Comparative Study of Atmospheric Particulate Matter Size Distribution in East and West Tehran, Iran

Balal Oroji

Kharazmi University, Faculty of Biological Sciences, Department of Plant Biology,
Tehran-Tehran, Iran

E-Mail: Balaloroji@khu.ac.ir
ORCID: 0000-0001-8691-8397

Abstract

In order to investigate the particle size distribution pattern of atmospheric suspended particles in Tehran, simultaneous sampling was conducted at six stations located in the western (ST1 to ST3) and eastern (ST4 to ST6) halves of the city. Mass concentrations were measured across nine size fractions ranging from particles larger than 11 µm to those smaller than 0.4 µm. The results indicated that at the western stations, the highest mass concentrations were mainly observed in the coarser particle fractions (11-7 µm and ≥11 µm), with maximum values of 19.6 and 16.3 µg.m^{-3} recorded at ST2 and ST1, respectively. This pattern suggests the dominance of mechanical sources and road dust resuspension in the western part of the city. In contrast, the eastern half of Tehran exhibited an increasing trend in concentration within the finer fractions (less than 2.1 µm), with the highest value measured at ST6 in the <0.4 µm fraction (18.7 µg.m^{-3}). Additionally, in the 0.7-0.4 µm and 2.1-1.1 µm ranges, eastern stations showed higher concentrations compared to the western stations. This shift in size distribution pattern-from coarse-particle dominance in the west to fine-particle dominance in the east-may be attributed to differences in land use, traffic density, combustion-related sources, as well as topographic conditions and prevailing wind patterns across Tehran. Overall, the findings indicate a greater contribution of combustion-related and secondary fine particles in the eastern half, whereas the western half appears to be more influenced by primary sources and coarse particle resuspension. These results highlight the importance of region-specific management strategies for effective control of particulate matter pollution in the megacity of Tehran.

Keywords: Atmospheric Particulate Matter, Particle Size Distribution, Urban Air Quality, Spatial Variation

Resumen

Para investigar el patrón de distribución del tamaño de partícula de las partículas atmosféricas suspendidas en Teherán, se realizó un muestreo simultáneo en seis estaciones ubicadas en las mitades occidental (ST1 a ST3) y oriental (ST4 a ST6) de la ciudad. Se midieron las concentraciones de masa en nueve fracciones de tamaño que iban desde partículas mayores de 11 µm hasta aquellas menores de 0,4 µm. Los resultados indicaron que en las estaciones occidentales, las concentraciones de masa más altas se observaron principalmente en las fracciones de partículas más gruesas (11-7 µm y ≥11 µm), con valores máximos de 19,6 y 16,3 µg.m^{-3} registrados en ST2 y ST1, respectivamente. Este patrón sugiere el predominio de fuentes mecánicas y la resuspensión de polvo de la carretera en la parte occidental de la ciudad. En contraste, la mitad oriental de Teherán exhibió una tendencia creciente en la concentración dentro de las fracciones más finas (menos de 2,1 µm), con el valor más alto medido en ST6 en la fracción <0,4 µm (18,7 µg.m^{-3}). Además, en los rangos de 0,7-0,4 µm y 2,1-1,1 µm, las estaciones orientales mostraron concentraciones más altas en comparación con las estaciones occidentales. Este cambio en el patrón de distribución de tamaño, del predominio de partículas gruesas en el oeste al predominio de partículas finas en el este, puede atribuirse a las diferencias en el uso del suelo, la densidad del tráfico, las fuentes relacionadas con la combustión, así como las condiciones topográficas y los patrones de viento predominantes en Teherán. En general, los hallazgos indican una mayor contribución de partículas finas secundarias y relacionadas con la combustión en la mitad oriental, mientras que la mitad occidental parece estar más influenciada por fuentes primarias y la resuspensión de partículas gruesas. Estos resultados resaltan la importancia de las estrategias de gestión específicas de la región para el control efectivo de la contaminación por material particulado en la megaciudad de Teherán.

1. Introduction

Despite industrial advancements in recent years, improvements in air quality have stalled not only in less developed countries but also in many regions worldwide, and this trend continues at an alarming rate. This situation has led to the formation of “black clouds” of urban atmospheric pollution, exacerbating atmospheric stability issues. Such conditions have contributed to an increase in hospital visits by patients suffering from asthma, Chronic Obstructive Pulmonary Disease (COPD), and cardiovascular diseases, as well as a rise in the consumption of chemical medications (Kelly *et al*., 2015). Rapid urbanization has also resulted in elevated concentrations of fine and coarse particulate matter in the air, making this phenomenon one of the most critical environmental challenges of the century in developing countries (Zweifel *et al*., 2009; Thompson *et al*., 2013). Daily human exposure to particles emitted from fossil fuel combustion in both mobile and stationary sources, as well as particles originating from heating systems and cooking processes in confined spaces, poses significant health risks (WHO, 2013b). Research on pregnant women exposed to prolonged $PM_{2.5}$ has shown that post-delivery, biological complications and long term disturbances in overall neonatal health emerge. Low birth weight and preterm birth are among these adverse outcomes (Ritz *et al*., 2008; Sapkota *et al*., 2012; Proietti *et al*., 2013). Limited studies have addressed the health effects associated with residing in areas where individuals are continuously exposed to traffic related pollutants. However, some research has identified air pollution as a novel risk factor for type 2 diabetes mellitus (T2DM), with strong evidence linking these effects to NO_2 exposure (Raaschou-Nielsen *et al*., 2013; Puett *et al*., 2011a; Puett *et al*., 2011b; Kramer *et al*., 2010; Ranft *et al*., 2009; Guxens and Sunyer, 2012). In the United States, Pope et al. evaluated data collected from 51 cities over an extended period between 1980 and 2000, as provided by the American Cancer Society, regarding long-term exposure to $PM_{2.5}$. They reported that the implementation of air quality regulations and the subsequent reduction in $PM_{2.5}$ concentrations between 1980 and 2000 contributed to an overall increase of approximately 2.7 years in life expectancy among the affected populations (Pope *et al*., 2009)

