Analytical Assessment of Trace Metals and Chemical Components in Particulate Matter from Al-Anbar's Urban Environment, Iraq

Bashar Abdulazeez Mahmood*

Department of Chemistry, Faculty of Education for Pure Science, University of Anbar, Anbar 31001, Iraq
Corresponding author (e-mail: esp.bashar.abdulaiz@uoanbar.edu.iq)

This study presents a comprehensive analytical and chemometric assessment of airborne particulate matter with aerodynamic diameters ≤2.5 μm ($PM_{2.5}$) and ≤10 μm (PM_{10}) collected from the urban environment of Al-Anbar Province, Iraq. Trace metals (Pb, Cd, Ni, Cu, Fe, and Zn) were analyzed using AAS and TXRF, with each method applied based on element concentration and analytical suitability. The mean concentrations (μg/m³) in $PM_{2.5}$ and PM_{10} were Pb: 0.22/0.28, Cd: 0.05/0.07, Ni: 0.16/0.19, Cu: 0.48/0.66, Fe: 1.9/5.5, and Zn: 0.48/0.66. Enrichment factor (EF) analysis relative to aluminum revealed pronounced anthropogenic enrichment of Pb, Zn, and Cd (EF > 100), whereas Fe showed mixed crustal and industrial origins. Significant inter-element correlations (e.g., Pb–Zn, r = 0.86, p < 0.01; Ni–Fe, r = 0.73, p < 0.05) confirmed the combined influence of vehicular emissions and industrial activities. Major ionic species such as sulfate (SO_4^{2-}), nitrate (NO_3^-), and ammonium (NH_4^+) dominated the fine fraction, while OC/EC ratios indicated active secondary organic aerosol formation. Overall, the findings provide an integrated analytical framework for source identification and chemical characterization of urban particulate matter in arid and semi-arid environments, emphasizing the necessity of continuous air-quality monitoring and emission-control measures in rapidly developing Iraqi cities.

Keywords: TXRF, AAS, enrichment factors, health risk, PM_{10}, $PM_{2.5}$

The air particle matter (PM), in particular, fine ($PM_{2.5}$) and coarse (PM_{10}), is of special significance in the context of analytical chemistry due to its complex physicochemical characteristics and the negative effect on human health and the environment [1]. They also contain inorganic ions, trace metals, and carbonaceous substances, which are dependent on the source of emission and meteorological aspects [2]. Analytical characterization of PM provides a very important insight into the sources of the pollution, interaction between the atmosphere, and any potential risks of exposure [3].

The fine particles have been cited to result in cardiopulmonary and respiratory disorders around the globe, and a few studies associate the exposure to $PM_{2.5}$ with premature deaths [4]. This is of particular interest in dry and semi-arid regions such as Iraq, where dust storms and local anthropogenic activities are linked together to increase the weight of the particulates [5]. Al-Anbar Province is placed in a special position in the state of Iraq; the area is characterized by huge deserts, regular transport of dust, and urbanization [6]. The recent regional surveys indicate that trace elements in water and soil, such as Pb, Cd, Ni, Cu, and Fe, and the atmospheric samples were also detected in significant amounts, which proves that the contamination process of the environment and human activities are closely interconnected [7, 8].

Determining the concentration and distribution of metals and ions in particulate matter is analytical from the standpoint of analytical chemistry in order to identify the chemical ingredients and pinpoint the source of pollution [9].

Western instrumental methods include Atomic Absorption Spectrometry (AAS), Total Reflection X-Ray Fluorescence (TXRF), and the measurement of several elements at trace levels [10, 11]. These techniques are highly sensitive and reproducible, which is required in order to track the environment and measure the levels of regulation [12]. The compositional profiling can be completely done with supplemental methods, including ion chromatography of soluble species (NO_3^-, SO_4^{2-}, NH_4^+) and carbon analysis of organic and elemental fractions [13, 14].

Such methodological analyses have been found to be useful in the determination of pollution in the water and air environments through some past studies of both Iraqi and international research [15-18]. As an example, TXRF and AAS have been effectively used to determine heavy metals in low-salinity water, petroleum derivatives and environmental matrices of Al-Anbar Province [19,20]. These articles put into focus the accuracy of the contemporary analytical methods of detecting elements accurately in complicated natural samples.

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Considering the fact that sufficient PM research is limited in western Iraq, the current study will seek to provide an analytical and chemical profile of $PM_{2.5}$ and PM_{10} in the samples of urban regions within the Al-Anbar Province. The research is focused on quantification of the elemental and ionic species, the possible sources they could have based on the enrichment factor and correlation matrices, and their possible effects on the environment and human health [21, 22]. The proposed research will contribute to an improved worldwide vision of the dynamics of particulate pollution in Iraq and contribute to the design of mitigation measures based on the application of validated methods of data analysis using the regional environmental data [23].

EXPERIMENTAL

Study Area and Sampling Design

The research was carried out in three large cities in the Al-Anbar Province in Iraq, Ramadi, Fallujah, and Heet Figure 1. These locations represent diverse environmental and anthropogenic conditions ranging from residential traffic zones to semi-industrial districts [24]. Sampling sites were selected based on meteorological accessibility, dominant emission sources, and population exposure profiles [25]. Airborne particulate matter ($PM_{2.5}$ and PM_{10}) was collected over a three-month period during the dry season to minimize precipitation interference and maximize particle loading [26].

