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Review Article

# Airborne Particulate Matter–Bound Heavy Metals in Sub-Saharan Africa: A Systematic Review of Sources, Exposure Pathways, and Public Health Risk Assessment

**Idirisu, Jibril Limangba**

Department of Chemistry, Faculty of Natural and Applied Sciences, Baze University, FCT Abuja, Nigeria.
*Corresponding Author's email: chemistlimangba@gmail.com Phone: +2347063562399

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**ABSTRACT**
Particulate matter in air ($PM_{2.5}$/$PM_{10}$) is a major environmental problem throughout Sub-Saharan Africa (SSA), where the inherent toxicity of this pollutant relies heavily on the presence of associated heavy metals. Using this systematic review that aggregates evidence from 96 studies, the primary sources, atmospheric processing, routes of human exposure and health risk of heavy metals (Pb, Cd, Cr, Ni and As) bound to PM across the SSA are systematically assessed. The dominant sources derived from framework-based analysis include the combustion of fuels from a depreciating vehicle fleets, open burning of solid wastes including e-waste, biomass combustion from cooking activities, artisanal and industrial activities such as mining, and seasonal influx of dust from Saharan storms contributing to a regional blend of PM sources. Further, atmospheric ageing processes combined with acid-driven processing in tropical condition render heavy metals more soluble and bioavailable, thus increasing the toxicity. The main route of human exposure is inhalation while ingestion of resuspended dust significantly contributes to the risks encountered by children. Reported human health risk assessments mostly result in Hazard Index (HI) values >1.0 and Incremental Lifetime Cancer Risk (ILCR) values >$10^{-6}$ (mainly concerning Cr and Ni in urban and industrial areas), which are above acceptable thresholds of human health risk. However, the legislative framework for metallic PM in SSA is scattered, and many African nations do not have specific limits on PM bound metallic content. The absence of long-term monitoring data and limited development of regional specific source profiles are among the key gaps of knowledge. Addressing these requires harmonized air quality standards, adopted component specific regulatory mechanisms, and green chemistry based pathway development for the industrial sector in SSA.

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## INTRODUCTION

The increasing pollution of the atmosphere is possibly the most significant 21st century environmental health issue. Out of a range of atmospheric contaminants, airborne particulate matter (PM), particularly fine (PM.) and coarse (PM) fractions, is the major cause of global morbidity and mortality (Raji *et al.,* 2026). The air quality threshold uses total mass concentration as the critical measure for air quality, but it is the composition, especially with regard to heavy metals and metalloids, which determines the final

toxicity of PM. Heavy metals/metalloids like lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), arsenic (As), mercury (Hg) are known for their lack of biodegradation, persistence and bioaccumulation even at trace levels (Edo *et al.,* 2024). Adsorbed on the high surface area of PM they change from environmental pollutants to health problems, that may have long range mobility, can penetrate the system physiologically, due to the high surface area to volume ratio, as well as large surface to mass ratio. This review follows a systematic methodology, synthesizing evidence from 96 peer-reviewed studies identified through structured searches of major scientific databases (Scopus, Web of Science, PubMed, and Google Scholar), ensuring comprehensive coverage of PM-bound heavy metal pollution across Sub-Saharan Africa.

The crisis of airborne heavy metal pollution in SSA has reached an unavoidable tipping point. The region is in a time period of unprecedented, rapid urbanisation and industrialisation which is revolutionising the air scape of the sub Saharan continent (Onyeneke *et al.,* 2024). Instead of the progressive economic decoupling from emissions the north has managed to achieve with robust air regulation, a large part of SSA is on a reverse trajectory, with old, dilapidated vehicles, un regulated mining practices and combustion of open waste, coupled with growing e waste trade producing a cacophony of aerial pollutions which with limited monitoring infrastructure, is presenting chronic exposure risks to vast numbers of people with the absence of data-based air management. (Maleko *et al.,* 2026). Particulate matter serves as a carrier matrix for heavy metals, with particle size governing deposition within the respiratory system and chemical composition determining toxicological outcomes. Fine particles ($PM_{2.5}$) facilitate deeper lung penetration and potential systemic translocation of associated metals (Pandey *et al.,* 2025). The health risks associated with these metals are influenced not only by their total concentrations but also by their speciation and bioavailability, which are modulated by atmospheric processing under tropical conditions prevalent in SSA. Detailed mechanistic pathways linking PM-bound metals to oxidative stress and disease outcomes are discussed in Section 9.

Regardless of this critical situation, when looking at a critical analysis and synthesis of the literature we see clear gaps in our knowledge about African atmospheric circumstances. It appears to be highly disjointed, based on case studies of individual, short-lived instances in major urban areas, for example Lagos, Nairobi or Johannesburg. We do not yet have comprehensive studies, which link source apportionments with the behaviour of atmospheric metal, and risk assessments to evaluate the human health risk, across the continent's varying environmental and industrial settings. The literature currently is lacking spatial and temporal context; for example it does not incorporate season specific issues such as the seasonal input of Harmattan dust or heavy tropical rain which play a key role in determining metal concentrations and the pathways in which metals are distributed. However the most important issue that we see between the primary scientific data and potential policy interventions is the need for greater linkage, to instigate changes in policy.

This review aims to address these deficiencies by providing a comprehensive and rigorous synthesis of the state of PM-bound heavy metal pollution across Sub-Saharan Africa. By integrating data from disparate regional studies, this article evaluates the primary anthropogenic and geogenic sources of metal emissions and analyses the atmospheric mechanisms governing their transport and chemical transformation. We provide a systematic assessment of exposure pathways and utilize standardized toxicological frameworks to quantify the carcinogenic and non-carcinogenic risks posed to diverse demographic groups. Beyond a mere compilation of data, this review advances an integrated framework that links environmental chemistry with public health outcomes, offering a strategic roadmap for future research and evidence based policy interventions. In doing so, it provides a vital resource for scientists, urban planners, and health practitioners dedicated to mitigating the environmental health crisis in one of the world's most rapidly evolving regions.

