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RESEARCH ARTICLE

Human Health Risk Assessment with Heavy Metal Exposure from in locations around Power Generation Using Dust, Hair, and Blood Biomonitoring

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ABSTRACT

Unreliable grid electricity in rapidly developing cities such as Erbil, Iraq, has led to heavy reliance on diesel power generators. However, the occupational health risks of chronic heavy metal exposure for workers at these facilities remain poorly quantified. This study, therefore, assessed contamination levels and human uptake of lead (Pb), mercury, arsenic, nickel, zinc, copper, and cobalt using an integrated environmental–biological monitoring approach. Dust, scalp hair, and blood samples were collected from 60 workers at 20 local power plants and from 15 rural residents (controls). Metal concentrations were measured by an X-ray fluorescence device, and pollution was evaluated using the Geo-accumulation Index (I_{geo}) and Pollution Load Index (PLI). Power plant dust showed extreme Zn contamination (I_{geo} = 5.20) and heavy Cu contamination (I_{geo} = 3.70), with a PLI of 5.03 versus 0.65 in controls. Workers had significantly higher metal levels in hair and blood than controls ($P \leq 0.001$). Strong positive correlations between dust and biological samples (e.g., Pb hair–dust: r = 0.878) confirmed that airborne dust is a major exposure pathway. Workers with >11 years of service accumulated substantially higher metal burdens than those with 1–5 years. These findings demonstrate that occupational exposure to power generators poses a serious, cumulative health risk. We recommend installing dust suppression and ventilation systems, providing personal protective equipment, and implementing routine biomonitoring of blood and hair to detect early bioaccumulation and prevent long-term toxicity.

Keywords: Heavy metal exposure, health risk assessment, power generation, human biomonitoring, geo-accumulation index

INTRODUCTION

The widespread use of small diesel and gasoline generators in settings with unreliable or insufficient grid electricity has been documented as a common response to chronic power shortages, resulting in significant emissions of air pollutants with implications for local air quality and human health.[1,2] In rapidly developing cities such as Erbil, electricity production often relies on fossil fuel combustion, which raises concerns about air pollution and related health risks. Among the most harmful pollutants produced during fuel combustion are heavy metals, which can persist in the environment and accumulate in living organisms over time.[3]

Heavy metals such as lead (Pb), mercury (Hg), arsenic (As), nickel (Ni), zinc (Zn), copper (Cu), and cobalt (Co) can attach to airborne particles and eventually settle as dust. Humans may be exposed to these metals through inhalation, ingestion, or skin contact, and they can later be detected in biological materials such as blood and scalp hair, which serve as reliable biomarkers of exposure.[4-6] Continuous exposure to these toxic elements may lead to serious environmental and health problems, as heavy metals tend to persist, accumulate in the body, and cause long-term toxic effects.[7,8] Continuous exposure to emissions from diesel-powered generators places workers and nearby residents at risk of various health problems. Petroleum fumes can be metabolized into harmful compounds that affect vital organs such as the liver and kidneys, potentially causing cellular damage and tissue degeneration.[9] Furthermore, several heavy metals are recognized as human carcinogens. Chronic exposure may disrupt DNA synthesis and repair mechanisms, alter gene expression, and induce oxidative stress, leading to neurological disorders and increased cancer risk.[10]

Environmental monitoring of settled dust is an effective method for assessing contamination levels and identifying pollution hotspots. Dust particles act as carriers for toxic metals

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released from various human activities. Biological monitoring further improves exposure assessment, as individuals living or working near industrial sites often show elevated heavy metal levels in biological samples. For example, steel factory workers exhibited significantly higher metal concentrations in scalp hair compared with rural residents, indicating occupational exposure. Similarly, workers at gas stations in Erbil showed increased concentrations of Pb, Hg, As, Ni, Zn, Cu, and Co in dust, hair, and blood samples, linking prolonged exposure to adverse health outcomes.[5,11]

Hair analysis is useful for detecting long-term accumulation of metals, whereas blood analysis reflects more recent exposure. Combined biomonitoring provides a comprehensive understanding of exposure pathways and biological responses.[9,12,13] Integrating scalp hair, blood, and dust analyses provides a multimatrix approach that strengthens exposure assessment by capturing environmental contamination, chronic accumulation, and recent internal dose.[14,15]

The central problem addressed in this study is the lack of a comprehensive assessment of occupational exposure to heavy metals among workers in local power generation facilities in Erbil, particularly using integrated environmental and biological monitoring approaches. Although previous studies in the literature have evaluated heavy metal contamination in dust or single biological matrices – such as scalp hair or blood – among industrial workers and gas station employees in Erbil, these approaches remain limited in capturing the full extent of exposure pathways and internal accumulation.

To address this gap, the present study aims to evaluate heavy metal contamination and its health risks by integrating dust analysis with biological monitoring (scalp hair and blood) among generator workers and comparing the findings with a control population. Based on the results obtained, this objective has been successfully achieved. The study demonstrates significantly elevated concentrations of heavy metals in polluted sites compared to control areas, with extreme contamination levels for Zn and high contamination for Cu, as confirmed by Igeo and PLI indices. The findings also reveal that metal accumulation increases with years of occupational exposure and age, indicating a cumulative effect. Therefore, this study not only fills a critical research gap by providing the first integrated dust–hair–blood assessment for power generation workers in Erbil but also offers clear evidence of significant occupational health risks associated with prolonged exposure to generator emissions.

MATERIALS AND METHODS

Subjects

This research took place from September 2024 to May 2025. Individuals aged between 20 and 60 were split into two distinct groups, whereby the initial group, recognized as a test group, contained 60 individuals who were employed at 20 different local power-generating stations in Erbil, a city in northern Iraq. These persons had different lengths of work experience varying from 1 to 5 years ($n = 21$), 6 to 10 years ($n = 24$), and 11 years or more ($n = 15$) (where the n = number of employees). Erbil sits at an altitude of 414 m above sea level, positioned at longitude 43°15’ E and latitude 35°11’ N. The weather characteristics of chilly winters, moderate springs, and hot summers are akin to semi-arid zones.[16] The second group, referred to as the control group, involved 15 healthy individuals residing in uncontaminated rural mountainous areas in the Razga village in Qaladiza City, located 162.6 km away from Erbil city. This city is situated at a longitude of 45°8’55” E and a latitude of 36°22’30” N with an elevation of 1078 m above sea level, Figure 1. All contributors were briefed on the objectives of the study and provided their consent by signing up.

Dust Sampling

In September 2024, 60 dust samples were collected from 20 local power generation stations, along with 15 samples from a control area. Dust was gathered by holding clear zip-lock bags close to the ground and using a hand brush. Each location was sampled 3 times to make the results accurate and reliable. Sampling was done during the day to avoid moisture from dew, and the same method was used at all stations to keep the process consistent.

