Global NEST Journal, **28** (XX), pp 1-10
Available online: 25/08/2026

Spatial Assessment of Airborne Atmospheric Heavy Metals Across Key Monitoring Stations in Baghdad

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Abstract

The present study concerns the geographical assessment of atmospheric airborne heavy metals in the main monitoring stations of Baghdad during the months of May and June 2025. The heavy metals of interest are Lead (Pb), cadmium (Cd), nickel (Ni), Iron (Fe), Copper (Cu) and zinc (Zn). Air samples were collected with standardized one hour sniffer-based sampling, and the levels of heavy metals were determined in a laboratory. Geostatistical mapping and spatial interpolation were used to visualize distribution patterns and pollution hotspots across the metropolitan landscape. Results show a clear spatiotemporal variability driven by sources of legacy contamination, seasonal weather, industrial pollutants and traffic intensity. In both months, high atmospheric dispersion of river-channel airflow dynamics resulted in continually lower levels of heavy metals in the areas along the Tigris River, especially in central Al-Karkh and parts of Al-Khadimiya. However, high Zn concentrations, above 14 ppm in May, were observed near Karadaa and Al-Zafaraniya where there is a lot of traffic, construction and private generator use. Most of the metals showed higher concentrations in May (e.g., Cr: 0.84–2.31 ppm) than in June (0.231–1.16 ppm) which can be indicative of seasonal changes in air stability and emission strength. Fe showed the opposite trend, increasing from 4.05-9.91 ppm in May to 6.06-10.2 ppm in June. This increase was probably because of stronger summer winds and increased dust resuspension. Furthermore, spatial maps show much lower Fe concentrations along the Tigris corridor, supporting the moderating effect of dispersion due to river transport. The results show the combined impact of seasonal weather patterns and anthropogenic emissions on airborne metal pollution in Baghdad and highlight the urgent need for focused air quality control measures in high exposure areas.

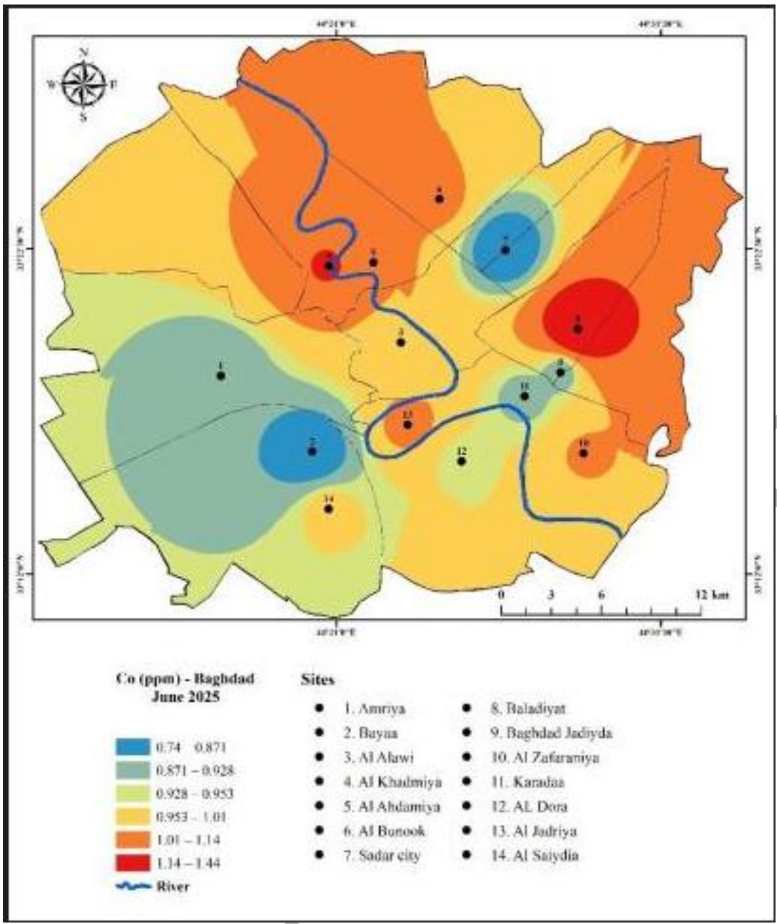
Keywords: Atmospheric Heavy metals, Air pollution, Baghdad, GIS Mapping.