Recently, findings from the Swiss Study on Air Pollution and Lung Diseases in Adults (SAPALDIA) were published concerning air pollution and respiratory disease in adults. According to this report, in eight communities surveyed in 1991 and again in 2002, the annual mean PM_{10} concentration decreased by 5-6 $\mu g.m^{-3}$. This reduction in particulate levels was associated with a corresponding decline in the annual rate of lung function deterioration (Downs *et al*., 2007). These studies, along with other research, have examined the relationship between long-term air pollution exposure and mortality (Katsouyanni *et al*., 2001; Hoek *et al*., 2002; Filleul *et al*., 2005). It is noteworthy that, today, air pollution has surpassed drinking water contamination as a primary environmental concern and has become a leading cause of premature mortality in recent years (Leoeule *et al*., 2012; Krewski *et al*., 2009). According to the World Health Organization's latest report in 2012, approximately 3.7 million people in urban and rural open air environments died as a result of air pollution (WHO, 2014). Additionally, in recent years, mortality associated with low concentrations of particulate matter (PM) has also been significant (Ostro *et al*., 2006; Naess et *al*., 2007; Crouse *et al*., 2012; Meister *et al*., 2012). These findings indicate that, alongside the scarcity of potable water, air pollution has emerged as a major global environmental challenge in recent years (OECD, 2014). Schneider et al. (2009) reported that reductions in symptoms such as regular cough, chronic cough with phlegm, wheezing, and shortness of breath may be associated with decreases in particulate matter (PM) concentrations (Schindler *et al*., 2009). In a separate study conducted in Switzerland on nine cohorts of children between 1992 and 2001, a link was observed between reductions in ambient PM_{10} concentrations and improvements in respiratory health, including decreased incidence of chronic cough, bronchitis, common colds, mild nocturnal dry coughs, and pulmonary inflammation (Bayer-Oglesby *et al*., 2005). The results suggest that health improvements can occur to some extent following reductions in particulate matter concentrations. However, with current knowledge, it is not possible to definitively identify individual characteristics or sources with regard to their health effects. Moreover, no specific source or concentration of particulate matter can be considered entirely without adverse effects. Nonetheless, the pathogenic potential of particulate matter may operate through various mechanisms (EPA, 2009; WHO, 2013a; HEI, 2013a). Components with direct adverse effects on health have been identified through extensive research, including large-scale studies such as the WHO REVIHAAP Project (Review of Evidence on Health Aspects of Air Pollution) and other systematic investigations in this field (WHO, 2013a; HEI, 2013a; WHO, 2012; HEI, 2010; HEI ,2013b). These components include chemical constituents such as black carbon (BC), organic carbon (OC), secondary inorganic particles, particle size (coarse and ultrafine), and sources (e.g., road traffic). Furthermore, research indicates that short-term exposure to black carbon can be more hazardous than exposure to PM_{10} or $PM_{2.5}$, although black carbon alone cannot be considered solely responsible for adverse effects. Some researchers suggest that these particles in the atmosphere, as indicators of primary combustion related to traffic (such as organic compounds), are relatively less harmful compared to overall particulate mass (WHO, 2012).

Organic carbon (OC) is a complex and heterogeneous mixture of primary and secondary airborne particles. Given common combustion sources, OC can co-occur with black carbon. Therefore, assessing the potential toxicity of specific OC compounds is challenging, as there is insufficient evidence to distinguish between the toxicity of primary versus secondary OC particles. Nevertheless, studies have demonstrated associations between OC exposure and respiratory disorders as well as cardiovascular events (Kim *et al*., 2008; Kim *et al*., 2012; Hildebrandt *et al*., 2009; Ito *et al*., 2011; Son *et al*., 2012; Zanobetti and Schwartz, 2009; Ostro *et al*., 2010). Long-term exposure to OC has been linked to ischemic cardiovascular diseases and, ultimately, increased mortality (Anderson *et al*., 2010). Epidemiological evidence also indicates that short-term exposure to sulfate is associated with cardiovascular and respiratory mortality, as well as hospital admissions for heart and lung conditions (Kim *et al*., 2012; Ito *et al*., 2011).

Moreover, studies have reported physiological changes in the heart, including ventricular dysfunction and endothelial impairment, correlated with daily sulfate exposure (Anderson *et al*., 2010; Bind *et al*., 2012).