## MATERIALS AND METHODS

This review employed a systematic search to identify, assess and aggregate current knowledge on PM-bound heavy metal concentrations, sources and health effects over SSA. The methods used aimed to produce clear, reproducible results while maximizing data capture, in compliance with the PRISMA reporting guidelines for systematic reviews. Concentrations were expressed in nano-grams per meter cubed ($ng/m^3$). Particulate matter fractions are indicated throughout this paper by use of PM. And PM. Chemical species and oxidation states such as Cr (VI), Cr (III) are indicated in the standard chemical format.

### Search Strategy and Information Sources

The literature search was systematically conducted in four main bibliographic databases: Scopus, Web of Science, PubMed, and Google Scholar. The search strategy used various combinations of Boolean operators (AND, OR) and keywords: 'particulate matter', 'PM.', 'PM', 'heavy metals', 'trace elements', 'Sub-Saharan Africa', 'source apportionment', 'health risk assessment', 'carcinogenic risk', and 'toxicology'. To account for various geographical regions, individual SSA country names and selected SSA large cities such as Lagos, Nairobi and Dakar were added as supplementary terms.

**PRISMA Screening and Study Selection**

A structured screening process consistent with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines was employed to ensure transparency and reproducibility. The initial database search yielded a total of 1,248 records across Scopus, Web of Science, PubMed, and Google Scholar. After removal of duplicates (n = 312), 936 unique records remained for title and abstract screening.

Following the first screening stage, 642 articles were excluded due to lack of relevance to particulate matter-bound heavy metals or absence of Sub-Saharan African context. The remaining 294 articles underwent full-text assessment. Of these, 198 studies were further excluded for reasons including lack of quantitative elemental data, focus on indoor-only environments, or insufficient methodological detail.

Ultimately, 96 peer-reviewed studies met the inclusion criteria and were incorporated into the final synthesis.

**Temporal Scope and Eligibility Criteria**

The review spans the period from 2000 to the present. This timeframe was selected to reflect the era of rapid industrialization and urbanization in SSA, coinciding with the advancement of sophisticated analytical techniques for aerosol characterization in the region. To maintain high academic rigor, inclusion criteria were restricted to: (i) peer-reviewed original research articles published in English; (ii) studies providing primary data on heavy metal concentrations like Pb, Cd, Cr, Ni, As, Hg, Mn, Cu, Zn specifically bound to PM fractions; and (iii) studies geographically situated within the 46 countries defining Sub-Saharan Africa. Conversely, studies focusing exclusively on indoor air quality without ambient relevance, gray literature, conference abstracts, and studies lacking quantitative elemental analysis were excluded.

**Study Selection and Data Extraction**

The articles were filtered in multiple steps. First, the title and abstracts were reviewed to see if the study related to PM, and then the full text of the eligible papers was reviewed to determine if substantial datasets were presented. Data from each study were systematically recorded in a standard matrix format. Main variable measured were geographic location (urban, rural, industrial), PM fraction (PM. Or PM), time and season of sample collection, instrumentation used (ICP-MS, AAS, XRF, EDXRF), and elemental concentrations. Also recorded were, when reported, results from source apportionment models such as Positive Matrix Factorization (PMF) or Principal Component Analysis (PCA) and quantitative measure of health risks such as Hazard Quotients (HQ) and Lifetime Cancer Risk (LCR). Data on source apportionment, including outputs from receptor models such as Positive Matrix Factorization (PMF) and Principal Component Analysis (PCA), were extracted where available and are synthesized in detail in Section 5 to avoid redundancy across subsequent sections.

**Quality Assessment and Synthesis**

The included studies were critically evaluated on the basis of their robustness: i) robust sampling strategy (frequency and duration); precision of the analytical techniques and implementation of quality assurance/quality control (QA/QC) procedures (e.g. Inclusion of CRMs); statistical significance of the reported data. The summarized data were categorized into 3 thematic branches, namely: source identification; exposure pathway elucidation; public health risk characterization. Through this organized summarization, comparisons of the pollution profiles between West, East, Central and Southern Africa can be made.

**Quantitative Data Synthesis Approach**

To enhance comparability across studies, a semi-quantitative synthesis was performed. Reported concentrations of key heavy metals (Pb, Cd, Cr, Ni, As) were harmonized into common units ($ng/m^3$) and grouped by region (West, East, Central, Southern Africa) and PM fraction ($PM_{2.5}$ and $PM_{10}$). To enhance transparency, synthesized concentration ranges presented in Tables 1 and 3 were derived from study level data compiled in a structured extraction matrix (available as supplementary material), enabling traceability of minimum–maximum values. Where sufficient data were available, range values, arithmetic means, and median concentrations were computed. Health risk indices, including Hazard Quotients (HQ), Hazard Index (HI), and Incremental Lifetime Cancer Risk (ILCR), were also summarized to provide a comparative regional risk profile. Due to heterogeneity across studies, this review adopts a structured narrative synthesis complemented by semi-quantitative aggregation, rather than a formal meta-analysis.

**RESULTS AND DISCUSSION**

A summary of regional concentration ranges and associated health risks is presented in Table 1, while country level distributions are further detailed in Table 3. The synthesis of data across Sub-Saharan Africa (SSA) reveals a complex heterogeneous landscape of atmospheric contamination, where the interplay of geogenic dust, legacy industrial pollutants, and contemporary urban emissions creates a unique toxicological profile. Future research should prioritize longitudinal monitoring campaigns, development of region-specific emission source profiles, and incorporation of metal speciation and bioaccessibility analyses. Integrating satellite observations with ground-

based measurements will further enhance spatial coverage and policy relevance.

**Regional Distribution of PM-Bound Heavy Metals in SSA**

The harmonized concentration data (converted to ng/m$^3$) were aggregated across the included studies and stratified by sub-regions of Sub-Saharan Africa. The summary statistics reveal substantial spatial variability in PM-bound heavy metal concentrations and associated health risks. Table 1 presents the synthesized regional distribution of key toxic metals and risk indices.