Received: 18/06/2026,

Accepted: 15/08/2026,

Available online: 25/08/2026

Graphical abstract



1. Introduction

Heavy metals are trace elements having an atomic density greater than 5 g/cm 3. Examples of heavy metals are lead (Pb), cadmium (Cd), nickel (Ni), iron (Fe), copper (Cu) and zinc (Zn). These metals are mainly associated with particle matter in the atmosphere and are considered as hazardous metals because of their toxicity, persistence and their ability to bioaccumulate in ecosystems and biological tissues (Alloway *et al.* 2013). Airborne heavy metals have been shown in many studies to travel over long distances and remain suspended for long time before deposition, thus affecting the quality of air both locally and regionally (Ali *et al.* 2015). Heavy metals are present in the atmosphere from both natural and anthropogenic sources. Natural sources are weathering of rocks, windblown dust and volcanic eruptions. However, anthropogenic sources dominate in metropolitan regions, mainly due to industrial processes, vehicle emissions, waste incineration, metallurgy, electricity generation and combustion of oil (Jomova *et al.* 2025). Generally, heavy metals are more concentrated in urban areas because there is a lot of human activity. Traffic emissions are one of the main causes, due to tire wear (Zn), brake pad abrasion (Cu, Pb, Cd) and lubricating oil combustion (Ni, Cr), especially in cities with high vehicle density (Jeong *et al.* 2020). Airborne heavy metal pollution is also largely due to industrial processes, such as steel mills, power plants, cement manufacture and metal refining (Ferreira-Baptista and De Miguel 2005). High levels of Ni and V are often observed in fossil fuel-dependent regions, such as many cities in the Middle East, due to the combustion of heavy fuel oil and diesel generators (Senior *et al.* 2000) This is especially the case in Baghdad, where diesel generators are commonly used for power because of the grid's instability. Heavy metals are non-biodegradable and hence have long lasting effects on the ecosystem. Once deposited, they may contaminate soil, water and vegetation, disturbing the natural balance (Kabata-Pendias, 2011). Heavy metals can contaminate soil through airborne pathways and influence the microbiological activity, plant growth and food safety (Giller *et al.* 2009). The process of bioaccumulation and biomagnification further increases the likelihood of these metals like Pb and Cd to enter the human food chain. Heavy metal atmospheric depositions on water surfaces can be damaging for aquatic habitats, by changing water chemistry and the health of organisms (Nicolau et al. 2009). It is therefore important to measure airborne heavy metals to assess environmental impacts beyond air quality. Heavy metals have been well studied for their health effects. Lead exposure affects the nervous system and children are particularly vulnerable to developmental delays (World Health Organization. (2021)). Cadmium exposure can lead to carcinogenic hazards, skeletal damage and kidney failure (Lars Järup, & Agneta Åkesson *et al.* 2009). Nickel and chromium VI compounds are human carcinogens, and have been linked to nasal and lung cancers (International Agency for Research on Cancer 2012). Studies have shown that heavy metals attached to particulate matter can get deep into the respiratory system and lead to neurological abnormalities, cardiovascular diseases and chronic respiratory diseases (Marilena Kampa, & Elias Castanas 2008). Monitoring heavy metals components is important as their presence significantly increases the toxicity of $PM_{2.5}$. Geographic Information Systems (GIS) have become indispensable tools in the monitoring of the environment due to their capability of mapping the distribution of pollutants and detecting hotspots. Predictive models of contamination dispersal are frequently developed based on spatial interpolation techniques such as Kriging and Inverse Distance Weighting (IDW) (Ning Zheng *et al.* 2010). GIS has been applied to evaluate heavy metals in urban air environments in several studies. GIS-based spatial mapping showed the distribution trends of heavy metals in PM over the industrial areas and identified clusters related to specific emission sources (Coudon *et al.* 2019). These methods have been promising in environmental management, risk assessment and urban planning. The air quality in Baghdad has deteriorated due to rapid urbanization, increased car traffic, industrial activities, and reliance on fossil fuel generators. (Al-Dabbas *et al.* 2018) reported high PM and associated heavy metals concentrations in several locations, with Pb, Ni and Cr in some locations exceeding international standards. Other studies also showed that dust storms, military operations and infrastructure deterioration are among the problems that worsen air quality problems (Habeeb *et al.* 2015). However, the spatial scale of existing studies is restricted and they often focus on individual sites rather than a coordinated multi-station study. This difference emphasizes the need to apply advanced Analytical and GIS techniques to conduct a comprehensive study of the spatial heterogeneity of airborne heavy metals in Baghdad. This study's primary goal is to do a geographical assessment of airborne heavy metals across a few Baghdad monitoring stations and identify any possible environmental effects. The particular goals established by this study are:

(i) Measurement of concentrations of selected major heavy metals (Pb, Cd, Ni, Cu, Zn, and Fe.) in ambient air at selected urban monitoring sites;

(ii) Comparison of measured concentrations with national and international standards of air quality; (iii) Analysis of spatial variation and identifying pollution hot spots using GIS-based mapping;

(iii) Identification of major anthropogenic sources contributing to heavy metal emissions in Baghdad;

(iv) Suggest improvements in air quality monitoring, mitigation practices and policy development.

