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Assessment of PM_{10} Atmospheric Particle Concentrations and Heavy Metals Levels in the Air of Gorgan City, Iran

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ABSTRACT

Introduction: With increasing industrialization and urbanization, particulate matter (PM_{10}) has become one of the major air pollutants and a critical concern for environmental and public health. Therefore, this study aimed to assess seasonal/annual variations of PM_{10}-bound heavy metals in Gorgan, compare them with WHO/international data, and identify potential sources via correlation analysis.

Methods: cross-sectional experimental study was conducted between March 2023 and March 2024 in Gorgan, Golestan province, Iran. Sampling was performed every six days throughout the study period according to the U.S. Environmental Protection Agency (EPA) method. A total of 52 samples were collected to determine PM_{10} and heavy metals concentrations. Samples were taken from a central urban station using a BGI Omni FT ambient air sampler.

Results: Results showed that PM_{10} concentrations ranged from a minimum of 20.83 µg/m³ in early November to a maximum of 277.78 µg/m³ in early February, with a mean ± SD of 69.3 ± 49.82 µg/m³ across the study period. Seven trace elements were analyzed, and their annual mean concentrations followed the order: Cd <Co < Cr < Ni < Cu < Pb < Zn. Strong positive correlations were observed among several metals, particularly Cu, Cr, and Ni, with nearly linear relationships.

Conclusion: The findings demonstrated that PM_{10} levels in Gorgan slightly exceeded the WHO 24-hour guideline, with more pronounced fluctuations on a monthly scale. Among the heavy metals, Zn, Pb, and Cu exhibited the highest concentrations, peaking during winter.

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Introduction

Climate change has been identified by the World Health Organization (WHO) as one of the greatest health threats of the twenty-first century. Alongside this global issue, air pollution remains a major environmental determinant of public health

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and economic stability in many societies [1]. The severity of air pollution is largely associated with the absence of bypass infrastructure, proximity of industrial facilities to residential neighborhoods, and extensive use of fuels with low combustion quality [2, 3]. In addition, poor air circulation intensifies the accumulation of hazardous pollutants such as particulate matter (PM), volatile organic compounds (VOCs), nitrogen oxides (NOx), carbon monoxide (CO), heavy metals, and persistent organic pollutants [1].

Particulate matter (PM) is a critical air pollutant that adversely affects environmental integrity and human health [4]. PM arises from a range of natural and human-induced sources. Volcanic eruptions, wildfires, dust events, and sea-salt aerosols contribute naturally, while industrial operations, combustion processes, vehicle exhaust, and tobacco smoke are key anthropogenic contributors [5, 6]. Based on their size, PM is commonly classified into three major categories: coarse, fine, and ultrafine particles. Exposure to suspended particulate matter (SPM) has been linked to a wide range of short- and long-term health effects, including cardiovascular diseases, pulmonary disorders, eye irritation, headaches, and cancers, ultimately contributing to premature mortality [7]. Determining the atmospheric concentration of particles with an aerodynamic diameter ≤ 10 µm (PM_{10}) is crucial not only because of their detrimental health effects but also for developing strategies to reduce air pollution. The toxicity of suspended particles depends on both their size and chemical composition; however, the major health risks are primarily attributed to their chemical constituents [8, 9]. Particulate matter (PM) may contain heavy metals such as lead (Pb), cadmium (Cd), nickel (Ni), copper (Cu), chromium (Cr), manganese (Mn), vanadium (V), zinc (Zn), and arsenic (As), all of which pose serious risks to human health. The principal exposure pathways for these contaminants are inhalation, ingestion, and skin contact [4]. Major contributors to atmospheric metal contamination include smelting processes, fossil fuel burning, mining activities, and road traffic emissions, with particularly high impacts observed in urban and industrialized areas [10, 11]. The environmental persistence of heavy metals constitutes a major concern, as they remain stable for extended periods and bioaccumulate in multiple environmental compartments—air, soil, water, and living tissues. Chronic exposure, even at trace levels, may lead to disturbances in biological functioning [12].