The levels of Pb, Hg, As, Ni, Zn, Cu, and Co were measured using an X-ray fluorescent spectrometer. All measurements were carried out in the laboratory with a Thermo Scientific Genius 9000 X-ray fluorescence (XRF) instrument.[17,18]

Hair Sampling

This study was conducted at 20 local power generation stations and included 60 workers from these facilities. To assess exposure to heavy metal pollution, scalp hair samples were collected from the 60 workers in polluted areas, along with samples from 15 individuals living in a clean environment to serve as controls. At each station, three hair samples were collected to ensure accuracy and reliability. The samples were immediately placed in pre-labeled plastic bags, sealed tightly, and stored safely for later processing.[19] Each sample was trimmed with scissors to weigh about 200–250 mg and then cleaned with ethanol.[20] The samples were cut into 0.3 cm pieces and combined to produce a representative subsample.[12] Following the International Atomic Energy Agency guidelines, the hair samples were washed with ethanol, rinsed 3 times with distilled water, washed again with ethanol, and finally rinsed with distilled water. The cleaned samples were then dried in an oven at 75°C for 15–25 min. After preparation, the samples were analyzed to detect the presence of Pb, Hg, As, Ni, Zn, Cu, and Co using XRF spectrometry with a Sky Instrument Genius device.[11]

Blood Sampling

Venous blood samples were collected from 60 workers in polluted areas and from 15 individuals in a clean environment as controls. At each station, three blood samples were collected to ensure accuracy and reliability. Each blood sample (3 mL) was drawn from the antecubital vein of participants using sterile disposable syringes after disinfecting the site with 70% isopropyl alcohol. The samples were immediately transferred into pre-labeled serum separator gel tubes.[21] All blood samples were kept at room temperature for 30 min to allow complete clot formation before processing.[22] After this step, the gel tubes were centrifuged at 3000 rpm for 15 min

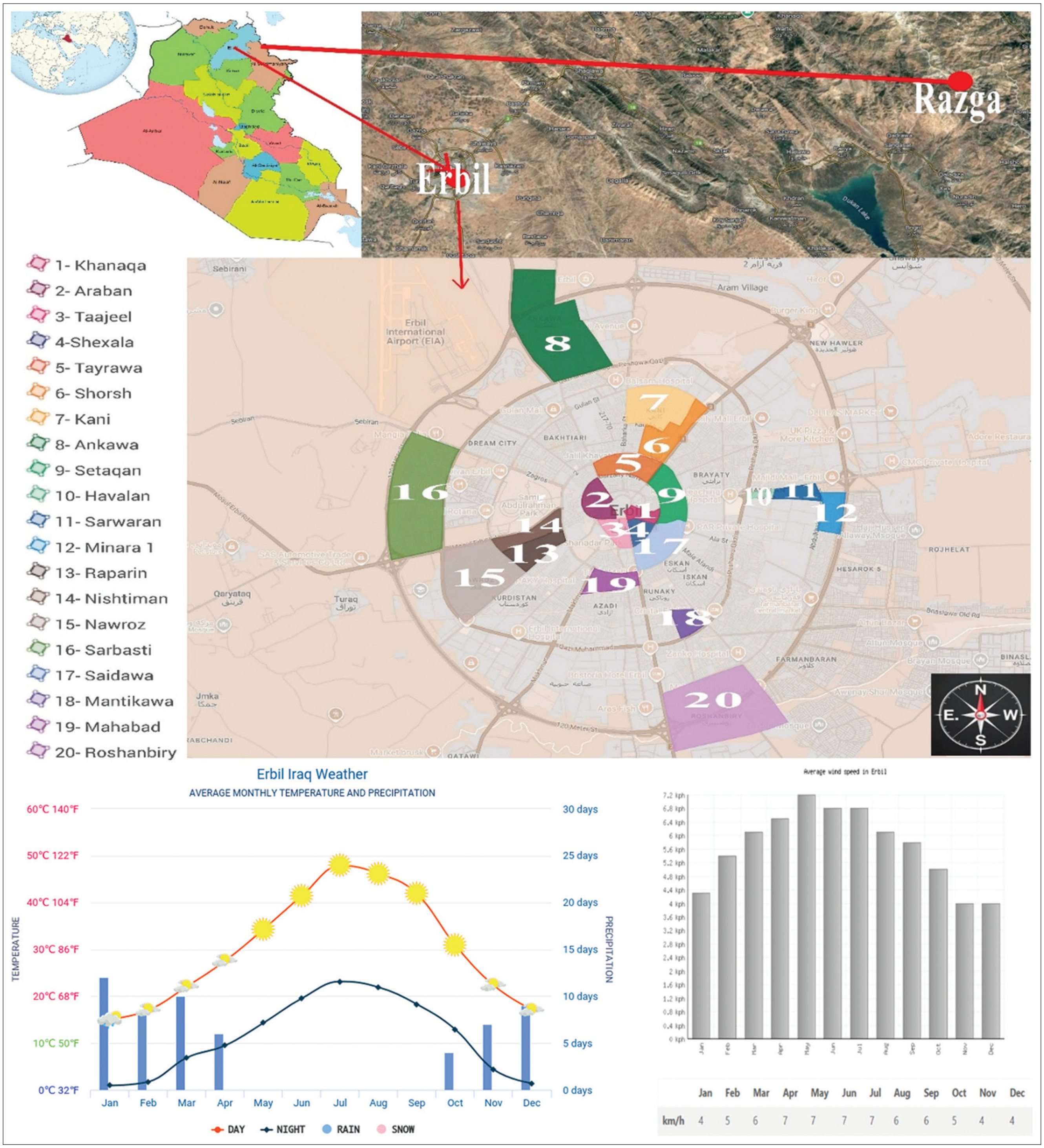

Figure 1: Map of study locations, highlighting the contaminated Erbil power generation site and the unpolluted Razga village. The power stations were chosen because they run every day and release heavy metals. The control samples came from a quiet area to provide a baseline. This control site was selected based on advice from station staff, who said it was a common dust hotspot during cleaning. After collection, the samples were quickly wrapped, labeled with station details and Global Positioning System coordinates, and packed in cardboard boxes to keep them safe until laboratory analysis

at 4°C to separate the serum from the cellular components.[23] Later, analysis was conducted to detect the presence of Pb, Hg, As, Ni, Zn, Cu, and Co by X-ray fluorescent spectrometry, Sky Instrument Genius.[24]

Contamination Evaluation Model

This investigation used the Geo-accumulation index (I_{geo}) and the pollution load index (PLI) to assess the level of metallic pollution in contaminated areas of Erbil province and in uncontaminated sites in Razga village. The PLI is an integrated measure of heavy metal contamination that is calculated using contamination factors (CFs), which compare metal concentrations to background levels. CF is essential because it determines the contribution of each metal and directly affects the accuracy and reliability of the PLI.