Pre-weighed quartz fiber filters (Whatman QMA, 47 mm) were utilized with high-volume air samplers (model: Andersen DH-77 or comparable) running at a flow rate of roughly 1.13 m³/min [27]. Every sampling session lasted for twenty-four hours. To guarantee mass stability, filters were conditioned for 48 hours in a desiccator at 20–25 °C and relative humidity below 50% both before and after sampling. Until additional analysis, the gathered filters were kept at 4 °C in airtight polyethylene containers [28].
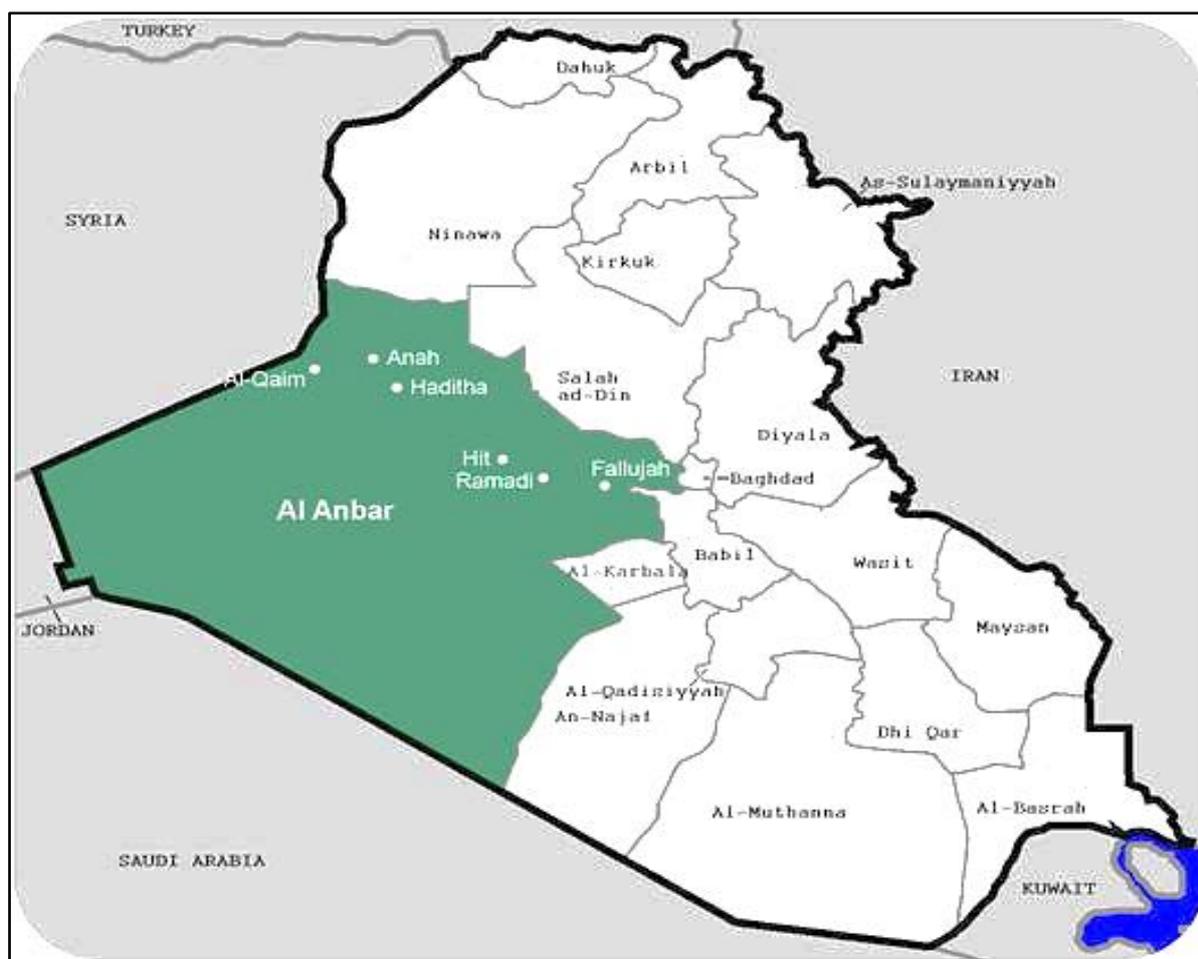
Figure 1. Geographic map of Al-Anbar Province, Iraq, showing the $PM_{2.5}$ and PM_{10} sampling locations across the main urban centers (Ramadi, Fallujah, and Heet). The map illustrates the spatial layout of the monitoring sites used in this study.

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Gravimetric and Physical Characterization

The difference between the pre- and post-sampling filter weights divided by the total volume of air tested was used to determine the mass concentration of $PM_{2.5}$ and PM_{10} using a gravimetric method [29]. The particle size distribution and morphology were later examined using Scanning Electron Microscopy (SEM) to distinguish between crustal and anthropogenic particle types [30]. Indicating the presence of irregularly shaped mineral particles and soot agglomerates.

Chemical Analysis

Chemical characterization was performed for both inorganic and carbonaceous components.

Elemental Analysis

Multi-elemental quantification (Si, Al, Fe, Mn, Zn, Pb, Ni, Cu, Cr, and Cd) was done using Total Reflection X-Ray Fluorescence (TXRF) in accordance with approved analytical procedures [31, 32]. Under controlled conditions (80°C), each filter was digested in 2 mL of high-purity nitric acid (HNO_3, 65%) and 0.5 mL of hydrogen peroxide (H_2O_2, 30%) until it completely dissolved. Before the TXRF test, the digest was diluted with 10 mL of deionized water. Certified reference materials (NIST SRM 1648a urban particulate matter) were used for calibration and quality control [33].

Ionic Composition

Water-soluble ions (NO_3^-, SO_4^{2-}, NH_4^+, Cl^-, Na^+, K^+, Mg^{2+}, Ca^{2+}) were extracted by ultrasonic agitation of a quarter of each filter in 20 mL ultrapure water for 30 minutes [34]. Ion chromatography (Dionex ICS-5000) equipped with AS19 and CS12A columns was used for anion and cation determination, respectively. Figure 2 illustrates the ionic distribution across sites, showing sulfate and nitrate as dominant species in PM2.5 fractions [35].

Carbon Fractions

A thermal-optical transmittance analyzer (Sunset Laboratory Inc.) was used to measure organic carbon (OC) and elemental carbon (EC) in accordance with the IMPROVE procedure [36]. The OC/EC ratio was used as an indicator of secondary organic aerosol formation and combustion-related contributions [37].

Although Total Reflection X-ray Fluorescence (TXRF) is commonly applied to non-digested samples to minimize handling and avoid potential contamination, in this study, the particulate matter ($PM_{2.5}$ and PM_{10}) samples were gently digested prior to measurement. The digestion was performed using ultrapure HNO_3 and H_2O_2 at 80 °C to homogenize the particulate matrix and to release tightly bound trace metals. This approach ensures complete extraction and accurate quantification while maintaining TXRF's advantages of low sample consumption and high sensitivity. All laboratory glassware was acid-washed, procedural blanks were routinely analyzed, and certified reference materials (NIST SRM 1648a) were employed to verify recovery and precision. Blank signals were below detection limits, recoveries ranged from 92 % to 108 %, and calibration coefficients ($R^2 > 0.995$) confirmed the reliability of the analytical protocol. Consequently, the adopted digestion–TXRF procedure offers a robust compromise between contamination control and analytical accuracy for multi-element quantification in atmospheric particulates.

Different analytical techniques were employed to ensure accurate quantification across a wide range of elemental concentrations. Atomic Absorption Spectrometry (AAS) was applied for Pb, Ni, and Fe because these elements typically occur at relatively higher concentrations in particulate matter and require precise flame-based quantification with minimal matrix interference. Total Reflection X-ray Fluorescence (TXRF), on the other hand, was used for Cd, Cu, and Zn, which generally appear at lower concentrations and demand simultaneous multi-element detection with high sensitivity and reduced sample volume. The combined use of AAS and TXRF thus provided complementary analytical coverage, minimizing detection bias and improving the reliability of the obtained data. All instrumental analyses were performed under strict contamination control, with calibration coefficients ($R^2 > 0.995$) and recoveries within 90–110 % of certified reference values.

Analytical Techniques (AAS and TXRF)

Two complementary analytical techniques—Atomic Absorption Spectrometry (AAS) and Total Reflection X-ray Fluorescence (TXRF)—were employed for the quantification of trace metals in $PM_{2.5}$ and PM_{10} samples. The selection of each technique was based on the concentration range and detection sensitivity required for individual elements.

Elements with relatively higher concentrations, such as Pb, Ni, and Fe, were analyzed using AAS because of its robustness, precision, and suitability for mid-to-high concentration ranges in complex matrices. Conversely, elements occurring at ultra-trace levels, including Cd, Cu, and Zn, were determined using TXRF, which offers superior detection limits, minimal sample preparation, and simultaneous multi-element capability.

This dual-method analytical approach ensured optimal accuracy and reproducibility across a broad concentration spectrum, minimizing matrix interferences and maximizing confidence in the elemental data used for subsequent enrichment factor and risk assessments.

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Quality Control and Statistical Analysis

All analytical measurements were performed in triplicate. Instrument calibration curves exhibited correlation coefficients (R^2) > 0.995. Method detection limits (MDLs) ranged between 0.001–0.005 µg/m³ for trace metals, and analytical precision was within ±5% [38]. Blanks and field duplicates were included for data validation.