2. Methodology

2.1. *Study Area*

The study was conducted in Baghdad, the capital of Iraq, located in the Mesopotamian plain of the Asian continent. Iraq is located between 29.5° and 37.22° north latitude and 38.45° and 48.45° east longitude. Baghdad is situated on the Tigris River, near the center of the country. The local air quality is impacted by the dense urban form, traffic, mixed residential and industrial zones, power generators and construction activity. The city is divided into two main parts: Karkh and Rusafa. Each part comprises several districts with distinct emission sources and population densities. Due to high temperatures, very little rainfall, intense solar radiation, and frequent dust events, the climate of the city is classified as a hot desert climate according to the Köppen–Geiger classification. These factors directly influence the formation and dispersion of airborne pollutants including particulate-bound heavy metals.

2.2. *Monitoring Stations*

Air sampling was carried out at 14 representative monitoring sites in Baghdad as shown in **Figure 1**. The stations were selected to represent a range of urban environments, including mixed-use areas, residential neighborhoods, commercial areas, industrial areas, and high-traffic corridors. **Table 1** provides all the station names with their exact GPS locations. Monitoring stations were chosen based on a mix of logistical, scientific and environmental factors, in order to make sure there was spatial representativity. It includes several stations on either side of the city, which is divided by the Tigress River. The selected stations were Karkh side (Amriya, Bayaa, Al Alawi, Khadmiya, Dora, Jadriya, Saiydia) and Rusafa side (Ahdamiya, Bunook, Sadr City, Baladiyat, Baghdad Jadiyda, Zafaraniya, Karadaa).In addition to providing a reasonable spatial distribution throughout Baghdad and a good diversity of emission sources, this distribution enables comparison between metropolitan areas with high and low densities. Each station area's features, activities, and classification (Commercial, Residential, or Industrial) are well described in **Table 1**. To ensure representative atmospheric sampling, sample locations were chosen to exclude obstacles like walls, trees, and direct sources of heavy pollution like chimney outlets. The study was carried out in May and June of 2025, which is one of the most crucial times for monitoring air pollution in Baghdad because of the frequent dust storms, rising temperatures, increased use of electricity and generators, and a discernible increase in particulate matter during this time. As a result, it is appropriate for analyzing the concentrations of heavy metals in ambient air.

2.3. *Meteorological Conditions During the Study Period*

Meteorological conditions have a significant impact on the behavior, dispersion and deposition of air pollutants. **Figure 2** shows the data of temperature, wind speed and relative humidity collected during the study period.

2.4. *Sampling and Analysis Methodology*

As previously mentioned, heavy metals air samples were collected at the 14 stations in Baghdad. Portable air sniffer collected samples of airborne particulates; The Sniffer instrument is appropriate for a fast assessment of urban air quality, since it is designed for a short time interval sampling with real-time particle detection. The equipment was adjusted to avoid sample barriers such as buildings, walls and vegetation. The sniffer inlet was placed 1.5-2 m above the ground level, which represents the breathing zone for human exposure. All samples were collected in the open air. Sampling was done for one hour at each site under uniform meteorological conditions, and three samples were taken during the day. The mean concentration of the three replicates was calculated to improve precision and reduce temporal variability. Samples were sent to the laboratory on the same day to ensure the accuracy and consistency of the analytical results. The filter samples were analyzed by GC-Mass Spectrometer to determine the concentrations of ambient heavy metals (Cd, Fe, Cu, Zn, Ni and Pb). Sniffer filter samples were acid digested with a mixture of nitric acid ($HNO3$) and perchloric acid ($HClO4$) following normal EPA digestion procedures (EPA Method 3050B). The digested material was filtered through 0.45 µm membrane filters. The prepared extracts were injected into GC-MS for quantitative analysis.

Table 1. Air sampling stations coordinates and characteristics.

Sampling St. No	Area Name	Latitude (N)	Longitude (E)	Area Characteristics
St.1	Amriya	33.18	44.17	Commercial / Residential
St.2	Bayaa	33.15	44.20	Industrial / Repair garages
St.3	Al Alawi	33.19	44.23	commercial / Residential / Construction Sites
St.4	Al Khadmiya	33.21	44.20	Commercial+ Residential
St.5	Al Ahdamiya	33.22	44.22	Garage / Governmental complex / residential towers / Park
St.6	Al Bunook	33.23	44.24	Residential / River bank / Restaurant complex
St.7	Sadr City	33.22	44.26	Commercial
St.8	Baladiyat	33.19	44.28	Residential / Commercial / Hospital complex / Governmental buildings
St.9	Baghdad Al-Jadida	33.18	44.28	Residential / Car repair workshops
St.10	Al Zafaraniya	33.15	44.29	Residential / commercial
St.11	Karadaa	33.17	44.27	Commercial / Car parks
St.12	Al Dora	33.15	44.25	Residential / Commercial / University complex
St.13	Al Jadriya	33.16	44.23	Residential / commercial / Factory / Power plant station
St.14	Al Saiydia	33.14	44.20	Refinery / Malls / University complex

Figure 1. Air Sampling stations in Baghdad in the current study.