Constant 1.5 is the correction factor due to the variation of deviation in the background values. The I_{GEO} for every heavy metal is classified into $I_{geo} \leq 0$ (uncontaminated), $0 < I_{geo} \leq 1$ (uncontaminated to moderately contaminated), $1 < I_{geo} \leq 2$ (moderately contaminated), $2 < I_{geo} \leq 3$ (moderately to heavily contaminated), $3 < I_{geo} \leq 4$ (heavily contaminated), $4 < I_{geo} \leq 5$ (heavily to extremely contaminated), and $I_{geo} > 5$ (extremely contaminated).[14] The I_{geo} for each heavy metal was calculated using the following equation: [11]

$$I_{geo} = \log2 \, [Cn/1.5Bn] \quad (1)$$

In this study, Cn represents the calculated concentration of a heavy metal in the dust sample, whereas Bn refers to the geochemical background value of that metal. For this investigation, Bn was taken as the background value of the local soil.[5]

The CF is the concentration of metal in the dust divided by the metal background value:

$$CF = C_{metals}/C_{\text{background value of that metal}} \quad (2)$$

PLI was used to evaluate the degree of heavy metal pollution in the areas studied. A PLI value <0 is considered to be no pollution, whereas a PLI >0 indicates that the area was polluted.[25] PLI was calculated by the following equation:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \ldots CFn} \quad (3)$$

where CF = contamination factor of the metal and n = number of metals.

Statistical Analysis

Statistical analysis was carried out using the Statistical Package for the Social Sciences (version 29), and results were expressed as mean ± standard error to clearly represent variability. An independent Student's t-test was applied to compare the concentrations of heavy metals in dust, scalp hair, and blood between unpolluted and contaminated sites. Pearson correlation analysis was further used to examine the relationships between heavy metal concentrations in dust, hair, and blood. To compare heavy metal levels in hair and blood across different workplace groups and years of employment, analysis of variance was conducted. When significant differences were observed, Tukey's *post hoc* test was applied to identify specific group differences. For all statistical tests, $P \leq 0.05$ was considered statistically significant.

RESULTS AND DISCUSSION

Heavy Metal Content in Dust

The concentrations of heavy metals in dust collected from polluted and control sites are presented in Figure 2. The results revealed significant differences between the two locations, with all studied metals showing markedly higher levels in the polluted site compared to the control site ($P \leq 0.001$).

In the control site, the concentrations of metals in dust from highest to lowest were as follows: Pb (1.63), Hg (0.01), As (4.93), Ni (53.49), Zn (32.87), Cu (25.65), and Co (8.32) mg/kg. In contrast, in the polluted site, the metal concentrations followed this order: Pb (11.86), Hg (0.03), As (49.02), Ni (119.59), Zn (3662.62), Cu (392.46), and Co (16.83) mg/kg. The lowest metal concentration detected in the control site was Hg (0.01 mg/kg), whereas the highest was Ni (53.49 mg/kg). In the polluted site, Hg also showed the lowest value (0.03 mg/kg), whereas Zn recorded the highest concentration (3662.62 mg/kg) among all studied metals. These findings indicate a substantial enrichment of heavy metals in dust from the polluted area.

Today, the health of ecosystems, living organisms, and humans is at risk due to exposure to toxic heavy metals.[26] The working environment around the local power generation industry has drawn increasing attention from investigators, who study the effects of pollutants released by factories on human health.[27] At the local power generation site, the concentrations of all these metals except lead exceed the World Health Organization (WHO) limits, indicating significant heavy metal pollution in the area. In contrast, the rural site shows metal concentrations below the WHO limits for all studied metals except nickel. This suggests that the rural area is generally clean and not significantly contaminated with heavy metals. Toxic heavy metals and chemical compounds released from factories become suspended in the air as dust. Carried by the wind over long distances, this dust contaminates ecosystems far from the source.[28] Dust particles can enter the human respiratory system through the mouth and nose. These particles often contain toxic metals, which can harm human health. Health risks include breathing problems, vision loss, damage to body organs, and even death.[29] As a result, the buildup of dust containing high levels of heavy metals can provide important data on the potential health and environmental risks they pose.[30] This study examines the concentration of metallic elements at local power generation sites, focusing on pollutants released into the air and their potential harmful effects on workers' health. The findings support previous research on heavy metal contamination in dust, confirming the pollution sources and associated health risks.[31]

Pollution Assessment Index

The I_{geo}, CF, and PLI values for the analyzed metals, which indicate contamination levels at polluted sites compared to control areas, are presented in Table 1 and Figure 3. According to the I_{geo} index, Co at the polluted site, with a value of (0.16), falls within the category of uncontaminated to moderately contaminated. Ni, with an I_{geo} value of (1.99), is classified as moderately contaminated. As at (2.44), it falls into the category of moderately to heavily contaminated. Cu, with a value of (3.70), indicates heavy contamination, whereas Zn, at (5.20), reflects extreme contamination. In contrast, Pb with (−0.29) and Hg with (−1.00) are considered uncontaminated. The PLI at power generation sites is significantly high, with a value of 5.03, indicating substantial heavy metal contamination in

