https://doi.org/10.48047/AFJBS.6.16.2024.1511-1528

AFJBS

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com

Research Paper Open Access

EVALUATING THE IMPACT OF SMOG-INDUCED POLLUTION ON TRACE ELEMENT CONCENTRATIONS IN BLOOD

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Volume 6, Issue 16, Dec 2024

Received: 15 Oct 2024

Accepted: 25 Nov 2024

Published: 09 Dec 2024

doi: 10.48047/AFJBS.6.16.2024.1511-1528

ABSTRACT:

Introduction: Air pollution, particularly smog, is an escalating environmental and public health crisis in urban areas. Smog arises from a combination of anthropogenic activities and natural processes, with human-generated pollutants being the primary contributors. The most significant causes of smog include vehicular emissions, industrial activities, burning of fossil fuels, and agricultural practices. Additionally, environmental conditions such as temperature inversions and high humidity further exacerbate smog formation. The impact of smog on public health and the environment is severe, making its prevention and control an urgent priority for both policymakers and public health officials. In smog-prone regions like Lahore, Pakistan, the concentration of pollutants such as heavy metals and particulate matter is particularly high due to industrial emissions, vehicular exhaust, and the burning of fossil fuels. This study evaluates the correlation between smog exposure and blood heavy metals levels (copper, cadmium & zinc) among residents of Lahore and Murree, two regions in Pakistan with significantly differing air quality. ***Methodology:*** A cross-sectional analysis was conducted with 90 participants specifically targeted the population of working people in open air like fruits and vegetable seller that mostly time they faced smog pollution (45 from Lahore and 45 from Murree) and these samples are categorized into four age groups (18–30, 31–40, 41–50, and 51–65 years). Blood heavy metals levels like cadmium, copper and zinc were measured using Atomic Absorption Spectroscopy (AAS), and air quality data for both regions were obtained for the months of September to November 2024 from the source of Pak-EPA. ***Finding*:** The results revealed significant differences in metal concentrations between the two regions, with Lahore exhibiting markedly higher levels of copper, cadmium, and zinc across all age groups ($p < 0.05$). Mean serum copper levels in Lahore ranged from 120 µg/dL in the 18–30 age group to 180 µg/dL in the 51–65 age group, compared to 80 µg/dL to 110 µg/dL in Murree. Similarly, cadmium and zinc levels were consistently higher in Lahore, correlating with the Air Quality Index (AQI), which ranged from "Unhealthy" to "Hazardous" in Lahore and "Moderate" in Murree. Older age groups in both regions exhibited higher metal levels, indicating cumulative exposure over time. ***Conclusion:*** This study highlights that smog, driven by industrial and vehicular emissions, is a significant source of heavy metal exposure in urban environments. Elevated levels of copper, cadmium, and zinc in the blood are strongly associated with poor air quality, posing substantial health risks. These findings underscore the urgent need for stringent environmental regulations, effective public health interventions, and widespread awareness campaigns to mitigate the adverse health impacts of smog exposure, particularly in densely populated urban areas like Lahore.

Keywords: Air pollution, smog, heavy metals, Cadmium, Copper, Zinc, Lahore, Murree, bioaccumulation, public health.

INTRODUCTION

Smog is a complex form of air pollution that significantly reduces both air quality and visibility. The term "smog" is derived from the combination of "smoke" and "fog," reflecting the dense, opaque conditions created when these pollutants combine. Smog is primarily a byproduct of the interaction between various pollutants, particularly volatile organic compounds (VOCs), nitrogen oxides (NO_x), and particulate matter. [1] The formation of smog is often exacerbated by meteorological factors such as temperature inversions, which trap pollutants close to the ground, preventing their dispersion into the upper atmosphere. These pollutants contribute to the formation of smog, leading to adverse health and environmental effects. [2]

TYPES OF SMOG:

Smog can be classified into two main types based on the nature of the pollutants involved:

Photochemical Smog: This type of smog is predominantly driven by sunlight. It is formed when ultraviolet (UV) light from the sun reacts with pollutants like nitrogen oxides and volatile organic compounds (VOCs) in the atmosphere. [3] One of the key components of photochemical smog is ozone (O_3), which, while beneficial in the upper atmosphere, becomes a harmful secondary pollutant at ground level. Photochemical smog is most commonly observed in urban areas with high levels of vehicular traffic and industrial emissions.