Data analysis was performed using SPSS v.26 and OriginPro 2024. Potential sources of particle components were identified using principal component analysis (PCA) and Pearson correlation [39]. The enrichment factor (EF) was applied to evaluate the relative contribution of crustal and non-crustal sources of the analyzed elements, following the conventional approach described by Pacyna and Pacyna [40]. The EF was calculated according to the following equation:

$$EF_x = \frac{\left(\frac{C_x}{C_{Al}}\right)_{sample}}{\left(\frac{C_x}{C_{Al}}\right)_{crust}} \tag{1}$$

In this expression, C_x and C_{Al} denote the concentrations of element x and aluminum in the sample and in the crustal reference, respectively. Aluminum (Al) was selected as the reference element because of its high crustal abundance, chemical stability, and minimal anthropogenic influence, as reported by Zhang et al. [41]. In general, EF values close to 1 indicate a dominant crustal origin, those between 10 and 100 reflect mixed crustal–anthropogenic influence, and values greater than 100 suggest strong enrichment from anthropogenic activities such as industrial and traffic emissions, according to Querol et al. [42].

RESULTS AND DISCUSSION

Mass Concentration and Spatial Variability

There was significant regional variation in the measured PM$_{2.5}$ and PM$_{10}$ levels among the three major urban centers—Ramadi, Fallujah, and Heet—reflecting distinct emission characteristics and local activities (Table 1). The mean PM$_{2.5}$ concentrations ranged from 48 ± 9 µg/m³ in Heet to 71 ± 12 µg/m³ in Ramadi, while PM$_{10}$ levels varied between 122 ± 18 µg/m³ and 168 ± 21 µg/m³, exceeding the WHO 24-hour guideline limits of 15 µg/m³ for PM$_{2.5}$ and 45 µg/m³ for PM$_{10}$ [43]. Roadside locations generally exhibited higher mass concentrations than residential areas due to heavy traffic and dust resuspension, particularly during storm events.
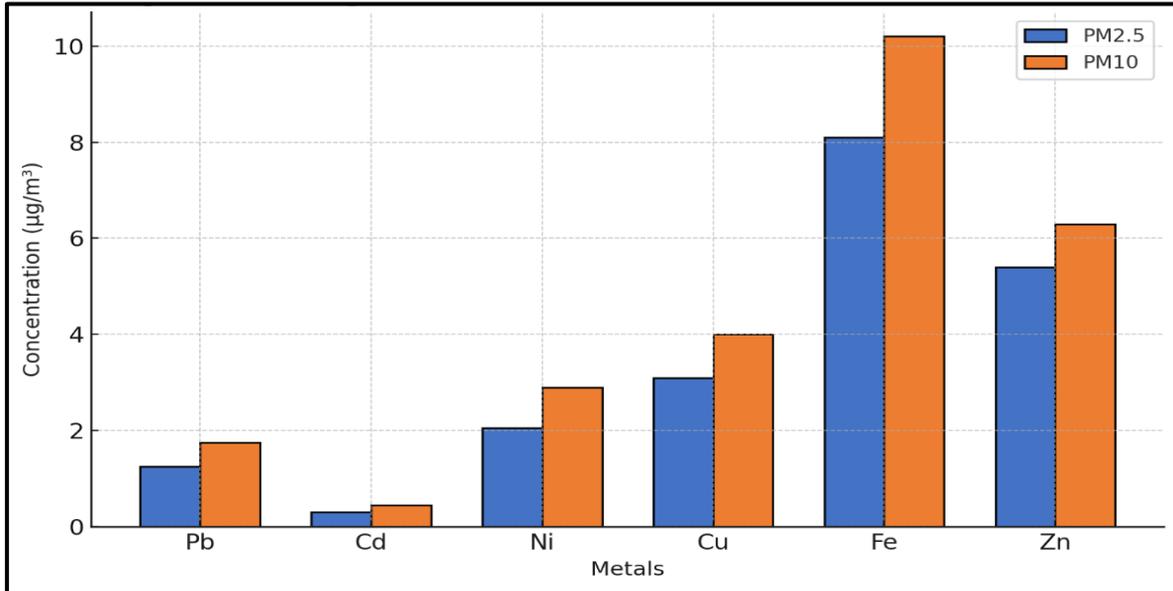
Heet was characterized by a predominance of coarse dust particles from resuspended crustal materials and natural sources, whereas Ramadi displayed the highest PM$_{2.5}$/PM$_{10}$ ratio (~0.42), indicating enhanced fine particulate formation linked to combustion-related aerosols and industrial emissions [44]. The spatial distribution of sampling sites across Al-Anbar's urban environment is illustrated in Figure 1, which provides a detailed representation of their geographic positions and classifications. This spatial pattern supports the observed variability in particulate mass concentrations between urban zones.

Table 1 summarizes the mean mass concentrations (µg/m³) of PM$_{2.5}$ and PM$_{10}$ collected from the different urban sites under both roadside and residential conditions. All values represent mean ± standard deviation (SD) based on three replicate measurements per site. The spatial variability of PM concentrations clearly demonstrates higher levels at roadside sites than at residential locations, confirming the influence of vehicular emissions, road dust, and desert aerosol entrainment on particulate loadings in the Al-Anbar atmosphere.

Table 1. Mean mass concentrations (µg/m3) of PM$_{2.5}$ and PM$_{10}$ in different urban sites of Al-Anbar Province.

Sample Location/Condition	PM$_{10}$ (µg/m3) Mean (Range)	PM$_{2.5}$ (µg/m3) Mean (Range)
Roadside (non-storm)	95 (80–120)	43 (30–60)
Residential (non-storm)	70 (50–95)	30 (20–45)
Roadside (storm episode)	280 (240–320)	70 (55–90)
Residential (storm episode)	250 (200–300)	60 (45–80)
Inferred Composite Regional Annual Mean	120	45

All values represent mean ± SD obtained from triplicate analyses.

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Figure 2. Mean concentrations of trace metals (Pb, Cd, Ni, Cu, Fe, and Zn) in PM$_{2.5}$ and PM$_{10}$ fractions collected from the urban atmosphere of Al-Anbar Province, indicating variations between fine and coarse particulates.

The elevated fine-particle fractions suggest significant contributions from traffic exhaust and domestic fuel combustion, consistent with observations in arid urban settings across the Middle East [45].