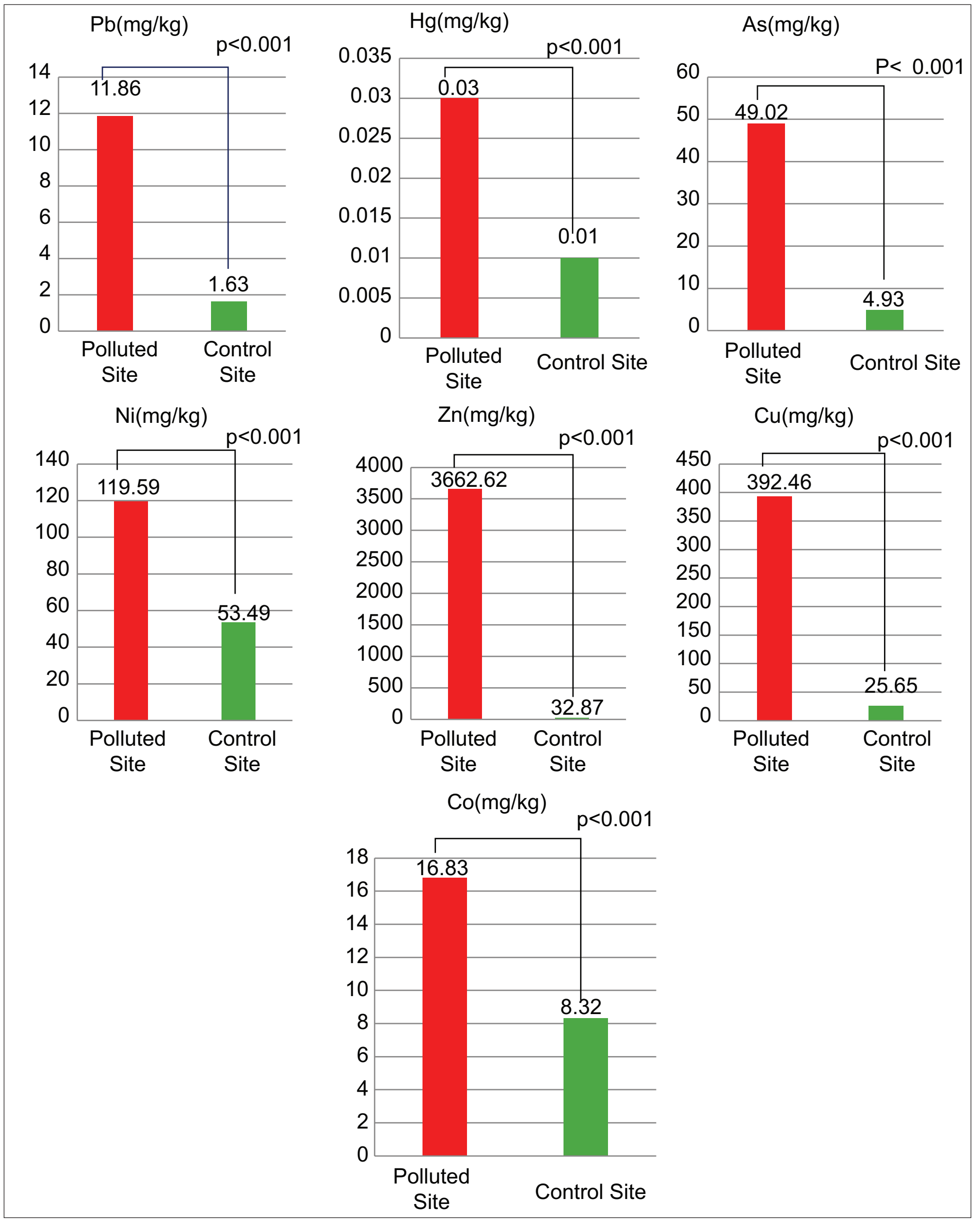

Figure 2: Mean ± standard error of dust metal level in polluted and control sites. According to the WHO, the standard permissible limits for heavy metals in soil are as follows: Lead at 100, arsenic at 40, nickel at 50, zinc at 300, and copper at 36 mg/kg[32,33]

Table 1: Dust heavy metal assessments utilizing the I_{geo}, CF, and PLI in power generation and rural areas compared to the soil backgrounds of the area

Heavy metals (mg/kg)	The polluted area within Erbil			Unpolluted area of Razga village			Background value mg/kg[34]
	Mean	I_{geo}	CF	Mean	I_{geo}	CF	
Pb	11.86	−0.29	1.22	1.63	−3.15	0.16	9.7
Hg	0.03	−1	0.75	0.01	−2.58	0.25	0.04
As	49.02	2.44	8.17	4.93	−0.86	0.82	6
Ni	119.59	1.99	5.97	53.49	0.83	2.67	20
Zn	3662.62	5.20	55.49	32.87	−1.59	0.49	66
Cu	392.46	3.70	19.62	25.65	−0.22	1.28	20
Co	16.83	0.16	1.68	8.32	−0.85	0.83	10
PLI	5.03			0.65			

I_{geo}: Geo-accumulation index, PLI: Pollution load index, Pb: Lead, Hg: Mercury, As: Arsenic, Ni: Nickel, Zn: Zinc, Cu: Copper, Co: Cobalt, CF: Contamination factors

Heavy Metal	Polluted Area (Erbil)	Control Area (Razga village)
Pb I_{geo}	−0.29	−3.15
Pb CF	1.22	0.16
Hg I_{geo}	−1.00	−2.58
Hg CF	0.75	0.25
As I_{geo}	2.44	−0.86
As CF	8.17	0.82
Ni I_{geo}	1.99	0.83
Ni CF	5.97	2.67
Zn I_{geo}	5.20	−1.59
Zn CF	55.49	0.49
Cu I_{geo}	3.70	−0.22
Cu CF	19.62	1.28
Co I_{geo}	0.16	−0.85
Co CF	1.68	0.83
PLI	**5.03**	**0.65**

Figure 3: Pollution assessment indices for heavy metals in dust (I_{geo}, CF, and PLI – Polluted and Control Sites). Red = Extreme/Heavy/Very high contamination (I_{geo} > 3, CF > 5, PLI > 1 strongly). Orange/Yellow = Moderate to heavy (I_{geo} 1–3). Yellow: 1–2 (moderately contaminated). Green = Uncontaminated to low (I_{geo} ≤ 0, CF < 1–2). I_{geo}: Geo-accumulation index, PLI: Pollution load index, Pb: Lead, Hg: Mercury, As: Arsenic, Ni: Nickel, Zn: Zinc, Cu: Copper, Co: Cobalt, CF: Contamination factors

these areas. In contrast, the I_{geo} values at the rural control site are all below 1, Pb (−3.15), Hg (−2.58), As (−0.86), Ni (0.83), Zn (−1.59), Cu (−0.22), and Co (−0.85), suggesting no contamination. In addition, the PLI at the control site is 0.65, which is also below 1, confirming minimal pollution.

The present findings are in strong agreement with studies conducted by[5] Erbil City, which reported elevated concentrations of heavy metals in environmental and biological samples, particularly Zn and Cu, in areas affected by industrial and fuel-related activities. Their study highlighted that generator emissions and occupational exposure significantly contribute to heavy metal accumulation in urban environments. Similarly,[35] documented increased levels of heavy metals in environmental samples collected from Erbil, with notable enrichment of Zn, Cu, and As in polluted locations compared to control areas. Both studies are consistent with the current results in demonstrating that Zn and Cu are the most prominent contaminants in Erbil's environment. At the same time, Pb and Hg tend to show relatively lower concentrations.

Heavy Metals Concentrations in Scalp Hair

This study compared the levels of metals in the hair of workers employed at a local power generation facility with those of individuals living in a rural area far from pollution sources. The results showed that workers in power generation had significantly higher concentrations of heavy metals in their hair compared to the control group. As illustrated in Figure 4, workers employed at local electricity generators had significantly higher levels of heavy metals in their scalp hair compared to individuals living in clean rural areas. The concentration of Pb, Hg, As, Ni, Zn, Cu, and Co in the hair of power generation workers is substantially elevated, with values of 8.74, 0.07, 3.75, 173.13, 710.29, 626.41, and 1.66 mg/kg, respectively. In contrast, the hair from the rural population demonstrates significantly lower concentrations of these metals: 4.34, 0.03, 0.77, 49.32, 240.71, 155.33, and 0.52 mg/kg. Among the metals detected at the polluted site, Zn and Cu had the highest concentrations (710.29 and 626.41 mg/kg), whereas Hg had the lowest (0.07 mg/kg).

The correlation analysis between heavy metals in scalp hair and dust showed several strong and significant associations, as illustrated in Table 2. Pb (r = 0.878**) exhibited the highest correlation, indicating that dust exposure is strongly reflected in hair levels. Cu (r = 0.762**) and Co (r = 0.713*) also showed strong positive correlations, whereas Hg (r = 0.550*), As (r = 0.613*), Ni (r = 0.542*), and Zn (r = 0.560*) demonstrated moderate but significant correlations.