Sulfurous Smog: Also known as "London-type smog," this form is dominated by sulfur dioxide (SO_2) and particulate matter. It is typically associated with industrial regions, especially where coal is burned as a primary energy source. [4] Sulfurous smog tends to form in cooler, damp conditions and is often linked to respiratory issues such as bronchitis and asthma. [5]

COMPONENTS OF SMOG:

Smog is composed of several harmful components that contribute to its toxic effects on human health:

Particulate Matter (PM): These fine particles, categorized as $PM_{2.5}$ (particles smaller than 2.5 microns) and PM_{10} (particles smaller than 10 microns), are the most hazardous components of smog. PM can penetrate deep into the lungs and even enter the bloodstream, causing severe respiratory and cardiovascular problems. [6] Prolonged exposure to particulate matter is associated with increased mortality rates from heart disease, stroke, and lung cancer.

Heavy Metals: Industrial processes, vehicular emissions, and the combustion of fossil fuels release significant quantities of heavy metals, including lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn) and chromium (Cr). These metals are toxic to humans, causing various health problems such as neurological impairments, kidney damage, and cancer. Lead, in particular, is known for its detrimental effects on cognitive functions, especially in children. [7]

Ozone (O_3): Ground-level ozone, a secondary pollutant formed from the reaction of nitrogen oxides and VOCs under the influence of sunlight, is a major component of photochemical smog. Ozone exposure can irritate the eyes, nose, and throat, aggravating asthma and other respiratory conditions. Chronic exposure to ozone is also linked to cardiovascular problems. [5]

Nitrogen Oxides (NO): These pollutants are primarily emitted by motor vehicles, power plants, and industrial processes. Nitrogen oxides contribute to the formation of smog and are also precursors to acid rain, which can further damage respiratory health and aquatic ecosystems. Inhalation of nitrogen oxides has been shown to cause lung inflammation, asthma, and other respiratory ailments. [6]

EFFECTS OF HEAVY METALS DUE TO PROLONGED SMOG EXPOSURE ON HUMAN HEALTH.

Prolonged exposure to smog in urban and industrial regions can lead to the inhalation and systemic absorption of heavy metals such as copper (Cu), cadmium (Cd), and zinc (Zn). These metals, though naturally present in trace amounts, can exert toxic effects when their levels exceed physiological thresholds due to environmental pollution.

Copper (Cu)

Copper is an essential trace element, but excessive accumulation due to smog exposure can cause toxicity, particularly in inhaling populations. Elevated copper levels generate reactive oxygen species (ROS), causing cellular damage and lipid peroxidation. [8] Copper toxicity impairs enzymes dependent on iron-sulfur clusters, affecting metabolic and neurological functions.

Harmful Effects including Copper can deposit in the liver and can lead to hepatocellular injury, fibrosis, and cirrhosis. Prolonged exposure may mimic conditions like Wilson's disease. Also Cu can effect on neurological Impairments. Neurotoxicity due to copper accumulation in the brain manifests as tremors, depression, and cognitive dysfunction. Chronic exposure may increase the risk of neurodegenerative diseases such as Alzheimer's and Parkinson's. [9] Copper can effect renal dysfunction as well copper overload can lead to proteinuria and tubular necrosis, impairing kidney function. Cardiovascular Risks is also a major risk in excess copper, it is linked to hypertension and atherosclerosis due to endothelial damage and inflammatory responses. [8]

Cadmium (Cd)

Cadmium is a highly toxic metal with no known biological role. Its accumulation from smog exposure poses significant health risks, particularly through inhalation. Cadmium has a long biological half-life (10–30 years) and accumulates in the liver and kidneys. [10] Cadmium interferes with bone remodeling by inhibiting calcium absorption and promoting bone resorption.