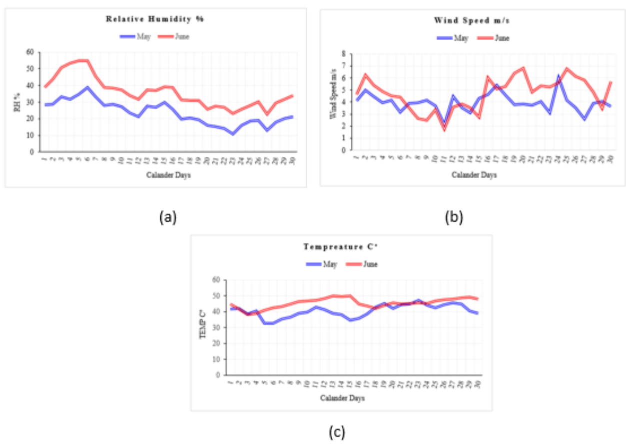


Figure 2. Meteorological surface data of the study area during the study period (temperature, wind speed and relative humidity).

3. Results and Discussion

3.1. *Lead (Pb) Dispersion*

Figure 3 shows the regional distribution of lead (Pb) concentrations over Baghdad in May and June 2025, highlighting temporal and spatial variability, indicating dynamic pollution sources and environmental factors influencing dispersion patterns. The figure indicates a potential public health risk as Pb concentrations in several districts exceed internationally recommended criteria for urban air quality. There are clear differences in Pb values between the two sampling months. The concentration in May 2025 is 0.71 to 1.79 ppm; very high values are seen in Al-Saidyia (Site 14), Bayaa (Site 2) and parts of Al-Zaafaraniya (Site 10). These hotspots are shown by values in the orange-red zones of the map, which represent high to extremely high Pb intensity. In contrast, June 2025 exhibits a slightly smaller but still large distribution range of 0.66–1.13 ppm. The most prominent hotspot in June shifts towards Al-Jadriya (Site 13) and Baghdad Jadida (Site 9) where Pb values reach the top end of the June range. The magnitudes appear smaller in some areas as compared to May. This month-to-month difference is probably due to seasonal weather. Baghdad in the month of May is usually marked by dust storms, higher wind speeds and lower rainfall, all of which have been proven to increase heavy metal resuspension and atmospheric transport (Omar Ali Al-Khashman. 2013). Some hot spots may be affected by local emissions, but lower Pb concentrations in June may be related to early summer air stability and reduced dust activity. Both maps show persistent Pb hotspots, mainly in the south and southeast of Baghdad. The spatial patterns are consistent with the industrial, traffic and population-dense areas of Baghdad where air pollution has historically been associated with power plants, oil refining operations in the Dora neighborhood, and high traffic routes. In line with the findings of (Abdul Hameed et al. 2013), the current study in Baghdad revealed that these sources emit higher heavy metals. These hotspots close to these areas show that human activity is still going on. But the pattern of the Tigris River is very interesting. In both months, areas near the river with relatively lower levels of Pb (blue-green areas) include central parts of Al-Karkh and parts of Al-Khadimiya (Sites 3-5). This could be because of better air dispersion and less traffic. The reduction of airborne metal concentrations along the river corridors has been demonstrated feasible in humid microenvironments (Raju et al., 2025). Industrial activity, heavy traffic, seasonal weather and legacy contamination all influence Pb pollution in Baghdad based on the data from May and June 2025. While June results were slightly lower than May, many parts of the country still have high Pb levels, highlighting the importance of continued monitoring and targeted emission control measures.

