ORIGINAL ARTICLE

Atmospheric Concentrations, Seasonal Variations, and Health Risk Assessment of $PM_{2.5}$, PM_{10}, and SO_2 in Tehran Metropolis, Iran

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Abstract

Background: This study evaluates the seasonal and annual variations of $PM_{2.5}$, PM_{10}, and SO_2 concentrations in Tehran's ambient air from 2019 to 2021 and assesses their associated health risks.
Methods: Non-carcinogenic health risks were quantified using the U.S. Environmental Protection Agency (EPA) methodology. Sobol sensitivity analysis was conducted in R (version 4.1.2), and ArcGIS (version 10.8.1) was used to map the spatial distribution of pollutants.
Results: The annual mean concentrations of $PM_{2.5}$, PM_{10}, and SO_2 ranged from 28.24–32.34 µg/m³, 69.57–82.22 µg/m³, and 14.94–17.98 µg/m³, respectively, exceeding WHO air quality guidelines. $PM_{2.5}$ and SO_2 levels were highest in the west and southwest, while PM_{10} was most prevalent in the east and northeast. The hazard quotient (HQ) for $PM_{2.5}$ and PM_{10} exceeded 1 in 8- and 12-hour exposure scenarios, indicating significant health risks. However, the HQ for SO_2 remained below 1 across all exposure durations, suggesting no immediate health threat. At 3-hour exposures, the HQ for $PM_{2.5}$ and PM_{10} was below 1, underscoring the role of exposure duration in health risks. Sobol sensitivity analysis identified $PM_{2.5}$ concentration as the most influential factor affecting health risk.
Conclusion: The findings highlight the urgent need for regulatory interventions to mitigate $PM_{2.5}$ and PM_{10} pollution in Tehran, particularly in high-exposure regions. Effective control measures should prioritize reducing emissions to protect public health.

Please cite this article as: Ahmadian F, Rajabi S, Azhdarpoor A. Atmospheric Concentrations, Seasonal Variations, and Health Risk Assessment of $PM_{2.5}$, PM_{10}, and SO_2 in Tehran Metropolis, Iran. J Health Sci Surveillance Sys. 2025;13(2):161-173.

Keywords: Air pollutants, Health risk assessment, Particulate matters, Sulfur dioxide, Sobol sensitivity analysis

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Received: 07 January 2025
Revised: 05 February 2025
Accepted: 10 March 2025

Introduction

Today, rapid industrialization and urbanization release a variety of pollutants into the atmosphere. Therefore, air pollution is considered as the most important environmental problem in the world.[1] It is estimated that air pollution causes 8.9 million deaths worldwide, accounting for 7.6% of total annual death rates and resulting in 103.1 million lost healthy life years.[2] Air pollution is the presence of substances in the air in concentrations that have adverse effects on people, animals, and plants. These substances may be mixtures of solid and liquid particles (particulate matters such as $PM_{2.5}$ and PM_{10}), gases (such as NO_2, NO, SO_2, O_3), biological aerosols, atmospheric agents, biological aerosols, or atmospheric agents that can be dispersed, transported or deformed at any time.[3-5] The scale of the problem is expanding rapidly due to the high urbanization rate.[6]

The situation is worsening in developing countries with more urbanization, industrialization, and a rapidly growing population.[7] Iran is a developing country facing air pollution problems. In many Iranian cities, air pollution has reached dangerous levels, with concentrations of some pollutants in large cities in Iran three times higher than national standards and World Health Organization (WHO) air quality guidelines.[8]

Particulate matter (PM) is considered one of the most harmful air pollutants released from biological and anthropogenic sources or formed by atmospheric reactions.[9] PM is a subset of air pollution and represents a complex mixture of suspended particles in the air with varying composition, shape, size, and optical properties depending on their origin.[10] The two main PMs that are considered as criteria for air pollutants are $PM_{2.5}$ and PM_{10}.

$PM_{2.5}$ is defined as fine particles having a diameter of 2.5 microns or less, which can only be observed with an electron microscope. These are mostly generated through different types of combustion processes, such as power plants, automobiles, burning wood for homes, and some industrial processes.[11] Various toxic substances in $PM_{2.5}$ can pass through the nose hair filtering, reach the end of the respiratory tract with airflow, accumulate by diffusion, and damage other body parts by air exchange in the lungs.[12] Different epidemiological studies have found strong associations between long-term $PM_{2.5}$ exposure and premature mortality due to ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), and lung cancer (LC). The effects of $PM_{2.5}$ exposure also include morbidity, including chronic respiratory conditions like bronchitis, asthma, and cataracts.[13]

PM_{10} are coarse particles containing $PM_{2.5}$ and particles up to 10 microns in diameter. These particles are breathable and can be generated from vehicle dust on the roads and grinding operations.[11] Increased PM_{10} concentration has been reported to increase non-accidental mortality.[2] Inhaling PM_{10} can irritate and infect the lungs. Long-term exposure to PM_{10} may result in pulmonary, cardiovascular, and lung cancer.[14]

Sulfur dioxide (SO_2) is one of the most important pollutants in the atmosphere, which is produced by vehicles and burning oil and coal in industries.[15] SO_2 can contribute to visibility degradation, haze formation, and acid rain in the atmosphere. In addition, high levels of SO_2 exposure may lead to increased cardiorespiratory mortality and morbidity.[16] It was shown that exposure to SO_2 was associated with respiratory symptoms, such as wheezing and shortness of breath, total respiratory mortality, increased risk of asthma, and worsening of existing respiratory disease.[17]

Environmental health risk assessment is the process of recognizing potential risks to public health caused by exposure to environmental toxicants.[18] Risk assessment can aid in identifying the risky pollutants' priority risks and choosing effective control methods that reduce people's exposure to pollutants and mitigate their adverse health impacts. In addition, risk assessment studies can determine the proportion of each exposure route to a specific environmental pollutant.[19, 20] This set of data can then be utilized to develop standards, which is a significant and valuable part of risk assessment studies. This is because the distribution of pollutants through exposure routes varies around the world.[21]

Sobol sensitivity analysis is a powerful technique for understanding the sensitivity of a model to its input parameters, providing a systematic way to identify and quantify the importance of each parameter in contributing to the variability of the model's output. The goal is to understand which input parameters have the most significant impact on the variability of the model's output.[22] Atmospheric concentrations, seasonal variations, and health risk assessment of $PM_{2.5}$, PM_{10}, and SO_2 with appropriate approaches are essential to evaluating the effectiveness of the implemented air pollution control measures. Air quality policy and decision-makers can use these factors as a useful tool to modify and revise air pollution control strategies to reduce pollutant concentrations and their health effects. Therefore, this study was designed to investigate the seasonal variations of $PM_{2.5}$, $PM_{10,}$ and SO_2 concentrations in the ambient air of Tehran and determine the health risks of these pollutants. Up to now, Sobol's sensitivity analysis has not been used for $PM_{2.5}$, $PM_{10,}$ and SO_2 risk assessment. In this study, we used Sobol's sensitivity analysis to find relevant input parameters and assess their impact on the variance of exposure outcomes.