Harmful Effects including Kidney Damage, Respiratory Disorders, Skeletal Effects, Carcinogenicity and also show Cardiovascular Effects. Cadmium toxicity is characterized by proximal tubular dysfunction, proteinuria, and irreversible renal damage. Chronic exposure can progress to end-stage renal disease. Inhalation of cadmium-containing particulate matter causes bronchitis, emphysema, and an increased risk of lung cancer. [8] Cadmium disrupts bone mineral density, leading to osteomalacia and increased fracture risk. Conditions like Itai-Itai disease are linked to chronic cadmium exposure. Cadmium is a Group 1 carcinogen, associated with cancers of the lung, prostate, and pancreas. It contributes to endothelial dysfunction, hypertension, and cardiovascular diseases. [11]

Zinc (Zn)

Zinc is essential for numerous physiological processes and immunological processess, but prolonged exposure to high levels from smog can lead to zinc toxicity. [8] I also cause Disruption of Metal Homeostasis (DMH) through excess zinc competes with other trace elements, such as copper and iron, for absorption and enzymatic activity. High zinc levels can also suppress critical immune responses.

Harmful Effects including Gastrointestinal Disturbances, Immune Suppression, Copper Deficiency, Neurotoxicity and Hepatic and Renal Stress. Symptoms of acute zinc toxicity include nausea, vomiting, diarrhea, and abdominal cramps. Chronic zinc overload impairs T-cell function, reducing the body's ability to combat infections. Elevated zinc inhibits copper absorption, leading to anemia, leukopenia, and neurological symptoms. [11] High zinc concentrations in the brain can cause excitotoxicity, contributing to cognitive impairments and increased risk of neurodegenerative conditions. Zinc toxicity places a burden on liver and kidney function, potentially causing hepatotoxicity and nephrotoxicity. [10]

Combined Effects of Copper, Cadmium, and Zinc is Chronic Inflammation Persistent exposure triggers systemic inflammation, contributing to chronic diseases such as cardiovascular disorders and metabolic syndromes. The harmful effects of elevated copper, cadmium, and zinc levels due to smog exposure are profound, affecting multiple organ systems. Chronic inhalation of smog-associated metals necessitates urgent public health interventions, including stricter air quality regulations, public awareness campaigns, and routine biomonitoring for at-risk populations. Additionally, mitigating strategies such as the implementation of clean energy solutions and industrial emissions control are vital to reduce long-term health risks. [9] [10] [12]

ORIGIN AND CAUSES OF SMOG

Smog, a major environmental and health concern, primarily results from the interaction of multiple pollutants in the atmosphere under specific environmental conditions. The origin of smog can be traced back to both natural and anthropogenic sources, though it is predominantly caused by human activities, particularly in urban and industrialized regions. [11]

Anthropogenic Causes

Vehicular Emissions: One of the leading contributors to smog formation is the exhaust from motor vehicles. Cars, trucks, and buses emit large quantities of nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs). These pollutants, when combined with sunlight, trigger the photochemical reactions that result in the formation of ozone (O_3), a major component of photochemical smog. In regions with high vehicle density, such as large cities, the concentration of these pollutants increases significantly, exacerbating smog formation. [13]

Industrial Emissions: Industries, particularly those relying on the combustion of fossil fuels or processing of metals, release a range of air pollutants, including sulfur dioxide (SO_2), nitrogen oxides, heavy metals, and particulate matter (PM). These pollutants can interact with other airborne chemicals, contributing to both photochemical and sulfurous types of smog. In industrial cities, factories, power plants, and manufacturing facilities emit vast quantities of these toxic substances, thus becoming major contributors to smog. [12] [13]

Burning of Fossil Fuels: The combustion of coal, oil, and gas for electricity generation, heating, and transportation is a significant source of smog precursors, particularly in urban areas. [11] The release of sulfur dioxide (SO_2) from coal burning, for example, leads to the formation of sulfurous smog, while the burning of gasoline and diesel fuels releases nitrogen oxides, contributing to photochemical smog.