The concentrations of heavy metals in scalp hair samples in workers at the local power generator showed a clear and statistically significant increase with longer years of occupational exposure compared to controls, as shown in Table 3. Pb levels rose from 4.34 mg/kg in the control group to 9.03 mg/kg in workers with more than 11 years of exposure, whereas Hg increased from 0.033 to 0.121 mg/kg. As concentrations also rose steadily, reaching 6.98 mg/kg in the longest exposure group compared to 0.77 mg/kg in controls. Ni levels were markedly higher in exposed groups, with 204.87 mg/kg in workers with 11 or more years compared to 49.32 mg/kg in controls. Zn and Cu, both essential trace elements, showed substantial increases, with Zn rising from 240.71 to 748.26 mg/kg and Cu from 155.33 to 683.24 mg/kg. Co levels also increased moderately, from 0.52 mg/kg in controls to 1.64 mg/kg in the longest exposure group.

These findings indicate that scalp hair is a sensitive biomarker for monitoring cumulative exposure to heavy metals. Extended occupational exposure to power generation is associated with a progressive and measurable increase in toxic metal accumulation in hair.

The concentrations of heavy metals in hair samples varied significantly across age groups, showing a progressive increase with advancing age, as shown in Table 4. Pb levels rose from 7.64 mg/kg in individuals aged 20–30 to 9.59 mg/kg in those aged 41 and above, whereas Hg increased from 0.052 to 0.094 mg/kg. The concentrations of As also rose steadily, reaching 7.68 mg/kg in the oldest group compared to 3.58 mg/kg in the youngest group. Ni levels were higher in older individuals, with 203.53 mg/kg in those aged 41 and above compared to 146.78 mg/kg in the 20–30 group. Zn and Cu, both essential trace elements, showed significant increases with age, with Zn rising from 623.75 to 808.95 mg/kg and Cu from 568.48 to 647.84 mg/kg. Co levels also increased moderately, from 1.54 mg/kg in the youngest group to 1.76 mg/kg in the oldest group. All differences were statistically significant, with p-values below 0.01 for most metals. These findings indicate a clear age-related trend in metal accumulation, where younger workers show lower concentrations and older workers display

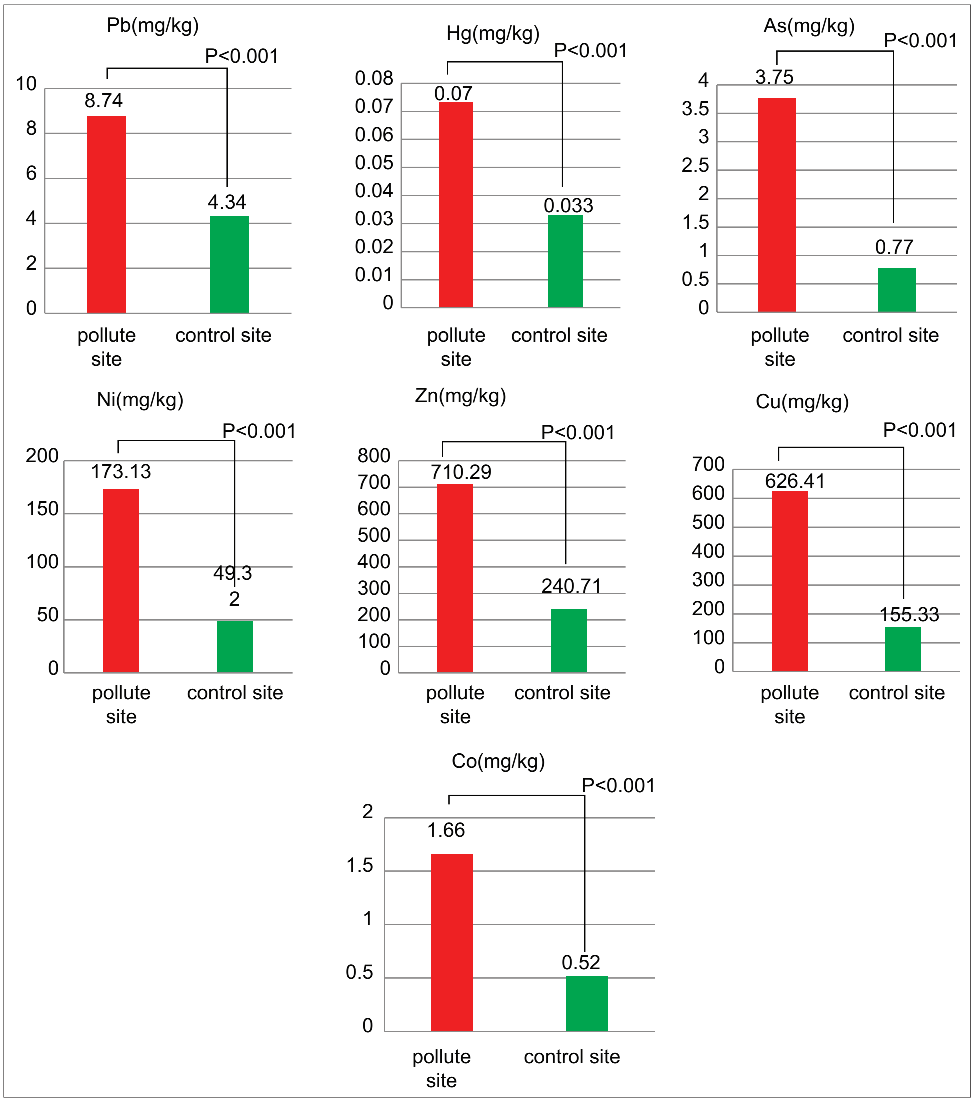

Figure 4: Mean ± standard error of scalp hair metal level in polluted and control sites

Table 2: Pearson correlation (r) between heavy metals in dust and scalp hair

Heavy metals in dust	Heavy metals in scalp hair						
	Pb	Hg	As	Ni	Zn	Cu	Co
Pb	0.878**						
Hg		0.550*					
As			0.613*				
Ni				0.542*			
Zn					0.560*		
Cu						0.762**	
Co							0.713*

*Correlation is significant at the $P \leq 0.05$ level. **Correlation is significant at the $P \leq 0.01$ level. A positive correlation was found between each heavy metal in dust and scalp hair. Increasing metal levels in dust reflect the increase in them in the hair. Pb: Lead, Hg: Mercury, As: Arsenic, Ni: Nickel, Zn: Zinc, Cu: Copper, Co: Cobalt

higher levels, reflecting cumulative occupational exposure and possible age-related changes in metabolism.

