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Assessment of Air Pollutant Risk in Tehran on Athletes' Health in Relation to Outdoor Sports: A Case Study of Particulate Matter Less Than 2.5 Microns (PM2.5)

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ABSTRACT

The aim of this study is to evaluate the environmental and health risks associated with particulate matter less than 2.5 microns (PM2.5) in Tehran. This research is applied in terms of its outputs. Initially, data for the year 2023 were collected and analyzed through air pollution monitoring stations in the area. Based on the Kriging interpolation method and pollutant weighting, the corresponding raster was produced separately and classified based on minimum and maximum ranges. Finally, according to the Air Quality Index (AQI) table, the level of health safety significance was categorized and the relevant map was generated. Using the IO technique, the spatial layer of sensitive and vulnerable land uses was overlaid on the regional surface along with the carbon monoxide pollutant layer. The results indicated that District 10 of Tehran Municipality, with an average concentration of 42 micrograms per cubic meter, is the most polluted area in Tehran with respect to this pollutant. Furthermore, the highest levels of PM2.5 pollutants were recorded in the central and southern halves of the area. Additionally, the most polluted month of the year was November, with an average concentration of 56 micrograms per cubic meter. In terms of the air quality index based on the type of pollutants, this region experienced 104 days categorized as unhealthy or unhealthy for sensitive groups. The environmental and health risk assessment for this pollutant, based on the William Fine method, determined a risk score of 105, indicating a moderate risk level. Therefore, corrective and emergency actions are required to control the hazard.

Keywords: Particulate matter, risk assessment, air pollution, sensitive land uses, Tehran.

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Introduction

Urban air pollution remains one of the most pressing public health and environmental concerns in developing megacities, particularly in metropolitan regions like Tehran. Among the numerous pollutants that compromise urban air quality, fine particulate matter with an aerodynamic diameter less than 2.5 microns (PM2.5) is considered one of the most hazardous due to its ability to penetrate deep into the respiratory system and enter the bloodstream (1). Tehran, as one of the most densely populated and industrialized cities in the Middle East, consistently faces high concentrations of PM2.5, stemming from a combination of vehicular emissions, industrial processes, meteorological conditions, and geographic constraints (2, 3).

PM2.5 is composed of a complex mixture of solid and liquid particles, including organic chemicals, metals, and dust particles. These particles are primarily emitted from combustion engines, particularly diesel vehicles, industrial activities, and residential heating (4). In cities like Tehran, where vehicle emissions play a dominant role in urban pollution, traffic congestion and outdated transportation infrastructure further aggravate this issue (2). Studies show that PM2.5 is not only a localized problem but also subject to long-range atmospheric transport, meaning external sources of pollution can influence local air quality through transboundary mechanisms (5).

The health implications of long-term exposure to PM2.5 are well-established. Scientific literature links elevated PM2.5 levels to increased rates of respiratory diseases, cardiovascular disorders, and premature mortality (1, 6). The ultrafine nature of these particles allows them to bypass upper respiratory defenses, depositing in alveolar regions and initiating systemic inflammatory responses (7). Moreover, the neuropsychological and mental health effects of air pollution have garnered attention in recent years. PM2.5 has been associated with higher levels of stress, anxiety, and depression, suggesting a broader psycho-social impact (8-10).

In Tehran, several modeling efforts have been undertaken to predict pollutant dispersion and simulate future scenarios of air pollution management (11, 12). System dynamics modeling has revealed that without substantial regulatory interventions, PM2.5 concentrations will continue to exceed safe thresholds in many parts of the city. In particular, Tehran's basin-like geography exacerbates the issue by trapping pollutants during periods of atmospheric inversion, especially in the winter months (13). Urban development, population growth, and a rising number of motor vehicles have intensified the emission rates, further challenging mitigation strategies.

From an environmental justice perspective, PM2.5 pollution is not uniformly distributed across Tehran. Vulnerable populations—particularly those residing in densely populated, lower-income southern districts—are disproportionately exposed to hazardous pollutant levels. Exposure risk is also elevated among populations engaging in outdoor activities, such as athletes, street vendors, and children attending open-air schools (14). Notably, the interaction between urban land-use planning and pollution distribution plays a critical role in determining localized health risks, especially for those living near major roads, industrial zones, or construction sites (15).

Public perception of air quality and risk awareness among citizens is also an important dimension in managing environmental hazards. In Tehran, studies have shown that knowledge regarding the health effects of air pollution remains insufficient, especially among youth and school-aged populations (14). This gap between perceived and actual risk can hinder public support for necessary regulatory measures. Efforts to raise awareness, improve public transportation infrastructure, and implement clean energy technologies have been initiated but often lack coordination and long-term political commitment (16).