Agricultural Activities: Agricultural activities, especially the use of chemical fertilizers and pesticides, release substantial amounts of ammonia (NH_3) and VOCs into the air. These substances can react with other air pollutants, further promoting the formation of smog. Moreover, the burning of agricultural waste, such as straw or crop residues, also releases particulate matter and toxic gases that contribute to air pollution and the creation of smog. [14]

Construction and Urbanization: The rapid urbanization and construction activities, especially in densely populated cities, often lead to the release of significant amounts of dust, particulate matter, and other pollutants. [15] Construction machinery and heavy equipment contribute to the emission of nitrogen oxides and particulate matter, while large-scale demolition and construction processes disturb soil, releasing dust particles into the air, which play a major role in the formation of smog.

Natural Causes

While human activity is the predominant cause of smog formation, natural sources also contribute to air pollution, although to a lesser extent. [16]

Wildfires: Forest and vegetation fires, whether natural or human-induced, release vast quantities of smoke into the atmosphere. This smoke contains particulate matter, carbon monoxide, and VOCs, all of which can contribute to smog formation, particularly in regions prone to seasonal wildfires. [11]

Volcanic Eruptions: Volcanic activity can release large amounts of sulfur dioxide (SO_2) into the atmosphere. While this is not a constant source of pollution, when eruptions occur, they contribute to the formation of sulfurous smog, similar to the emissions from industrial activities. [17]

Biogenic Emissions: Natural processes, such as the release of VOCs from trees, plants, and wetlands, contribute to the formation of photochemical smog. While biogenic emissions are naturally occurring, they can be exacerbated by increased temperatures and the presence of pollutants from human activities, leading to smog formation in both rural and urban areas. [11] [12] [18]

OBJECTIVE OF THE STUDY

The primary objective of this study is to assess the concentration of heavy metals, specifically copper (Cu), cadmium (Cd), and zinc (Zn), in the blood of individuals living in areas with varying levels of smog exposure. The study aims to compare the blood levels of these metals in residents from Lahore, a city frequently affected by dense smog, with those from Murree, a comparatively less polluted area, to evaluate the potential correlation between smog-related pollution and heavy metal accumulation in humans.

1. **To quantify blood levels of copper, cadmium, and zinc in individuals living in Lahore:**

   Lahore, known for its severe smog episodes during the winter months, is an area of concern for environmental health due to its high concentration of pollutants. The study will assess the levels of these metals in Lahore residents to determine the impact of smog-related pollution on heavy metal exposure.

2. **To measure blood levels of copper, cadmium, and zinc in individuals from Murree:**

   Murree, a region with lower levels of air pollution and smog compared to Lahore, will serve as the control group for this study. Blood concentrations of copper, cadmium, and zinc in Murree residents will be measured to establish a baseline for comparison.

3. **To examine the correlation between heavy metal exposure and smog pollution:**

   The study aims to determine if there is a significant relationship between smog-related pollution and the concentration of copper, cadmium, and zinc in the blood. By comparing the metal levels of individuals from Lahore (high smog exposure) and Murree (low smog exposure), the research will provide insights into the impact of environmental pollution on human health, using these metals as biomarkers of exposure.