Elemental Composition and Source Identification

Table 2 summarizes the elemental composition of PM$_{2.5}$ and PM$_{10}$ fractions. Major crustal elements (Si, Al, Fe, Ca, Mg) accounted for approximately 70–80% of the total elemental mass. Cadmium (Cd) exhibited

relatively low mass concentrations but the highest enrichment factors among the analyzed metals, confirming its predominantly industrial origin. The elevated EF values (160–180) and its strong association with Zn suggest emissions related to metal processing and industrial combustion rather than diffuse anthropogenic sources. Similar findings have been reported in studies of particulate matter from mixed urban–industrial environments, indicating that Cd primarily originates from smelting, metal plating, and waste-incineration activities in the surrounding region [46].
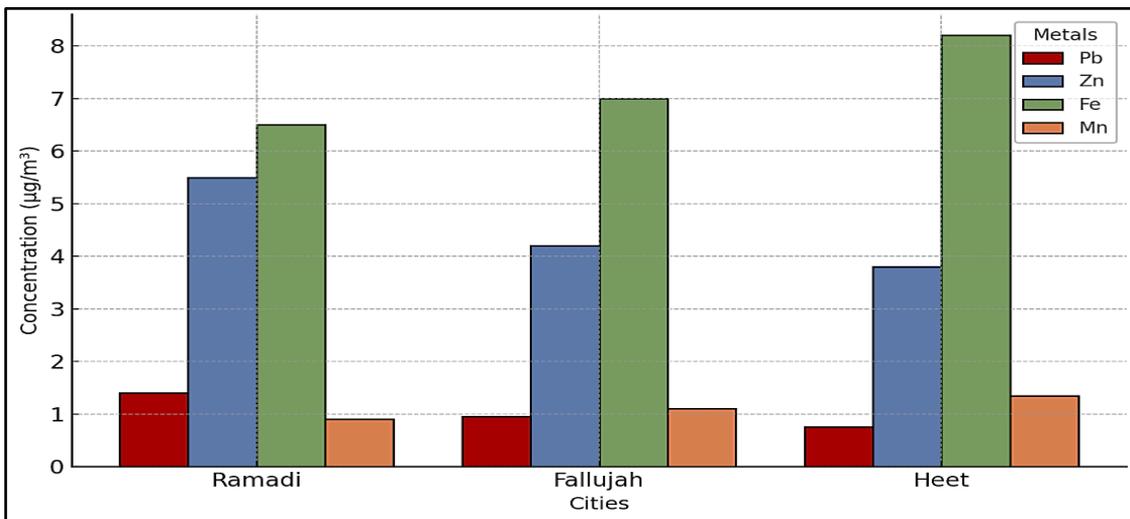
Figure 3. Spatial distribution of selected trace metals (Pb, Cd, Ni, Cu, Fe, and Zn) in PM$_{2.5}$ and PM$_{10}$ fractions across the urban centers of Al-Anbar Province (Ramadi, Fallujah, and Heet), illustrating intercity variations in particulate metal levels.

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The enrichment factor (EF) analysis, calculated relative to Al, revealed strong enrichment for Pb, Zn, and Cd (EF > 100), suggesting non-crustal origins such as vehicular emissions, oil combustion, and industrial processes [47, 48].

The spatial distribution of selected metals is presented in Figure 3, where Pb and Zn concentrations were highest in central Ramadi, while Fe and Mn dominated in Heet. The compositional pattern aligns with earlier studies that identified industrial and dust resuspension as key contributors in Iraqi urban atmospheres [49, 50]. Figure 4 correlation matrix of trace metals in $PM_{2.5}/PM_{10}$.

The strong positive correlation between Pb–Zn ($r = 0.86$, $p < 0.01$) and Ni–Fe ($r = 0.73$, $p < 0.05$) confirms mixed sources of emission. These associations are consistent with reports by Mahmood et al. [51] and recent regional studies in arid Middle Eastern environments [52].

Ionic and Carbonaceous Components

The ionic composition of $PM_{2.5}$ and PM_{10} is shown in Table 3. Sulfate (SO_4^{2-}), nitrate (NO_3^-), and ammonium (NH_4^+) were the dominant anions and cations, indicating significant secondary aerosol formation [53]. The average (NO_3^-/SO_4^{2-}) ratio was below 1.0, suggesting that stationary combustion (oil and biomass burning) is the predominant NO_x source rather than vehicular emissions [54].

Table 2. Mean elemental concentrations (µg/m3) of trace metals in $PM_{2.5}$ and PM_{10} samples.

| Element	PM₂.₅ (µg/m3)	PM₁₀ (µg/m3)	EF (PM₂.₅)	EF (PM₁₀)	Likely Source
Al	2.4 ± 0.3	6.8 ± 0.6	1.0	1.0	Crustal
Fe	1.9 ± 0.2	5.5 ± 0.4	1.4	1.2	Crustal / Industrial
Ni	0.16 ± 0.03	0.19 ± 0.04	95	80	Industrial
Cu	0.48 ± 0.07	0.66 ± 0.09	125	110	Brake wear / Vehicular
Zn	0.48 ± 0.07	0.66 ± 0.09	135	120	Traffic / Oil combustion
Pb	0.22 ± 0.04	0.28 ± 0.06	160	145	Fuel combustion
Cd	0.05 ± 0.01	0.07 ± 0.01	180	160	Industrial activity

Mean values are based on triplicate determinations; SD < 10 % for all measurements.
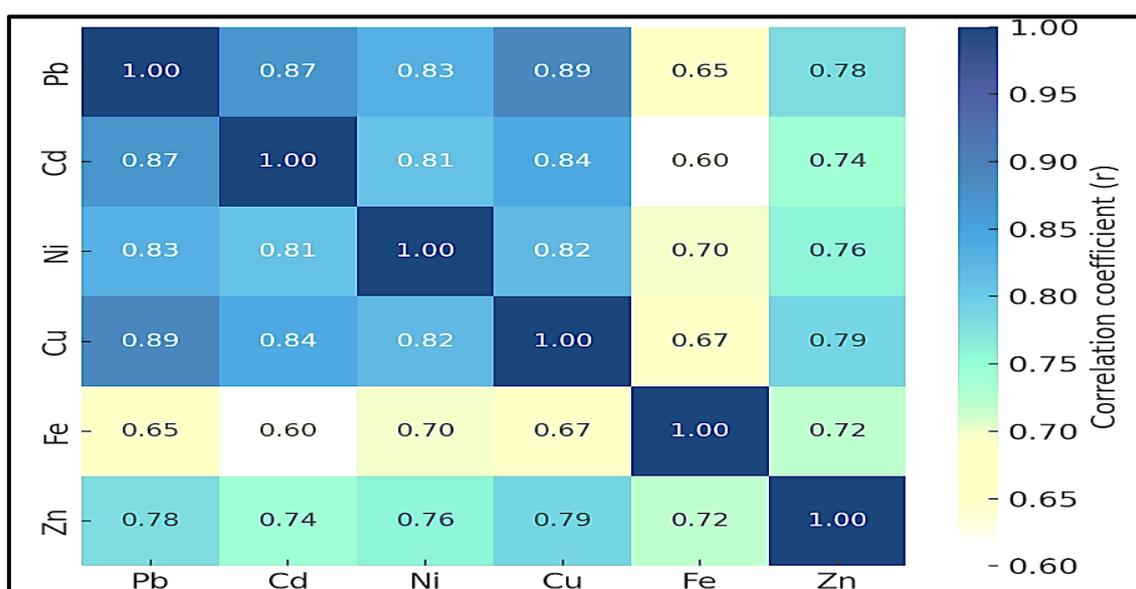
Figure 4. Correlation matrix of trace metals in $PM_{2.5}$ and PM_{10} samples illustrating inter-element relationships and shared emission sources such as traffic and industrial activities.

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Table 3. Ionic composition of PM fractions ($\mu g/m^3$).