Methods

Study Area

Tehran, the capital of Iran, is a fast-growing metropolis facing serious environmental and health problems due to air pollution.[23] The center of the city is on latitude 35°41′ N and longitude 51°26′ E. Tehran is located at an altitude of 1000 to 1800 meters above sea level, on the southern slope of the Alborz Mountain range. This city has a mellow and mild climate with hot summers. The maximum temperature is 29°C and the minimum temperature is 0.1°C. Tehran is surrounded by high mountains on both sides, has a population of 9.5 million, and is characterized by high levels of particulate matter and gaseous pollutants that adversely affect the environment and human health.[24, 25] Tehran's wind direction is from the northwest to the southeast. As a result, the wind transports air pollution from various parts of the city, including cities in

Tehran's northwest (such as Karaj), to the megacity's south and southeast.[26]

Data Collection and Analysis

Several air quality monitoring stations (AQMs) are currently in operation in Tehran to raise public awareness about air quality. These AQMs monitor the levels of PMs, nitrogen dioxide, ozone, sulfur dioxide, and carbon monoxide and show them to the public on Pollution Indicator Boards. Data on ambient $PM_{2.5}$, PM_{10}, and SO_2 concentrations were obtained from the 23 AQMs in Tehran. Figure 1 shows the location of some AQM sites. The average seasonal concentration of $PM_{2.5}$, PM_{10}, and SO_2 from 2019 to 2021 was determined by averaging all available data across the monitoring stations.

Health Risk Assessment

The non-carcinogenic risk is determined by the exposure risk value, while the carcinogenic risk is determined by the lifetime carcinogenic risk caused by human exposure to carcinogenic compounds. The non-carcinogenic health risk of $PM_{2.5}$, PM_{10}, and SO_2 was assessed based on the United States Environmental Protection Agency methodology (EPA).[27] In this study, three scenarios were considered with three exposure times of 3, 8, and 12 hours.

The process for estimating health risk involves the following three steps: (1) Determining exposure concentration, (2) determining Reference Dose (RfD), and (3) calculating the hazard quotient.

Human exposure to the toxic effects of PM_{10}, $PM_{2.5,}$ and SO_2 mainly occurs via inhalation. Therefore, the exposure concentration (EC) via inhalation was calculated by the following equation:[28]

$$EC = \frac{C \times IR \times ET \times EF \times ED}{BW \times AT} \quad \text{(Eq. 1)}$$

Where EC is the average daily dose of the pollutant (µg/kg.day), C is the concentration of the pollutant in the atmosphere (µg/m³), IR is inhalation rate (m³/day), ET is exposure time or event (hr./day), EF is exposure frequency (days/year), ED is exposure duration (years), BW is the average body weight of the receptor over the exposure period (Kg), and AT is averaging time (days).

RfD is an estimate of continuous inhalation exposure that is unlikely to negatively impact a person's health over their lifetime. We used the WHO annual mean air quality guideline (AQG) levels of $PM_{2.5}$, PM_{10}, and SO_2 as the reference concentration (RfC) to estimate the RfD of these pollutants due to the lack of information about their RfD. Therefore, the values of 5 µg/m³, 15 µg/m³, and 40 µg/m³,[29] were used as RfC of $PM_{2.5}$, PM_{10}, and SO_2, respectively; then, RfD values were calculated by the following equation:[30]

$$RfD = \frac{\text{RfC (inhalation reference concentration } {}^{\mu g}/_{m^3}) \times \text{Assumed inhalation rate } ({}^{m^3}/_{day}) \times 1}{\text{BW (Kg)}} \quad \text{(Eq. 2)}$$

After the *EC* values were calculated, the non-carcinogenic risk was determined for each pollutant by calculating the hazard quotient.

$$HQ = {}^{EC}/_{RfD} \quad \text{(Eq. 3)}$$

Where HQ is the hazard quotient and RfD is the reference dose (µg/m³). An HQ value >1 indicates that there is a greater chance of non-carcinogenic effects.[31-33] A summary of the values used for the health risk assessment calculation is presented in Table 1.

Sobol Sensitivity Analysis

The Sobol sensitivity analysis with the Monte Carlo approach was used to determine the significant