The governance of air pollution control in Iran presents both institutional and technological challenges. Despite regulatory frameworks developed under the Ministry of Health and the Department of Environment, enforcement remains limited due to resource constraints and overlapping institutional responsibilities (17). Green management strategies in public institutions, such as hospitals and schools, have been proposed as localized interventions to reduce emissions and promote sustainability (17). However, such approaches are yet to be widely adopted.

Globally, comparisons with cities facing similar challenges—such as Ahvaz in Iran or petrochemical industrial zones in Southeast Asia—highlight the importance of integrated and sustainable air quality management frameworks (3, 18). Approaches such as emissions inventories, real-time air monitoring, and predictive modeling have proven effective in identifying high-risk zones and informing spatial planning. In this regard, Tehran's limited investment in smart environmental monitoring systems has constrained the ability of policymakers to respond proactively to pollution episodes (12).

Moreover, international studies underscore the significance of natural green spaces in mitigating the psychological and physiological burden of air pollution. Lifelong exposure to greenspace has been linked to lower risks of conditions like premenstrual syndrome and improved general well-being (19). For a megacity like Tehran, which suffers from green space inequities and high urban density, integrating ecological health into city planning could serve as a co-benefit strategy for air pollution mitigation.

In the context of this study, special attention is paid to PM2.5 levels in areas that involve outdoor physical activity, such as large urban parks and open-air sports facilities. Athletes and recreational users of these spaces are among the most vulnerable groups, as they inhale greater volumes of air during physical exertion, thereby increasing exposure to pollutants (6). The health implications are not just limited to short-term respiratory issues but include long-term reductions in lung capacity and performance endurance, particularly in children and the elderly (20).

The research presented here adopts an integrated methodological framework involving spatial analysis, risk assessment, and environmental modeling to examine the distribution and health risks of PM2.5 in Tehran. Using tools such as Kriging interpolation, AQI classification, and the William Fine risk assessment matrix, this study offers a comprehensive approach to identifying critical zones of environmental vulnerability. This aligns with earlier efforts that emphasized the importance of cross-disciplinary approaches in urban environmental studies (4, 9).

Ultimately, the significance of this research lies in its ability to bridge the gap between environmental data and actionable health policy. As Tehran continues to urbanize and its population grows, understanding the spatial distribution of PM2.5 and its health impacts is essential to prioritize interventions and allocate resources effectively. It is not enough to monitor pollutants; a multi-stakeholder strategy involving public health professionals, urban planners, environmental scientists, and civic organizations is essential to tackle this complex challenge holistically (8, 10, 16).

In sum, this study contributes to the expanding body of literature on urban air pollution by offering a case-specific investigation into Tehran's PM2.5 exposure patterns, with a focus on vulnerable land uses and health risks. The results are expected to inform both academic discourse and policy development, advocating for more sustainable and health-oriented urban planning in Iran and comparable urban settings.

Methods and Materials

This research is applied in nature in terms of its objective, survey-based in terms of data collection method, and comparative-analytical in terms of data analysis method. Initially, general data related to Tehran's particulate pollutants (PM2.5) were collected and analyzed from the Air Pollution Monitoring Center and the Tehran Air Quality Control Company. For this purpose, statistical data from 24 active stations over the period from January 21, 2019, to January 21, 2020, were collected and analyzed. To extract valid results and accurate information, the data and statistics were pre-processed.

In the next step, spatial layers of large-scale outdoor sports complexes and urban parks were mapped in ArcView software. Finally, the extracted data from the studied stations were cross-referenced with the Air Vision database.

Subsequently, based on the table of average pollutant concentrations at the selected stations, the weight values for each pollutant were entered into the corresponding table. Using the Kriging method, rasters were generated based on pollutant weight and classified according to minimum and maximum ranges. For estimating values using the Kriging method, various techniques exist; in this study, the conventional Kriging method was employed. The general formula for Kriging is based on the following equation:

$$zo = \Sigma(w_i \times z_i)$$

In this equation, zo represents the estimated values, w_i denotes the weights, and z_i are the sample values. The weights depend on the degree of correlation between the sample points and the estimated points, and their sum is always equal to 1. Therefore, for particulate pollutants with a diameter less than 2.5 microns, this method was repeated, and the output was mapped.

Finally, based on the Air Quality Index (AQI) table, which adheres to EPA standards (2004), the level of health safety significance was classified and mapped. The basis for measuring pollutant levels was the Air Quality Index, which ranges from 0 to 500. The higher the index, the more polluted the air and the greater the impact on health (Table 1).

