коммерциялық, көліктік және жасыл аймақтар арасындағы тәуліктік және маусымдық айырмашылықтарды анықтау үшін бағаланды. Кеңістіктік заңдылықтар QGIS базасындағы географиялық ақпараттық жүйе (ГАЗ) шеңберінде кригинг интерполяциясы әдісін қолдану арқылы қосымша зерттелді. Нәтижелер ластаушы заттар концентрациясының айқын кеңістіктік әртүрлілігін көрсетті: PM_{2.5} және PM₁₀ жоғары деңгейлері негізінен өнеркәсіптік аймақтарда, ұйымдасқан өнеркәсіптік аудандарда, халық тығыз орналасқан тұрғын үй кешендерінде және қазба отынымен тұрмыстық жылытылатын орындарда байқалды. Қысқы мезгілдегі PM_{2.5} ең жоғары концентрациясы 543,05 мкг/м³ құрады, ал CO₂ максималды өлшенген концентрациясы 803 ppm-нен асты. Керісінше, қалалық саябақтарда және өсімдік жамылғысы мол аймақтарда әдетте ластаушы заттардың төмен концентрациясы тіркелді. Зерттеу нәтижелері жер пайдалану сипаттамалары мен қалалық белсенділік үлгілері жергілікті ауа сапасын айқындайтын маңызды факторлар болып табылатынын көрсетеді. Өнеркәсіптік шығарындыларды бақылауды, таза жылыту жүйелерін, қаланы жасылдандыруды кеңейтуді, тұрақты ұтқырлықты және аз шығарындысы бар энергетикалық стратегияларды қала құрылысын жоспарлауға интеграциялау Эскишехирдегі атмосфералық жағдайды жақсартуға ықпал етуі мүмкін.

Түйін сөздер: қалалық ауа сапасы; PM_{2.5}; PM₁₀; көміртек диоксиді; кеңістіктік талдау; кригинг интерполяциясы; ГАЗ; тұрақты қалалық жоспарлау.

Оценка пространственно-временной динамики качества городского воздуха по функциональным зонам на примере города Эскишехир (Турция)

Aylin Cicek, Ilknur Zeren Cetin

Аннотация. Загрязнение городского воздуха является одной из основных экологических проблем в быстро развивающихся городах, где промышленная деятельность, плотность населения, энергопотребление, бытовое отопление и транспорт могут взаимодействовать, влияя на состояние атмосферы. В данном исследовании изучены пространственно-временные

характеристики концентраций PM_{2.5}, PM₁₀ и CO₂ на десяти участках, представляющих различные типы землепользования и городской активности в Эскишехире (Турция). Натурные измерения проводились с использованием анализатора взвешенных частиц SEM DT-9880 и анализатора CO₂ EXTECH Easyview 80 в утреннее и вечернее время в зимний и летний периоды. Полученные данные были проанализированы для выявления суточных и сезонных различий между промышленными, жилыми, коммерческими, транспортными и зелёными зонами. Пространственные закономерности также были изучены с применением метода кригинга (Kriging interpolation) в среде географической информационной системы на базе QGIS. Результаты выявили выраженную пространственную неоднородность концентраций загрязняющих веществ: повышенные уровни PM_{2.5} и PM₁₀ наблюдались преимущественно в промышленных зонах, организованных промзонах, густонаселённых жилых массивах и местах с печным/бытовым отоплением на ископаемом топливе. Максимальная зимняя концентрация PM_{2.5} составила 543,05 мкг/м³, а максимальная измеренная концентрация CO₂ превысила 803 ppm. Напротив, в городских парках и районах со значительным озеленением зафиксированы более низкие концентрации загрязнителей. Полученные результаты свидетельствуют о том, что особенности землепользования и характер городской активности являются важными факторами, определяющими состояние местного воздуха. Интеграция контроля промышленных выбросов, более чистых систем отопления, расширения зелёных насаждений, устойчивой мобильности и низкоэмиссионных энергетических стратегий в городское планирование может способствовать улучшению качества атмосферного воздуха в Эскишехире.

Ключевые слова: качество городского воздуха; PM_{2.5}; PM₁₀; диоксид углерода; пространственный анализ; интерполяция кригингом; ГИС; устойчивое городское планирование.