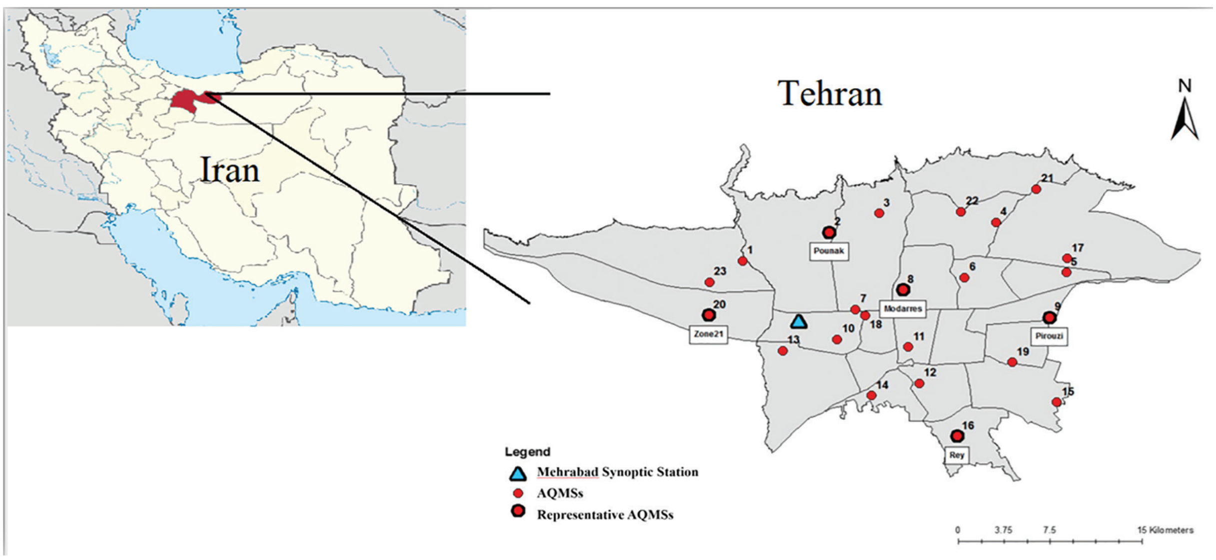

Figure 1: Map of the study area and sampling site (designed by the author)

Table 1: Parameters description for non-carcinogenic health risk assessment

Parameter	Value	Unit	Reference
C	-	μg/m^3	This study
IR	20	m^3/day	[34]
ET	3	hr.	This study
	8		
	12		
EF	350	days	[31]
ED	30	years	[31]
BW	68.1	Kg	[34]
AT	30	years	[31]
RfC	5 μg/m^3 for $PM_{2.5}$		[29]
	15 μg/m^3 for PM_{10}		
	40 μg/m^3 for SO_2		

C: Concentration; IR: Inhalation rate; ET: Exposure time; EF: Exposure frequency; ED: Exposure duration; BW: Body weight; AT: Averaging time; RfC: Reference concentration

input parameters along with their influence on the variance of the exposure results.[35] The Sobol Sensitivity Indices (SIS) indicate the proportion of the partial variable compared to the total variable. The first SI term is known as the First Order Sensitivity Index (FOSI), and it describes the influence of a single variable on the variation in model outputs. The second term is known as the Second Order Sensitivity Index (SOSI), which describes the influence of variable interaction. Finally, the Total Order Sensitivity Index (TOSI) is utilized to calculate the variable's overall influence on the final variance. A sensitivity index greater than 0.1 (very sensitive), 0.01-0.1 (sensitive), and less than 0.01 (insensitive) represent those input variables that are notably relevant, conspicuous, and unresponsive, respectively.[19] In this study, Sobol sensitivity analysis was performed using the R-platform version 4.1.2 ('EnvStats', 'sensobol', 'Enviro-PRA' packages).

Spatial Distribution

The Arc-GIS program (10.8.1 version) was used to show the spatial distribution of $PM_{2.5}$, PM_{10}, and SO_2 concentrations in the ambient air of Tehran. Inverse Distance Weighted (IDW) was used for pollution concentration interpolation. IDW is one of the most basic and often-used interpolation methods.[36]

Results and Discussion

Pollutant Concentration

Table 2 summarizes the average concentrations of $PM_{2.5}$, PM_{10} and SO_2 during the period of study; also, the average annual $PM_{2.5}$, PM_{10} and SO_2 concentrations in 2019, 2020, and 2021 were shown in Figures 2, 3, and 4, respectively. The annual average mass concentration of $PM_{2.5}$ was 30.17±8.2 μg/m^3 in 2019, 28.24±6.52 μg/m^3 in 2020, and 32.34±8.37 μg/m^3 in 2021, which is much higher than the limit of annual concentration of $PM_{2.5}$ according to the WHO air quality guidelines (5 μg/m^3).[29] The reason may be the local pollutants surrounding the area, rise in the use of motor vehicles, use of low-quality fuels, use of old and poorly maintained automobiles, and weak control of vehicle exhaust emissions.[30, 37] Regarding the regional transmission characteristic of PMs, which is influenced by wind patterns and the location of emission sources, the desert region to Tehran's south, southeast, and west has an impact on the level of pollutant concentration.[38, 39]

Table 2: Average concentration of $PM_{2.5}$, PM_{10} and SO_2 in 2019-2021

Year	Season	$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)	SO_2 (μg/m^3)
2019	Winter	27.78	68.47	6.46
	Spring	19.81	54.64	3.78
	Summer	34.58	83.18	11.11
	Fall	38.5	82.58	6.11
2020	Winter	33.62	73.70	6.72
	Spring	20.11	54.23	3.66
	Summer	25.81	76.12	5.64
	Fall	33.41	74.23	6.8
2021	Winter	38.41	82.17	8.27
	Spring	23.11	69.29	4.68
	Summer	27.17	82.06	5.11
	Fall	40.68	95.35	8.62

$PM_{2.5}$: Particulate Matter with a diameter of 2.5 micrometers or smaller; PM_{10}: Particulate Matter with a diameter of 10 micrometers or smaller; SO_2: Sulfur Dioxide