Table 1. Air Quality Index (AQI) Guide

Pollution Range (Breakpoints)	PM2.5 (µg/m³)	Conceptual Air Quality Level	Health Importance Level	AQI
0 – 15.4	0 – 15.4	Clean	Air quality is satisfactory; no health risk.	0 – 50
15.5 – 35	15.5 – 35	Healthy	Air quality is acceptable; slight risk for sensitive individuals during intense activity.	51 – 100
35.1 – 65.4	35.1 – 65.4	Unhealthy for Sensitive Groups	Air quality is unhealthy for sensitive groups; long exposure should be reduced.	101 – 150
65.5 – 150.4	65.5 – 150.4	Unhealthy	Air quality is unhealthy for the general public; long-term exposure is not recommended.	151 – 200
150.5 – 250.9	150.5 – 250.9	Very Unhealthy	Health warning conditions for all individuals; activities should be minimized.	201 – 300
> 251	> 251	Dangerous	Air quality is dangerous; outdoor activity is hazardous for everyone.	301 – 500

Iran's air pollutant standards are calculated based on the Ministry of Health guidelines (2011) for short-term standards and the Environmental Protection Agency (2017) for long-term standards, aligned with EPA and WHO benchmarks. Table 3 lists the permissible limits for PM2.5 (35 µg/m³ daily, 12 µg/m³ annually).

Table 2. Permissible Limits for Particulate Pollutants (PM2.5)

Pollutant	Permissible Limit (Standard)	Period
Fine Particulate Matter (PM2.5)	35 µg/m³	Daily
	12 µg/m³	Annual (Iran standard)

The William Fine method was used for risk assessment, calculated by the formula:

$R = C \times E \times P$

Table 3. Risk Assessment Calculation Using the William Fine Method

Risk Assessment	Consequence Value (C)	Probability of Occurrence (E)	Exposure Level (P)
Very Severe Damage	100	Continuous	10
Severe Damage	40	High	7
Moderate Damage	15	Medium	4
Minor Damage	5	Low	2
No Damage	1	Very Low	1

Findings and Results

Table 4 shows the average concentration of PM2.5 at air pollution monitoring stations during the study period. According to this data, the region with the highest average concentration of this pollutant (42 µg/m³) was District 10 of the Tehran Municipality. Conversely, the lowest concentration (10 µg/m³) was recorded in District 4.

Table 4. Average PM2.5 Concentration in 2019 in Tehran

Concentration	District	Concentration	District	Concentration	District
37	18	42	10	20	1
36	19	37	11	30	2
36	20	38	12	38	3
37	21	38	13	10	4
29	22	33	14	19	5
		22	15	29	6
		33	16	23	7
		36	17	21	8
				39	9

Figure 1 presents the annual average concentration of PM2.5 particles during the study period (2019), visualized through the size of circles located at stations across Tehran. It is evident that larger circles indicate higher annual average concentrations. As shown, excluding the Sadr station, the highest concentrations were recorded in stations located in central and southwestern Tehran, which are more affected by dust flows.

According to Figure 1, the highest PM2.5 concentrations are observed in areas more exposed to dust from outside Tehran. Notably, in addition to traffic and dust phenomena, the activity of stationary pollution sources such as construction work around the stations also contributes significantly to pollutant emissions. Moreover, the cumulative concentration trends of PM2.5 at various times of the day during the study period revealed two peak points: one at 9:00 a.m. and another at midnight.

Figure 2 displays the monthly average PM2.5 concentration across 2019. This pollutant comprises a wide range of ultrafine particles smaller than 2.5 microns, primarily generated from combustion processes, particularly in motor vehicles such as diesel-powered cars. Under stable atmospheric conditions and dust events, PM2.5 accumulates in the city's air over consecutive days. Many of the polluted days in 2019 were caused by this pollutant. The monthly average concentration shows the lowest values in October, May, and March. Conversely, the highest concentrations were recorded in December and January due to cold weather, increased atmospheric stability, and temperature inversion, all of which cause pollutant accumulation.

Figure 3 shows that in terms of the Air Quality Index (AQI), during the study period (2019), Tehran experienced 30 days of clean air, 221 days of healthy air, 52 days of unhealthy air for sensitive groups, and 4 days of unhealthy air overall (see Table 5).