Given the detrimental effects of heavy metals on both human health and ecosystems, numerous investigations have been carried out globally to quantify their environmental levels [9, 13]. Arsenic, cadmium, and nickel have been classified by the International Agency for Research on Cancer (IARC) as Group 1 human carcinogens, with established associations with lethal cancers of the lung, trachea, and bronchi [1]. Lead has been categorized as a probable human carcinogen (Group 2A) and is known to cause neurological and renal damage [14]. Chronic exposure in children has been associated with developmental delays and deficits in learning [15]. Elevated airborne copper (Cu), frequently used in industry, is associated with oxidative stress and liver damage [16]. In general, exposure to heavy metals may disrupt neurological function, impair renal health, interfere with bone development, and cause damage to various other organs [17, 18]. Recently, the European Parliament and Council proposed updated guidelines for ambient air quality and cleaner air in Europe. According to this proposal, the annual limits for PM_{10} are reduced from 40 µg/m³ to 20 µg/m³, and for PM2.5 from 25 µg/m³ to 10 µg/m³, with the introduction of a new daily limit for PM2.5 [19]. Risk-based evaluation of toxic metal exposure in indoor and outdoor environments across China revealed that zinc recorded the highest concentrations, whereas lead showed the lowest. Notably, the lifetime cancer risk (LCR) estimates for arsenic and cadmium were above the acceptable limits in specific cities [20]. Additionally, a study examining the impact of PM_{10} on mortality in Bogotá from 1998 to 2006 found that increases in PM_{10} concentrations were associated with acute respiratory-related deaths [21]. More recently, two studies reported that PM_{10} levels in Santa Marta

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exceeded the international precautionary threshold of 50 µg/m³ [21]. Despite the growing body of research on urban air pollution in Iran, comprehensive data on PM_{10} and its associated heavy metal content remain scarce for many mid-sized cities, particularly those with distinct climatic and geographical characteristics. Gorgan, the capital of Golestan Province, exemplifies such a city. It features a temperate climate with high humidity in summer and cold winters—conditions that can substantially affect the atmospheric dispersion, transformation, and deposition of particulate-bound pollutants. Moreover, rapid urbanization and increased vehicular traffic in recent years have heightened concerns about local air quality, yet no systematic monitoring or characterization of PM_{10}-bound trace elements has been conducted in this region. This study addresses this critical knowledge gap by providing the first year-round dataset on PM_{10} and its associated heavy metals (Zn, Cu, Cr, Cd, Pb, Ni, and Co) in Gorgan's urban atmosphere. Accordingly, the specific objectives of this investigation were to: (1) determine the seasonal and annual concentration profiles of PM_{10} and the selected heavy metals; (2) compare the measured concentrations with World Health Organization (WHO) air quality guidelines and findings from comparable international studies; and (3) evaluate inter-element correlations to identify potential common sources. We hypothesized that heavy metal concentrations would exhibit significant seasonal variations, with peak levels in winter driven by increased fossil fuel combustion, and that strong positive correlations among specific metals would indicate shared anthropogenic emission sources, particularly traffic-related and industrial activities.

Materials and Methods

Study Area

This experimental cross-sectional study was conducted between March 2023 and March 2024 in Gorgan, the capital of Golestan Province, located in northeastern Iran. Gorgan is situated at latitude 36.50°N and longitude 54.26°E, at an altitude of 160 meters above sea level. The city has a temperate climate characterized by hot, humid summers and cold winters. Gorgan comprises three distinct topographical regions: plains, piedmonts, and mountains. The prevailing wind direction is from the west and southwest. According to the most recent census, the population of Gorgan is approximately 500,000 inhabitants.

Sampling and Analytical Procedures

Air sampling was conducted on a weekly basis (once every 7 days) over a 12-month period from March 2023 to March 2024, yielding a total of 52 samples. Samples were collected at a fixed monitoring station located in the city center, using a BGI OMNI FT ambient air sampler operating at a constant flow rate of 5 L/min, in accordance with the U.S. Environmental Protection Agency (EPA) reference method for PM_{10} [22].

Particulate matter (PM_{10}) was collected on quartz microfilters. Before and after sampling, all filters were conditioned in a desiccator for at least 24 h to eliminate moisture. The filters were weighed using a microbalance with 0.001 mg precision, and PM_{10} mass concentrations (µg/m³) were calculated gravimetrically based on the difference in filter weights ($W_2 – W_1$).

For heavy metal analysis, the loaded filters were digested using a mixture of nitric acid and perchloric acid in a 10:1 (v/v) ratio, following NIOSH Method 7300 (23). The digested solutions were filtered and stored in polyethylene bottles under refrigeration (4°C) until analysis. Heavy metal concentrations (Zn, Cu, Cr, Cd, Pb, Ni, and Co) were determined using voltammetry with a 797 VA Computrace polarograph (Metrohm, Switzerland).