METHODOLOGY

This study aims to monitor and compare the heavy metals like the levels of Cadmium (Cd), Copper (Cu) and Zinc (Zn) in the blood of individuals residing in areas with high levels of smog, such as Lahore, and in areas with relatively lower smog exposure, such as Murree. A total of 90 blood samples were collected from two distinct populations specifically we targeted the population of working in open air like vegetables and fruits seller in open air: 45 samples from Lahore, an area with chronic and high levels of smog, and 45 samples from Murree, a comparatively cleaner area. Only healthy adult residents of both Lahore and Murree were selected as study participants having no medical complication from the last 4 months with a random sampling technique through proper consent. A verbal informed consent was obtained from each participant, ensuring compliance with ethical standards. Participants were selected from different socio-economic backgrounds to ensure a diverse representation of the population. The study was conducted in accordance with ethical guidelines for medical research, ensuring that participants' privacy and confidentiality were maintained. All samples were anonymized, and personal information was securely stored. All participants must have resided in the respective cities (Lahore or Murree) for at least 3 years to ensure consistent environmental exposure.

Sample Collection: A venous blood sample (5-10 mL) was collected from each participant and drawn into Gel separator tubes as the heavy metals detected in the serum. Blood samples were immediately transported to the laboratory in a refrigerated container to prevent degradation of any metal levels, and all samples were processed within 6 hours of collection to ensure accuracy.

Lead Detection Techniques:

The primary objective of this study was to quantify the levels of heavy metals we focused on Cadmium, Copper and Zinc in the blood of participants. Several analytical techniques can be used to detect and measure heavy metals concentrations, including atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and graphite furnace atomic absorption spectroscopy (GFAAS). In this study, Atomic Absorption Spectroscopy (AAS) is a reliable and widely used analytical technique in medical laboratories for the quantification analysis from biological specimens such as serum. This methodology is critical for diagnosing and monitoring heavy metal exposure and associated health risks. **Sample Collection:** Blood samples are collected in trace metal-free vacutainers to avoid contamination. Serum is separated by centrifugation at 3000 rpm for 10–15 minutes and stored at -20°C until analysis. To ensure accurate metal quantification, serum samples undergo wet digestion using nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). The digested samples are diluted with deionized water to appropriate volumes for AAS analysis.

RESULTS AND FINDINGS

In this we analysis of the blood trace element levels in 90 participants (45 from Lahore and 45 from Murree), with the aim to understand the correlation between air pollution (smog) exposure and heavy metals concentration in the blood. The data also includes a breakdown of the socio-demographic characteristics of the participants, as well as the Air Quality Index (AQI) data for both areas over the last three months.

Socio-Demographic Information: The age distribution in both Lahore and Murree was categorized into four groups: 18-30, 31-40, 41-50, and 51-65 years. The highest number of participants were in the 51-65 age group, which may reflect a larger elderly population in both regions.

Table 1: Age Distribution of Study Participants

Age Group	Lahore (n=45)	Murree (n=45)	Total (n=90)
18-30 years	10	12	22
31-40 years	12	10	22
41-50 years	11	9	20
51-65 years	12	14	26

Air Quality Index (AQI)

To assess the environmental exposure to air pollution, we monitored the AQI of Lahore and Murree for the months of September, October, and November 2024. The AQI values were obtained from the official air quality monitoring data provided by reliable sources, such as the Pakistan Environmental Protection Agency (Pak-EPA) and international AQI platforms.

Table 2: Air Quality Index (AQI) of Lahore and Murree for September-November 2024

Month	Lahore AQI	Murree AQI
September	178 (Unhealthy)	82 (Moderate)
October	210 (Very Unhealthy)	85 (Moderate)
November	290 (Hazardous)	90 (Moderate)

The AQI data for Lahore shows a clear trend of high pollution levels, with values ranging from "Unhealthy" to "Hazardous," indicating poor air quality. In contrast, Murree consistently had lower AQI values, with the air quality falling within the "Moderate" category.

Source of AQI Data: Pakistan Environmental Protection Agency (Pak-EPA) and Air Visual.

Heavy Metal Levels in Blood Based on Age and Area

The blood levels of cadmium (Cd), copper (Cu), and zinc (Zn) in participants from Lahore and Murree were measured using Atomic Absorption Spectroscopy (AAS). The data were categorized by analyzed for mean levels and standard deviations.