Hair plays an important role in monitoring heavy metals.[36,37] Human hair can absorb heavy metals as an excretory system and as metabolic products. It can incorporate metals into its structure throughout the growth phase. As a result, heavy metal concentrations in hair can represent the average level in the human body, reflecting the population's duration of exposure to heavy metals.[20] The results obtained in this study are consistent with the findings of,[11] who

Table 3: Mean±standard error of heavy metal concentration (mg/kg) in the worker's scalp hair across various durations of employment in power generation and control

Years of working	Pb	Hg	As	Ni	Zn	Cu	Co
Control (*n*=15)	4.34±0.39[c]	0.033±0.008[c]	0.77±0.06[d]	49.32±8.71[d]	240.71±70.13[c]	155.33±20.23[c]	0.52±0.23[b]
1–5 (*n*=22)	8.43±0.91[b]	0.051±0.016[b]	3.69±0.59[c]	130.81±2.41[c]	667.76±90.17[b]	584.25±68.39[b]	1.53±0.11[a]
6–10 (*n*=18)	8.93±1.25[a]	0.062±0.01[b]	4.87±0.71[b]	172.30±25.51[b]	731.77±41.89[a]	614.31±77.32[ab]	1.78±0.13[a]
11 and more (*n*=20)	9.03±0.72[a]	0.121±0.03[a]	6.98±1.28[a]	204.87±11.63[a]	748.26±59.20[a]	683.24±31.88[a]	1.64±0.11[a]
P-value	0.008	0.003	0.015	0.002	0.001	0.004	0.006

Post hoc analysis with Tukey's test, groups sharing the same letter show no differences. *n*: Number of workers. Significant differences are present between groups with different letters, Pb: Lead, Hg: Mercury, As: Arsenic, Ni: Nickel, Zn: Zinc, Cu: Copper, Co: Cobalt

Table 4: Mean±standard error of heavy metal concentrations (mg/kg) in the scalp hair of workers across different age groups in power generation

Ages	Pb	Hg	As	Ni	Zn	Cu	Co
20–30 (*n*=23)	7.64±1.45[b]	0.052±0.01[b]	3.58±0.80[b]	146.78±13.80[b]	623.75±78.01[b]	568.48±95.60[b]	1.54±0.08[a]
31–40 (*n*=19)	8.87±1.04[ab]	0.088±0.04[a]	4.41±0.58[b]	157.38±24.47[b]	714.89±28.04[ab]	665.24±28.05[a]	1.65±0.10[a]
41 and more (*n*=18)	9.59±0.36[a]	0.094±0.03[a]	7.68±0.89[a]	203.53±19.54[a]	808.95±70.96[a]	647.84±57.87[a]	1.76±0.13[a]
P-value	0.001	0.004	0.004	0.009	0.006	0.003	0.003

Post hoc analysis with Tukey's Test, groups sharing the same letter show no differences. *n*: Number of workers. Significant differences are present between groups with different letters, Pb: Lead, Hg: Mercury, As: Arsenic, Ni: Nickel, Zn: Zinc, Cu: Copper, Co: Cobalt

reported significant differences in heavy metal concentrations in the hair of workers exposed to pollutants compared to individuals living in rural areas far from pollution sources. The study revealed that welders in the United Arab Emirates had elevated concentrations of Pb and Ni in their hair compared to non-exposed individuals. Pb and Ni levels were significantly higher among workers with longer daily exposure and increased years of welding experience, reaching their highest levels in those with more than 20 years of work. These findings confirm that hair is a reliable indicator of long-term exposure to Pb and Ni, emphasizing the importance of occupational hazard awareness and regular health assessments for welders.[38]

Heavy metal exposure can lead to serious health problems. For example, arsenic exposure is associated with cancers such as skin, lung, and bladder cancer. Lead exposure may cause developmental delays and kidney problems. Mercury has been connected to the lungs, eyes, skin, excretory systems, and neurological damage. Other metals, including nickel, are known to cause respiratory problems and are recognized as carcinogenic.[39] Prolonged exposure to environmental pollutants was found to increase the accumulation of metals in scalp hair.[36] Because hair structure remains consistent, metals are gradually incorporated and retained within it. This makes hair a valuable indicator for monitoring metal exposure, especially in cases of long-term or sustained exposure. In addition, the concentration of metals in body tissues serves as a historical record of environmental exposure and biological changes over time.[5,40]

Overall, the results confirm that scalp hair is a reliable biomarker for monitoring long-term exposure to heavy metals and highlight the importance of protective measures and health monitoring for workers, particularly those with extended years of service.[41] Older workers are usually exposed to these environments for longer periods. Because of this extended exposure, they tend to accumulate more heavy metals over time. As a result, their hair often shows higher concentrations of heavy metals compared to younger workers, who have not been exposed for as long.[42,43]

Concentration of Heavy Metals in Blood

Workers in local power generation show significantly higher levels of heavy metals in their blood compared to individuals living in clean rural areas, as shown in Figure 5. The concentration of heavy metals in the blood of local electricity generator workers is substantially elevated. Measured values are: Pb (8.38), Hg (0.05), As (2.47), Ni (99.78), Zn (227.03), Cu (389.18), and Co (1.30) mg/kg. In contrast, the blood of individuals from rural areas demonstrates significantly lower concentrations of these metals. Recorded values are: Pb (5.18), Hg (0.01), As (0.80), Ni (28.24), Zn (84.72), Cu (90.71), and Co (0.84) mg/kg. Among the metals detected at the polluted site, Zn and Cu had the highest concentrations (227.03 and 389.18 mg/kg), whereas Hg had the lowest (0.05 mg/kg).

The correlation analysis between heavy metals in blood and dust revealed several significant associations, as shown in Table 5. Pb (r = 0.716*), Hg (r = 0.722*), As (r = 0.610*), Cu (r = 0.650*), and Co (r = 0.510*) all showed statistically significant positive correlations, suggesting that dust exposure contributes meaningfully to systemic levels of these metals. Ni (r = 0.413) and Zn (r = 0.439) displayed weaker, non-significant correlations, indicating that their presence in blood may be influenced more by dietary intake or physiological regulation than by dust exposure. Overall, these findings highlight that environmental dust is an important source of toxic metal exposure, particularly for Pb, Hg, As, Cu, and Co, whereas essential elements such as Zn and Ni appear less reliably reflected in blood through dust levels. This supports the role of dust monitoring as a complementary tool for assessing environmental exposure risks, especially for toxic metals with strong correlations.