Quality control measures included the following: (i) the use of field blanks (one blank per 10 samples) to correct for potential contamination during handling and transport; (ii) pre-baking of quartz filters at 450°C for 4 hours to remove organic impurities; and (iii) calibration of the sampler before each sampling campaign using a certified flow meter. The limit of detection (LOD) and limit of quantification (LOQ) for each heavy metals were calculated as 3 and 10 times the

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standard deviation of blank measurements, respectively. The LOD values (in ng/m³) were: Zn: 0.5, Cu: 0.2, Cr: 0.1, Cd: 0.05, Pb: 0.3, Ni: 0.15, and Co: 0.08. Concentrations below the LOD were replaced with LOD/√2 for statistical analysis.

Statistical Analysis

Quantitative data are expressed as mean ± standard deviation (mean ± SD). Prior to parametric testing, the normality of data distribution was assessed using the Shapiro–Wilk test. All variables met the normality assumption ($p > 0.05$), justifying the use of parametric tests. One-way analysis of variance (ANOVA) was used to compare PM_{10} and heavy metal concentrations across seasons. When ANOVA indicated significant differences ($p < 0.05$), Tukey's HSD post-hoc test was applied for pairwise comparisons. Pearson correlation coefficients were calculated to evaluate linear relationships between variables. All statistical analyses were performed using STATA version 18 (StataCorp, USA). Graphical visualizations, including correlation matrices and scatterplots, were generated using R software (version 4.2) with the 'ggplot2' package. Statistical significance was set at a two-tailed p-value < 0.05 for all analyses.

Results

PM_{10} Concentrations

To assess pollution levels and their association with nearby dust sources, the variations in PM_{10} and heavy metal concentrations in Gorgan were analyzed over a 12-month period. The results showed that PM_{10} concentrations ranged from a minimum of 20.83 µg/m³ in early November to a maximum of 277.78 µg/m³ in early February, with a mean ± standard deviation of 69.3 ± 49.82 µg/m³ over the study period (Table 1). These values are slightly higher than the World Health Organization's 24-hour guideline of 50 µg/m³. Seasonal mean concentrations ranged from 65.97 ± 36.72 µg/m³ in spring to 71.58 ± 50.34 µg/m³ in summer, with no statistically significant differences observed between the seasons ($p = 0.992$) (Table 2). Monthly variations showed the highest concentration in July (114.58 µg/m³) and the lowest in January (43.40 µg/m³) (Figure 1).

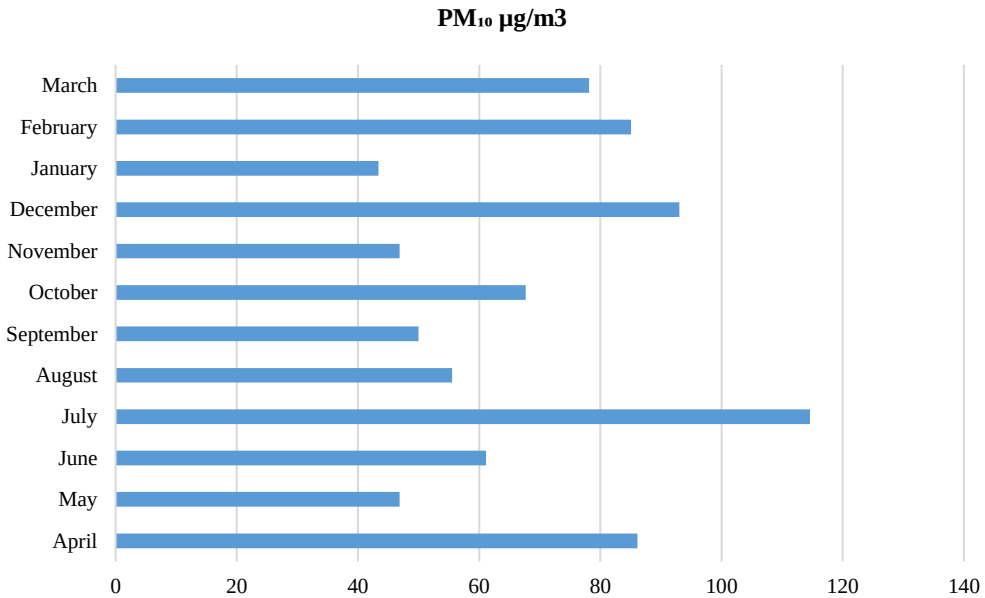


Figure 1: Monthly variations of PM_{10} concentrations in Gorgan.