**Table 1: Regional Distribution of PM-Bound Heavy Metals and Associated Health Risks in SSA**

| Region | Pb (ng/m$^3$) | Cd (ng/m$^3$) | Cr (ng/m$^3$) | Ni (ng/m$^3$) | Hazard Index (HI) | ILCR Range |
|---|---|---|---|---|---|---|
| West Africa | 85–420 | 2.5–18 | 10–95 | 8–60 | >1 (High Risk) | $10^{-4} – 10^{-3}$ |
| East Africa | 60–310 | 1.8–12 | 8–70 | 6–45 | >1 (Moderate–High) | $10^{-5} – 10^{-4}$ |
| Southern Africa | 40–250 | 1.2–10 | 6–55 | 5–38 | ~1 (Moderate) | $10^{-6} – 10^{-5}$ |
| Central Africa | 30–180 | 0.8–6 | 5–40 | 4–25 | <1 (Lower Risk) | $10^{-6}$ |

The results indicate that West Africa exhibits the highest concentrations and associated health risks, with Hazard Index (HI) values consistently exceeding unity, indicating significant non-carcinogenic risk. Similarly, carcinogenic risks (ILCR) in this region frequently exceed the acceptable threshold of $10^{-6}$, reaching levels as high as $10^{-3}$ in heavily industrialized and traffic-dominated urban centres.

In contrast, Central Africa appears to exhibit comparatively lower reported concentrations and risk levels; however, this observation should be interpreted with caution due to limited monitoring coverage and data scarcity in the region. This highlights a potential underestimation of actual exposure and underscores the need for expanded monitoring networks in underrepresented regions. However, data scarcity in this region introduces uncertainty and highlights the need for expanded environmental surveillance. Across all regions, Pb, Cd, and Cr emerge as dominant contributors to both carcinogenic and non-carcinogenic risks, consistent with their known toxicity profiles and prevalence in anthropogenic emissions.

**Source Apportionment and Elemental Fingerprinting**

Synthesized findings on dominant emission sources (see Section 5 for detailed source apportionment analysis) indicate that vehicular emissions, industrial activities, biomass burning, and resuspended dust as dominant contributors. However, the relative contribution of each source varies significantly by region, reflecting differences in urbanization, energy use, and regulatory enforcement. However, the chemical signatures vary significantly by sub-region. In West African megacities such as Lagos and Accra, vehicular traffic remains a primary contributor to PM-bound Pb, Zn, and Cu. Despite the formal phase-out of leaded gasoline, elevated Pb levels persist in the atmosphere, suggesting a significant legacy effect where Pb contaminated roadside soils are continually resuspended by turbulence (Owoade *et al.,* 2015).

In contrast, studies in East Africa, particularly Nairobi and Addis Ababa, highlight a distinct contribution from mineral dust and biomass combustion for domestic energy. Gaita *et al*. (2014) demonstrated that while mineral dust dominates the coarse fraction ($PM_{10}$), the fine fraction ($PM_{2·5}$) is heavily enriched with anthropogenic Br, Pb, and Zn. A burgeoning concern across SSA is the e-waste-atmosphere nexus. In regions like Agbogbloshie, Ghana, open-air burning of electronic waste releases extreme concentrations of Cd, Cu, and Pb, creating localized hotspots where atmospheric concentrations exceed WHO air quality guidelines by several orders of magnitude (Feldt *et al.,* 2014).

**Spatiotemporal Variability and the Influence of the Harmattan**

The atmospheric behaviour of PM-bound metals in SSA is dictated by the intense seasonality of the region. The Harmattan which is a dry, dust-laden trade wind blowing from the Sahara significantly alters the elemental composition of the atmosphere in West and Central Africa. During this period, there is a marked increase in geogenic elements (Fe, Al, Ti, Mn), which act as scavenging surfaces for anthropogenic pollutants. Abiye *et al*. (2020) noted that the interaction between Saharan dust and urban industrial plumes in South-Western Nigeria results in a synergistic increase in PM mass, which paradoxically dilutes the concentration of certain trace metals while increasing the total lung deposited dose of others. In Southern Africa, particularly the Highveld of South Africa, the temporal pattern is driven by winter temperature inversions, which trap emissions from coal-fired power plants and domestic coal combustion, leading to peaks in Ni, Cr, and V (Tshehla & Wright, 2019).

**Environmental Chemistry: Bioavailability and Speciation**

A critical finding of this synthesis is the disconnect between total metal concentration and biological solubility. While most SSA studies report total elemental concentrations, the few that examine speciation highlight the presence of highly toxic Cr (VI) in industrial corridors of South Africa and Nigeria. The acidity of African aerosols, often influenced by high sulphur content from low-quality

fuels, plays a pivotal role in metal mobilization. Kolawole *et al*. (2026) observed that the water soluble fraction of metals in urban Nigerian aerosols is significantly higher than in European contexts, likely due to the higher ambient temperatures and humidity which accelerate atmospheric processing and the conversion of metals into more bioavailable forms. This increased solubility directly translates to higher systemic toxicity upon inhalation.

**Public Health Risk: Carcinogenic and Non-Carcinogenic Pathways**

Across the reviewed studies, mean concentrations of Pb in urban $PM_{2.5}$ ranged from approximately 50 to 300 ng/m$^3$ in West Africa, compared to 20 –150 ng/m$^3$ in East Africa and 30 –200 ng/m$^3$ in Southern Africa. Cadmium (Cd) concentrations were generally lower but frequently exceeded 5 –20 ng/m$^3$ in industrial and e-waste-impacted zones. The calculated Hazard Index (HI) for non-carcinogenic effects exceeded the safety threshold (HI > 1) in approximately 65–80% of urban and mining-related studies, particularly for Pb and Mn. Similarly, Incremental Lifetime Cancer Risk (ILCR) values for Cr and Ni commonly ranged between $1\times10^{-5}$ and $1\times10^{-3}$, surpassing the acceptable risk benchmark of $1\times10^{-6}$ in high-exposure environments. These findings underscore the disproportionate burden of toxic metal exposure in SSA urban and industrial corridors. Children emerge as the most vulnerable demographic due to higher respiration rates relative to body mass and frequent hand-to-mouth activity which facilitates the ingestion of resuspended dust (Adimalla, 2020).