3.2. *Zink (Zn) Dispersion*

Figure 4 shows the temporal and spatial variations of the zinc (Zn) concentrations in Baghdad during May and June of 2025. Traffic density, industrial activity, weather and urban land use all influence this volatility. Zn is commonly released from sources that coincide with the spatial hotspots as shown in the maps, for example trash burning, metal processing plants, vehicle tire wear, lubricating oil combustion and industrial stack emissions. Similar regional patterns of zinc in urban air have been reported in large cities (Józef M. Pacyna, & Elisabeth G. Pacyna 2001). Zinc (Zn) values ranged from 5.4-16.7 ppm in May to 7.7-10.7 ppm in June. May data show a wider distribution and higher maximum values, in particular near Karadaa (Site 11) and Al Zafaraniya (Site 10) where Zn was greater than 14 ppm. In contrast, the Zn levels in June are more moderate but regionally consistent. This discrepancy could be attributable to metrological considerations like increased atmospheric stability, warmer temperature and decrease in wind speed in June and increase in traffic load and density in May. Similar studies have shown the influence of such variables on airborne concentrations of heavy metals (Omar Ali Al-Khashman 2013; Querol et al. 2004. Adamiec et al., 2016). According to map study May has a more pronounced Zn anomaly, June shows more uniform amounts around the city. Again, both maps show a variable concentration gradient near the Tigris River, mostly driven by changes in wind flow, turbulence and reduced dust resuspension. Similar phenomena have been reported in other studies (Diana Sánchez-Rodríguez et al. 2015). The measured Zn concentrations (5–17 ppm) are mostly comparable with the range previously reported for other crowded cities such as Cairo 6–30 ppm; (Khodeir et al. 2012), Istanbul 8–22 ppm; (Sezgin et al. 2003). and Guangzhou 4–19 ppm; (Duong Lee 2011).

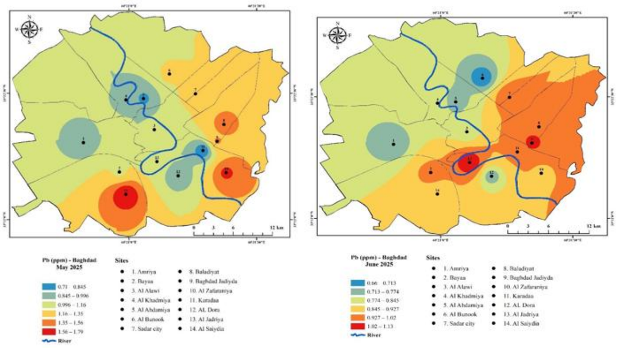


Figure 3 Spatial distribution of atmospheric lead (pb) concentrations across Baghdad during May and June 2025

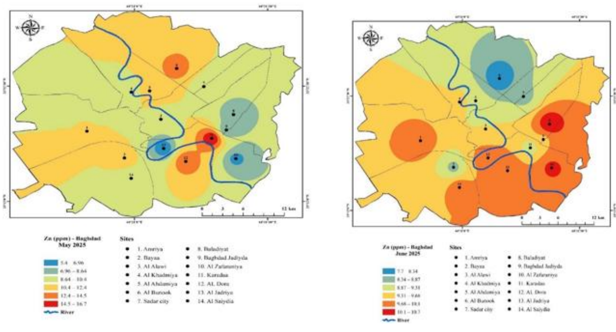


Figure 4. Spatial distribution of atmospheric zinc (Zn) concentrations across Baghdad during May and June 2025

3.3. *Cadmium (Cd) Dispersion*

GIS-based interpolation maps for May and June 2025 reveal marked regional variations in the concentrations of cadmium (Cd) in the air across Baghdad. The distribution patterns seen are influenced by the density of urban areas, traffic loads, industrial areas, emissions from generators and weather fluctuations between the two months. **Figure 5** GISarc map of the quantities and distribution of cadmium heavy metals in Baghdad as determined by the gathered air filter samples.

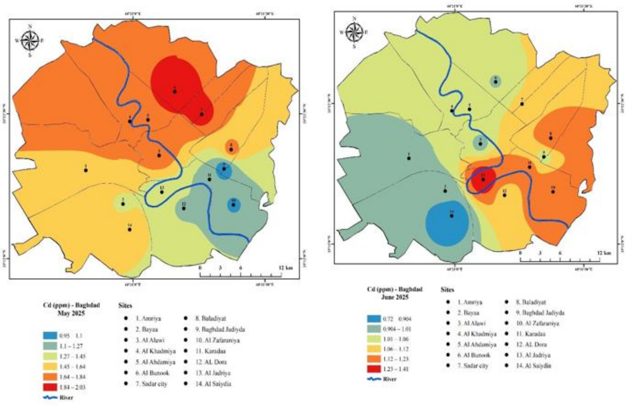


Figure 5. Spatial distribution of atmospheric cadmium (Cd) concentrations across Baghdad during May and June 2025