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Table 1: Summary comparison of PM_{10} concentrations obtained in the present study with those reported in other studies conducted in Iran and other countries (expressed in µg/m³).

Ref	Duration	PM_{10}	Place	
Current study	March 2023 to March 2024	69.3	Gorgan	
Aldeen et al. 2025[23]	October and November 2023	85.11 72.82	the National Iraqi Museum The Natural History Museum	Baghdad
Adly et al. 2025[24]	December 2020 to December 2024 2020 2021 2022 2023 2024	 127.7 130.2 132.9 135.5 138.3	Saudi Arabia (Makkah)	
Kebe et al. 2025[4]	In 2018 and 2019	232.318 209.854	Hlm (industrial site) Yoff (coastal and urban site)	Senegal
Shahsavani et al. 2025[20]	summer of 2019	78.12	iran(Shiraz)	
Hamidi et al. 2025[25]	2008–2019 January February March April May June July August September October November December	223.4 177.09 265.19 179.08 192.43 192.43 346.9 388.18 189.59 188.04 167.46 143.77 148.97	iran(Ahvaz)	
Alharbi et al. 2024 [26]	April–December2023	223.12	Saudi Arabia(Riyadh)	
Zeb et al. 2024 [27]	December 2017 to February 2018 (winter)	586	Pakistan(Khyber Pakhtunkhwa)	
Lara et al. 2023 [28]	May 2019 to September 2020	31	Spain(Gijon)	
Ahmad et al. 2023 [29]	winter 2019	279.73	Pakistan (Lahore)	
Esform et al. 2022[30]	September 2019 to March 2020	97.5	Iran(Birjand)	
Zeb et al. 2022 [31]	winterseason(2018)	505.06 255.04 238.48	industrial urban suburban	Pakistan(Nowshera)
Sirithian et al. 2022[32]	(January to April) from 2016 to 2020.	73.86 64.58	urban rural	Thailand
Usman et al. 2022[33]	year of 2019	64	Pakistan(Hindu KushRegion)	
Kliengchuay et al. 2021[34]	July 2009 to December 2017	42.98	Thailand (Lamphun)	
Liu et al. 2020[35]	February to March 2016	98	China(Tian'jin)	
Gupta et al. 2020[36]	January 2013 to December 2018	136.25	Bangladesh	
Shahid et al.	March and April of 2010	438	Pakistan (Karachi)	

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Ref	Duration		PM10	Place
2018[37]				
Farsani et al. 2018[38]	normal days	autumn	131	Iran (Ahvaz)
		winter	189	
		spring	145	
		summer	127µg	
	Duststorm	autumn	410	
		winter	742	
		spring	300	
		summer	278	
Di Vaio et al. 2018[39]	February 2013- October 2013			Italy (Acerra)
	autumn		30.22	
	winter		39.6	
	spring		33.85	
	summer		35.46	
Munir et al. 2017[40]	January 2014 to September 2015		44.53	Saudi Arabia (Makkah)
Alam et al. 2014[41]	March and April of 2010		406.2	Pakistan (Lahore)
Sharma et al. 2014[42]	January 2010 to December 2011		191.4	India (Delhi)

Table 2: Mean and standard deviation of PM₁₀ and heavy metal concentrations by season in Gorgan City.

	Season					
	Spring	Summer	Autumn	Winter	Total	Test
PM10	65.972 (36.721)	71.581 (50.348)	71.047 (41.778)	68.866 (73.818)	69.311 (50.312)	0.992
Zn	226.714 (75.242)	277.385 (108.586)	461.538 (223.071)	541.500 (96.514)	370.731 (186.583)	< 0.001
Cu	13.532 (5.625)	7.507 (2.668)	27.999 (8.825)	40.082 (5.227)	21.769 (13.901)	< 0.001
Cd	2.529 (0.823)	2.438 (0.747)	3.500 (0.998)	4.300 (1.437)	3.158 (1.250)	< 0.001
Pb	82.286 (33.160)	56.000 (26.331)	157.846 (54.714)	178.667 (39.204)	116.846 (63.864)	< 0.001
Cr	6.720 (2.374)	4.046 (1.911)	9.359 (2.675)	13.009 (1.755)	8.162 (3.928)	< 0.001
Co	3.953 (1.397)	2.333 (1.147)	4.417 (1.099)	5.955 (0.844)	4.126 (1.697)	< 0.001
Ni	13.439 (4.748)	8.091 (3.822)	18.718 (5.349)	26.019 (3.511)	16.325 (7.856)	< 0.001