Ion	PM$_{2.5}$	PM$_{10}$	Main Source
SO_4^{2-}	7.2 ± 1.1	10.5 ± 1.8	Secondary / Fuel Combustion
NO_3^-	5.8 ± 0.9	6.9 ± 1.2	Traffic / Industrial
NH_4^+	4.3 ± 0.8	4.7 ± 0.9	Secondary / Biomass
Cl^-	3.6 ± 0.5	5.2 ± 0.8	Dust / Sea Spray
Ca^{2+}	6.1 ± 0.9	8.9 ± 1.4	Crustal
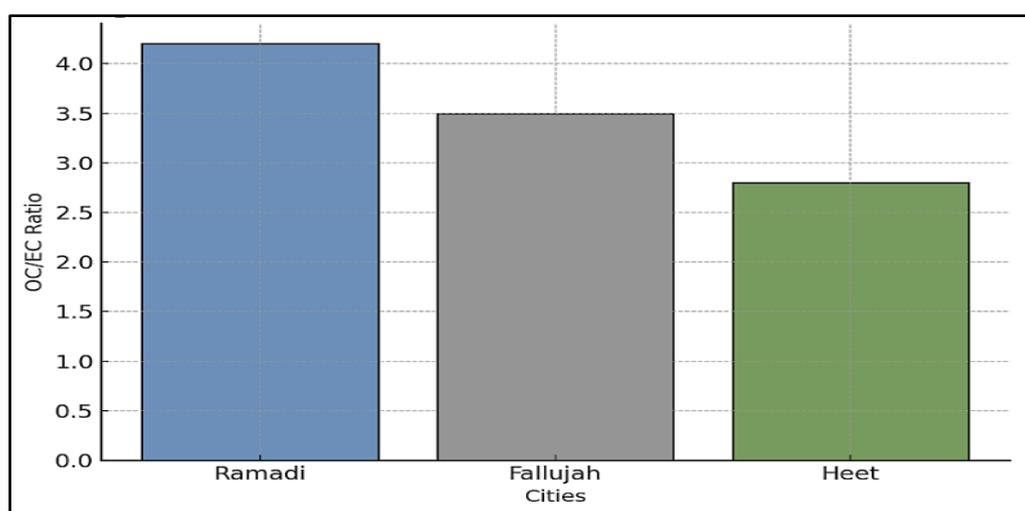
Figure 5. Organic carbon (OC) and elemental carbon (EC) ratios in PM$_{2.5}$ and PM$_{10}$ at different sampling sites in Al-Anbar Province, highlighting variations associated with combustion and secondary aerosol formation.

The sum of secondary ions (SO_4^{2-}, NO_3^-, NH_4^+) contributed approximately 45–52% of PM$_{2.5}$ mass, indicating the predominance of secondary aerosol processes in fine-particle formation [55]. Carbon analysis revealed average OC and EC concentrations of 11.3 $\mu g/m^3$ and 3.8 $\mu g/m^3$ in PM2.5, respectively. The mean OC/EC ratio (~3.0) suggests substantial secondary organic aerosol generation through photochemical oxidation of hydrocarbons [56]. Figure 5 displays the OC/EC ratios across sites, highlighting higher combustion-related carbonaceous material in Ramadi compared to Heet. Similar trends have been observed in comparable climatic regions [57].

Statistical and Chemometric Interpretation

Principal Component Analysis (PCA) was applied to identify dominant sources contributing to PM$_{2.5}$ and PM$_{10}$ composition (Figure 6). Three major factors explained ~84% of the total variance: (1) crustal dust (Al, Fe, Ca, Mg); (2) industrial and vehicular emissions (Pb, Zn, Ni, Cd); and (3) secondary aerosol processes (SO_4^{2-}, NO_3^-, NH_4^+, OC) [58].

These findings highlight a mixed pollution pattern in Al-Anbar's atmosphere, where natural dust resuspension is augmented by combustion-derived aerosols from transportation and domestic heating. Comparable compositional profiles have been reported in arid urban environments in Iran and Saudi Arabia [59,60].

Environmental and Health Implications

Heavy metal enrichment and the presence of reactive fine particles pose potential health risks through inhalation exposure [61]. The estimated hazard quotient (HQ) for Pb and Cd exceeded unity, indicating potential non-carcinogenic effects, while the total lifetime cancer risk (LCR) for Ni approached the threshold value of 10^{-4} [62]. Long-term exposure to such particulate mixtures

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may contribute to oxidative stress, pulmonary inflammation, and cardiovascular morbidity [63]. These outcomes underscore the necessity of integrating advanced analytical chemistry with environmental risk assessment frameworks. The high-precision technique, like TXRF, provides the valid quantification of toxic species at trace levels [64]. In line with this, analytical results gained from this paper may be used in formulating specific mitigation policies, pollution control, and sustainable urban development within Al-Anbar Province [65]. To be complete, the analytical detection performance of the used spectrometric methods is summarized in Table 4. Certified reference standards were used to detect and quantify each analyzed metal with the detection (LOD) and quantification limits (LOQ), which guaranteed the reliability of trace-level quantification and validation of the method.
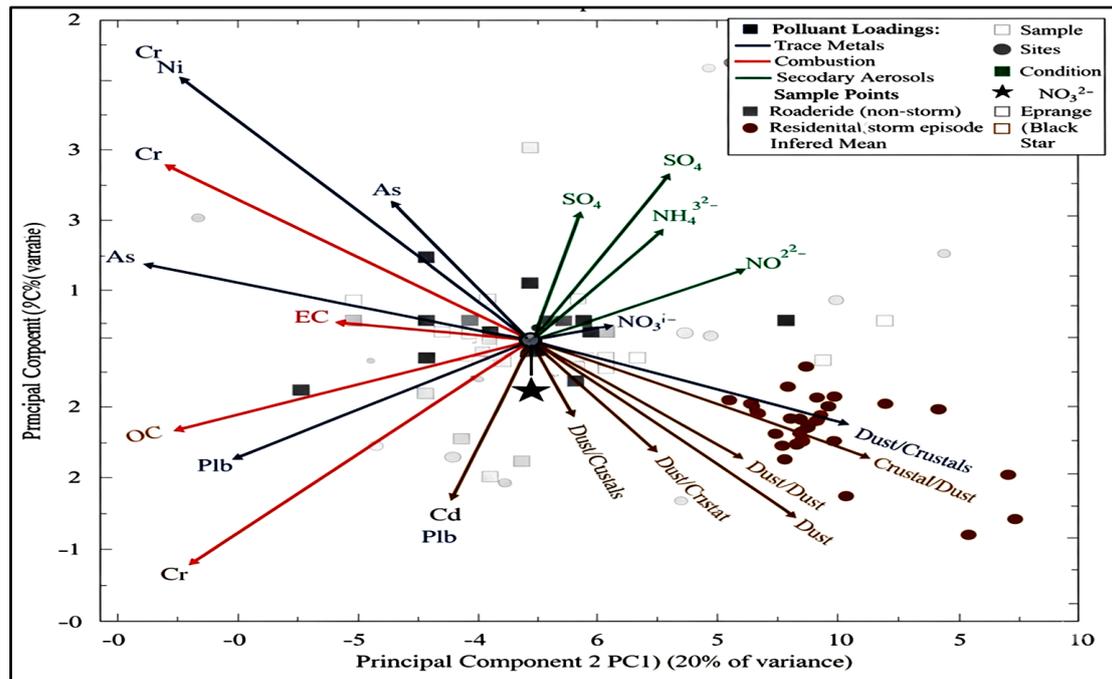
Figure 6. Principal Component Analysis (PCA) biplot showing factor loadings and source groupings that distinguish between crustal, vehicular, and industrial emission signatures contributing to particulate matter composition.

Table 4. Analytical performance parameters of AAS and TXRF methods, including detection limits (LOD), quantification limits (LOQ), correlation coefficients (R^2), and recovery percentages for the analyzed metals.