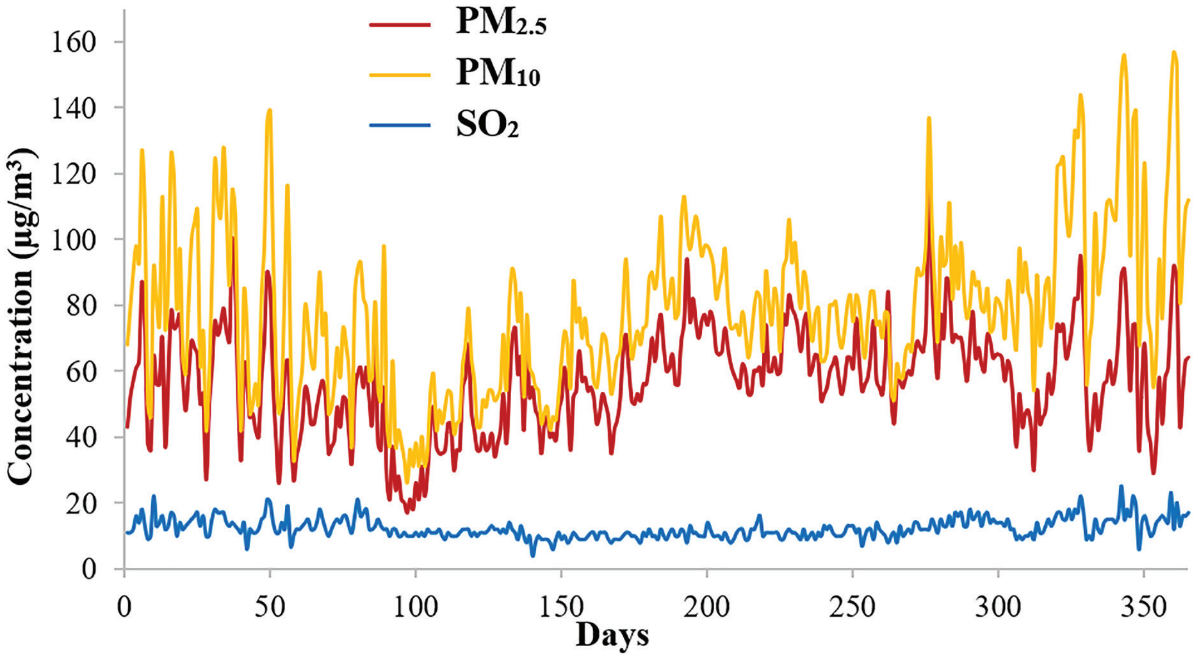

Figure 2: Variations of $PM_{2.5}$, PM_{10}, and SO_2 concentration in 2019.

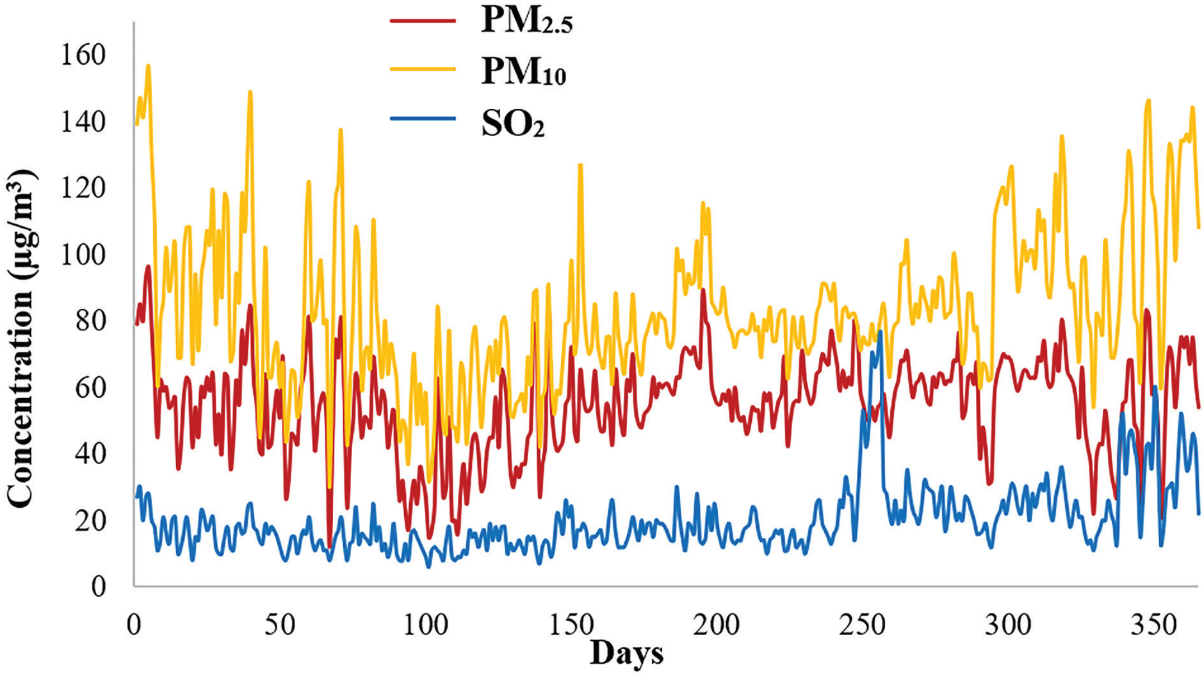

Figure 3: Variations of $PM_{2.5}$, PM_{10}, and SO_2 concentration in 2020

Although geographic conditions influence pollutant dispersion, considering that $PM_{2.5}$ content is mainly influenced by two factors, that is emissions from combustion sources and the creation of secondary particles in the atmosphere, high levels of $PM_{2.5}$, particularly at traffic stations, can be attributed to moving emission sources.[40] According to research by Heger et al. (2018), mobile sources account for the majority (about 70%) of PM emissions (vehicles). The remaining emissions are produced from non-transportation sources, including energy conversion (20% from power plants and refineries), industry (7%), household and commercial (2%), and gas terminals (1%). According to other research, ambient $PM_{2.5}$ air pollution causes more than 4,000 premature deaths in Tehran each year. Also, high $PM_{2.5}$ concentrations lead to an increase in emergency room visits, particularly for respiratory problems.[37] Any policy plan that targets the efficient reduction of $PM_{2.5}$ in ambient air and a reduction in the health burden needs to balance emission limits in all of these sectors and sources. Focusing on a single source will not result in effective improvements, and it will most likely waste economic resources.[41] To reduce $PM_{2.5}$ pollution, a variety of air pollution control policies can be implemented, such as enhancing industrial emission standards, rectification of coal-fired boilers, planning to roll out old industrial facilities, supporting clean fuels in the domestic sector, enhancing vehicle emission standards, and so on.[42] The Iranian government should work to develop strict vehicle emission standards to reduce car emissions. Also, the quality of the gasoline used in vehicles needs to be improved.[30]

The annual average mass concentration of PM_{10} was 72.22±11.73 µg/m^3 in 2019, 69.57±10.27 µg/m^3 in 2020, and 82.22±10.64 µg/m^3 in 2021, which is higher than the limit of annual concentration of PM_{10} according to the WHO air quality guidelines (15 µg/m^3).[29] PM_{10} was shown to be a serious air pollutant in Tehran. It is well known that PM_{10} contributes to greenhouse gas emissions that warm the climate.[43] The main anthropogenic sources of this pollution are fossil fuel and biomass combustion, motor vehicles, and industrial activities.[44] In a study, results showed that the effect of clean-up activities such as the Natural Gas Vehicle Supply (NGVS) program and emission control retrofits, which were supposed to result in zero emissions of fine particles, did not result in an overall reduction in PM_{10} levels.[45] Another study found that more than 90% of the dust-related PM_{10} concentrations in Tehran during the investigated dust events were caused by deserts in Iraq and Syria.[46]