Examples of such regions are Al Bunook (St. 6) and Sadr City (St. 7) which show extremely high Cd levels (~1.64-2.03 ppm). The highest Cd concentrations move northward and northeastward in the May map. Heavy traffic, a large number of private generators and a large number of construction projects in those places where such sources are known to be able to release Cd and other metals (Marilena Kampa, & Elias Castanas. 2008) may have a relatively high concentration in these places. Also, May's dominant northwesterly winds could transport contaminants to the northeast, boosting readings in that direction. This conclusion is also supported by further research (Saad Z. Jassim, & Jeremy C. Goff. 2006). Also, places such as Al Ahdamiya (St. 5), Baladiyat (St. 8) and Baghdad Jadidya (St. 9) have moderate to high numbers. Lower levels are seen in the districts of Saiydia and Amriya, in western Baghdad. Some studies have shown that the levels of particulate matter are generally higher in May during dust outbreaks at the beginning of the season (Goudarzi, *et al.* 2019), which may help in binding Cd to PM2.5 and PM10 particles. However, the map of June indicated low levels of Cd in the western parts of Baghdad (Amriya, Bayaa), with values between 0.72 and 1.01 ppm, with the concentrations gradually increasing in the city center and eastern parts of Baghdad. The highest hotspot is at Al Jadriya (St. 13) with a range of 1.23–1.41 ppm. Meanwhile moderate significant Cd concentrations are found in the neighboring districts like Karadaa (St. 11) and Al Dora (St. 12). In arid regions, Cd is known to be transported by dust, which is resuspended in June due to increasing temperatures and atmospheric instability. Dust events lead to major increases of the trace metal concentrations (Middleton *et al.* 2017; Al-Ansari *et al.* 2018). Traffic emissions along the Karrada-Jadriya corridors are also believed to be a significant contributor. Cadmium emissions are from brake wear, tyre abrasion and diesel engine exhausts (A. Thorpe, & R. M. Harrison 2008). Cd is found in generator emissions. The level is high in Karadaa, Jadriya, Zafaraniya, and Dora due to impurities in the fuel (Tiwari et al, 2021). St. 13 (Jadriya) is situated near congested bridges and road networks adjacent to rivers which causes the trapping of air pollutants due to reduced ventilation. These combined factors are attributed to the highest June Cd hotspot around St. 13 (Al Jadriya).

3.4. *Copper (Cu) Dispersion*

Figure 6 Distribution of copper (Cu) in the air of Baghdad in May and June 2025. Images reveal clear geographical and temporal variation driven by seasonal atmospheric dynamics and human activity. The June map generally shows a large increase in Cu concentrations in many districts over May, indicating a higher intensity of emissions and/or less efficient dispersion conditions in early summer. In May 2025, Cu values were on average 0.205-0.97 ppm and higher concentrations were recorded in the southern and southeastern regions, particularly in Al Sayudia (Site 14), Al Jadriya (Site 13) and Al Dora (Site 12). These areas are characterized by heavy traffic, mixed industrial workshops and close proximity to major fuel-combustion sources. The amount of Cu in urban air is often related to tire abrasion, metal production, brake wear of vehicles and fuel combustion processes (A. Thorpe, and R. M. Harrison 2008; Amato et al. 2014), as shown in earlier research. The Cu concentrations had changed to the range of 0.29–0.96 ppm by June 2025, but the high-intensity zones had clearly shifted. Sites in the south such as Baghdad Jadriya (Site 13) still showed high values but districts in the north and east such as Al Khadmiya (Site 4), Karrada (Site 11) and Al Zafaraniya (Site 10) were clearly showing a growth. A strong red zone in the north indicates an acceleration of emissions specific to June. This temporal increase is consistent with the higher temperatures, air stagnation and increased evaporative emissions that are often observed in Middle Eastern megacities throughout the summer (Zainab Al-Ani et al. 2015). Moreover, the proximity of the Tigris River appears to affect the spread of pollutants. Data from June suggest that sites immediately adjacent to the river (e.g., Sites 11 and 13) experienced localized high Cu concentrations, possibly reflective of thermal inversions and reduced vertical mixing in urban canyons adjacent to rivers. This phenomenon was also observed in other river-valley towns (Zhao *et al.* 2020). The spatial trend shows that in both months, Cu loading in Baghdad is significant and may have implications for respiratory and cardiovascular health. Although the values shown are in parts per million (ppm) which is a typical measurement for gases. Copper is a redox active metal and can cause oxidative stress in human lung tissue by generating reactive oxygen species (ROS) (Sven Becker *et al.* 2005). In some districts the loads are persistently high and classified as risk-priority for air quality management measures, namely Al Sayidia, Al Jadriya, Al Dora and Al Zafaraniya. These factors can help explain the reported increases in June and the lower dispersion of pollutants. Previous studies have shown that metal concentrations in the atmosphere of Baghdad tend to increase with the increase of atmospheric retention and combustion activities during summer (A. H. M. J. Al-Kubaisy, & W. K. Al-Mashhadani 2020). The spatial distribution of Cu enrichment in Baghdad is consistent with studies performed in other cities in the Middle East where urban metal emissions are mainly caused by industrial activities and abrasion from traffic (Tariq Hussein *et al.* 2021). The strong association of Cu hotspots with heavily travelled locations supports previous findings that brake lining wear is a major source of Cu in airborne particulate matter (A. Thorpe, & R. M. Harrison. 2008).