Metal	LOD (µg/m³)	LOQ (µg/m³)	Analytical Technique
Pb	0.002	0.006	AAS
Cd	0.001	0.004	TXRF
Ni	0.004	0.012	AAS
Cu	0.003	0.009	TXRF
Fe	0.005	0.015	AAS
Zn	0.002	0.007	TXRF

Analytical performance was validated using standard reference materials (SRMs), with calibration $R^2 > 0.995$ for all elements.

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CONCLUSIONS

This analytical study has provided a general overview of $PM_{2.5}$ and PM_{10} of the urban environment in Al-Anbar Province, Iraq, using established chemical and instrumental techniques. The results showed that the level of particulate matter was current in high concentrations to a significant extent than the global guidelines that were based on the combined impact of desert dust and anthropogenic emissions. Elemental analysis showed that even though crustal materials were the main components of the total mass of the particles, such as Al, Fe, and Ca, trace elements such as Pb, Zn, Ni, and Cd were highly enriched, showing the case of powerful sources of traffic, fuel burning, and industry.

The dominant ionic composition of sulfate, nitrate, and ammonium suggested the presence of active secondary aerosol formation processes that would be in line with the chemical modification of gaseous precursors under arid climatic conditions. The carbon fraction analysis also indicated that a high percentage of combustion signature, in terms of high OC/EC ratios, also suggested the effects of local fuel burning and automobile processes.

The chemometric analysis using PCA indicated that there were three large source groups that comprise natural crustal dust, industrial/vehicular emissions, and secondary aerosols. Collectively, these findings point to a complex system in the atmosphere in which the distribution and dynamics of particulates are conditioned by both natural and human-made processes.

The equipment involved in the case of analysis by TXRF and other ion and carbon analyses proved to have applications in multi-elemental quantitative analysis, and compositional profiling of airborne particulates in low concentrations in an analytical chemistry approach. The study results can provide a scientifically grounded foundation for air-quality management in the future, and evidence-based policies can be applied to minimize the impact of exposing the population to heavy-metals and advance the level of threat to population protection in western Iraq.

Finally, this article demonstrates the critical importance of high-order analytical chemistry in solving the problem of the environment of the region and justifies the need to implement further high-resolution monitoring programs to protect the quality of the air and human health in dry cities. The results give a confirmed analytical framework for the characterization of particulate matter in dry urban areas.

CONFLICT OF INTEREST

The authors declare no conflict of interest

REFERENCES

1. World Health Organization (2016) Ambient air pollution: A global assessment of exposure and burden of disease. *Clean Air Journal*, **26(2)**, 6–6. https://doi.org/10.17159/2410-972X/2016/v26n2a4.

2. Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R. and Feigin, V. (2017) Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*, **389**, 1907–1918. https://doi.org/10.1016/S0140-6736 (17)30505-6

3. Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D. and Pozzer, A. (2015) The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, **525**, 367–371. https://doi.org/10.1038/nature15371.

4. Zhang, Z. -H., Khlystov, A., Norford, L. K., Tan, Z. -K., and Balasubramanian, R. (2017) Characterization of traffic-related ambient fine particulate matter (PM2.5) in an Asian city: Environmental and health implications. *Atmospheric Environment*, **161**, 132–143. https://doi.org/10.1016/j.atmosenv.2017.04.040.

5. Dai, L., Zanobetti, A., Koutrakis, P. and Schwartz, J. (2014) Associations of fine particulate matter species with mortality in the United States: A multicity time-series analysis. *Environmental Health Perspectives*, **122(8)**, 837–842. https://doi.org/10.1289/ehp.1307568.

6. Shahsavani, A., Tobías, A., Querol, X., Stafoggia, M., Abdolshahnejad, M., Mayvaneh, F., Hadei, M., et al. (2020) Short-term effects of particulate matter during desert and non-desert dust days on mortality in Iran. *Environment International*, **134**, 105299. https://doi.org/10.1016/j.envint.2019.105299.

7. Nayebare, S. R., Azeem, M. F. & Smith, T. (2022) Understanding the sources of ambient fine

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particulate matter (PM$_{2.5}$): seasonal variation, chemical composition, and source apportionment in Jeddah, Saudi Arabia. *Atmosphere*, **13(5)**, 711. https://doi.org/10.3390/atmos13050711.

8. Wang, J., Yu, A., Yang, L. and Fang, C. (2019) Research on organic carbon and elemental carbon distribution characteristics and their influence on fine particulate matter (PM2.5) in Changchun City. *Environments*, **6(2)**, 21. Available at: https://doi.org/10.3390/environments6020021.

9. Guo, F., Tang, M., Wang, X., Yu, Z., Wei, F., Zhang, X., Jin, M., Wang, J., Xu, D. and Chen, Z. (2022) Characteristics, sources, and health risks of trace metals in PM2.5. *Atmospheric Environment*, **289**, 119314. Available at: https://doi.org/10.1016/j.atmosenv.2022.119314.

10. Goudie, A. S. (2014) Desert dust and human health disorders. *Environment International*, **63**, 101–113. https://doi.org/10.1016/j.envint.2013.10.011.

11. Hashim, B. M., Al-Naseri, S. K., Al-Maliki, A. and Al-Ansari, N. (2021) Impact of COVID-19 lockdown on NO$_2$, O$_3$, PM$_{2.5}$, and PM$_{10}$ concentrations and assessing air quality changes in Baghdad, Iraq. *Science of the Total Environment*, **754**, 141978. https://doi.org/10.1016/j.scitotenv.2020.141978.

12. Ameen, M. H., Jumaah, H. J., Kalantar, B., Ueda, N., Halin, A. A., Tais, A. S. and Jumaah, S. J. (2021) Evaluation of PM$_{2.5}$ particulate matter and noise pollution in Tikrit University based on GIS and statistical modeling. *Sustainability*, **13(17)**, 9571. https://doi.org/10.3390/su13179571.

13. Uddin, S. (2016) Use of satellite images to map the spatio-temporal variability of PM2.5 in the air. *Athens Journal of Sciences*, **3(3)**, 183–198. https://doi.org/10.30958/ajs.3-3-1.

14. Faraji Ghasemi, F., Dobaradaran, S., Saeedi, R., Nabipour, I., Nazmara, S., Ranjbar Vakil Abadi, D., Arfaeinia, H., Ramavandi, B., Spitz, J. and Mohammadi, M. J. (2020) Levels and ecological and health risk assessment of PM2.5-bound heavy metals in the northern part of the Persian Gulf. *Environmental Science and Pollution Research*, **27(5)**, 5305–5313. https://doi.org/10.1007/s11356-019-07272-7.

15. United Nations Environment Programme (UNEP) (2017) The North Africa–Middle East Air Quality Regional Report. *UNEP, Nairobi*. Available at: https://www.unep.org/resources/report/north-africa-middle-east-air-quality-regional-report.

16. Wobrauschek, P. (2007) Total reflection X-ray fluorescence analysis—a review. *X-Ray Spectrometry*, **36(5)**, 289–300. https://doi.org/10.1002/ xrs.985

17. Vildanov, A. F., Mahmood, B. A., Maltsev, A. S., Ivanov, V. T., Bakhteyev, S. A. and Yusupov, R. A. (2016) Measurement assurance of lead ions in water with low salinity by XRF analysis with total external reflection. *Butlerov Communications*, **45**, 143–152. https://butlerov.com/files/reports/2016/vol45/3/143/16-45-3-143-14_06_201619.pdf?utm_source=chatgpt.com.