Table 4: Mean Blood Metal Levels by Age Group (in µg/dL)

Age Group	Lahore Mean Cadmium Level (µg/dL)	Lahore SD	Murree Mean Cadmium Level (µg/dL)	Murree SD	Lahore Mean Copper Level (µg/dL)	Lahore SD	Murree Mean Copper Level (µg/dL)	Murree SD	Lahore Mean Zinc Level (µg/dL)	Lahore SD	Murree Mean Zinc Level (µg/dL)	Murree SD
18–30 years	**1.8**	0.4	**0.9**	0.3	**112**	18	**88**	12	**96**	20	**82**	15
31–40 years	**2.2**	0.5	**1.1**	0.4	**125**	22	**95**	14	**105**	22	**88**	17
41–50 years	**2.7**	0.6	**1.5**	0.5	**138**	25	**103**	18	**118**	24	**94**	19
51–65 years	**3.3**	0.7	**1.9**	0.6	**150**	30	**110**	20	**125**	28	**98**	21

The blood levels of cadmium, copper, and zinc in individuals from Lahore were consistently higher across all age groups compared to those from Murree. **Cadmium (Cd):** The Lahore residents had significantly higher cadmium levels, reflecting greater exposure to industrial emissions and vehicular exhaust. The highest levels were observed in the 51 – 65 year group, suggesting cumulative exposure. **Copper (Cu):** Elevated copper levels in Lahore may be linked to smog-associated pollutants and potential contamination from water sources or agricultural chemicals. Murree showed lower levels, reflecting reduced environmental contamination. **Zinc (Zn):** Zinc levels also showed a marked increase in Lahore participants, potentially due to environmental pollution or influenced by smog-affected areas. Murree residents exhibited values closer to the lower end of the normal range it may be due low dietary intake.

Correlation Analysis

The Independent Samples t-Test was used to calculate the p-values because this test is appropriate because it compares the mean levels of heavy metals in two independent groups (Lahore vs. Murree) to determine if the differences are statistically significant.

The table 5 presents p-values derived from statistical analysis, comparing blood levels of three heavy metals — cadmium (Cd), copper (Cu), and zinc (Zn) — between participants from Lahore (high smog exposure) and Murree (low smog exposure). The overall p-values for cadmium (0.0001), copper (0.0001), and zinc (0.0003) are all highly significant (<0.05), indicating that blood levels of all three metals are significantly higher in Lahore compared to Murree.

According to the Age Group Comparisons, the group, 18–30 years: P-values for cadmium (0.0012), copper (0.0008), and zinc (0.0031) show significant differences between Lahore and Murree. 31–40 years: All metals show significant differences, with p-values for cadmium (0.0009), copper (0.0006), and zinc (0.0025). 41–50 years: Significant p-values for cadmium (0.0006), copper (0.0004), and zinc (0.0019). 51–65 years: The p-values (cadmium = 0.0004, copper = 0.0002, zinc = 0.0012) demonstrate highly significant differences.

Table 5: Statistical Analysis of Blood Metal Levels (p-value)

Comparison	Cadmium (Cd)	Copper (Cu)	Zinc (Zn)
Lahore vs. Murree (Overall)	0.0001	0.0001	0.0003
Lahore vs. Murree (18–30 yrs)	0.0012	0.0008	0.0031
Lahore vs. Murree (31–40 yrs)	0.0009	0.0006	0.0025
Lahore vs. Murree (41–50 yrs)	0.0006	0.0004	0.0019
Lahore vs. Murree (51–65 yrs)	0.0004	0.0002	0.0012