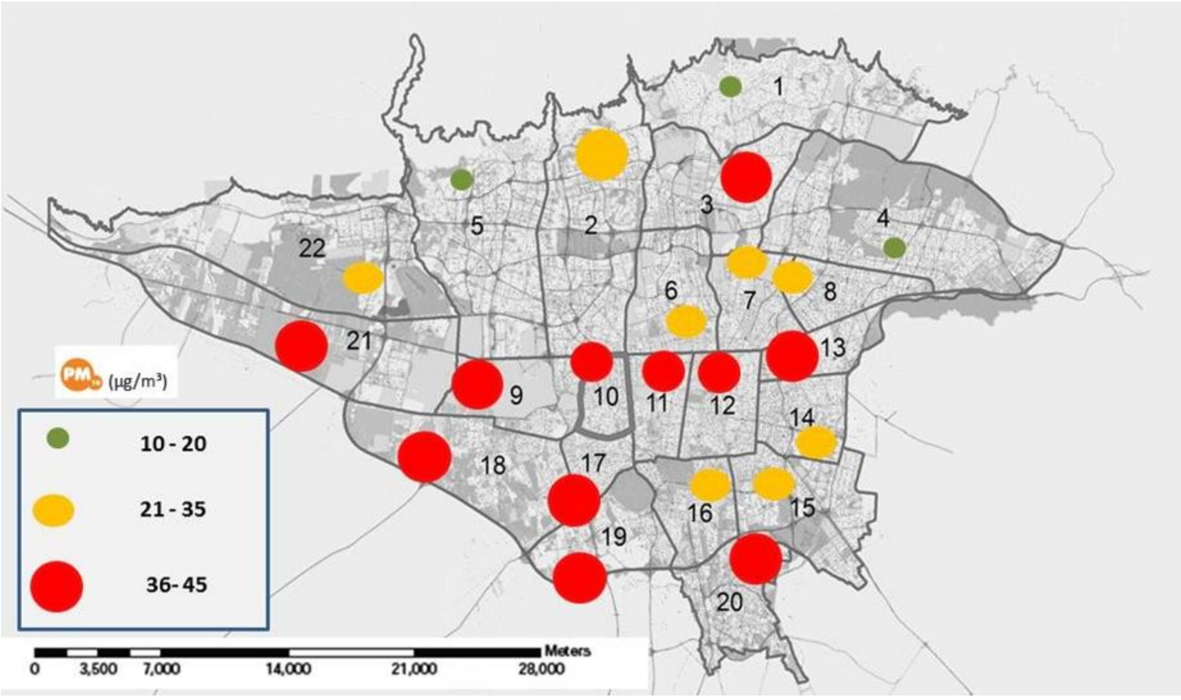

Figure 1. Annual Average Concentration of PM2.5 at Monitoring Stations in Tehran (2019)