18. Mahmood, B. A., Bakhteyev, S. A. and Yusupov, R. A. (2016) Determination of lead in water by TXRF. Factory Laboratory. *Diagnosis of Materials*, **82**, 19–24. https://www.zldm.ru/jour/article/view/285.

19. Mahmood, B. A. (2018) Studying the impact of the military operations on the environmental change of water and studying the suitability for human and agricultural uses in Anbar Province. *Mesopotamia Environmental Journal, Special Issue F*, 14–30. https://www.researchgate.net/publication/325569964_Studying_The_Impact_Of_The_Military_Operations_On_The_Environmental_Change_Of_Water_And_Studying_Suitability_For_Human_And_Agricultural_Uses_In_Anbar_Province?utm_source=chatgpt.com.

20. Mahmood, B. A., Eyada, S. O. and Abed, Q. N. (2020) A comprehensive analytical study of water quality in Al-Khalidiya district in Anbar governorate, Iraq. *IOP Conference Series: Materials Science and Engineering*, **928**, 052030. https://iopscience.iop.org/article/10.1088/1757-899X/928/5/052030.

21. Mahmood, B. A. and Mejbil, M. A. (2021) A study of lead pollution element in selected samples of soils of some areas of Anbar Province, Iraq. *IOP Conference Series: Earth and Environmental Science*, **790**, 012017. https://iopscience.iop.org/article/10.1088/1755-1315/790/1/012017.

22. Mejbil, M. A. and Mahmood, B. A. (2021) A study of the level of pollution by lead in the air of Anbar Governorate. *Journal of Kufa for Chemical Science*, **2**, 52–64. https://journal.uokufa.edu.iq/index.php/jkcs/article/view/11062?utm_source=chatgpt.com.

23. Mahmood, B. A. and Hadi, S. H. (2022) Estimation of the concentrations of some heavy metals in water in Anbar Province, Iraq. *Biochemical and Cellular Archives*, **22**, 3387–3399. https://connectjournals.com/file_html_pdf/3596301H_3387A.pdf?utm_source=chatgpt.com.

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Urban Environment, Iraq

24. Karim, M. Q. A. and Mahmood, B. A. (2022) A study of the effect of the discharge of a sewage treatment project on the water quality of the Euphrates River. *Annals of Forest Research*, **65**, 5438–5455. https://www.researchgate.net/publication/367241111.

25. Karim, M. Q. A. and Mahmood, B. A. (2023) Evaluation of the efficiency of the wastewater treatment plant in the Women's and Children's Hospital in Ramadi, Anbar, Iraq. *IOP Conference Series: Earth and Environmental Science*, **1222**, 012040. https://doi.org/10.1088/1755-1315/ 1222/1/012040.

26. Mahmood, B. A. (2023) Determination of some heavy metals in natural and industrial juices by the atomic absorption method. *Iraqi Journal of Humanitarian, Social and https://www. researchgate.net/publication/ 373512084.*

27. Abdelkarim, K. M. and Mahmood, B. A. (2024) Evaluation of heavy metal concentration in petroleum derivatives in Al-Anbar Governorate. *Journal of Al-Turath University College*, **39**, 249–255. https://iasj.rdd.edu.iq/journals/uploads/2025/06/12/93f475e4e0d6c4c54fa0bec4ac4bf203.pdf?utm_source=chatgpt.com.

28. Mahmood, B. A., Meteab, H. H. and Jubair, A. M. (2025) Determination of the concentration of some heavy metals in the pulp and peel of some citrus fruits using atomic absorption spectrometry. *International Journal of Environmental Impacts*, **8(1)**, 1–7. https://doi.org/10.18280/ijei.080101.

29. Zhan, Y., Xie, M., Zhao, W., Wang, T., Gao, D., Chen, P., Tian, J., Zhu, K., Li, S., Zhuang, B., Li, M., Luo, Y. & Zhao, R. (2023) Quantifying the seasonal variations in and regional transport of $PM_{2.5}$ in the Yangtze River Delta region, China: characteristics, sources, and health risks. *Atmospheric Chemistry and Physics*, **23(17)**, 9837–9852. https://doi.org/10.5194/acp-23-9837-2023.

30. Hernández-Mena, L., Murillo-Tovar, M., Ramírez-Muñíz, M., Colunga-Urbina, E., De La Garza-Rodríguez, I. and Saldarriaga-Noreña, H. (2011) Enrichment factor and profiles of elemental composition of PM2.5 in the city of Guadalajara, Mexico. *Bulletin of Environmental Contamination and Toxicology*, **87**, 545–549. https://doi.org/10.1007/ s00128-011-0369-x.

31. Fang, G. C., Wu, Y. S., Chou, T. Y. and Lee, C. Z. (2008) Organic carbon and elemental carbon in Asia: A review from 1996 to 2006. *Journal of Hazardous Materials*, **150(2)**, 231–237. https://doi.org/10.1016/j.jhazmat.2007.09.036.

32. Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., Harrison, R. M., Norford, L. and Britter, R. (2014) Ultrafine particles in cities. *Environment International*, **66**, 1–10. https://doi.org/10.1016/j.envint.2014.01.013.

33. Zanobetti, A., Schwartz, J. (2009) The effect of fine and coarse particulate air pollution on mortality: A national analysis. *Environmental Health Perspectives*, **117(6)**, 898–903. https://doi.org/10.1289/ehp.0800108.

34. Mahmood, B. A., Faris, S. S., AlBayati, A. T., Abdulkareem, N. T., Eyada, S. O. and Abed, Q. N. (2024) Analytical study of the radioactivity of some asphalt springs in the Heet city, Anbar Governorate, Iraq. *International Journal of Environmental Sciences*, **10(6s)**, 190–198. https://theaspd.com/index.php/ijes/article/view/409/354.

35. Naji, O. N., Mahmood, B. A. and Al-Ani, Y. (2025) Adsorption of ammonia from aqueous solutions using activated iron scrap particles. *International Journal of Environmental Impacts*, **8(4)**, 703–714. https://doi.org/10.18280/ijei.080408.

36. Dai, Q. -L., Bi, X. -H., Wu, J. -H., Zhang, Y. -F., Wang, J., Xu, H., Yao, L. and Jiao, L. (2015) Characterization and source identification of heavy metals in ambient PM_{10} and $PM_{2.5}$ in an integrated iron and steel industry zone compared with a background site. *Aerosol and Air Quality Research*, **15(3)**, 875–887. https://doi.org/10.4209/aaqr.2014.09.0226.

37. Li, H., Mazzei, L., Wallis, C. D. and Wexler, A. S. (2024) Detection of atmospheric particulate metals in near real-time: Tunnel, urban, and rural environments. *Aerosol and Air Quality Research*, **24(10)**, 240117. https://doi.org/10.4209/aaqr. 240117.

38. Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D. and Pozzer, A. (2015) The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, **525**, 367–371. https://doi.org/10.1038/nature15371.

39. Shahid, I., Kistler, M., Mukhtar, A., Guo, X., Bauer, H. and Puxbaum, H. (2016) Chemical composition and mass closure of particulate matter in Pakistan: Implications for source apportionment. *Atmospheric Environment*, **128**, 114–123. https://doi.org/10.1016/j.atmosenv.2015.12.005.

40. Pacyna, J. M. and Pacyna, E. G. (2001) An assessment of global and regional emissions of trace metals to the atmosphere from anthropogenic sources worldwide. *Environmental Reviews*, **9(4)**, 269–298. https://doi.org/10.1139/a01-012.