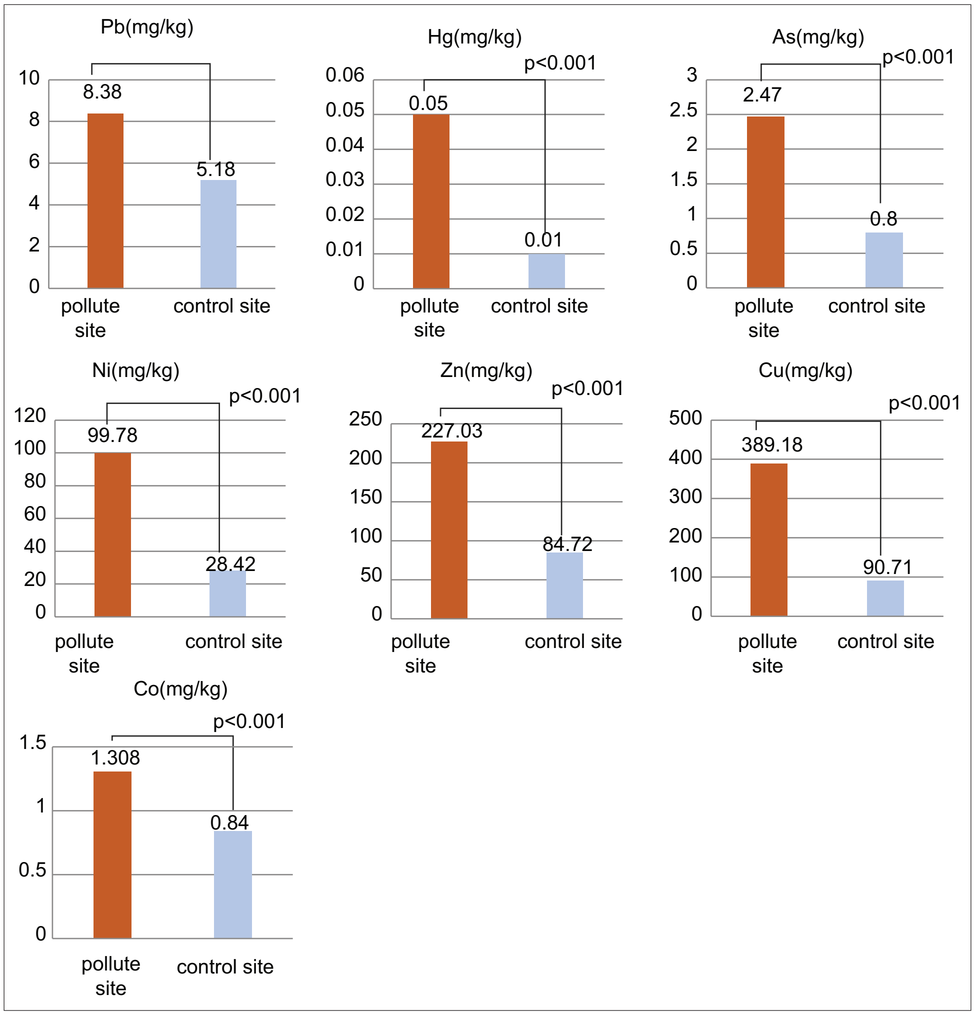

Figure 5: Mean ± standard error of blood metal level in polluted and control sites

Table 5: Pearson correlation (r) between heavy metals in dust and blood

Heavy metals in dust	Heavy metals in blood						
	Pb	Hg	As	Ni	Zn	Cu	Co
Pb	0.716*						
Hg		0.722*					
As			0.610*				
Ni				0.413			
Zn					0.439		
Cu						0.650*	
Co							0.510*

*Correlation is significant at the $P \leq 0.05$ level. A positive correlation was found between each heavy metal in dust and blood. Increasing metals in dust reflects the increase of them in the blood, Pb: Lead, Hg: Mercury, As: Arsenic, Ni: Nickel, Zn: Zinc, Cu: Copper, Co: Cobalt

The concentrations of heavy metals in workers increased significantly with years of occupational exposure compared to controls, as shown in Table 6. Pb rose from 5.18 mg/kg in controls to 9.33 mg/kg in those with more than 11 years of exposure, whereas Hg increased from 0.01 to 0.07 mg/kg, and As from 0.80 to 2.88 mg/kg. Ni levels were markedly higher in exposed groups, reaching 108.7 mg/kg compared to 28.42 mg/kg in controls. Similarly, Zn and Cu, which are essential trace elements, showed substantial rises, with Zn increasing from 84.72 to 254.72 mg/kg and Cu from 90.71 to 422.7 mg/kg. Co also rose moderately from 0.84 to 1.32 mg/kg. These statistically significant increases ($P < 0.01$ for most metals) suggest that prolonged occupational exposure leads to bioaccumulation of both toxic and essential metals.

The concentrations of heavy metals varied significantly across age groups, showing a progressive increase with advancing age, as shown in Table 7. Pb levels rose from 8.04 mg/kg in workers aged 20–30 to 9.67 mg/kg in those aged 41 and above, whereas Hg increased from 0.02 to 0.07 mg/kg across the same groups. As concentrations also rose steadily, reaching 3.08 mg/kg in the oldest group compared to 1.91 mg/kg in the youngest. Ni levels were higher in older workers, with 112.8 mg/kg in those aged 41 and above compared to 95.1 mg/kg in the 20–30 group. Zn and Cu, both essential trace elements, showed significant increases with age, with Zn rising from 228.12 to 245.90 mg/kg and Cu from 379.6 to 417.3 mg/kg. Co levels also increased moderately, from 1.23 mg/kg in the youngest group to 1.31 mg/kg in the oldest.

The correlation analysis revealed that blood and scalp hair concentrations of certain heavy metals were strongly associated, as shown in Table 8. With Pb (r = 0.920**), As (r = 0.810**), Hg (r = 0.730*), and Co (r = 0.731*) showing significant positive correlations, suggesting that hair can serve as a reliable biomarker for systemic exposure to these toxic elements. Ni also showed a moderately significant correlation (r = 0.551*), indicating partial reliability, whereas Zn (r = 0.290) and Cu (r = 0.371) exhibited weak and non-significant correlations, likely reflecting the influence of homeostatic regulation or external contamination of hair.

Research has been conducted to evaluate the blood serum concentrations of various trace elements, including Pb and Co, among individuals occupationally exposed to environmental hazards.[44] The mean serum concentrations of Pb were significantly higher among the exposed group compared to the control group. Similarly, Co concentrations showed a marked increase among exposed individuals compared to controls. Pb is known to be toxic all over the world; lead is a heavy metal and is present in trace amounts in the human body. In adults, Pb blood levels <10.0 mcg/dl are considered normal. Any reading between the range of 10.0–25.0 mcg/dl is a sign that the individual has been regularly exposed to lead.[45] The reference levels for acceptable Pb in the blood are below 5 ug/dL in adults and below 3.5 ug/dL in children, whereas

Table 6: Mean±standard error of heavy metal concentration (mg/kg) in the workers' blood across various durations of employment in power generation and control

Years of working	Pb	Hg	As	Ni	Zn	Cu	Co
Control (*n*=15)	5.18±0.27[c]	0.01±0.00[b]	0.80±0.02[c]	28.42±3.75[c]	84.72±2.74[d]	90.71±7.70[c]	0.84±0.07[b]
1–5 (*n*=22)	8.54±0.61[b]	0.02±0.00[b]	1.89±0.63[b]	91.7±3.90[b]	209.42±27.53[c]	356.3±50.64[b]	1.21±0.09[a]
6–10 (*n*=18)	8.56±0.60[b]	0.05±0.01[a]	2.32±0.48[ab]	104.9±37.30[a]	237.91±26.84[a]	409.30±43.29[a]	1.31±0.06[a]
11 and more (*n*=20)	9.33±0.53[a]	0.07±0.02[a]	2.88±0.32[a]	108.7±17.80[a]	254.72±23.20[a]	422.70±24.70[a]	1.32±0.11[a]
P-value	0.001	0.001	0.001	0.001	0.009	0.006	0.001

Post hoc analysis with Tukey's Test, groups sharing the same letter show no differences. *n*: number of workers. Significant differences are present between groups with different letters, Pb: Lead, Hg: Mercury, As: Arsenic, Ni: Nickel, Zn: Zinc, Cu: Copper, Co: Cobalt

Table 7: Mean±standard error of heavy metal concentration (mg/kg) in the blood of workers across different age groups in power generation.