Epidemiological data indicate that short-term exposure to coarse particles (2.5–10 µm) significantly impacts cardiovascular and respiratory health, including premature mortality (Meister *et al*., 2012; Peng *et al*., 2008; Atkinson *et al*., 2010; Mann *et al*., 2010; Oiu *et al*., 2012). Systematic reviews present varying conclusions regarding the health effects of fine particulate matter ($PM_{2.5}$) (EPA, 2009; Brunekreef and Forsberg, 2005; EPA, 2013). Research on the long-term impact of coarse particles on public health is limited, and cardiovascular mortality or morbidity linked to these particles has not been widely reported (Puett, 2011b). However, toxicological evidence shows that coarse particles can act as carriers for toxic substances, similar to $PM_{2.5}$ (Graff *et al*., 2009; Wegesser *et al*., 2008). Limited data and insufficient studies contribute to the scarcity of findings regarding coarse particulate matter, due in part to differences in deposition and inhalation mechanisms. Ultrafine particles (<0.1 µm) exhibit unique properties, including a strong tendency to agglomerate and form composite particles, rendering them more toxic than $PM_{2.5}$ or coarse particles. Beyond particle size and penetration into the respiratory tract, ultrafine particles have highly active surfaces that can adsorb toxic chemicals, penetrate internal organs, remain airborne for extended periods, and travel long distances. Given their significant potential health impacts in humans and animals, research on ultrafine particles is limited, with studies such as those conducted by the Health Effects Institute (HEI) providing valuable insights (HEI, 2013b). Epidemiological investigations consistently demonstrate strong adverse effects of ultrafine particles (Ruckerl *et al*., 2011; Weichenthal, 2012). HEI findings suggest that current evidence on the health impacts of ultrafine particles can be considered indicative of the primary pathways through which $PM_{2.5}$ exerts its harmful effects (HEI, 2013b).

Toxicological studies have demonstrated that the patterns of deposition, resuspension, and particle transport play a critical role in environmental perturbation processes (Kreyling *et al*., 2010). Considering the prevalence of diesel engines and the use of diesel fuel for powering buses and taxis in many industrialized countries, it is well-established that these engines emit significantly higher particulate matter compared to gasoline engines equipped with three catalytic converters. Diesel engine exhaust particles (DEPs) release substantial quantities of particulate matter into the atmosphere in most major cities worldwide (Quality of Urban Air Review Group, 1996). The toxicological characteristics, particle size, and chemical and surface properties of these exhaust-generated particles are noteworthy, with approximately 80% of DEP particles having an aerodynamic diameter of less than 1 µm. Notably, DEPs possess a highly adsorptive carbon core, which facilitates the deep lung transport of active metal oxides and polycyclic aromatic hydrocarbons.

In addition to traffic density, health impacts are influenced by proximity to transportation corridors as well as the condition of both light and heavy diesel vehicles (Janssen *et al*., 2003; Gowers *et al*., 2012). In 2012, the International Agency for Research on Cancer (IARC) classified diesel engine exhaust as a carcinogenic agent, providing evidence of its association with lung cancer and limited evidence linking it to bladder cancer (IARC, 2012). Although most research has focused on diesel exhaust and roadside health effects, non-exhaust sources also constitute a significant subject for investigation (Van der Gon, *et al*., 2013). Particles generated from tire wear on heavily trafficked roads are gradually emerging as a health concern, potentially surpassing exhaust emissions in significance, with some evidence indicating associations with cardiovascular and pulmonary problems (Riediker *et al*., 2004; Gottipolu *et al*., 2008; Gasser *et al*., 2009; Mantecca *et al*., 2009). Given the sensitivity of this issue, the siting of critical and densely populated areas has always been a fundamental principle in public health considerations, and this principle now significantly influences urban planning and growth patterns. Tehran, as one of the major cities facing severe air pollution challenges globally, experiences hazardous air quality on many days of the year, particularly during cold periods associated with temperature inversion events. Moreover, due to its geographical setting, topography, and prevailing wind directions, addressing this issue and implementing preventive and control measures is crucial.

Given the high risk of inhaling atmospheric particles for residents in polluted areas, understanding the behavior of particulate matter in Tehran is of critical importance and must be considered in all aspects of urban development (Oroji *et al*., 2021). The presence of a substantial number of military facilities in the eastern and northeastern parts of Tehran, combined with the circulation and movement patterns of atmospheric pollutants, underscores the importance of assessing the region’s exposure to both the quantity and quality of particulate matter. Awareness of this exposure is essential for guiding future control measures to mitigate this environmental threat. Therefore, this study aims to evaluate the threat posed by atmospheric particles in the eastern and northeastern districts of Tehran and to assess the vulnerability of residents in these areas to various particle types based on their size.

2. Materials and Methods

2.1. Geographical Location of the Study Area

Tehran is located at the southern foothills of the Alborz mountain range, geographically spanning between 51°05′ to 51°53′ E longitude and 35°34′ to 35°59′ N latitude (Amini, and Emami, 2004) (Figure 1). The elevation of Tehran relative to mean sea level varies from 1.700 m in the northern areas, 1.200 m in the central part, to 1.100 m in the southern regions, resulting in a general north to south slope across the city. In addition to this overall gradient, local topographical irregularities within the city influence air pollution dynamics. Tehran Province is separated from its northern neighbor, Mazandaran, by the Alborz mountain range. These elevations increase from west to east, reaching their maximum at Mount Damavand. In the eastern section, the Savadkuh and Firuzkuh mountains connect to the Shahmirzad highlands. Other notable elevations in the province include Hasanabad and Namak Mountains south of Bibi Shahrbanu, Aghaghadr in the southeast, and the Ghasr e Firoozeh highlands in the east. Plains constitute another natural feature of the province, extending from Hashtgerd to the Varamin plain. Due to their gentle slope from the northeast to the southwest, these plains provide favorable conditions for human settlement. The expansion and increasing density of urban areas in these regions reflect this suitability. Alluvial plains, forming a part of these areas, have an elevation of approximately 790 m above sea level and are considered the lowest-lying regions in the province. The climate of the province is generally temperate in mountainous areas and semi-arid in the plains. Atmospheric pressure shows its maximum increase in late autumn and early winter, with the highest precipitation occurring in March (Oroji *et al.*, 2019). Therefore, the geographical and geological characteristics of the region play a significant role in controlling, stabilizing, and removing atmospheric particles and may render certain areas more vulnerable than commonly assumed.