402   Bashar Abdulazeez Mahmood

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Urban Environment, Iraq

41. Zhang, Y. -L. and Cao, F. (2015) Fine particulate matter (PM2.5) in China at a city level: chemical composition, sources, and spatial distribution. *Scientific Reports*, **5**, 14884. https://doi.org/10.1038/srep14884.

42. Fakhri, N., Stevens, R., Downey, A., Oikonomou, K., Sciare, J., Afif, C. and Hayes, P. L. (2024) Source apportionment of PM2.5 in Montréal, Canada, and health risk assessment for potentially toxic elements. *Atmospheric Chemistry and Physics*, **24**, 1193–1212. https://doi.org/10.5194/acp-24-1193-2024.

43. Cheng, I., Zhang, L., Blanchard, P., Graydon, J. A. and St. Louis, V. L. (2012) Source-receptor relationships for speciated atmospheric mercury at the remote Experimental Lakes Area, northwestern Ontario, Canada. *Atmospheric Chemistry and Physics*, **12(4)**, 1903–1922. https://doi.org/10.5194/acp-12-1903-2012.

44. Wang, J., Zhang, S., Qiu, X., Li, K., Li, J., Ren, Y. & Zhang, X. (2024) Characteristics and health risks of PM2.5-bound metals in a central city of northern China: a one-year observation study. *Aerosol and Air Quality Research*, **24(3)**, 230165. https://doi.org/10.4209/aaqr.230165.

45. Raoof, Z. M. and Kadhum, S. A. (2024) Heavy metal sources and particulate matter (PM) concentration in the street dust in Samawa, Iraq. *AIP Conference Proceedings*, **3229**, 050016. https://doi.org/10.1063/5.0235898.

46. Kampa, M. and Castanas, E. (2008) Human health effects of air pollution. *Environmental Pollution*, **151(2)**, 362–367. https://doi.org/10.1016/j.envpol.2007.06.012.

47. Balasubramanian, R. and Qian, W. B. (2004) Characterization and source identification of airborne trace metals in Singapore. *Journal of Environmental Monitoring*, **6**, 813–818. https://doi.org/10.1039/B407523D.

48. He, L. Y., Hu, M., Huang, X. F., Zhang, Y. H. and Tang, X. Y. (2006) Seasonal pollution characteristics of organic compounds in atmospheric fine particles in Beijing. *Science of the Total Environment*, **359(1-3)**, 167–176. https://doi.org/10.1016/j.scitotenv.2005.05.044.

49. Wang, J., Zhou, H., Chun, X., Wan, Z., Liu, C. and Gong, Y. (2024) Source-specific health risks of PM2.5-bound toxic metals in Wuhai, a semi-arid city in northwest China. *Science of the Total Environment*, **907**, 168180. https://doi.org/10.1016/j.scitotenv.2023.168180.

50. Wang, Y., Zhuang, G., Tang, A., Yuan, H., Sun, Y., Chen, S. and Zheng, A. (2005) The ion chemistry and the source of PM2.5 aerosol in Beijing. *Atmospheric Environment*, **39(21)**, 3771–3784. https://doi.org/10.1016/j.atmosenv.2005.03.013.

51. Zhi, M., Zhang, X., Zhang, K., Ussher, S. J., Lv, W., Li, J., Gao, J., Luo, Y. and Meng, F. (2021) The characteristics of atmospheric particles and metal elements during winter in Beijing: Size distribution, source analysis, and environmental risk assessment. *Ecotoxicology and Environmental Safety*, **211**, 111937. https://doi.org/10.1016/j.ecoenv.2021.111937.

52. Chow, J. C., Watson, J. G., Edgerton, S. A. and Vega, E. (2002) Chemical composition of PM2.5 and PM10 in Mexico City during winter 1997. *Science of the Total Environment*, **287(3)**, 177–201. 10.1016/s0048-9697(01)00982-2.

53. Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., Harrison, R. M., Norford, L. and Britter, R. (2014) Ultrafine particles in cities. *Environment International*, **66**, 1–10. https://doi.org/10.1016/j.envint.2014.01.013.

54. Zhang, R., Wang, G., Guo, S., Zamora, M. L., Ying, Q., Lin, Y., Wang, W., Hu, M. and Wang, Y. (2015) Formation of urban fine particulate matter. *Chemical Reviews*, **115(10)**, 3803–3855. https://doi.org/10.1021/acs.chemrev.5b00067.

55. Molina, L. and Molina, M. J. (2002) Air Quality in the Mexico Megacity: An Integrated Assessment. https://doi.org/10.1007/978-94-010-0454-1.

56. Harrison, R. M. and Yin, J. (2000) Particulate matter in the atmosphere: Which particle properties are important for its effects on health? *Science of the Total Environment*, **249(1-3)**, 85–101. https://doi.org/10.1016/S0048-9697(99)00513-6.

57. Kim, K. -H., Kabir, E. & Kabir, S. (2015) A review on the human health impact of airborne particulate matter. *Environment International*, **74**, 136–143. https://doi.org/10.1016/j.envint.2014.10.005.

58. Kelly, F. J. and Fussell, J. C. (2012) Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. *Atmospheric Environment*, **60**, 504–526. https://doi.org/10.1016/j.atmosenv.2012.06.039.

59. Dominici, F., Peng, R. D., Barr, C. D. and Bell, M. L. (2010) Protecting human health from air pollution: Shifting from a single-pollutant to a multipollutant approach. *Epidemiology*, **21(2)**, 187–194. https://doi.org/10.1097/EDE.0b013e3181cc86e8.

403 Bashar Abdulazeez Mahmood

Analytical Assessment of Trace Metals and Chemical Components in Particulate Matter from Al-Anbar's Urban Environment, Iraq

60. Kangas, L., Kukkonen, J., Kauhaniemi, M., Karppinen, A., Petäjä, T. & Timonen, H. (2024) The contribution of residential wood combustion to the PM2.5 concentrations in the Helsinki metropolitan area. *Atmospheric Chemistry and Physics*, **24(2)**, 1489–1507. https://doi.org/10.5194/acp-24-1489-2024.

61. Srimuruganandam, B. and Nagendra, S. S. (2012) Source characterization of PM10 and PM2.5 mass using a chemical mass balance model at urban roadside. *Science of the Total Environment*, **433**, 8–19. https://doi.org/10.1016/j.scitotenv.2012.05.082.

62. Vicente, E. D. & Alves, C. A. (2018) An overview of particulate emissions from residential biomass combustion. *Atmospheric Research*, **199**, 159–185. https://doi.org/10.1016/j.atmosres.2017.08.027.

63. World Bank (2022) Iraq Country Climate and Development Report (CCDR). *Washington, DC: World Bank*. https://doi.org/10.1596/38250.

64. United Nations Environment Programme (2017) North Africa and Middle East Air Quality Regional Report. *Nairobi: UNEP*. Available at: https://www.unep.org/resources/report/north-africa-middle-east-air-quality-regional-report.

65. Mahmood, B. A., Al-Ani, Y., Mohammed, K. A. and Eyada, S. O. (2018) The feasibility of using plastic wastes to improve the properties of natural asphalt. *Journal of Engineering and Applied Sciences*, **13(21)**, 8929–8934. https://makhillpublications.co/files/published-files/mak-jeas/2018/21-8929-8934.pdf.