Ages	Pb	Hg	As	Ni	Zn	Cu	Co
20–30 (*n*=23)	8.04±0.81[b]	0.02±0.00[c]	1.91±0.61[b]	95.10±16.30[b]	228.12±34.19[b]	379.60±36.77[b]	1.23±0.08[b]
31–40 (*n*=19)	8.70±0.58[b]	0.05±0.01[b]	2.10±0.27[b]	97.40±13.80[b]	228.03±28.27[b]	391.40±44.20[ab]	1.30±0.05[a]
41 and more (*n*=18)	9.67±0.28[a]	0.07±0.02[a]	3.08±0.46[a]	112.80±34.19[a]	245.90±26.20[a]	417.30±37.90[a]	1.31±0.09[a]
P-value	0.008	0.001	0.003	0.004	0.001	0.005	0.001

Post hoc analysis with Tukey's test, groups sharing the same letter show no differences. *n*: Number of workers. Significant differences are present between groups with different letters, Pb: Lead, Hg: Mercury, As: Arsenic, Ni: Nickel, Zn: Zinc, Cu: Copper, Co: Cobalt

Table 8: Pearson correlation (r) between heavy metals in scalp hair and blood

Heavy metals in scalp hair	Heavy metals in blood						
	Pb	Hg	As	Ni	Zn	Cu	Co
Pb	0.920**						
Hg		0.730*					
As			0.810**				
Ni				0.551*			
Zn					0.290		
Cu						0.371	
Co							0.731*

*Correlation is significant at $P \leq 0.05$ levels, **Correlation is significant at $P \leq 0.01$ levels. A positive correlation was found between each heavy metal in scalp hair and blood. Increasing metals in scalp hair reflects the increase of them in the blood, Pb: Lead, Hg: Mercury, As: Arsenic, Ni: Nickel, Zn: Zinc, Cu: Copper, Co: Cobalt.

the critical or hazardous levels are 70 ug/dL or greater in adults and 20 ug/dL or greater in children.[46,47]

Data from the National Health and Nutrition Examination Survey revealed that the interaction of chronic physiological stress and Pb level in the blood significantly increased the risk of cardiovascular mortality. In low and middle-class countries, pollution with heavy metals is associated with cardiovascular disease because their populations are exposed to these environmental pollutants.[29] Aligned with the current findings, previous results suggest that generator workers may show elevated levels of specific metals – such as Pb, Zn, and Cu in their blood serum. These increased levels can have significant health implications, particularly for workers with prolonged exposure.[44] The correlations between concentrations of potentially toxic elements in blood samples and levels in dust deposits collected over approximately 14 days were moderate for Zn and As.[48] Levels of heavy metals were found to increase with both age and work duration.[49] Prolonged exposure due to continuous work shifts results in higher intake levels of heavy metals. Our study calculated the intake based on factors such as the concentration of metals in the air, inhalation rates, and exposure duration. The findings indicate that longer exposure leads to higher intake and, consequently, greater health risks. For example, workers with 30 years of work were found to have statistically significantly increased health concerns, such as hypertension, cardiovascular illnesses, and hepatic insufficiency.[15,50]

The statistically significant differences across age groups emphasize the cumulative nature of heavy metal toxicity, underscoring the need for age-sensitive monitoring, preventive strategies, and stricter workplace safety measures to protect long-term worker health. Older workers often exhibit higher levels due to cumulative exposure over time, especially in industries such as fuel stations, oil refineries, and cement plants.[51,52] Age-based analysis indicated that heavy metal levels increased progressively with age, recording the highest concentrations.[53] Research measured Pb, Zn, and Cu in blood serum. Results indicated that older workers had significantly higher concentrations, reflecting bioaccumulation from prolonged exposure.[51] A health risk assessment found that long-term exposure to refinery pollutants increased heavy metal levels in blood, with age positively correlated to concentration. Younger workers showed lower levels compared to those with decades of service.[50]

The central objective of this study was to determine whether occupational exposure to heavy metals among power generation workers in Erbil could be reliably detected through an integrated environmental-biological monitoring framework (dust, hair, and blood). Our results unequivocally support this premise. The strong positive correlations between dust and biological samples (e.g., Pb hair–dust: $r = 0.878$; Pb blood–dust: $r = 0.716$) confirm that airborne dust is a major exposure pathway. Thus, the data fully demonstrate what we set out to prove: power generation facilities are a significant source of heavy metal exposure, and multi-matrix biomonitoring effectively captures both environmental contamination and human uptake.

In my interpretation, the extreme Zn and Cu levels in dust (3662.62 and 392.46 mg/kg, respectively) arise from the widespread use of lubricating oils, engine wear, and corrosion of metal components in diesel generators – a previously under-quantified source. The moderate but significant correlations for Hg and As ($r = 0.550$–0.613) suggest that these toxic metals originate from fuel impurities rather than direct additives.

The implications are clear and actionable. First, occupational health agencies in Erbil and similar cities should mandate routine blood and hair biomonitoring for power plant workers, especially those with >5 years of service. Second, engineering controls – dust suppression (wet sweeping), high-efficiency ventilation, and enclosed generator cabins – should be implemented immediately. Personal protective equipment (N95 masks, gloves) is a short measure but not a substitute for source control. Third, our data support relocating power generators away from residential areas, as the high PLI (5.03) indicates that surrounding communities are also at risk.

Several limitations must be acknowledged. First, our sample size is modest (60 workers and 15 controls), which may limit statistical power for subgroup analyses. Second, we did not measure indoor dust at workers' homes so that non-occupational exposure could contribute to the observed levels. Third, we did not collect urine samples, which would have helped distinguish recent versus cumulative exposure. Fourth, the cross-sectional design prevents us from establishing causality – we cannot rule out that some workers had pre-existing elevated metal levels.

In summary, this study not only fills a critical data gap but also provides a methodological template for occupational risk assessment in low- and middle-income countries where diesel generators are ubiquitous. Finally, we recommend that the wider research community investigate the cumulative health impact of mixed metal exposures (toxic + essential) rather than focusing on single metals, as our data show that co-accumulation of Zn and Cu with Pb and As is the real-world scenario.

CONCLUSION

This study demonstrates that occupational exposure to emissions from power generators in Erbil leads to significant environmental contamination and human bioaccumulation of heavy metals. Using a multi-matrix approach (dust, hair, and blood), it shows strong links between environmental and internal exposure, with airborne dust as a key pathway. Metal accumulation increases with age and employment duration, confirming cumulative exposure. Compared to single-matrix studies, this approach provides a more reliable framework for assessing occupational risk. High contamination levels, especially for Zn and Cu, and elevated PLI values highlight serious health concerns, emphasizing the need for improved ventilation, dust control, and routine biomonitoring. Limitations include a small sample size and a cross-sectional design. Future studies should be longitudinal and broader in scope, while stricter regulations and continuous monitoring are recommended to protect workers and nearby communities.

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