The annual average mass concentration of SO_2 was 17.98±8 µg/m^3 in 2019, 14.94±3.8 µg/m^3 in 2020, and 17.47±5.4 µg/m^3 in 2021, which is less than the limit of annual concentration of SO_2 according to the WHO air quality guidelines (40 µg/m^3). The energy production sector, which represents the usage of fossil fuels, is the main source of SO_x in the ambient air of Tehran.[47] The sulfur content of diesel fuel used by mobile and roadway sources has been reduced by more than 98% since the end of 2016 (Sulfur content reduced from 4000 ppm to almost 75 ppm), resulting in considerable reductions in SO_2 production and emissions from mobile sources.[48] Government choices can influence fuel consumption and urban green space by raising public awareness and people's intentions. A study by Ebrahimi et al. (2021) showed that fuel consumption and urban green space can be changed by government decisions, raising public awareness and people's intentions. According to this study, the reduction of gasoline and gas oil consumption and the increase of green space area reduce SO_2 pollutant concentrations up to 2.096, 1.617, and 2.265 percent, respectively, extremely effective at decreasing pollution caused by these pollutants. If all three of these adjustments occur together, the concentration of this pollutant will be reduced by around 5.9%, mitigating many of the difficulties created by the increase in SO_2 concentration. Source apportionment analysis in Tehran revealed that sulfate might make up to 40% of total $PM_{2.5}$ contributions made in the city; therefore, SO_2 is still a concern for Tehran's air quality.[48]

During the study, the average concentrations of $PM_{2.5}$ and SO_2 were highest in winter with average concentrations of 36.58 and 21.72 µg/m^3, respectively. The average concentrations of PM_{10} were highest in the fall, with average concentrations of 84 µg/m^3. The average concentrations of $PM_{2.5}$, PM_{10}, and SO_2 were lowest in spring with average concentrations of 21 µg/m^3, 59.3 µgm^3, and 10.52 µg/m^3, respectively. Seasonal variations of $PM_{2.5}$, $PM_{10,}$ and SO_2 during the period of study are shown in Figure 5. The highest concentrations of pollutants in winter and

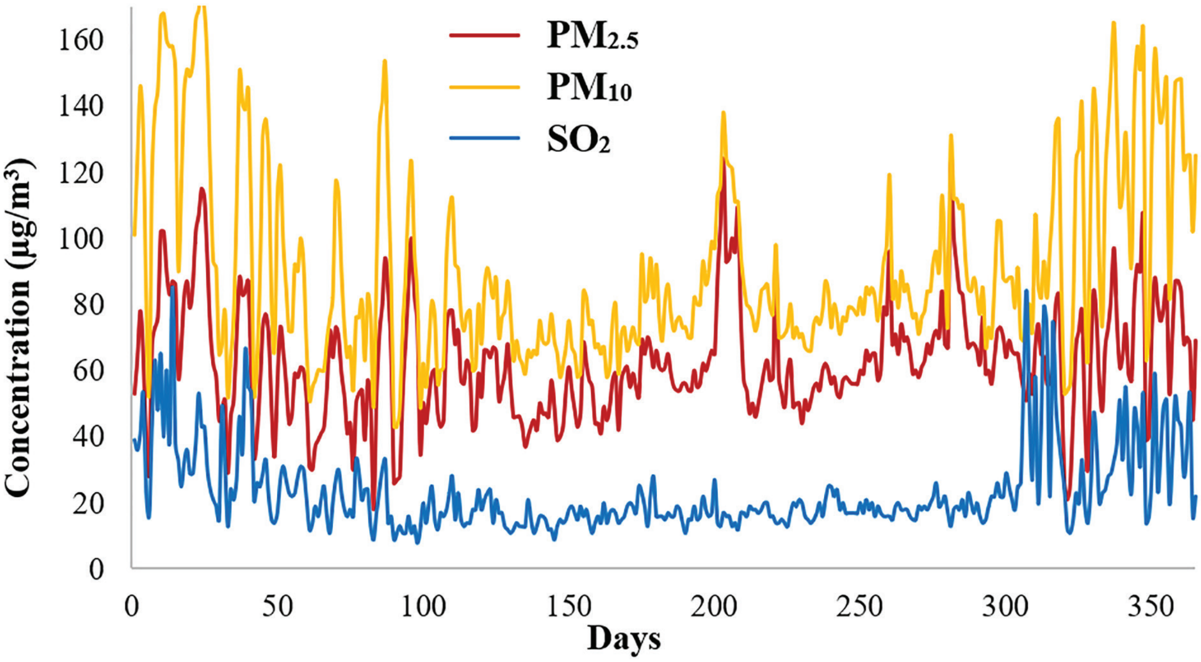

Figure 4: Variations of $PM_{2.5}$, $PM_{10,}$ and SO_2 concentration in 2021 (Pictures prepared by the author)