2.2. Sampling Method

This research was conducted between 2020 and 2021. A sampling station was selected in the eastern part of Tehran (Hakimiyeh district) for sample collection. Another station was chosen in the western part of the city, in the Azadi Square area. In this study, a new and advanced sampling technique was employed to determine the concentration and aerodynamic size distribution of atmospheric particles and to assess the regional risk associated with these particulates. For this purpose, a 1 ACFM (CFM equivalent to one cubic foot per minute) ambient cascade impactor was used for particle collection. The cascade impactor operates at a constant flow rate of 28.3 L/min, supplied by a continuous vacuum pump, and consists of eight aluminum stages (Papastefanou, 2008). The stages have effective cutoff diameters of 11, 7.0, 4.7, 3.3, 2.1, 1.1, 0.7, and 0.4 μm, corresponding to stages 0, 1, 2, 3, 4, 5, 6, 7, and F, respectively. Stage 0 serves solely as the nozzle plate. Stage F comprises the collection plate of stage 7 along with a backup filter. Stages 0 through 6 include a unified air-inlet section containing 400 nozzles, while stage 7 contains 201 nozzles. The inlet diameter is approximately 3.125 inches.

The nozzle diameters decrease progressively from the upper to lower stages, ranging from 0.0625 inches in stage 0 to 0.01 inches in stage 7. Each stage is equipped with a removable stainless-steel or glass collection substrate (3.25 inches in diameter). The outlet section of each stage is approximately 0.75 inches larger than the collection plate, allowing non-impacted particles to bypass the plate and move to the subsequent stage (Papastefanou, 2008). The smaller nozzles increase the jet velocity sequentially across the eight stages, enabling the impaction of progressively finer particles onto the collection discs of each lower stage (Papastefanou, 2008). For this research, 6 stations including 3 points in the western part and 3 stations in the eastern part of the study area were selected for sampling. The sampling results are shown in Table 1. Sampling was carried out 3 times per month. The sampling duration for each run ranged from 72 hours to 7 days. After sampling, the collection plates were carefully weighed, and based on the mass of particles accumulated on each plate and the total volume of sampled air, the concentration and mass fraction of the particles were calculated. This procedure was repeated for each sampling event with the cascade impactor.