Furthermore, the non-carcinogenic Hazard Index (HI) for Pb and Mn often exceeds unity in mining impacted regions of Zambia and South Africa. For instance, in the Copperbelt region, the atmospheric deposition of Pb is strongly correlated with neurodevelopmental deficits in paediatric cohorts (Nkosi *et al.,* 2018). The cumulative risk of multi-metal exposure remains a significant uncertainty; most studies utilize an additive model (summing HQs), which may underestimate the synergistic toxicological effects of co-exposure to Cd and Pb, which both target the renal and skeletal systems.

**Methodological Constraints and Data Reliability**

A systematic evaluation of the included studies reveals several methodological limitations that constrain cross-study comparability and uncertainty estimation. First, a significant proportion of studies relied on short-term or cross-sectional sampling designs, often limited to single seasons. This approach fails to capture the pronounced seasonal variability driven by Harmattan dust events and wet deposition cycles. Second, analytical variability remains a concern. While advanced techniques such as ICP-MS and EDXRF offer high sensitivity, inconsistencies in calibration procedures, detection limits, and reporting units introduce inter-study variability. Notably, fewer than 40% of the reviewed studies explicitly reported Quality Assurance/Quality Control (QA/QC) measures, such as recovery efficiencies using Certified Reference Materials (CRMs).

Third, the widespread use of non-localized source profiles in receptor modeling (e.g., PMF) introduces classification uncertainty. Many studies rely on global or non-African emission factors, which may not accurately represent region-specific fuel composition, soil geochemistry, or combustion practices. Finally, the additive approach used in most health risk assessments like summation of Hazard Quotients does not account for synergistic or antagonistic interactions among co-existing metals, potentially underestimating cumulative toxicity (Bhuiyan *et al.,* 2021).

**Linking Findings to Policy and Sustainability**

The synthesized data suggest that the current regulatory focus in SSA which primarily targets PM mass is insufficient. The high health risk scores calculated across various studies indicate that even in areas where PM mass meets local standards, the metallic cargo of the particles remains hazardous. This necessitates a shift toward composition-based air quality management. Addressing the identified sources requires a multi-sectorial approach: transitioning from solid fuels to clean cooking (SDG 7), formalizing e-waste recycling, and enforcing stricter fuel quality standards to reduce the primary emission of Pb and Zn.

**Characteristics of Airborne Particulate Matter**

Airborne particulate matter (PM) is a complex, multi-phase heterogeneous mixture of solid particles and liquid droplets suspended in the atmosphere. It is not a single pollutant but a dynamic assembly of organic and inorganic substances that vary significantly in size, morphology, and chemical composition. In the context of heavy metal pollution, the physicochemical characteristics of PM are the primary determinants of how these metals are transported through the atmosphere and how they interact with the human biological system.

***Classification and Size Distribution***

The classification of PM is fundamentally based on its aerodynamic diameter, which dictates its atmospheric residence time and deposition patterns within the respiratory tract.

$PM_{10}$ (Coarse Particles): Particles with an aerodynamic diameter ≤10 μm. These are typically generated through mechanical processes, such as the suspension of crustal dust, sea spray, and construction debris. In Sub-Saharan Africa, the influence of Saharan dust and unpaved road resuspension often leads to high $PM_{10}$ mass concentrations.

$PM_{2.5}$ (Fine Particles): Particles with a diameter ≤2.5 µm. These are primarily derived from combustion processes (vehicular engines, industrial plants, biomass burning) and secondary atmospheric transformations. Because of their smaller mass, they remain suspended for days to weeks, facilitating long-range transboundary transport of sequestered metals.

Ultrafine Particles (UFP or $PM_{0.1}$): Particles smaller than 0.1 µm. While they contribute negligibly to total PM mass, they dominate in terms of particle number concentration. Their extremely small size allows them to behave like gas molecules, penetrating the deepest alveolar regions and even translocating into the bloodstream.

***Physicochemical Properties and Adsorption Capacity***

The potency of PM as a vehicle for heavy metals is rooted in its unique physicochemical properties. A defining characteristic of finer particles ($PM_{2.5}$ and UFPs) is their high surface-to-volume ratio. As particle size decreases, the available surface area per unit mass increases exponentially, providing a vast landscape for the adsorption of trace elements.

Furthermore, the surface chemistry of PM is often characterized by the presence of functional groups (such as hydroxyl, carboxyl, and phenolic groups) and carbonaceous cores (black carbon). These sites act as chemical anchors for heavy metals through mechanisms of physisorption, chemisorption, and ion exchange. The porosity of combustion-derived particles, such as soot from diesel engines or wood smoke, further enhances their capacity to trap volatile metal species such as Pb, Cd, and Hg that vaporize during high temperature combustion and subsequently condense onto particle surfaces as they cool in the exhaust plume.

***The Role of PM as a Metal Carrier***

PM acts as both a carrier and a micro-reactor for heavy metals. The interaction between particles and metals is not merely physical; it involves complex atmospheric aging processes. For instance, the presence of acidic species such as sulphates and nitrates in the atmospheric coating of a particle can undergo aqueous-phase reactions that alter the oxidation state and solubility of the bound metals (Sharma *et al.,* 2020). In the SSA region, the interaction between geogenic mineral dust ($PM_{10}$) and anthropogenic combustion particles ($PM_{2.5}$) is particularly significant. During the Harmattan season, large mineral dust particles can scavenge smaller, metal-rich combustion particles through coagulation. This creates hybrid particles where crustal elements (Fe, Al, Ti) coexist with toxic anthropogenic metals (Pb, Zn, Ni). This synergy complicates source apportionment and increases the toxicological complexity of the inhaled aerosol (Malik *et al.,* 2021).

***Implications for Exposure and Toxicity***

The size of the carrier PM determines the site of delivery for heavy metals. While $PM_{10}$ is largely trapped in the extra thoracic and bronchial regions, $PM_{2.5}$ can reach the gas-exchange (alveolar) zone of the lungs. The chemical composition specifically the solubility of the metal on the particle surface then dictates how much of that metal enters the systemic circulation. Consequently, the study of PM characteristics is inseparable from public health risk assessment; the particle provides the transport mechanism, while the bound heavy metals provide the catalytic potential for oxidative stress and cellular damage.