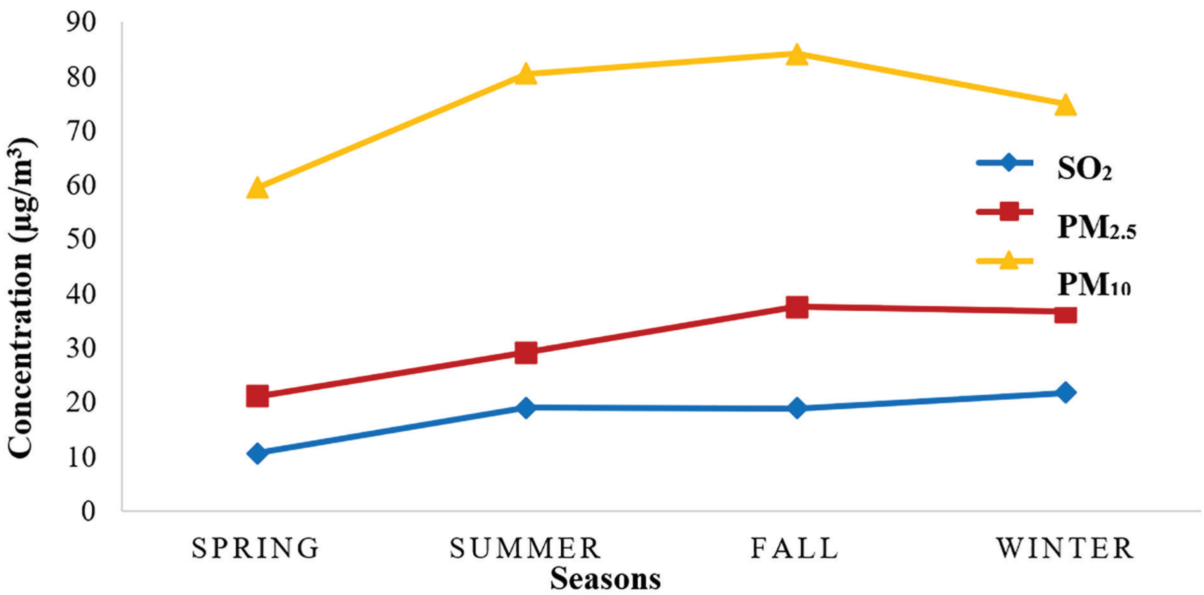

Figure 5: Seasonal variations of $PM_{2.5}$, PM_{10}, and SO_2 (designed by the author)

fall are associated with increased use of fossil fuels for heating, increased traffic density, and a combination of unfavorable weather conditions such as stagnant weather, higher haze, reduced sunny days, temperature inversion, and lower boundary layer.[38, 43] This finding indicates that the residential sector and heating systems may significantly worsen air quality during the colder months of the year.[49] Furthermore, the mountain ranges in the north of Tehran stop the flow of the humid wind and prevent the polluted air from leaving the city. Thus, in winter, the lack of wind and cold air traps polluted air within the city.[50] The average concentrations of PM_{10} were highest in the fall, because in this season pollen grains, being larger, can potentially aggregate with smaller particulate matter in the air, forming larger particles that fall within the PM_{10} size range. In addition, deciduous plants shed their leaves, and there might be increased plant material in the air, which could contribute to the overall PM_{10} load.[51] Also, construction and development projects can release dust and particulate matter into the air. Fall is a common time for such activities, and construction-related emissions can contribute to higher PM10 concentrations.[52] Also, the average concentration of PM_{10} (82.75 µg/m³) was high in summer because the Middle East dust storm was responsible for the excessive concentration of PM_{10} during summer in Tehran.[53] Lower spring concentrations of pollutants may be related to unstable weather conditions and wet deposition during the New Year holiday.[54] The results of this study were consistent with those of the study by Faridi et al. (2018), which found that the most polluted seasons were identified in winter and summer and were least polluted in spring for PM2.5 in Iran.

Health Risk Assessment

In this study, only the inhalation pathway was analyzed because it is an important pathway for exposure to $PM_{2.5}$, PM_{10}, and SO_2 outdoors. The results obtained from the risk assessment of $PM_{2.5}$, PM_{10}, and SO_2 via inhalation are shown in Table 3. The mean HQ values via inhalation exposure to $PM_{2.5}$ were 0.72, 1.93, and 2.9 for exposure time scenarios of 3, 8, and 12 hours, respectively. The mean HQ values via inhalation exposure to PM_{10} were 0.6, 1.6, and 2.4 for Exposure time scenarios of 3, 8, and 12 hours, respectively. HQ values greater than 1 indicate unacceptable exposure levels with significant chronic non-cancer risks for the target organs, and therefore, more attention and research should be paid to the non-carcinogenic risks of these pollutants in Tehran's

Table 3: Non-carcinogenic risks of $PM_{2.5}$, PM_{10} and SO_2 via inhalation in Tehran (2019-2021)

	Concentration (µg/m³)		EC (µg/kg.day)			HQ		
			3h	8h	12h	3h	8h	12h
$PM_{2.5}$	Average	30.25	1.06	2.83	4.25	0.72	1.93	2.9
	Max	47.5	1.67	4.45	6.68	1.13	3.03	4.55
PM_{10}	Average	75.24	2.64	7.06	10.59	0.6	1.6	2.4
	Max	109.75	3.86	10.3	15.45	0.87	2.3	3.5
SO_2	Average	15.46	0.54	1.45	2.17	0.04	0.12	0.18
	Max	20.94	0.73	1.96	2.9	0.06	0.16	0.25

EC: Exposure concentration; HQ: Hazard Quotient; $PM_{2.5}$: Particulate Matter with a diameter of 2.5 micrometers or smaller; PM_{10}: Particulate Matter with a diameter of 10 micrometers or smaller; SO_2: Sulfur Dioxide ambient air. The results of this health risk assessment are sensitive to exposure time. An increase in exposure time to 8 hours and even to 12 hours resulted in a major change in HQ values. Therefore, there are potential risks related to air pollution for outdoor job workers who spend hours every day outside in ambient air. PM air pollution is widely known to be harmful to human health. Studies have found a strong exposure-response relationship between $PM_{2.5}$ and both long and short-term effects, which are largely caused in the sick, elderly, or children.[55] In comparative risk assessments conducted, exposure to fine particulate matter ($PM_{2.5}$) was recognized as the greatest health risk of air pollution when estimating the global burden of illness. $PM_{2.5}$ particles penetrate deep into cells and the respiratory systems because of their small size of fewer than 2.5 micrometers, so they may cause a variety of adverse health effects.[41] Heavy metals may threaten human health by inhalation of $PM_{2.5}$ and PM_{10}.[39] Even though heavy metals make up only a small fraction of $PM_{2.5}$ and PM_{10}, they are carcinogenic and low biodegradable.[56] Similar results have been found in the ambient atmosphere of the Brazilian Amazon region with mean HQ values of 2.07 for $PM_{2.5}$, which is indicative of non-carcinogenic risk.[55] Similarly, Heydari et al. (2019) found that HQ values for $PM_{2.5}$ were >1 in the outdoor air of waterpipe cafés in Tehran, indicating an unacceptable risk to human health. Also, in the Yu et al.'s (2019) study, the health risks resulting from $PM_{2.5}$ exposure indicated a significant health risk for preschool children (93.74% greater than 1).