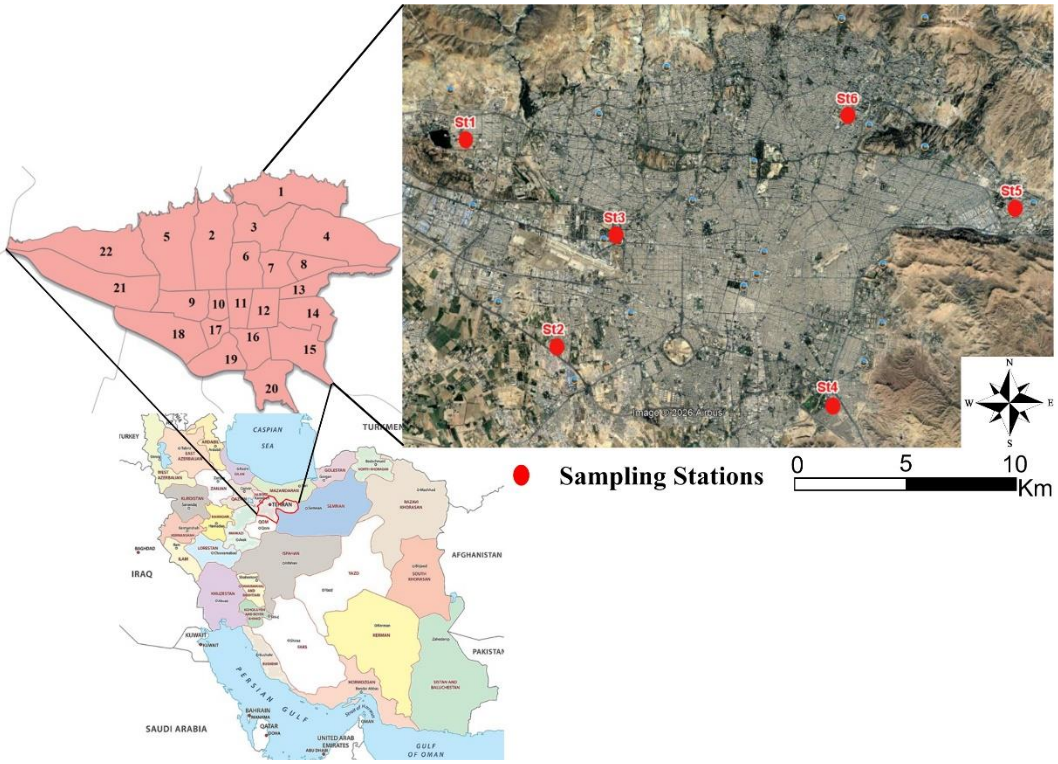

Fig. 1 Geographical location of the study area and sampling stations

3. Results and Discussion

The highest wind speed recorded in April 2020 was 17.1 m/s with a predominant wind direction of 260°. The monthly mean of maximum wind speeds during this month reached 15.2 m/s. In May, the maximum wind speed increased to 21.7 m/s blowing from 290°, while the regional average of maximum values was 18.5 m/s. Over the study period, June showed a maximum wind speed of 16 m/s, accompanied by a regional mean maximum of 15.1 m/s. During July, August, and September, the peak wind speeds were measured at 15.1, 14.2, and 13 m/s, respectively. The corresponding regional mean maximum wind speeds were 14.4 m/s in July, 15.0 m/s in August, and 11.1 m/s in September. The prevailing wind directions for these months were recorded as 220°, 290°, and 260°, respectively. In autumn, the maximum wind speed in October reached 15.3 m/s from 260°, followed by 15.5 m/s in November from 290°, and 15 m/s in December from 210°.

The regional mean maximum wind speeds for these months were 14, 14, and 13 m/s, respectively. During the winter months, maximum wind speeds showed relatively small variations, averaging 16.1 m/s, with the dominant wind direction centered around 270°. The regional mean maximum wind speeds for January, February, and March were recorded as 16, 14, and 16.4 m/s, respectively. Overall, the prevailing wind direction in the Hakimiyeh (East area) during the evaluation period was westerly (west to east), representing 25% of all recorded winds. In total, 38% of the winds observed in Tehran in 2020 were within the directional sector spanning northwest to southwest. The findings indicate that winds exceeding 6 m/s blowing from the west occur more frequently in spring than in other seasons. Additionally, during summer, while westerly winds remain dominant, southeastern winds also appear with notable frequency. These observations confirm that the highest proportion of winds stronger than 6 m/s from the west occurs in spring. Furthermore, in summer, despite the continued dominance of westerly winds, southeastern flows also contribute significantly. Monthly variations in wind speed for the sampling station are presented in Figure 2.

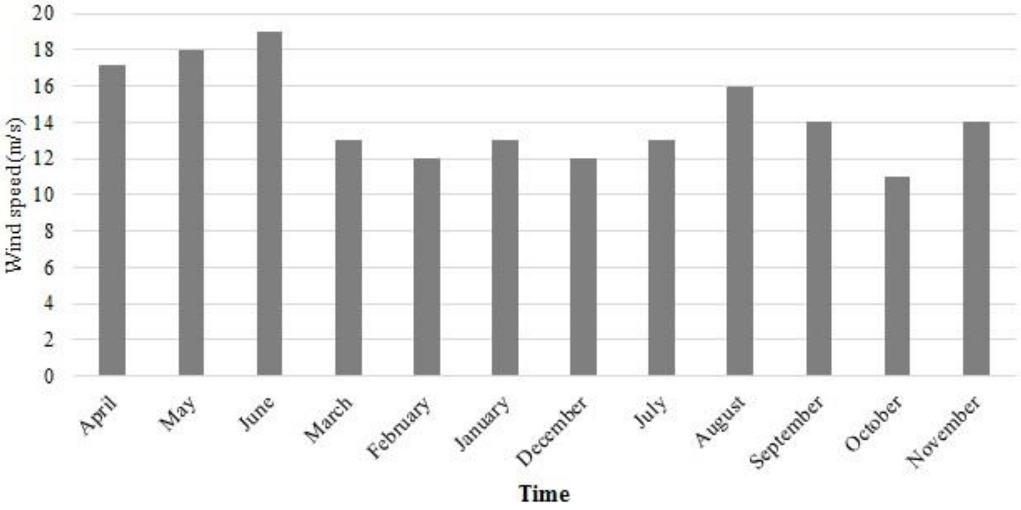

Fig. 2 Monthly variations in wind speed across the study area

The results of particle size distribution measurements at three stations: Azadi (ST3), Chitgar (ST1), and Tehransar (ST2) in the western half of Tehran show that the mass distribution pattern of particles largely follows a relatively similar trend, but significant differences are also observed in some size ranges. In general, the highest mass concentration at all three stations is related to coarser particles (diameter greater than 11 µm); this range has the highest contribution at Chitgar station with a value of 19.6 µg.m^{-3}, followed by Azadi station (18.9 µg.m^{-3}) and Tehransar (15.6 µg.m^{-3}). This indicates the dominant role of mechanical sources and surface dust re-emission (such as heavy traffic, construction activities, and surrounding soil surfaces) in the western half of Tehran, especially in the Chitgar area, which is affected by highways and open lands.

In the size range of 7–11 µm, the concentrations at all three stations are relatively high and close to each other (between 14.5 and 16.3 µg.m^{-3}), indicating a more uniform distribution of coarse particles over the area. Tehransar shows the highest value (16.3 µg.m^{-3}) in this range, which could be due to the impact of local traffic, construction activities, or horizontal transport of particles from adjacent areas. In the intermediate ranges (4.7–7 to 1.1–2.1 µm), the concentration changes are smaller and the values fluctuate in the range of 11 to 13 µg.m^{-3}. This relative uniformity indicates that the share of particles with a combined origin (mechanical-combustion) is almost similar at all three stations and is probably affected by the same atmospheric conditions and regional air mixing.