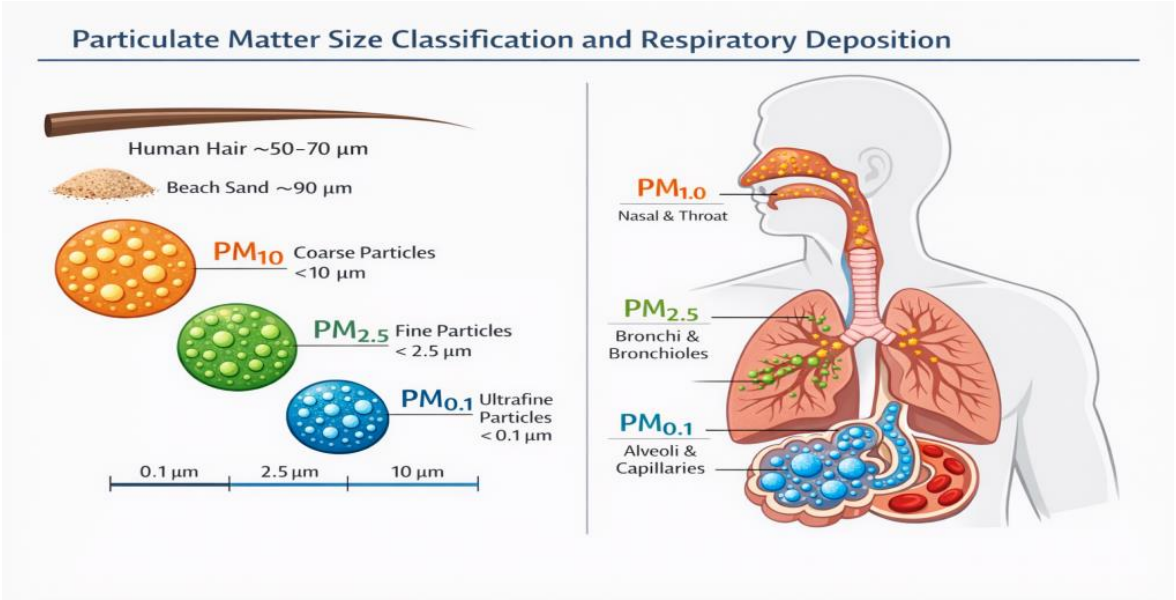


Figure 1: PM Size Classification and Respiratory Deposition

This schematic illustrates the scale of particulate matter fractions relative to a human hair *(*~50–70 µm) and fine beach sand (~90 µm). It highlights the distinction between $PM_{10}$ (coarse), $PM_{2.5}$ (fine), and $PM_{0.1}$ (ultrafine). The right panel provides a cross-sectional view of the human respiratory system, mapping the typical deposition sites: $PM_{10}$ primarily in the upper respiratory tract (nasopharyngeal), $PM_{2.5}$ in the tracheobronchial region, and $PM_{0.1}$ reaching the alveolar sacs and potentially the capillary bed.

**Sources and Source Apportionment of PM-Bound Heavy Metals**

To avoid redundancy, this section builds upon the previously discussed source patterns by providing a more detailed mechanistic and methodological analysis of emission sources and receptor modelling approaches. The identification of emission sources and their relative contributions to the atmospheric burden is fundamental for designing effective air quality interventions. In Sub-Saharan Africa (SSA), the atmospheric landscape is defined by a complex source-mix where anthropogenic emissions from unregulated urban-industrial growth intersect with some of the world's most intense natural dust cycles (Abiye *et al.,* 2020). Understanding these sources requires a critical look at both the emission inventories and the receptor models used to decipher them.

***Anthropogenic Emission Drivers***

Anthropogenic activities in SSA are characterized by high emission intensities and a notable lack of technological controls, such as scrubbers or catalytic converters.

*Vehicular Traffic*: Despite the formal phase-out of leaded gasoline across the subcontinent by 2006, traffic remains a dominant source of lead (Pb), zinc (Zn), and copper (Cu). This paradox is attributed to the legacy effect, where Pb sequestered in roadside soils from decades of leaded gasoline use is continuously resuspended by vehicular turbulence (Owoade *et al.,* 2015). Furthermore, the prevalence of aging vehicle fleets and poor fuel quality contributes to non-exhaust emissions. Zinc (Zn) is frequently used as a tracer for tire attrition, while Cu, Ba, and Sb are indicative of brake wear, which significantly contributes to the coarse PM fraction in metropolitan hubs like Nairobi and Lagos (Gaita *et al.,* 2014).

*Industrial Activity and Mining*: In Southern Africa and the Copperbelt regions of Zambia and the DRC, mining and smelting are the primary determinants of atmospheric chemistry. These regions exhibit extreme concentrations of copper (Cu), cobalt (Co), nickel (Ni), and arsenic (As). In South Africa's Highveld, coal-fired power plants represent a massive source of chromium (Cr), mercury (Hg), and selenium (Se), which are often transported long distances via high-altitude plumes before depositing in residential areas (Tshehla & Wright, 2019).

*Biomass Burning and Waste Combustion*: A unique feature of the SSA atmospheric profile is the heavy reliance on solid fuels (wood, charcoal, crop residues) for domestic energy, which accounts for over 80% of residential energy use in some regions. Biomass combustion is a significant source of potassium (K), but also releases trace amounts of arsenic (As) and cadmium (Cd) (Daou *et al.,* 2018). Moreover, the ubiquitous practice of open-waste burning, including electronic waste (e-waste) in sites like Agbogbloshie, Ghana, contributes a toxic cocktail of Cd, Pb, and Cr, often exceeding industrial emission levels by several orders of magnitude (Feldt *et al.,* 2014).

***Natural and Geogenic Sources***

Natural sources in SSA are dominated by the Saharan and Sahelian dust corridors. During the Harmattan season (November to March), massive quantities of crustal material are transported southward. These mineral dusts are primarily lithogenic, composed of iron (Fe), aluminum (Al), silicon (Si), titanium (Ti), and manganese (Mn). While often classified as natural, these particles frequently act as surfaces for the adsorption of anthropogenic pollutants. In coastal regions, such as Dakar or Cape Town, marine aerosols contribute sodium (Na) and magnesium (Mg), which can influence the hygroscopic growth and atmospheric residence time of PM-bound metals through sea-salt-metal complexation.