Heavy Metal Concentrations

Analysis of seven trace elements in ambient air samples yielded their annual mean concentrations, as shown in Table 3, with comparative data from other studies presented in Table 4. The mean concentrations followed the order: Cd (3.2 ± 1.23 ng/m³) < Co (4.1 ± 1.68) < Cr (8.2 ± 3.88) < Ni (16.3 ± 7.77) < Cu (21.8 ± 13.76) < Pb (116.8 ± 63.24) < Zn (370.7 ± 184.78). All metals exhibited considerable seasonal variations, with statistically significant differences ($p < 0.001$). Zinc (Zn) showed a continuous increasing trend from spring (226.7 ng/m³) to winter (541.5 ng/m³). For the other metals, the minimum concentrations were observed in summer, while the maximum concentrations were observed in winter. The ratio of seasonal variations (minimum/maximum) ranged from 1.76 for Cd to 5.34 for Cu, indicating a marked increase in metal concentrations during winter (Table 2).

Table 3: Annual mean concentrations of heavy metals in PM₁₀ (ng/m³).

	Zn	Cu	Cd	Pb	Cr	Co	Ni
mean	370.7 ± 184.78	21.8 ± 13.76	3.2 ± 1.23	116.8 ± 63.24	8.2 ± 3.88	4.1 ± 1.68	16.3 ± 7.77
min	150.0	2.8	1.2	24.0	1.9	1.1	3.7
max	870.0	51.7	6.1	240.0	16.7	7.4	33.3

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Table 4: Summary comparison of heavy metal concentrations associated with PM_{10} obtained in the present study and those reported in other studies conducted in Iran and other countries (ng/m³)..

Ref	Duration		Zn	Cu	Cd	Pb	Cr	Co	Ni	Location
Shahsavani et al. 2025 [20]	summer of 2019		33.08	102.04	_	17.61	_	_	82.15	Iran (Shiraz)
Alharbi et al. 2024[26]	April–December2023		9.06	10.97	0.04	1.11	3.75	0.25	1.72	Saudi Arabia (Riyadh)
Lara et al. 2023[28]	May 2019 to September 2020		9.4	9.2	0.19	9.4	3.2	0.21	1.7	Spain (Gijon)
Karimi et al. 2023[43]	2021 autumn		29.21	_	_	6/81	29/55	_	_	Iran (Tehran)
Esform et al. 2022[30]	September 2019 to March 2020		0.71	0.006	9.588	0.004	0.006	0.224	0.006	Iran (Birjand)
Rezayani et al. 2022[44]	April 2019 to March 2020		106.21	16.377	5.357	31.65	5.615	_	5.77	Iran (Tehran)
Karimi et al. 2022[45]	2021 spring		18.78	_	_	0/17	25/42	_	_	Iran (Tehran)
Karimi et al. 2022[46]	2021		23.99	_	_	Mar-49	27 /48	_	_	Iran (Tehran)
Joshirvani et al. 2021[47]	May to November 2017			_	1.78	7.44	2.72	_	_	Iran (Hamadan)
Shahid et al. 2018[37]	March and April of 2010		830	420	_	410	50	_	20	Iran (Birjand)
Farsani et al. 2018[38]	October 2012 to September 2013									Iran (Ahvaz)
	normal days	autumn	2.8	_	0.19	2.85	0.39	0.3	0.61	
		winter	7.95	_	0.22	5.7	1.05	0.85	1.58	
		spring	3.48	_	0.25	3.5	0.8	0.43	1.3	
		summer	2.89	_	0.2	3.1	0.66	0.35	1.1	
	Duststorm	autumn	4.02	_	0.51	3.67	1.55	1.45	1.79	
		winter	8.23	_	0.87	5.78	1.8	1.58	2.35	
		spring	4.3	_	0.48	4.4	1.4	0.66	2.1	
		summer	3.45	_	0.59	3.66	1	0.72	1.5	
Di Vaio et al. 2018[39]	February 2013-October 2013									Italy (Acerra)
	autumn		75.1	23.4	4.35	60.8	14.7	1.6	17.9	
	winter		76.6	17.3	4.77	50.6	19.7	3.8	16.7	
	spring		79.4	24.1	4.26	55.8	14.2	2.1	11	
	summer		45.7	19.2	3.8	59.9	14	2.52	10.2	
Dai et al. 2015[48]	February 2011 to January 2012		1018.6	154	4	195.2	19.2	2.4	10.7	iron and steel industry zone China
			794.6	117.1	3.8	158.7	7.5	1.1	6.2	background site