In the finer particle segment (diameter less than 1.1 µm), a slight decreasing trend in concentration is observed; the lowest values are in the 0.7–0.4 µm range at all three stations (between 8.6 and 9.2 µg.m^{-3}). However, in the smallest size range (≤0.4 µm), a relative increase is observed at Tehransar station (10.2 µg.m^{-3}), which is higher than Azadi and Chitgar. This increase could indicate a higher contribution of combustion sources (such as light and heavy vehicles, fossil fuel combustion, and secondary chemical processes in the atmosphere) at this station. In general, the particle size distribution at all three stations shows a weak multi-peaked pattern characterized by the dominance of the coarse mode, which is expected in the semi-arid climate of Tehran and under the influence of regional dust and surface re-emission.

Comparisons between stations show that Chitgar has the highest concentration in most of the coarser ranges, while Tehransar shows a higher contribution in the finer ranges (especially less than 0.4 µm). Azadi also recorded intermediate values in most of the ranges. These differences could be due to differences in land use, traffic density, proximity to highways, green spaces (such as Chitgar Park), as well as local wind flow patterns. Overall, the results show that in the western half of Tehran, the contribution of coarse particles is significant, but the significant presence of fine and ultrafine particles also indicates the role of combustion sources and secondary processes in the composition of urban aerosols; an issue that is of particular importance from the perspective of environmental health and air quality management, because finer particles have more harmful effects on human health due to their greater ability to penetrate the respiratory tract.

The monthly average concentration of suspended particles at sampling stations for a year is shown in Table 1. The results of particle size distribution sampling at three eastern stations in Tehran, including Khavaran (ST4), Piroozi (ST5), and Hakimieh (ST6), indicate a dominant pattern of concentration in fine particles and an increase in the proportion of particles with an aerodynamic diameter of less than 2.5 µm. In general, in all three stations, the trend of concentration changes from coarser particles (≥11 µm) to finer particles (≤0.4 µm) is increasing, indicating the dominance of combustion sources and secondary processes of particle formation in the eastern half of Tehran. The lowest concentration values are mainly observed in the range of 11 µm and larger (7.7 to 11.7 µg.m^{-3}), while the highest values are related to the smallest size fraction (≤0.4 µm), reaching 18.7 µg.m^{-3}, especially at Hakimieh station.

At Khavaran station, the particle distribution is relatively uniform but with a slight increase towards fine particles; the concentration has increased from 11.7 µg.m^{-3} in the range ≥11 µm to 13.4 µg.m^{-3} in the range ≤0.4 µm. This pattern indicates a combination of local mechanical sources (urban dust and surface resuspension) and combustion sources such as traffic. The significant contribution of particles in the ranges 2.1–1.1 and 0.7–0.4 µm (more than 12 µg.m^{-3}) indicates the important role of secondary fine particles resulting from photochemical reactions in the urban atmosphere. At Piroozi station, a significant concentration is observed in particles smaller than 1.1 µm, with the highest value recorded in the range ≤0.4 µm equal to 15.6 µg.m^{-3}. Also, the value of 14 µg.m^{-3} in the range of 2.1–1.1 µm indicates that particles in the $PM_{2.5}$ range constitute the dominant contribution. The relative decrease in the concentration in the coarser ranges (7–11 µm) could indicate limited local dust sources or faster deposition of these particles compared to fine particles. Overall, the pattern of Piroozi station indicates the dominance of urban combustion sources, especially heavy traffic and dense human activities in this part of the city.

At Hakimieh station, the highest concentration of particles is observed in the smallest size range (18.7 µg.m^{-3} at ≤0.4 µm), which is noticeably higher than the other two stations. This indicates the accumulation of ultrafine particles and the possibility of being affected by pollutant transport, atmospheric stability conditions, and secondary particle formation processes. High values (13.19 and 13.1 µg.m^{-3}, respectively) were also recorded in the ranges of 2.1–1.1 and 0.7–0.4 µm, indicating that the size structure at this station is strongly biased towards fine particles. From a health perspective, this situation is of particular importance, as particles smaller than 1 µm have the ability to penetrate deeply into the respiratory tract and even enter the bloodstream.

In a comparison of the three eastern stations, Hakimieh shows the highest concentration in ultrafine particles, while Khavaran has a more balanced distribution between coarse and fine particles, and Piroozi has recorded the highest concentration in the mid-range PM2.5. In general, the dominant contribution of particles below 2.5 µm at all three stations indicates that in the eastern half of Tehran, combustion sources (traffic, fossil fuels, and urban activities) and secondary atmospheric processes play the main role in the particulate matter load, while the contribution of coarse-grained mechanical sources is lower. This size distribution pattern can be used in pollution source analysis, modeling of particle residence time in the atmosphere, and health risk assessment, especially considering that finer particles have a longer residence time in the atmosphere and have a higher horizontal transport capability.

Table 1 Average concentration distribution of particulate matter at sampling stations

Particle diameter (µm)	Particle concentration (µg.m^{-3})					
	ST1	ST2	ST3	ST4	ST5	ST6
11 ≤	15.6	19.6	18.9	11.7	11.2	7.7
11-7	16.3	15.8	14.5	12.3	10.5	8.5
7-4.7	13.9	12.6	12.1	11.4	9.5	8.1
4.7-3.3	12.1	11.8	11.9	11.3	12.2	11.14
3.3-2.1	11.8	12.7	12.1	12.7	10.7	10.1
2.1-1.1	12.5	12.8	12	12.8	14	13.19
1.1-0.7	10.4	11.5	11.65	12.5	13.4	11.65
0.7-0.4	8.6	9.2	9.1	13.1	12.8	13.1
0.4 ≥	10.2	9.3	8.7	13.4	15.6	18.7