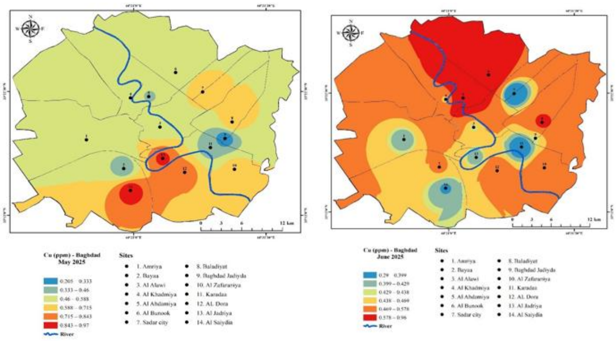


Figure 6. Spatial distribution of atmospheric copper (Cu) concentrations across Baghdad during May and June 2025

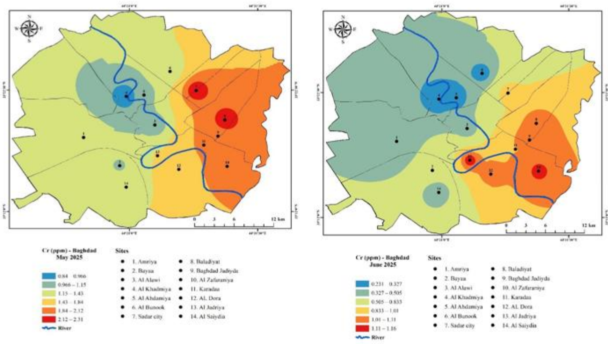


Figure 7. Spatial distribution of atmospheric Nickol (Ni) concentrations across Baghdad during May and June 2025.

3.5. *Nickel (Ni) Dispersion*

Figure 7 shows the maps of air-borne chromium (Cr) concentrations in Baghdad during May and June 2025. The spatial variability and the strong temporal decrease from May to June are very clear on the maps. These patterns are indicative of variations in local weather, urban activity levels and anthropogenic inputs. According to the statistics, Cr concentrations of May 2025 (0.84–2.31 ppm) were significantly higher than that of June 2025 (0.231–1.16 ppm). This decrease could be attributed to seasonal meteorology like increased temperatures and more atmospheric mixing in June that tend to dilute airborne contaminants (Al-Mousawi *et al.* 2021). Another reason that could explain this difference is the industrial and traffic activities during the beginning of summer, especially the reduction in the use of diesel generators after the spring high in Baghdad. This considerable variation in airborne pollutants' levels might also be mainly attributed to changes in the prevailing wind direction that are frequently stronger in June and help in the dispersion of particulate bound metals (Jassim *et al.* 2019). Such seasonal drops in airborne heavy metals have been seen in other Middle Eastern towns with similar meteorological trends (Fadhil, 2022). Maps of May and June indicate comparatively high concentrations of Cr in areas of the eastern and southeast, such as Al Zafaraniya (Site 10), Baghdad Jadriya/Jadiyda (Sites 9, 13), and Al Dora and Al Karadaa (Sites 11, 12). The regions with the highest Cr levels are highlighted in orange to red on both maps. They came to 2.12–2.31 ppm in May and 1.11–1.16 ppm in June. Industrial facilities with a concentration of fuel-based businesses, tiny electroplating shops, and several metal works in southeast Baghdad are potential contributors. In addition, car emissions are a significant source of airborne Cr, predominantly from brake wear (A. Thorpe, & R. M. Harrison. 2008), and are expected to rise in locations with major highways and bridges where traffic is dense. Increasing the emissions from fuel combustion of residential diesel generators in these areas, which may contribute significantly to Cr-bearing particles (Al-Khafaji *et al.* 2022). However, in western and northwestern sectors e.g. Amriya (Site 1) and Bayaa (Site 2), smaller quantities are often found (0.23-0.50 ppm in June; 0.84-1.15 ppm in May). These areas are marked by less congested traffic corridors, more open spaces with better ventilation, and less industrial density. Both maps show a band of lower concentrations near the Tigris River particularly around key neighborhoods such as Al Khadmiya (Site 4) and Al Bunook (Site 6). Probably due to less human activity along some river sections and increased air circulation along the river channel, which encourages dispersion. Additional research supports this analysis (Mayer *et al.* 2008).