Correlation Analysis

Table 5 presents the correlation coefficients between PM_{10} and the heavy metals. Cd exhibited the strongest correlation with PM_{10} ($r = 0.401$, $p = 0.002$). The correlation for Zn ($r = 0.263$, $p = 0.050$) was at the borderline of statistical significance, whereas the correlation for Cu ($r = 0.246$, $p = 0.068$) was not statistically significant. Pb, Cr, Co, and Ni exhibited positive but non-significant correlations with PM_{10}. In the correlation analysis among the metals, very strong and statistically significant relationships were observed between the metals. Cu showed the highest correlation with Pb, Cr, Co, and Ni. Pb exhibited strong correlations with Cr and Co. The correlation of Cr with Co and Ni

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was also very high. Cd showed very strong and significant correlations with Zn, Cu, Pb, Cr, Co, and Ni. These results are clearly illustrated in Figure 2.

Table 5: Pearson linear correlation coefficients for heavy metals in PM₁₀ samples.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) PM10	1.000							
(2) Zn	0.263 (0.050)	1.000						
(3) Cu	0.246 (0.068)	0.709 (< 0.001)	1.000					
(4) Cd	0.401 (0.002)	0.674 (< 0.001)	0.662 (< 0.001)	1.000				
(5) Pb	0.166 (0.221)	0.621 (< 0.001)	0.928 (< 0.001)	0.605 (< 0.001)	1.000			
(6) Cr	0.249 (0.064)	0.658 (< 0.001)	0.968 (< 0.001)	0.622 (< 0.001)	0.928 (< 0.001)	1.000		
(7) Co	0.223 (0.099)	0.516 (< 0.001)	0.879 (< 0.001)	0.563 (< 0.001)	0.849 (< 0.001)	0.953 (< 0.001)	1.000	
(8) Ni	0.249 (0.064)	0.658 (< 0.001)	0.968 (< 0.001)	0.622 (< 0.001)	0.928 (< 0.001)	1.000 (< 0.001)	0.953 (< 0.001)	1.000

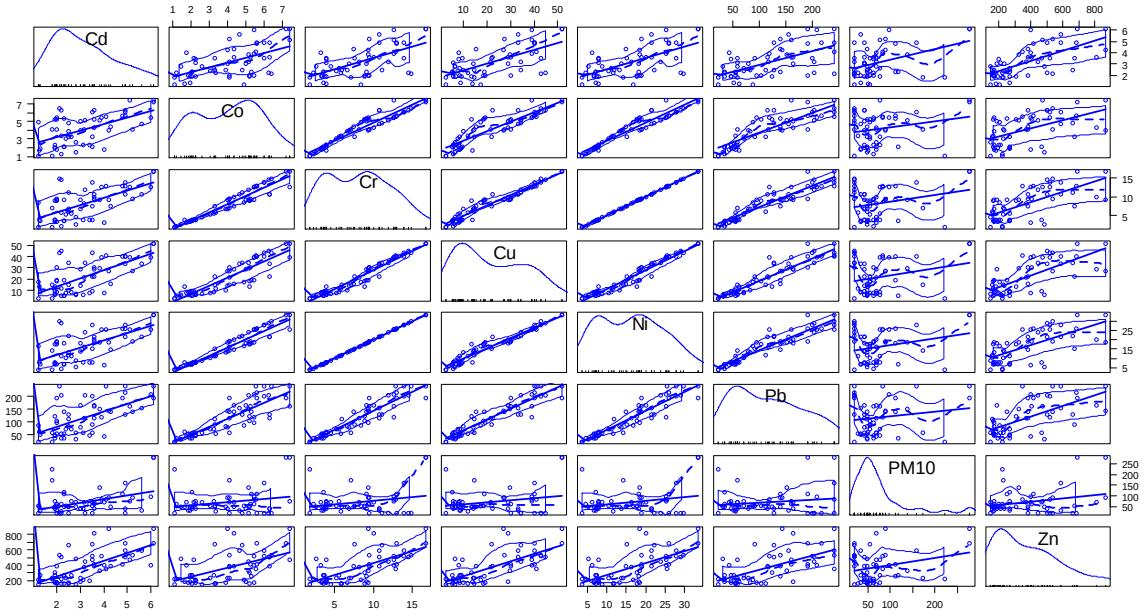


Figure 2: Graphical representation of correlation patterns between PM₁₀ and heavy metals.