According to the data provided by six sampling stations (three stations in the western half and three stations in the eastern half of Tehran), statistical analysis of particle size distribution indicates a significant difference in the mass concentration pattern between the two halves of the city. At stations ST1 to ST3 (western half), the highest mass concentration is observed in the range of coarser particles (11 µm and 7–11 µm); for example, in the 11 µm class, the concentration varies from 15.6 to 19.6 µg.m^{-3}. In contrast, at stations ST4 to ST6 (eastern half), the highest concentration is recorded in the range of finer particles (less than 0.7 and especially less than 0.4 µm), such that in the 0.4 µm and smaller class, the values have increased from 13.4 to 18.7 µg.m^{-3}. This pattern indicates the dominance of coarse particles with mechanical origin (road dust, construction activities and soil resources) in the west of Tehran and the dominance of fine particles with combustion origin (heavy traffic, industrial activities and fossil fuel combustion) in the east of the city.

In terms of correlation between stations, Pearson correlation coefficients qualitatively indicate two distinct clusters in the pattern of particle size changes. The western stations (ST1–ST3) show a strong positive correlation with each other in the coarse-grained classes, such that the trend of gradual decrease in concentration with decreasing particle diameter is almost similar. In contrast, the eastern stations (ST4–ST6) have a high positive correlation in the fine-grained classes, and the trend of increasing concentration is in line with decreasing particle size at these stations. Also, a negative correlation is observed between the coarse (≥7 µm) and fine (≤0.7 µm) classes in all stations; This means that as the proportion of coarse particles increases at a station, the relative proportion of fine particles decreases and vice versa. This inverse relationship indicates the dominant difference in emission sources and dynamic processes affecting particle size distribution in the two halves of the city. In general, the results of the correlation analysis show that the structure of particle size distribution in Tehran is influenced by the spatial pattern of pollutant sources, topographic conditions, and prevailing wind direction, and the western half can be described as having a coarse particle regime and the eastern half as having a fine particle regime. This statistical distinction can be a suitable basis for source apportionment analysis and for formulating targeted control policies at the regional scale of Tehran. The distribution chart of the average suspended particles collected for the sampling stations is shown in Figure 3.

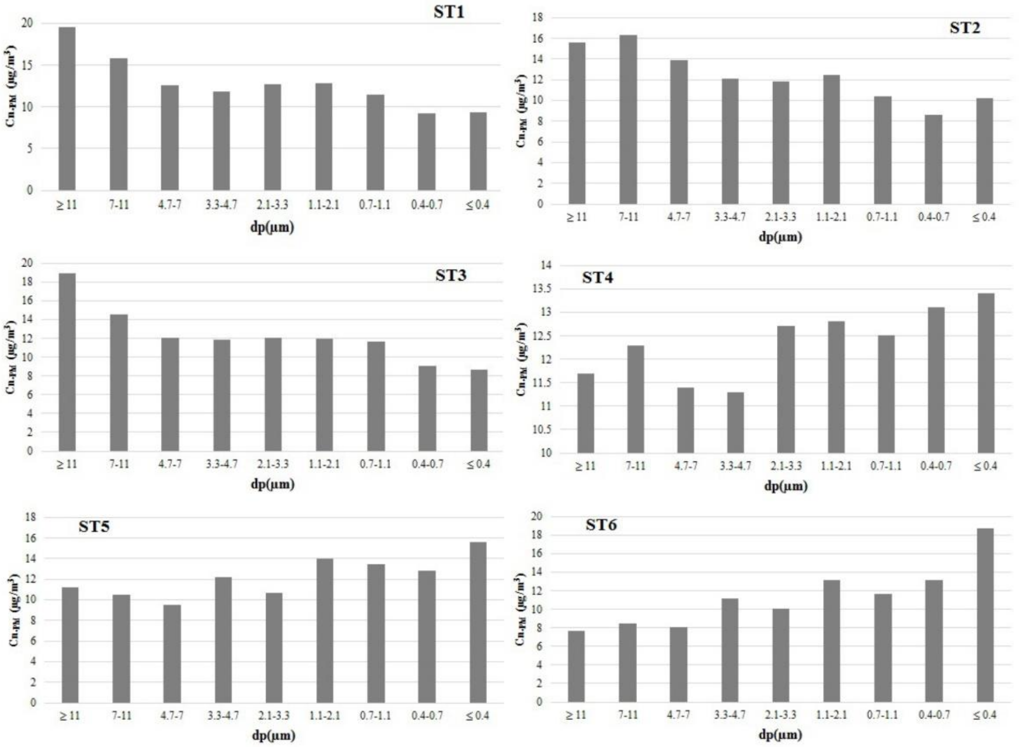

Fig. 3 Distribution diagram of suspended particles collected in the study area

The average concentration of sampling stations in the eastern and western regions of Tehran is shown in Table 2. Statistical analysis of the size-concentration distribution of suspended particles in the western half (stations 1 to 3) and eastern half of Tehran (stations 4 to 6) shows that the pattern of concentration changes in terms of particle diameter in the two parts of the city follows a reverse trend. In western Tehran, the highest mass fraction is related to coarse particles (≥11 and 7–11 µm) with averages of 18.03 and 15.53 $\mu g.m^{-3}$, and with decreasing particle diameter, a relative decreasing trend in concentration is observed, such that the relative minimum is recorded in the range of 0.7–0.4 µm (8.96 $\mu g.m^{-3}$). In contrast, in eastern Tehran, an increasing pattern towards fine particles is observed; the highest average concentration is in the range ≤0.4 µm (15.9 $\mu g.m^{-3}$) and then 0.7–0.4 µm (13 $\mu g.m^{-3}$), while the share of coarser particles is relatively lower. This difference indicates the dominance of sources of mechanical origin (such as resuspended dust and construction activities) in the west and the dominance of combustion and traffic sources in the east of the city.