The mean HQ values via inhalation exposure to SO_2 for all exposure time scenarios of 3, 8, and 12 hours were less than 1, which were 0.04, 0.12, and 0.18, respectively, indicating no non-cancer risks via the inhalation exposure pathway for SO_2. This is due to the concentration of SO_2 being less than air quality standards in the indoor air in Tehran. Furthermore, a 98% reduction in the sulfur content of diesel fuel used by mobile and highway sources has led to significant decreases in SO_2 concentrations in Tehran's ambient air since the end of 2016. As one study shows, the annual concentration of SO_2 in Tehran City, from 2005 to 2014, exceeded on standard level,[57] confirming that the reduction in the sulfur content of diesel fuel successfully decreased SO_2 concentration since the end of 2016. Similar results have been found in Matooane et al.'s (2003) study, in which, the risk level of SO_2 was low (Hazard Quotient <1) in South Durban; and only under the worst-case scenario (exposure 24 hr./day), there was a significant risk of developing health effects. Moreover, in the research by Thongthammachart et al. (2017), both short-term and long-term exposure to SO_2 and NO_2 from a newly developing coal power plant in Thailand was less than 1. Also, in research by Fouladi-Fard et al. (2022) on the effect of power plant fuel change on the air pollution (SO_2 and NO_X) of surrounding regions in Qom, Iran, similar findings have been observed that the SO_2 hazard quotients (HQ) values for all age groups were less than 1.

The highest average $PM_{2.5}$ and PM_{10} levels were observed in District 19 of Tehran, with concentrations of 47.5 µg/m³ and 109.75 µg/m³, respectively. Thus, the HQ values of $PM_{2.5}$ and PM_{10} for the exposure time of

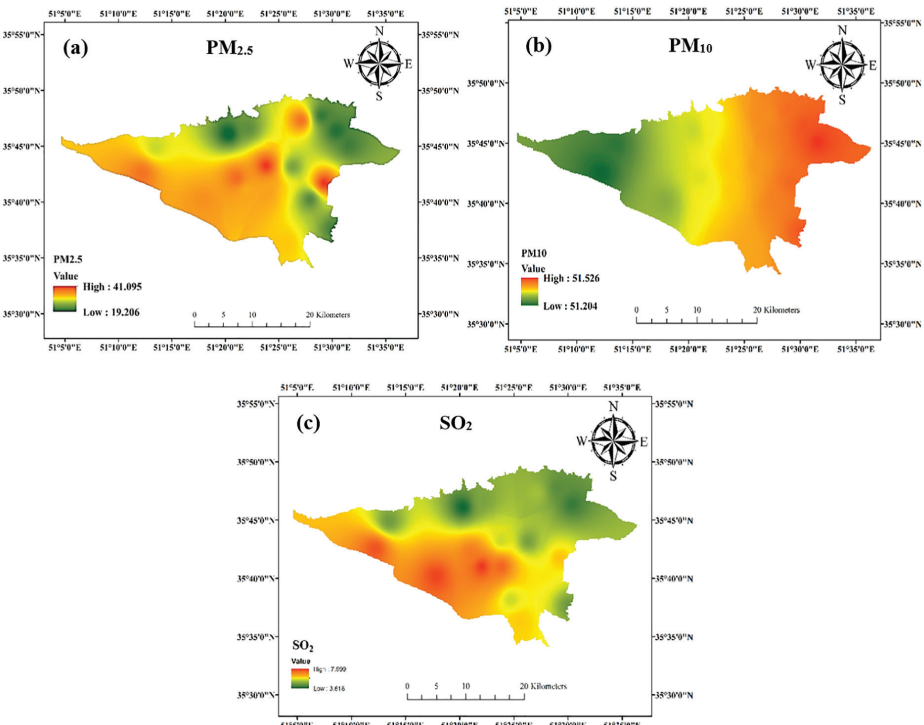

Figure 6: Spatial distribution of $PM_{2.5}$ (a), PM_{10} (b), and SO_2 (c) (designed by the author)

12 hours were 4.55 and 3.5, respectively. Therefore, there is a need for serious attention in District 19 of Tehran in terms of air pollution. Also, the HQ value of $pm_{2.5}$ was more than 1 for the exposure time of 3hr in District 19 of Tehran, so it seems unhealthy to stay outside for more than 3 hours in this area. The highest concentration of SO_2 was in District 10 of Tehran with an average concentration of 20.94 $\mu g/m^3$, and its HQ value for the exposure time of 12 hours was 0.25.

Spatial Distribution of Pollutants

Figure 6 shows the spatial distribution of the sampling area's typical annual concentrations of SO_2, $PM_{2.5}$, and PM_{10} in Tehran. The greatest $PM_{2.5}$ and SO_2 concentrations were found in the west and southwest of Tehran, as seen in Figure 6 (a-c). This area is located in an industrial area that emits pollutants from manufacturers like petroleum-based and gas refineries, electronics manufacturing facilities, cement and grinder industries, machinery repair shops, packaging companies, and companies that make plastic pipes, all of which harm the area's air quality.[58-60] On the other hand, Tehran City experiences a predominant northwest to southeast windrose, which has ultimately resulted in the increased concentration of $PM_{2.5}$ and SO_2 in these regions. Additionally, one of the other influencing variables linked to the rise in $PM_{2.5}$ and SO_2 concentration is the proliferation of industries in these regions.[61] Car exhaust fumes are partially responsible for the high PM_{10} concentrations in the east and northeast, which are situated in heavily trafficked regions. Consequently, human activities play a crucial role in the spread and dispersion of pollutants across diverse natural matrices.[62] Additionally, there are parks and forest areas in the east of Tehran, so plant pollen can increase the concentration of PM_{10} in these areas. According to research by Talebi et al. (2008), Isfahan's high-traffic areas have seen the greatest concentrations of PM_{10} and its associated heavy metals.