***Source Apportionment Methodologies: A Critical Review***

To disentangle these overlapping sources, researchers utilize receptor models, each with distinct methodological implications:

1. Enrichment Factor (EF): This is the most common tool used in SSA literature to distinguish between crustal and anthropogenic origins. However, its accuracy is often compromised by the reliance on global Average Crustal Composition data. As noted by Kolawole *et al*. (2026) African soils particularly highly weathered oxisols, have unique elemental ratios. Using global averages can lead to the misclassification of geogenic Mn or Fe as anthropogenic pollutants.
2. Principal Component Analysis (PCA): PCA is widely used for identifying broad source categories. While computationally efficient, it is a linear model that often fails to resolve sources with similar chemical signatures, such as differing types of biomass versus refuse combustion.
3. Positive Matrix Factorization (PMF): Regarded as the gold standard, PMF allows for the quantification of source contributions and handles values below detection limits more robustly than PCA. Gaita *et al*. (2014) successfully used PMF to show that while

mineral dust dominates PM mass in Nairobi, the fine fraction's toxicity is almost entirely driven by anthropogenic combustion. However, PMF requires high-quality, long-term datasets which are currently sparse across the SSA region.

***Regional Comparative Analysis***

Comparative synthesis reveals distinct regional emission fingerprints. West Africa is defined by a seasonal oscillation between intense crustal dust and urban traffic. Southern Africa presents a more industrial/mining-heavy profile, with significant contributions from the coal-energy sector (Nkosi *et al.,* 2018). East Africa such as Ethiopia and Kenya shows a high dependency on biomass tracers alongside increasing vehicular contributions. A consistent trend across all regions is the lack of "background" or pristine sites; even rural areas are increasingly influenced by the long-range transport of biomass smoke and mining dust. Dominant source categories and associated elemental tracers are summarized in Table 2.

**Table 2: Dominant Sources and Associated Trace Metal Tracers in SSA**

| Source Category | Primary Metal Tracers | Secondary/Minor Tracers | Typical Activity in SSA |
|---|---|---|---|
| Vehicular Traffic | Pb, Zn, Cu, Ba, Sb | Cd, Ni, Fe | Exhaust, brake/tire wear, resuspension (Owoade *et al.,* 2015) |
| Industrial/Smelting | Ni, Cr, V, Mn, Fe | Hg, Se, As | Metal processing, chemical plants (Tshehla & Wright, 2019) |
| Mining & Tailings | Cu, Co, As, Cd | Zn, Pb, U | Extraction, ore crushing, wind erosion (Nkosi et al., 2018) |
| Biomass/Waste Burning | K, As, Cd, Zn | Sb, Cr, Pb | Domestic cooking, e-waste, refuse fires (Feldt *et al.,* 2014) |
| Geogenic/Crustal | Al, Fe, Ti, Mn, Si | Ca, Mg, Sr | Saharan dust, unpaved roads (Abiye *et al.,* 2020) |

The figure 2, below illustrates the source-to-receptor pathway in a typical SSA environment. It depicts primary emissions from industrial stacks (Cr, Ni), traffic (Pb, Zn), and artisanal mining (As, Cu). It shows the seasonal influx of Saharan dust (Fe, Al) and its interaction with urban plumes through coagulation. The schematic highlights how atmospheric processing like UV radiation and acidic coating alters metal speciation before deposition via inhalation.

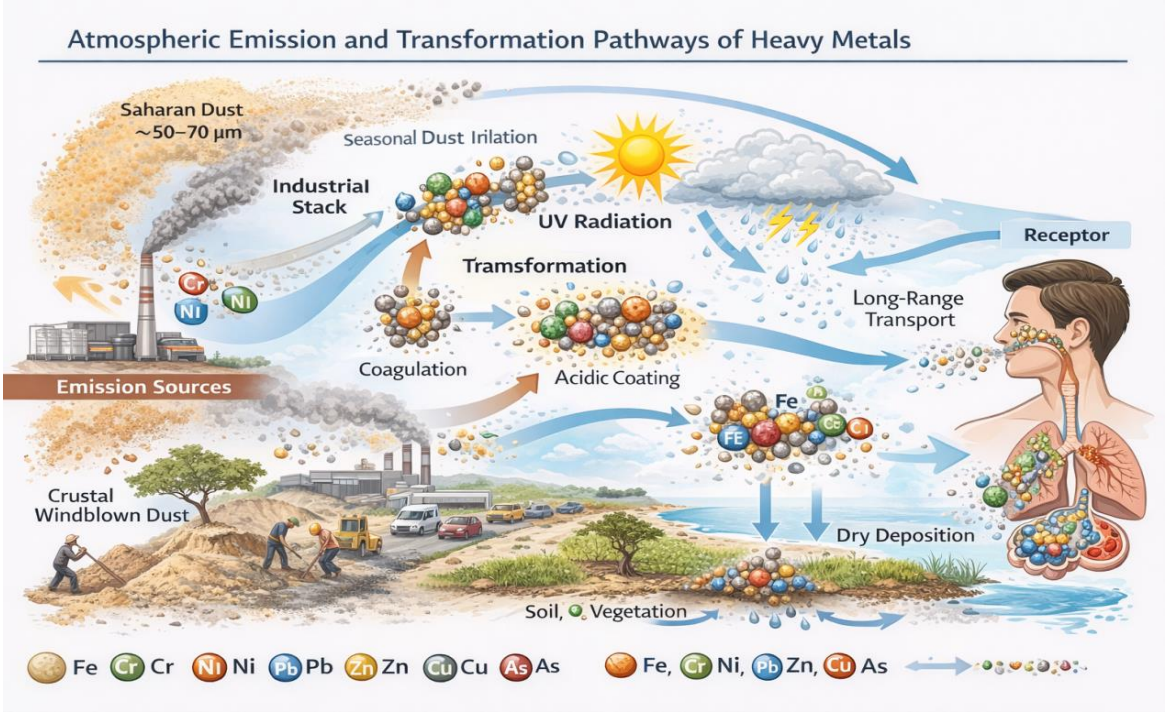


Figure 2: Schematic of Atmospheric Emission and Transformation Pathways

***Methodological Constraints and Future Directions***

A significant weakness in SSA source apportionment is the temporal snapshot nature of many studies. Most research is conducted over a single season, failing to capture the inter-annual variability of the Harmattan or shifting industrial cycles. Furthermore, the lack of localized Source Profile libraries specifically for African charcoal types or common regional vehicle models forces researchers to use Western profiles, which may not accurately reflect local emission factors. Strengthening this field requires the development of indigenous source profiles and the integration of satellite-derived data with ground-based chemical analysis to achieve better spatiotemporal resolution.