Comparison with International Studies

The average PM₁₀ and heavy metal concentrations in our study, along with the findings of other studies, are presented in Tables 1 and 4. The mean PM₁₀ concentration in Gorgan (69.3 µg/m³) was lower than the values reported for Ahvaz (223.4 µg/m³) (26), Riyadh (223.1 µg/m³) (27), and industrial sites in Senegal (232.3 µg/m³) (4), but higher than those for Gijon, Spain (31 µg/m³) (29), Lamphun, Thailand (43.0 µg/m³) (35), and Makkah (44.5 µg/m³) (41). The annual concentrations of Zn, Pb, and Cu were lower than the concentrations reported by Dai (2015) in China but considerably higher than those reported by Lara et al. (2023) in Spain and Rezayani et al. (2022) in Tehran. The mean concentrations of Ni

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and Co were higher than the values reported in Tehran, Spain, and China (29, 44). The mean concentration of Cd was lower than the values reported for Tehran and China but higher than those reported in Spain. The mean concentration of Cr was higher than the levels reported in Spain and Tehran but lower than those in industrial regions of China.

Discussion

Variations of PM_{10} Concentration

Results showed that PM_{10} concentrations ranged from a minimum of 20.83 µg/m³ in early November to a maximum of 277.78 µg/m³ in early February, with a mean ± standard deviation of 69.3 ± 49.82 µg/m³ over the study period (Table 1). These values are slightly higher than the World Health Organization's 24-hour guideline of 50 µg/m³. In the study conducted by Hamidi et al. (2025)[25], which investigated PM_{10} over an 11-year period (2008–2019) in Ahvaz, the mean concentration was reported as 223.4 µg/m³. Similarly, in a study by Kebe et al. (2025)[4] in Senegal, the PM_{10} concentrations were estimated at 232.318 and 209.854 µg/m³ at industrial and urban–coastal sites, respectively. Furthermore, Adly et al. (2025)[24], in a five-year study (2020–2024) in Makkah, observed an increasing trend in PM_{10} concentrations, which rose from 127.7 µg/m³ in 2020 to 138.3 µg/m³ in 2024. Overall, the annual mean concentrations reported in all these studies are higher than those in the present investigation. Research conducted in Ahvaz and Senegal demonstrated the substantial impact of natural sources on air pollution, whereas in Makkah, the observed rise in particulate matter concentrations was primarily linked to anthropogenic activities, including population growth, traffic emissions, and construction operations. In contrast, other studies conducted by Lara et al. (2023)[28] in Spain, Kliengchuay et al. (2021) [34] in Thailand, and Munir et al. (2017) [40] in Makkah reported PM_{10} concentrations of 31, 42.98, and 44.53 µg/m³, respectively. The observed values were not only less than those recorded in this study but also below the World Health Organization's 24-hour guideline of 50 µg/m³. This discrepancy may reflect the varying influence of different factors, such as local meteorological conditions, emission sources, climatic parameters, policy measures, or operational programs, on PM_{10} concentrations across different locations.

Shahsavani et al. (2025)[20] conducted a study in Fars province focusing on the summer season and reported a PM_{10} concentration of 78.12 µg/m³. Elevated summer concentrations were attributed to the large amounts of suspended particles entering the atmosphere due to the desiccation of extensive areas of Bakhtegan Lake, transported by winds. In another investigation, Ahmad et al. (2023)[29] carried out a winter study in Pakistan and reported a PM_{10} concentration of 279.73 µg/m³, which they linked to stagnant climatic conditions. Furthermore, Farsani et al. (2018)[38] examined the relationship between PM_{10} levels on normal days and dust storm days in Ahvaz. They found that the lowest PM_{10} concentrations on both normal and dust storm days occurred in summer (127 and 278 µg/m³, respectively), while the highest concentrations were observed in winter (189 and 742 µg/m³, respectively). Elevated PM_{10} concentrations, particularly in winter, may be associated with the combustion of fossil fuels, coal, and wood. Conversely, lower concentrations in autumn and summer could be due to reduced human activities and the less frequent occurrence of dust storms during these seasons.