In terms of statistical correlation between the size distribution pattern in the two halves of the city, the Pearson correlation coefficient between the average concentrations in the west and east for different diameter classes shows a strong negative correlation (r around -0.8 to -0.9), which indicates the opposite behavior of the particle size distribution in the two parts of the city. This negative correlation indicates that whenever the mass fraction of a diameter interval increases in the west, a relative decrease is observed in the same interval in the east, and vice versa. Also, in terms of relative contribution, in the west, about 41% of the total mass is related to particles larger than 4.7 µm, while in the east, more than 50% of the total mass is related to particles smaller than 2.1 µm. This statistical difference could be due to differences in land use patterns, traffic intensity, building density, and prevailing wind direction at the urban scale. Overall, statistical analysis of the results shows that there is a distinct spatial gradient in the particle size distribution between the west and east of Tehran, and the particle size structure in the two halves of the city differs significantly not only in terms of quantity but also in terms of correlation behavior; an issue that can be considered in modeling source identification and estimating the residence time of particles in the urban atmosphere.

Table 2 Average concentration and weight percentage of particles in the western and eastern areas of the region

Particle diameter (µm)	Particle concentration (µg.m^{-3})			
	Ave $_{\text{ST1-3}}$	W %	Ave $_{\text{ST4-6}}$	W %
11 ≤	18.03	16.02	10.2	9.47
11-7	15.53	13.8	10.43	9.68
7-4.7	12.86	11.43	9.66	8.97

4.7-3.3	11.93	10.6	11.54	10.71
3.3-2.1	12.2	10.84	11.16	10.36
2.1-1.1	12.43	11.05	13.33	12.37
1.1-0.7	11.18	9.94	12.51	11.62
0.7-0.4	8.96	7.97	13	12.06
0.4 ≥	9.4	8.35	15.9	14.76
	112.55	100	107.76	100

The results of this study indicate that atmospheric particles emitted from both stationary and mobile sources are gradually removed through multiple processes while being transported by the prevailing winds toward the eastern and northeastern areas. Consequently, fine particles capable of remaining suspended in the air for extended periods reach these regions, exposing the residents to elevated levels of particulate pollution. Moreover, considering that particulate matter with diameters smaller than 4 µm can penetrate the trachea, bronchi, and alveolar sacs (WHO, 2012), this issue becomes particularly critical. Prolonged exposure in these areas characterized by the presence of residential, administrative, and especially military facilities may substantially increase the risk of common air pollution related diseases. This challenge may lead to the daily inhalation of soot and dispersed particles originating from the combustion of fossil fuels by both mobile and stationary sources, as well as particles produced from heating systems and indoor cooking activities in confined spaces (WHO, 2013b). Findings from previous studies on pregnant women with long term exposure to $PM_{2.5}$ demonstrate that after childbirth, various biological complications and persistent impairments in overall infant health may emerge. Low birth weight and preterm delivery are among the documented adverse outcomes (Ritz *et al*., 2008; Sapkota *et al*., 2012; Proietti *et al*., 2013).

4. Conclusion

The adverse health impacts resulting from inhalation of hazardous air pollutants such as particulate matter (PM) have been unequivocally demonstrated. Fine particulate matter has been a major subject of extensive global research over recent decades, with substantial evidence linking both short term and long term exposure to PM with increased mortality. Diesel exhaust particles are now widely recognized as carcinogenic in most studies, and the potential of air pollution to contribute to adverse birth outcomes, diabetes, neurological disorders, and impaired cognitive performance has been firmly established. Currently, no indication exists of a threshold below which exposure to PM does not lead to negative health outcomes. Recent studies provide conclusive evidence of an association between long term exposure to $PM_{2.5}$ and mortality, even when ambient concentrations are below the annual WHO Air Quality Guidelines. Moreover, the findings indicate that reducing individual exposure to $PM_{2.5}$ and PM_{10} over specified time periods can significantly enhance life expectancy and improve respiratory health. Effective air quality management and particulate matter reduction require coordinated actions across multiple sectors including environment, transportation, energy, health, and housing at regional, national, and international levels. Considering the substantial mortality burden associated with road traffic related particulate emissions, integrated improvements in urban transportation policy are essential. Reducing traffic volume and transitioning to cleaner fuels or alternative technologies are critical priorities. Extensive research has documented the direct human exposure to airborne particulate matter and its contribution to a range of physical and psychological health disorders, emphasizing the damaging influence of atmospheric pollutants (Oroji *et al*., 2021; Oroji *et al*., 2019). Accordingly, the establishment of residential and administrative facilities along pathways of atmospheric pollution increases exposure risk and can exacerbate physical and mental health problems depending on occupational and environmental conditions. Therefore, implementing control programs and limiting new development projects in these high exposure zones must become central components of urban planning policies. Proper ventilation, standard heating and cooling systems, and improved quality of building infrastructure particularly doors and windows in residential, administrative, industrial, and laboratory environments constitute additional essential measures to prevent prolonged exposure to particulate matter in affected areas.

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