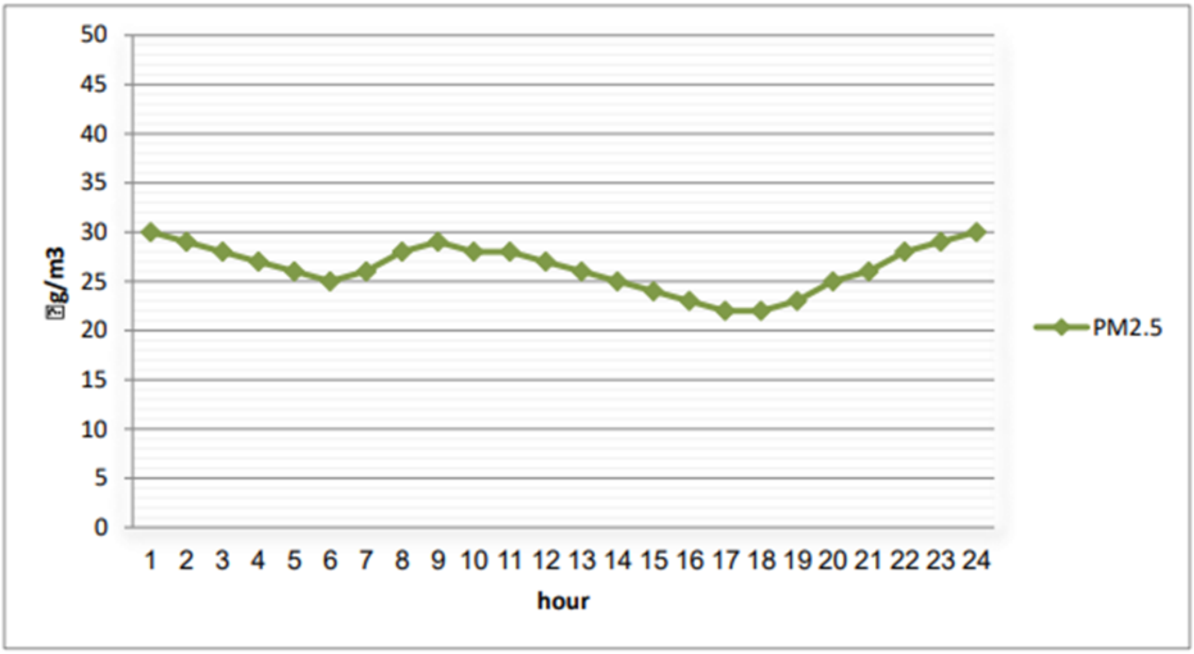

Figure 2. Monthly Variation in PM2.5 Concentration Across Tehran in 2019

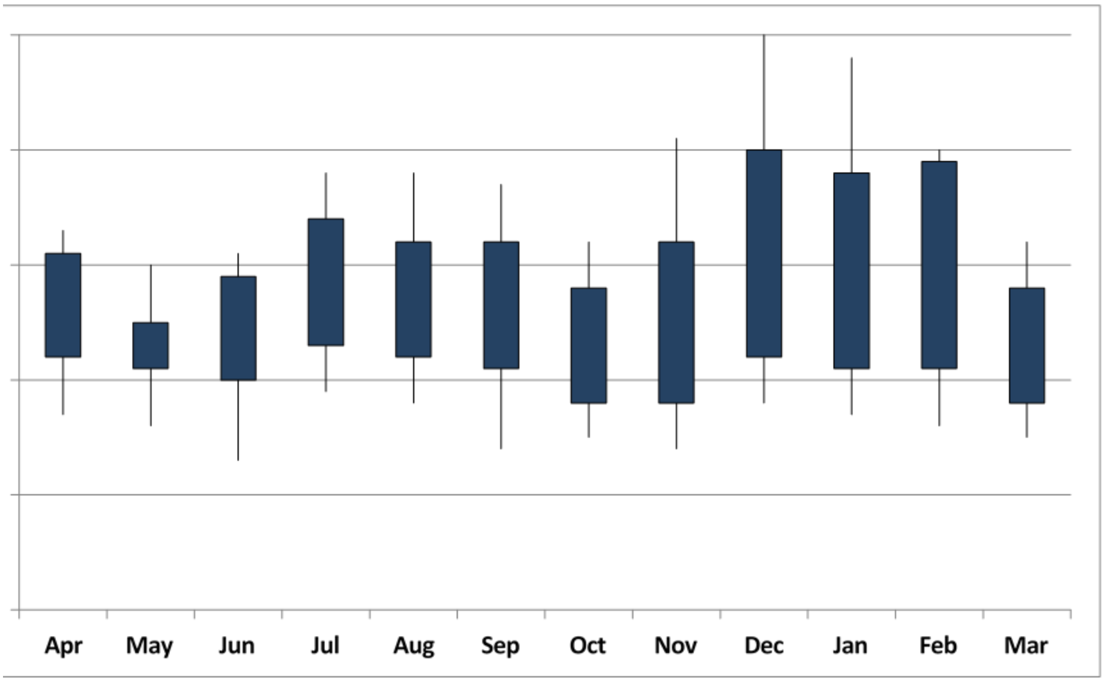

Figure 3. Air Quality Index (AQI) Classification of PM2.5 Days in Tehran During 2019

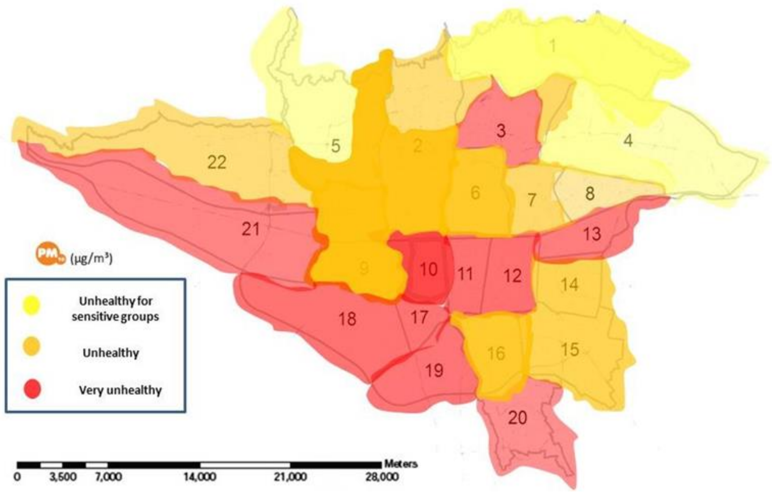

Figure 4. Cumulative Hourly Fluctuations of PM2.5 Concentration During a 24-Hour Period

Table 5. AQI-Based PM2.5 Status Across Tehran in 2019

Row	Location	Mean Pollutant AQI	Clean	Healthy	Unhealthy for Sensitive Groups	Unhealthy	Very Unhealthy	Dangerous
2	Tehran City	81	30	221	52	4	–	–