Sobol Sensitivity Analysis

Six input variables were used in the inhalation model, including concentrations of $PM_{2.5}$, PM_{10}, and SO_2 in the ambient air, body weight (BW), exposure frequency (EF), and inhalation rate (IR) (Table 1). *Sobol* Sensitivity analysis helped identify the most pertinent variables affecting non-carcinogenic health risks in the population. According to the findings, $PM_{2.5}$ content showed the highest impact on health risk (HQ=0.626), indicating its significance in assessing health risks in the population. Following $PM_{2.5}$, the factors were ranked in order of influence: EF (0.307) >BW (0.031) >PM_{10} (0.011) >IR (0.010) >SO_2 (0.001), with SO_2 being identified as relatively insensitive (Figure 7a). There were interactions between $PM_{2.5}$ and EF (with a total effect greater than the first-order effect), indicating their combined impact (Figure 7b). However, this interaction effect wasn't as apparent as other factors. The interaction diagram highlighted a notable interaction between $PM_{2.5}$ and EF, specifically $PM_{2.5}$-EF (0.012), which appeared to be beneficial. This study aligns with previous research that emphasizes the effectiveness of $PM_{2.5}$ in assessing non-carcinogenic health risks in populations.[63, 64] The findings emphasize the critical role of $PM_{2.5}$ concentration in assessing health risks, along with its interaction with exposure frequency (EF). The study underscores the significance of considering these factors when evaluating non-carcinogenic health risks associated with air pollution in Tehran's populace. The results of the Sobol sensitivity test conducted by Dabbour et al. for the three Jordanian cities show that there are substantial variations in the ways that lockdown measures and meteorological data

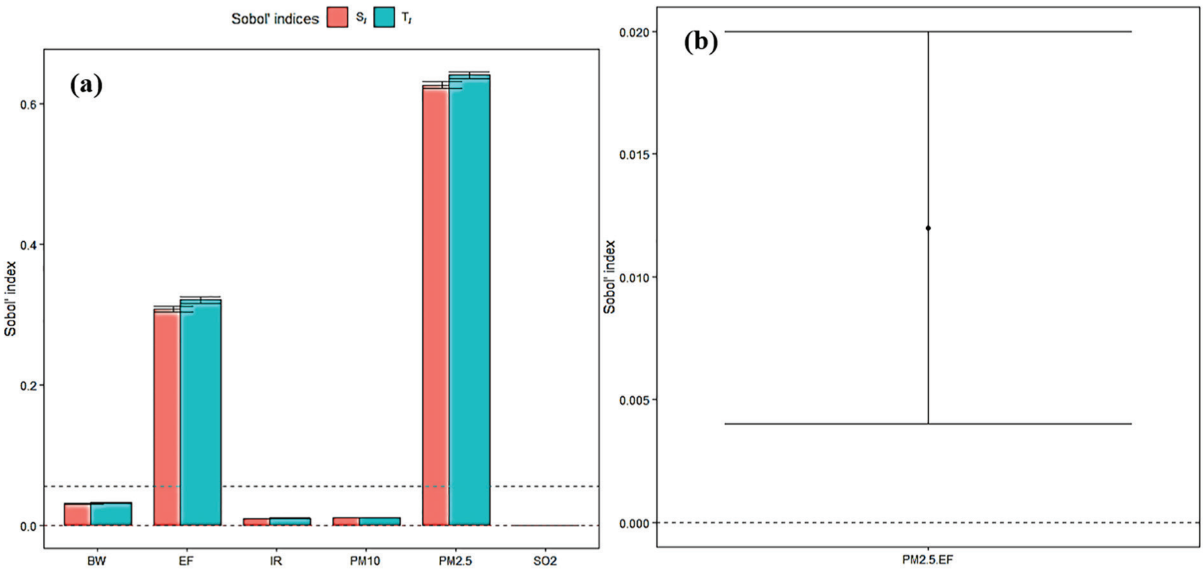

Figure 7: Sensitivity analysis based on the HQ considering first-order effect (S_i) and total effect (T_i) (a) and pair-wise interactions (b) (designed by the author)

affected the concentrations of four different pollutants (CO, NO_2, SO_2, and PM_{10}). The extensive statistical analysis showed that the observed changes in most of air pollutants are mostly caused by fluctuations in the weather. As such, meteorological considerations must be taken into account when assessing hazards associated with pollution sources and when analyzing the effects of changes in pollutant sources on air quality during the particular COVID-19 closure period.[65]

Conclusion

The annual average mass concentrations of $PM_{2.5}$ and PM_{10} were higher than the limited annual concentration of the WHO air quality guidelines. The annual average mass concentration of SO_2 was less than the limit of the annual concentration of SO_2 according to the WHO air quality guidelines. The level of health risk for $PM_{2.5}$ and PM_{10} with exposure time of 8 and 12 hours poses a risk. The level of health risk for SO_2 for all exposure times in Tehran city does not pose a risk. Considering that the concentration of PM by spending more than 8 hours can lead to risk for citizens, they should be outside for less than 8 hours. Overall, spending more than 8 hours outside the home poses issues, and it is recommended that time spent outdoors be limited to fewer than 8 hours, especially for outside jobs. Risk management should be done to control the impact of exposure to $PM_{2.5}$ and PM_{10} in Tehran. Tehran's west and southwest were discovered to have the highest concentrations of $PM_{2.5}$ and SO_2, while its east and northeast had the highest concentrations of PM_{10}. The $PM_{2.5}$ content was found to be the the population's most sensitive indicator in HQ, according to the results of the Sobol sensitivity analysis. The government should take control measures to reduce the concentration of $PM_{2.5}$ and PM_{10} in the air of Tehran city and periodically monitor the concentration of pollutants in the ambient air so as not to exceed the recommended safe limits.

Authors' Contribution

Fahimeh Ahmadian: Prepared and wrote the original draft; conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools, or data; andwrote the paper. Saeed Rajabi: Conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools, or data; wrote the paper. Abooalfazl Azhdarpoor: Conceived and designed the experiments; contributed reagents, materials, analysis tools, or data; and wrote the paper.

Acknowledgment

The present article was adopted from proposal number 25599 and ethical code of IR.SUMS.SCHEANUT.REC.1401.082 approved by Shiraz University of Medical Sciences.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data Availability

The datasets obtained in this study are available from the corresponding author upon reasonable request.

Conflict of Interest: None declared.

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