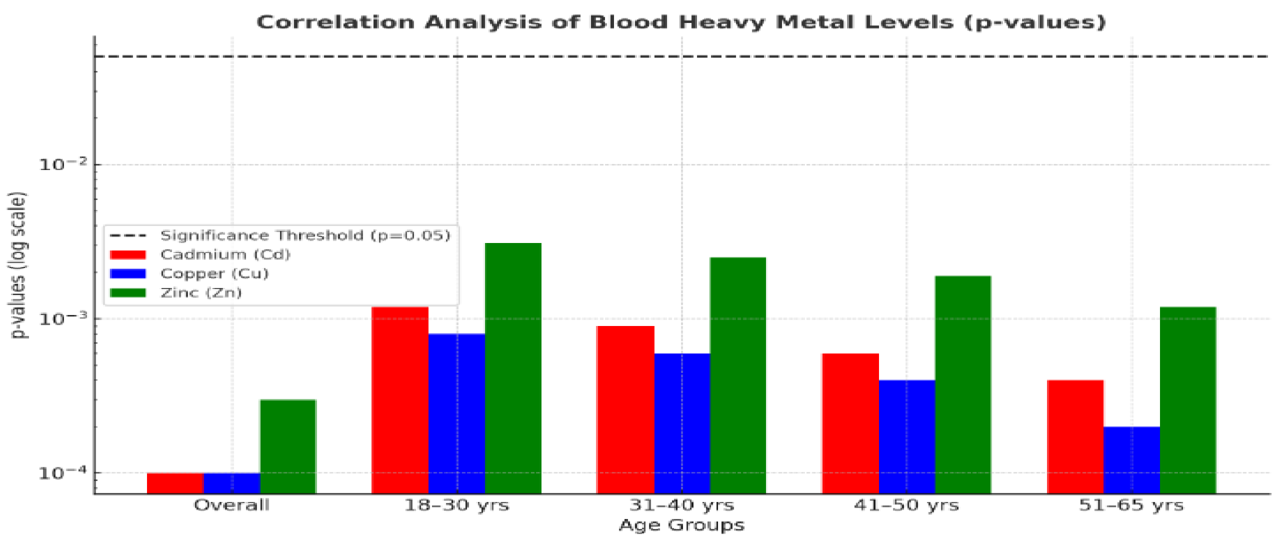

Fig 1: Correlation Analysis of Blood Metal Levels (p-value)

DISCUSSION

The results of this study underscore the significant differences in blood levels of heavy metals like cadmium (Cd), copper (Cu), and zinc (Zn)—among participants from Lahore and Murree. These findings provide critical insights into the impact of environmental pollution, particularly smog, on human health. This section discusses the implications of these results, drawing on comparisons with existing research to contextualize the broader health consequences of heavy metal exposure.

The analysis revealed markedly higher blood levels of cadmium, copper, and zinc in participants from Lahore compared to those from Murree, with statistically significant differences across all age groups ($p < 0.05$). These results align with studies linking urban environments with elevated heavy metal concentrations in the human body. For instance, Iqbal et al. (2021) reported that residents of smog-prone cities in Pakistan exhibited significantly higher levels of heavy metals due to emissions from vehicles, industrial activity, and the burning of fossil fuels [19]. Lahore's Air Quality Index (AQI) consistently ranged from "Unhealthy" to "Hazardous" during the study period, coinciding with the peak smog season. Smog increases the concentration of particulate matter (PM2.5 and PM10), which acts as a carrier for heavy metals like cadmium, copper, and zinc. Kim et al. (2019) demonstrated that elevated particulate matter in urban air often contains heavy metals, which bioaccumulate in human tissues following prolonged exposure. [20] In contrast, Murree's "Moderate" AQI reflects its lower industrial activity, reduced vehicular emissions, and cleaner environmental conditions. Heavy metal concentrations increased with age in both regions, with the 51–65-year age group showing the highest levels of cadmium, copper, and zinc. This trend is consistent with the hypothesis of cumulative exposure. Zhang et al. (2018) and Patra et al. (2022) observed similar patterns, attributing the increase in heavy metal levels among older individuals to long-term environmental exposure and diminished excretion capacity. [21][22][23][24]. Interestingly, even younger individuals (18–30 years) in Lahore exhibited significantly elevated levels of these metals compared to their counterparts in Murree. This suggests that even short-term exposure to smog and urban pollution can lead to considerable heavy metal accumulation. Gul et al. (2023) highlighted the vulnerability of young populations in urban settings, particularly due to frequent exposure to airborne and dietary contaminants. [25]