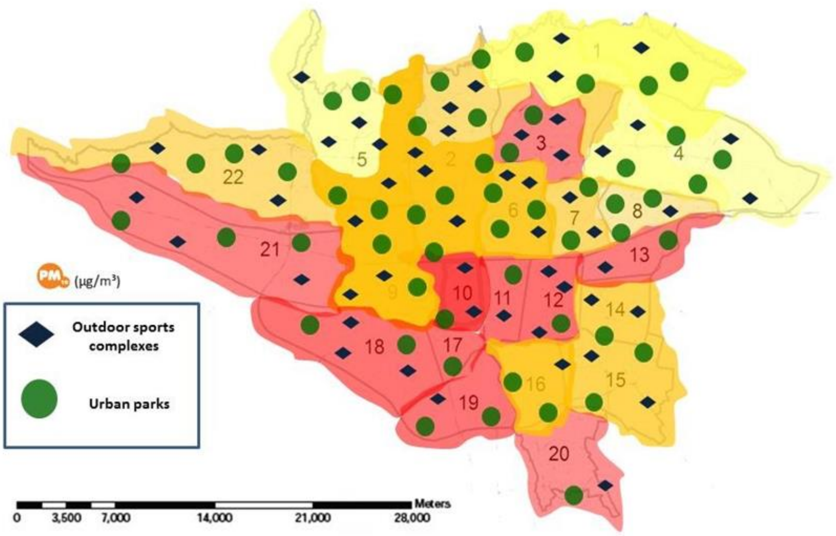

Figure 5. PM2.5 Zoning Map for Tehran in 2019

Based on the overlay of air pollution layers and maps of large-scale outdoor sports land uses and urban parks with outdoor sports facilities, a map of sensitive and vulnerable centers was generated. The figure illustrates the location of these identified centers in the study area.

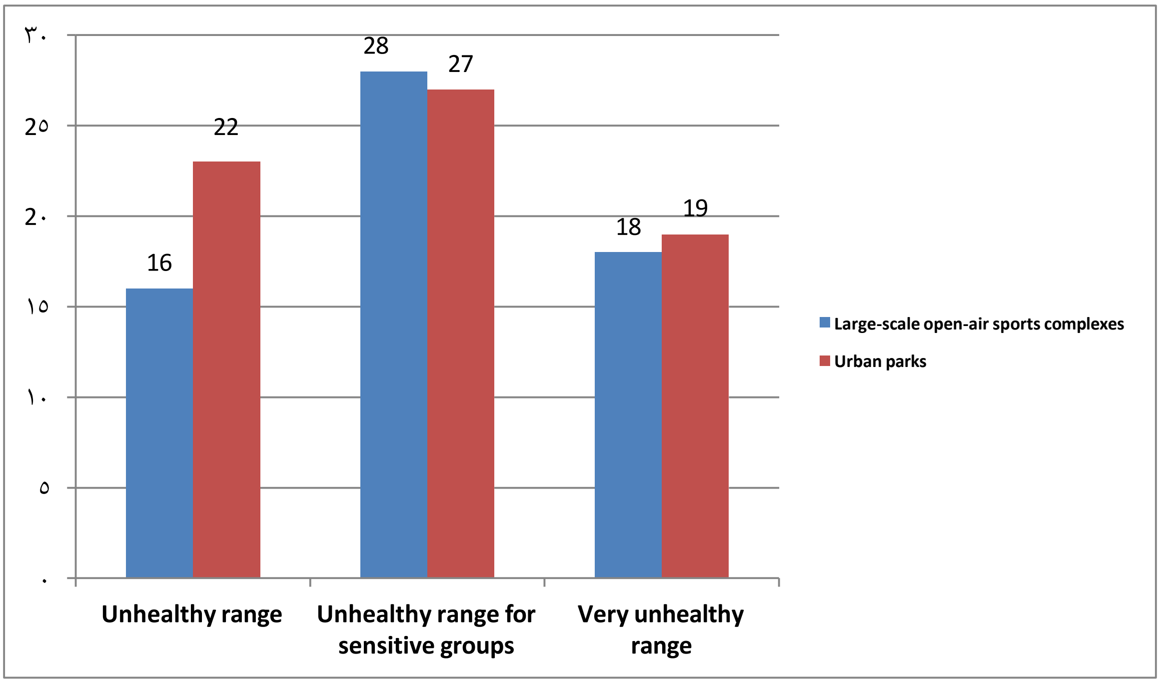

Figure 6. Map of Outdoor Sports Land Uses and Urban Parks with Sports Facilities

Based on the overlay of air pollution layers and maps of large-scale outdoor sports facilities and urban parks with outdoor exercise amenities, a map of sensitive and vulnerable centers was identified. The figure shows the location of these centers within the region.

Using the William Fine method guide, environmental and health risks associated with PM2.5 pollutants were evaluated and analyzed. To determine consequence severity, exposure rate, and probability rate, the assessment was conducted according to Table 6. Given that the average PM2.5 concentration in Tehran was 22 μg/m³, but reached a maximum level of 42 μg/m³, it was found that this exceeds more than 50% above the recommended standard. Thus, the risk consequence was categorized as "high" with a value of 7. Moreover, considering that out of 307 days of pollutant sampling, 104 days showed PM2.5-related pollution, the probability of occurrence is less than 50% (33%). The contact rate, based on database information, was assigned a value of 5.