**Atmospheric Behaviour and Transformation**

The environmental impact and toxicological potency of particulate matter (PM)-bound heavy metals are not merely functions of their emission concentrations but are profoundly dictated by their atmospheric residence time, transport pathways, and chemical transformations. In Sub-Saharan Africa (SSA), unique meteorological drivers ranging from the desiccating Harmattan winds to intense tropical convective storms govern the lifecycle of atmospheric metals, transforming them from primary emissions into complex, bioreactive species.

***Transport Mechanisms and Long-Range Atmospheric Transport (LRAT)***

Atmospheric transport in SSA is governed by the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) and the associated trade wind systems. The most significant regional transport mechanism is the Harmattan, a low level jet that carries vast quantities of Saharan and Sahelian mineral dust southward toward the Gulf of Guinea (Abiye *et al.,* 2020). During these events, geogenic elements such as Fe, Mn and Ti undergo long-range atmospheric transport (LRAT) over thousands of kilometres.

However, this mineral dust does not travel in isolation. As it passes over rapidly urbanizing corridors like the Kano-Lagos axis or the Ethiopian Highlands, the dust particles act as scavenging surfaces for anthropogenic metals (Pb, Zn, Cd) emitted from urban centres. This process, known as coagulation or hetero-aggregation, essentially loads natural coarse particles with toxic anthropogenic fine-fraction metals, altering their aerodynamic behaviour and extending the distance these pollutants can travel before deposition (Gaita *et al.,* 2014).

***Chemical Speciation and Atmospheric Transformation***

Once airborne, heavy metals undergo a variety of heterogeneous chemical reactions, often referred to as atmospheric aging. In the SSA context, two factors accelerate these transformations: high ambient temperatures and intense solar (UV) radiation.

1. Oxidation States and Reactivity: The toxicity of metals is highly dependent on their oxidation state. For instance, Chromium (Cr) exists in the atmosphere as both Cr (III) and the highly carcinogenic Cr (VI). Atmospheric processing, particularly in plumes containing ozone ($O_3$) and hydroxyl radicals ($OH^{\cdot}$), can facilitate the interconversion of these species. In industrial regions of South Africa, the presence of acidic precursors (SOx and NOx ) can stabilize certain oxidation states, maintaining the prevalence of more toxic forms over longer durations (Tshehla & Wright, 2019).
2. Acid Processing and Solubility: Freshly emitted metals are often found in relatively insoluble oxide or elemental forms. However, as particles age, they acquire coatings of secondary inorganic aerosols (sulphates and nitrates). In the humid tropical climates of Central and West Africa, these coatings undergo deliquescence, forming an acidic aqueous film around the particle core. This "acid processing" leaches metals from the internal matrix to the particle surface, significantly increasing their water solubility and, consequently, their bioavailability upon inhalation (Kolawole *et al.*, 2026).
3. Photochemical Transformations: High UV flux in the tropics promotes the formation of reactive oxygen species (ROS) on the surface of transition metals like Fe and Cu. These metals act as catalysts in the Fenton-like reactions within cloud droplets or deliquesced particles, leading to the production of further oxidative species that enhance the overall "oxidative potential" of the PM (Daou *et al.,* 2018).

***Deposition Processes***

The removal of metal-bearing PM from the atmosphere occurs through dry and wet deposition, the balance of which is strictly seasonal in SSA.

1. Dry Deposition: During the prolonged dry seasons, gravitational settling and turbulent diffusion are the primary removal mechanisms. Larger geogenic particles ($PM_{10}$) settle rapidly near sources, whereas finer, metal-rich particles ($PM_{2.5}$) rely on dry move-out, which is less efficient, leading to higher ambient concentrations and prolonged human exposure.
2. Wet Deposition: The onset of the monsoon or rainy season triggers intense "washout" (below-cloud scavenging) and "rainout" (in-cloud scavenging) processes. While wet deposition effectively "cleans" the atmosphere, it results in the concentrated flux of heavy metals into terrestrial and aquatic ecosystems. This transition represents a shift in exposure pathways from direct inhalation to indirect ingestion via contaminated water and crops (Adimalla, 2020).