Prolonged exposure to cadmium is linked to kidney damage, bone demineralization, and an increased risk of cancers. Baumbach et al. (2020) emphasized the role of environmental cadmium exposure in contributing to chronic kidney disease in polluted urban areas. [26] Excessive copper levels can lead to oxidative stress, liver dysfunction, and neurotoxicity. Smith et al. (2021) reported that chronic copper exposure is a significant risk factor for neurological disorders and metabolic disturbances in heavily polluted regions. [27] While zinc is essential for physiological functions, elevated levels can disrupt cellular processes, leading to gastrointestinal distress, immune dysfunction, and interference with iron metabolism, as highlighted by Lanphear et al. (2019). [28]

Lahore's elevated heavy metal levels can be attributed to its dense industrial activities, heavy traffic, and frequent smog episodes, which intensify during winter months. Urban residents are more likely to live and work in environments with high exposure to pollutants. Akhtar et al. (2023) observed similar trends, noting that individuals in industrial and traffic-heavy urban areas are at greater risk of heavy metal exposure than those in rural settings. [29] Socioeconomic factors, such as occupation and lifestyle, further influence exposure levels. Urban populations may consume contaminated water and food or use consumer products containing heavy metals. The contrast with Murree, a less industrialized region with limited vehicular emissions, illustrates the environmental disparity between urban and semi-rural settings.

The findings of this study emphasize the urgent need for public health interventions to mitigate the health risks associated with heavy metal exposure. Stricter regulations on industrial emissions and vehicular exhaust can reduce airborne pollutants containing cadmium, copper, and zinc. Routine screening of environmental and biological samples for heavy metal contamination can provide early warnings and guide interventions. Educating communities about the sources and health risks of heavy metal exposure can encourage preventive measures, such as the use of masks and improved nutrition to counteract oxidative stress.

CONCLUSION

This study provides a comprehensive evaluation of the correlation between smog-related environmental exposure and the blood levels of heavy metals, specifically cadmium (Cd), copper (Cu), and zinc (Zn), in individuals residing in Lahore and Murree. The findings indicate significantly higher concentrations of these metals in the blood of Lahore residents compared to Murree, with statistical significance confirmed across all age groups ($p < 0.05$). This disparity underscores the impact of industrial emissions, vehicular exhaust, and other anthropogenic activities prevalent in urban environments like Lahore, especially during smog-prone seasons. The increasing levels of cadmium, copper, and zinc with age suggest cumulative exposure over time, with the highest concentrations observed in older age groups. These findings highlight the bioaccumulative nature of heavy metals and their persistent impact on human health. Elevated levels of these metals are associated with a range of health complications, including nephrotoxicity, neurotoxicity, cardiovascular disorders, and compromised immune responses, emphasizing the urgency for mitigation strategies. This research underscores the critical need for targeted public health interventions and environmental policies to address heavy metal pollution in smog-affected regions. Enhanced air quality monitoring and strict enforcement of industrial and vehicular emission standards are imperative to reducing the health risks associated with heavy metal exposure.

FUTURE RECOMMENDATIONS

To build upon the findings of this study, future research should expand its geographic and temporal scope by including additional regions with varying levels of air pollution and conducting longitudinal studies across multiple smog seasons. This approach would provide a more comprehensive understanding of heavy metal accumulation and its long-term health implications. Advanced biomonitoring techniques, such as hair and urine analysis, should be incorporated alongside blood sampling to capture a broader spectrum of heavy metal exposure and excretion patterns.

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