Metals Associated with PM_{10}

The mean concentrations of zinc (Zn) and lead (Pb) across all seasons exceeded the values documented in studies conducted in Fars, Tehran, Ahvaz, and Italy[20, 43, 45, 46]. In contrast, the seasonal mean concentration of copper (Cu) was lower than the levels reported by Shahsavani et al. (2025)[20] and Di Vaio et al. (2018)[39]. The mean concentration of cadmium (Cd) was also below the values reported by Di Vaio et al. (2018)[39] and Farsani et al. (2018)[38]. Conversely, for cobalt (Co), the seasonal mean in the present study was higher than in these two studies. Overall, the differences reported can be attributed to variations in the

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sources of these compounds and the types of sampling locations. The substantial increase in metal concentrations during winter may be due to colder conditions, increased consumption of fossil fuels, and reduced precipitation. Human activities, such as industrial operations and traffic, play a significant role in the dispersion of heavy metals. The sources of heavy metals vary; for example:

- Nickel (Ni) originates from traffic emissions, industrial activities, gas refinerie, and fuel combustion[49-51].
- Copper (Cu) is associated with high-temperature processe, such as residential boilers and automobiles[49, 52].
- Lead (Pb) is primarily derived from tire wear,vehicle component corrosions, and lubricants[53].
- Chromium (Cr) mainlyoriginatess from agricultural activities, industrial operations, tire degradation, and greenhouse gas emissions[54, 55].

Consequently, heavy metals in urban air are diverse, complex, and strongly influenced by environmental conditions and seasonal variations.

Inter-Metal Correlations and Source Implications

In the correlation analysis of the metals, very strong and statistically significant relationships were observed. Positive correlations among many metals, particularly between Cu, Cr, and Ni, exhibited a very strong linear pattern with correlations approaching one. The scatter of data between PM₁₀ and Cd was more pronounced compared to other metals, indicating a significant relationship. These observations are fully consistent with the results presented in Table 4. In the study by Alharbi et al. (2024)[26], no significant positive correlation was observed for Cd, which differs from the observations of the current study. Similarly, the correlation results reported by Esform et al. (2022)[30] showed a significant relationship between PM₁₀ and Co, Cu, and Cr ($P < 0.05$), which does not align with our findings. In the Alharbi et al. (2024)[26] study, the correlation between Pb and Cd was significant, consistent with the present study; however, the correlation between Cu and Cd in their study was not positive, whereas in the present study this relationship was very strong and significant. The relationship between chromium (Cr) and nickel (Ni) was very strong and significant, which is consistent with findings from the Nanjing–Shanghai highway [30]. In the studies by Motesaddi Zarandi et al. (2019) and Esform et al. (2022), no significant correlation was observed between Pb and Cr, which does not match the results of the present study[56]. Overall, the observed high positive correlations indicate significant interrelationships among the elemental constituents of PM₁₀ during the sampling period, offering a clearer perspective on their likely origins and atmospheric interactions. Furthermore, the strong correlations observed between Cu, Cr, Ni, and Pb indicate the likely presence of a common source, particularly industrial and traffic-related activities (Figure 2).

Conclusion

The findings of this study reveal that, over the study period, PM ₁₀ levels in Gorgan were generally slightly above the 24-hour guideline established by the World Health Organization. Observed variations in pollutant concentrations were less influenced by seasonal changes; however, on a monthly scale, a relatively clear pattern was observed, with the highest concentrations in summer and the lowest in winter. Comparison with similar studies in other regions of the world suggests that climatic differences, local meteorological conditions, natural dust sources, and human activities can play a determining role in the levels of air pollution.

Regarding heavy metals associated with PM₁₀, the results showed that zinc (Zn), lead (Pb), and copper (Cu) exhibited the highest concentrations in the samples, typically reaching their peak levels in winter. This increasing trend can be attributed to cold weather conditions, increased fossil fuel consumption, and reduced precipitation. Additionally, strong correlations among certain metals, including Cu, Cr, Ni, and Pb, indicate the presence of common sources, particularly traffic and industrial activities.

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Ethical Considerations

Golestan University of Medical Sciences (IR.GOUMS.REC.1401.084).

Code of Ethics

IR.GOUMS.REC.1401.084

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

Not applicable.

Competing interests

The authors declare no conflicts of interest.

Author contributions

These authors contributed equally to this work and share first authorship.

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