3.6. *Iron (Fe) Dispersion*

Figure 8 depicts the spatial distribution patterns of atmospheric iron (Fe) concentrations in Baghdad in May and June 2025. These patterns exhibit large temporal and spatial variability due to the joint effect of the urban structure, anthropogenic actions and the prevailing weather. Fe levels in some areas were generally higher than the average urban background concentrations reported in the regional and global literature (Omar Ali Al-Khashman 2013), indicating the significant contribution of local emission sources. The results indicated that Fe concentrations were higher in June than in May. Fe concentrations varied from approximately 4.05–9.91 ppm in May to 6.06–10.2 ppm in June. This seasonal increase might be attributed to a number of variables including increased dust resuspension due to hot, dry and windy weather and an increase in traffic emissions (A. Thorpe, & R. M. Harrison 2008). The maps reveal that the southwest parts, especially Amiriya (Site 1), have the highest Fe hotspot (≈ 9–9.9 ppm). This area is known for its heavy traffic corridors, ageing car fleet, and active building projects, which produce Fe-rich particulate matter (PM) (Na Zheng *et al.* 2010). Values changed slightly with respect to geography in June but remained high in the western zones (≈ 8.3–9.6 ppm). Around Al-Jadriya (Site 13), the maximum zone of Fe levels is in June (≈ 9.6-10.2 ppm) whereas the levels are always high in both May and June maps. Dust traffic on bridges and dense population in residential and business areas at this location. The persistence of increased Fe indicates continued local emissions, which are likely dominated by small industrial workshops and transportation. Similar trends have been reported in other urban areas of the Middle East (Khodeir *et al.* 2012). The northeastern zones showed moderate-to-high Fe levels in both months. Dust-derived Fe is a product of the old residential zone in this area, which contains a high percentage of unpaved surfaces. The observed seasonal dust activity is reflected in a shift from moderate ranges in May (≈6-8 ppm) to higher values in June (≈8.3-9.6 ppm). Interestingly, the maps indicate relatively low Fe concentrations within the Tigris River channel, especially near Sites 4, 5 and 11. This is consistent with the expected channeling effect of the airflow over the river enhancing local pollution dispersion. The river-adjacent areas are usually better for airborne pollution dilution, as opposed to the heavily populated inland regions (He and Zhang 2019). Also, lower Fe levels are due to a colder environment and less resuspended dust.

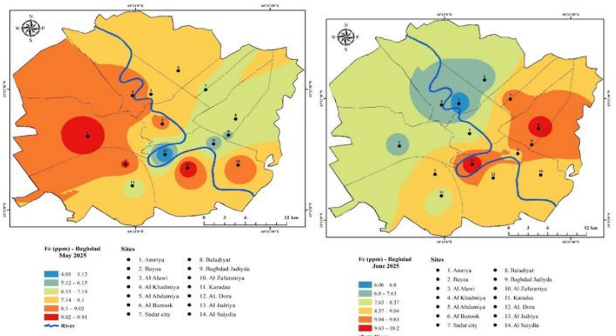


Figure 8. Spatial distribution of atmospheric iron (Fe) concentrations across Baghdad during May and June 2025

4. Conclusions

1. The results of the study lead to the following conclusions:
2. The results indicate continuous deterioration of air quality, with concentrations of heavy metals in ambient air in Baghdad in May and June 2025 exceeding global guideline values for several elements. The pattern suggests a rising influence of anthropogenic activities, especially open waste burning, industrial activities and transportation pollutants.
3. The seasonal fluctuation had a significant effect on the dispersion and accumulation of heavy metals. Heavy metals were found in higher concentrations in early summer. The increase in atmospheric metal loadings was driven by increased temperatures, reduced precipitation and increased dust intrusion.
4. Spatial analysis was conducted across sampling locations to detect the maximum pollution load in densely inhabited and industrially active districts. These results underscore the need for a geographically targeted management approach that targets high-risk areas, especially around roads, industrial complexes, and uncontrolled combustion activities.
5. The comparison of the datasets of May and June revealed increased interactions of emission dispersion with the onset of summer and increased extraction of metals like Cu, Cd, Zn, Ni, Pb and Fe. The timing of this seasonal intensification underscores the need for seasonal forecasting models to inform long-term air quality planning and regulatory decisions. The study's overall conclusion is that the amounts of heavy metal pollution found in Baghdad during the study period could be hazardous to the environment and public health, necessitating quick mitigation measures. Sustainable air quality management in the area requires bolstering monitoring networks, enforcing emission regulations, and incorporating cutting-edge analytical methods like GIS mapping and neural-network-based forecasting.

Acknowledgment

The authors acknowledge the scientific research commission, Baghdad, Iraq for offering all required facilities and support to accomplish this study.

Grant Support Details

The present research did not receive any financial support.

Conflict Of Interest

The authors affirm that they have no conflicts of interest with regard to this manuscript's publication. Furthermore, the authors have adhered to all ethical guidelines, including those against plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publishing and/or submission, and redundancy.

Life science Reporting

No life science threat was practiced in this research.

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