Table 6. Consequence (C), Contact Rate (E), and Probability Rate (P)

Aspect	Potential Consequences	C	E	P	Risk Value	Risk Level
PM2.5 Dispersion and Emission	Toxicity / Health Effects / Reduced Efficiency	7	5	3	105	Medium Risk

The final risk was evaluated using the William Fine method as follows:

Risk = Exposure Rate × Consequence Value × Probability Rate

105 = 3 × 7 × 5

Table 7. Summary of Risk Rating and Required Actions

Risk Level	Action Required	Score Range
High Risk	Immediate corrective actions required	> 200
Medium Risk	Emergency attention needed as soon as possible	90–199
Low Risk	Risk is monitored and controlled	< 89

Overall, based on Table 8, the risk score of 105 corresponds to an "emergency status" and a medium risk level, which requires prompt attention. The results showed that PM2.5 pollutants were not uniformly distributed across the study area, and significant variation was observed. Zoning maps revealed that the most polluted areas are located in the southern and central parts of the region. Furthermore, pollutant distribution does not follow a consistent pattern or display recognizable order. Analysis of spatial layers and mapped data revealed that a substantial portion of sensitive and vulnerable land uses are in direct and high contact with this pollutant.

The findings of this study align with the research conducted by Bahmanpour et al. (2013), which indicated that the types and patterns of air pollution in Tehran vary depending on the type of pollutant. However, the current findings only partially align with the study by Azizi et al. (2007), as their results showed that pollutant concentration in Tehran increases from north to south and west to east, with maximum concentrations in Districts 11 and 12 and minimum levels in Districts 4 and 21.

The environmental risk assessment of this pollutant in the study area revealed a risk score of 105, indicating a medium risk level, requiring emergency intervention. Overall, PM2.5 concentrations are higher in central and southwestern Tehran. Based on the recommended permissible level (25 μg/m³), it was concluded that except for Districts 1, 4, 5, 7, 8, and 15, the remaining districts of Tehran have average concentrations above the standard limit.

1. **Average and Maximum PM2.5 Concentration in Tehran**

- The average PM2.5 concentration in Tehran is 22 μg/m³.
- The maximum recorded level during the evaluation period was 42 μg/m³, which is over 50% higher than the recommended standard (25 μg/m³).
- Accordingly, the consequence severity is high, rated 7.

2. **Probability Rate**

- Out of 307 monitoring days, 104 days showed PM2.5 pollution.
- This constitutes 33% of the total days, resulting in a probability rate of 3 (moderate probability).

3. **Exposure Rate**

- According to database records, the exposure rate is 5.

Risk Calculation:

Based on the William Fine method:

Risk = Consequence (7) × Exposure (5) × Probability (3)

Risk Score = 105.

Discussion and Conclusion

The present study examined the spatial distribution and health risk assessment of PM2.5 pollutants in Tehran, with a particular focus on outdoor environments used for physical activity such as large urban parks and sports facilities. The results indicated significant spatial heterogeneity in pollutant concentrations, with District 10 exhibiting the highest annual average PM2.5 level (42 µg/m³), well above the national and WHO-recommended thresholds. In contrast, District 4 recorded the lowest concentration (10 µg/m³), suggesting that topography, land use, traffic density, and urban morphology strongly influence the distribution of air pollutants across Tehran. Additionally, seasonal variations revealed higher PM2.5 concentrations during the colder months of December and January, coinciding with increased atmospheric stability and temperature inversions, which limit pollutant dispersion and facilitate their accumulation in the lower atmosphere.

These findings are consistent with earlier simulations conducted on Tehran's air pollution patterns, which identified the southern and central parts of the city as the most polluted due to dense traffic networks and industrial activities (13). Moreover, the cumulative hourly distribution of PM2.5 revealed two daily peaks—one in the morning (9:00 AM) and another at midnight—corresponding to traffic rush hours and reduced atmospheric dispersion, respectively. This temporal pattern corroborates prior research on urban pollutant behavior and underscores the interaction between human activity patterns and pollutant dynamics (2, 4).

The health risk assessment using the William Fine method produced a risk score of 105, classifying PM2.5 exposure in the studied areas as a moderate risk that demands immediate attention. This outcome is significant, especially when considering the vulnerable groups who frequent outdoor recreational spaces. PM2.5, being respirable and capable of penetrating deep into the alveolar sacs, poses severe respiratory and cardiovascular risks, particularly during intense physical exertion (1, 6). The implications are far-reaching, especially for athletes, children, and the elderly, who are more susceptible to the adverse effects of fine particulate pollution.

The study also found that over one-third (33%) of the monitored days throughout the year exceeded safe PM2.5 thresholds, which supports findings from previous investigations highlighting Tehran's chronic exposure problem (11, 12). This prolonged exposure period increases the cumulative health burden on residents, potentially accelerating the development of chronic diseases such as asthma, bronchitis, and even stroke and dementia (9, 10). In a city where outdoor activity is culturally and recreationally significant, the potential for exposure during routine exercise further complicates the public health landscape.

The seasonal pattern observed in this study, where PM2.5 levels were highest in winter, reflects the influence of meteorological conditions and increased fuel consumption for heating. Similar findings have been reported in studies conducted in Ahvaz and other Iranian cities, where colder months are characterized by a sharp rise in PM2.5 due to a combination of residential combustion and atmospheric stagnation (3).

International studies have also documented the winter intensification of air pollution, with increased health risks related to thermal inversions and pollutant accumulation (18, 20).

Another notable outcome of this study was the high level of pollutant exposure in proximity to outdoor sports facilities and parks. The mapping of these areas in conjunction with pollutant distribution layers revealed a worrying trend: many of these recreational zones are located in districts where PM2.5 concentrations frequently surpass acceptable limits. This aligns with public health studies indicating that outdoor exercise under polluted conditions can exacerbate pulmonary inflammation and reduce lung function in both healthy individuals and those with pre-existing conditions (6, 19).

In addition to physiological effects, recent research has underscored the psychological impact of air pollution, linking PM2.5 exposure to increased levels of anxiety, depression, and stress-related disorders (8, 10). These effects are particularly relevant in urban environments where daily exposure to traffic congestion and air pollution can undermine mental well-being. The implications extend beyond individual health to broader societal outcomes, including reduced productivity and increased healthcare costs.

The study's findings also emphasize the importance of public awareness and environmental education. Previous investigations into air pollution awareness among Tehran residents, particularly schoolchildren, revealed limited knowledge regarding the causes and consequences of pollution (14). Without adequate understanding, citizens may fail to adopt preventive behaviors or support policy interventions aimed at reducing emissions. Education campaigns and community-based monitoring initiatives can bridge this knowledge gap and foster public engagement with air quality issues.

Technological and policy solutions must also be considered in light of these findings. As highlighted in recent reviews, strategies such as emission reduction technologies, clean energy adoption, and stricter enforcement of environmental standards have shown promise in mitigating urban air pollution (16). In Tehran, the implementation of predictive modeling tools such as bidirectional long short-term memory neural networks has improved pollutant forecasting, but the transition from data analysis to policy implementation remains slow and inconsistent (12).

Moreover, the complexity of urban pollution dynamics requires cross-sectoral collaboration. The integration of air quality management into urban planning, transportation, and public health sectors can produce more resilient and adaptive responses to pollution crises (17, 18). In this regard, the use of system dynamics modeling has been recommended to account for feedback loops and delays inherent in urban environmental systems (11). Such approaches can enhance the predictive capacity of policy models and inform evidence-based interventions.

At the international level, the study's implications resonate with findings from other densely populated and industrializing regions. For instance, the health impacts of PM2.5 in Southeast Asia and Sub-Saharan Africa have been extensively documented, particularly among vulnerable populations such as pregnant women and children (5, 15). These parallels suggest that global knowledge exchange and collaboration are essential for addressing shared environmental health challenges.

While this study provides valuable insights into PM2.5 distribution and health risks in Tehran, it is not without limitations. First, the study relies on fixed air quality monitoring stations, which may not fully capture micro-environmental variations, especially in areas with sparse sensor coverage. Second, the health risk assessment used generalized exposure and consequence rates, which do not account for individual differences in health status, physical activity levels, or socio-economic conditions. Third, the cross-sectional nature of the data limits the ability to determine causal relationships or long-term health outcomes directly attributable to PM2.5 exposure.

Future studies should incorporate high-resolution spatial and temporal data, possibly through mobile sensors and satellite-based remote sensing, to enhance the accuracy of exposure assessment. Longitudinal studies that track individual health outcomes in relation to air pollution exposure over time would provide more robust evidence for causality. Moreover, integrating socio-demographic variables such as age, income, and occupation into risk models can help identify particularly vulnerable subpopulations. Additionally, experimental designs evaluating the effectiveness of mitigation strategies—such as vegetation buffers, air filtration systems, and emission control technologies—would add practical value to academic findings.

To effectively address the risks posed by PM2.5 in Tehran, immediate policy attention is needed to regulate emissions from vehicular traffic and construction activities. Public access to real-time air quality data should be expanded, particularly in areas with high recreational use. Urban planners should prioritize the development of green infrastructure in pollution-prone districts to buffer air quality impacts. Health advisories should be tailored to specific population groups, especially during high-risk periods in winter. Schools, athletic facilities, and municipal agencies should collaborate to modify outdoor activity schedules during peak pollution hours to minimize health risks for vulnerable individuals.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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