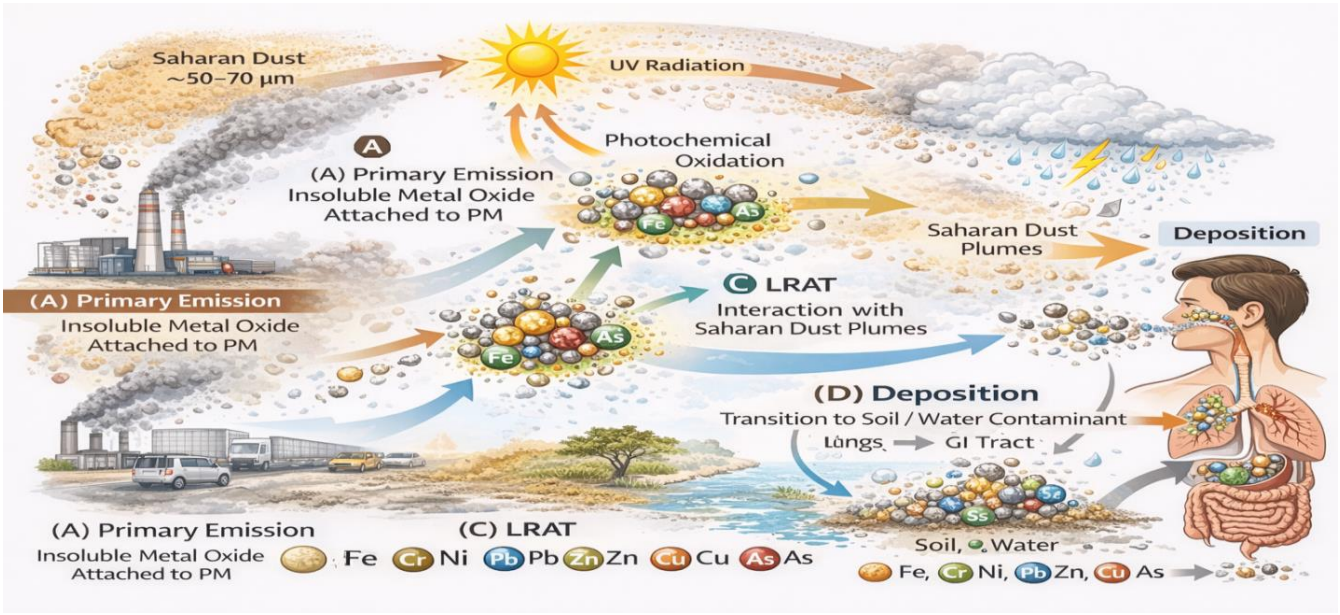


Figure 3: Conceptual Model of Atmospheric Metal Transformation

This figure 3 above, illustrates the lifecycle of a PM-bound heavy metal in the SSA atmosphere. (A) Primary emission of insoluble metal oxides from traffic/industry. (B) Atmospheric Aging: The particle acquires an acidic sulphate coating and undergoes UV-driven redox changes. (C) LRAT: Interaction with Saharan dust plumes. (D) Deposition: Transition from atmospheric pollutant to soil/water contaminant via wet/dry fallout, highlighting the shift in human exposure risk from the lungs to the gastrointestinal tract.

***Summary of Implications***

The atmospheric behaviour of metals in SSA suggests that the toxic load of a particle increases with its age and distance from the source due to increased solubility and the accumulation of secondary pollutants. This underscores the need for regional monitoring that accounts for atmospheric chemistry rather than focusing solely on mass concentrations at the point of emission.

**Levels and Distribution in Sub-Saharan Africa**

Regional distribution patterns are interpreted in the context of dominant emission sources previously detailed in Section 5. The concentrations and spatial distribution of particulate matter (PM)-bound heavy metals across Sub-Saharan Africa (SSA) are characterized by extreme heterogeneity, driven by the interplay between localized anthropogenic emission hotspots and broad-scale geogenic cycles. Unlike the relatively homogenized pollution profiles of European or North American cities, SSA presents a patchwork atmospheric landscape where concentrations often fluctuate by several orders of magnitude over short distances and between seasons.

***Regional Comparisons and Hotspots***

A comparative synthesis of the literature reveals distinct regional signatures in the atmospheric burden of trace elements.

*West Africa*: This region exhibits some of the highest PM mass concentrations globally, particularly during the Harmattan season. Studies in Nigerian metropolitan centres like Lagos and Ibadan consistently report Pb and Zn levels that exceed WHO air quality guidelines. Owoade *et al.* (2015) highlighted that while crustal elements (Fe, Al) dominate the total mass, the anthropogenic enrichment of Pb and Cu in the fine fraction ($PM_{2.5}$) is significantly higher in West African urban corridors compared to other sub-regions. In Ghana, the e-waste hub of Agbogbloshie represents a continental extreme for Cd and Pb concentrations, creating a localized toxicological profile that deviates sharply from the regional background (Feldt *et al.*, 2014).

*Southern Africa*: The atmospheric profile of Southern Africa is dominated by the industrial heartland of South Africa and the mining belts of Zambia and Zimbabwe. The Highveld region of South Africa serves as a primary source of Ni, Cr, and V due to the density of coal-fired power plants and petrochemical industries (Tshehla & Wright, 2019). Meanwhile, the Copperbelt region of Zambia displays globally significant levels of Cu and Co. Unlike West Africa, where traffic and dust are the primary drivers, the Southern African signature is heavily skewed toward metallurgical and energy-sector tracers (Nkosi *et al.*, 2018).

*East Africa*: East African urban centres like Nairobi and Addis Ababa typically report lower industrial metal concentrations compared to their Southern counterparts. However, they exhibit high levels of biomass combustion

tracers. Gaita *et al.* (2014) observed that while $PM_{2.5}$ mass in Nairobi is often lower than in Lagos, the concentrations of Br and Pb remain concerning, reflecting the continued influence of poorly regulated vehicular emissions and the use of solid fuels in high-density informal settlements.

***Urban vs. Rural Disparities***

The urban-rural divide in SSA is more pronounced than in developed regions due to the concentration of infrastructure and the lack of decentralized industrialization. Urban centres function as atmospheric "islands" of heavy metal contamination. In these cities, the concentration of anthropogenic metals (Pb, Zn, Cd) is typically 5 to 20 times higher than in adjacent rural areas (Adimalla, 2020). Conversely, rural atmospheres are characterized by lithogenic dominance, where Fe, Mn, and Ti are the primary species. However, rural areas are not entirely pristine; the seasonal transport of smoke from agricultural land clearing introduces significant pulses of As and Cd into rural environments, a phenomenon that is often overlooked in traditional air quality monitoring.

***Seasonal and Meteorological Influences***

Meteorology is the primary modulator of metal levels in the SSA atmosphere. The seasonality is binary: the dry season facilitates pollutant accumulation and dust resuspension, while the rainy season provides a temporary cleansing effect via wet deposition.

In West and Central Africa, the Harmattan wind creates a seasonal spike in crustal metals. Interestingly, studies have shown that during the Harmattan, the relative percentage of anthropogenic metals in the air may actually decrease due to the massive dilution effect of Saharan dust, even as the absolute mass of inhaled PM increases (Abiye *et al.*, 2020). In Southern Africa, the winter months coincide with strong thermal inversions. These stable atmospheric conditions trap pollutants near the surface, leading to pollution episodes where Ni and Cr concentrations can double compared to summer months (Tshehla & Wright, 2019). The synthesized country-level concentration ranges are presented in Table 3.

**Table 3: Reported Concentration Ranges ( ng/m³) of PM-bound Metals in Selected SSA Countries**

| Country | Region | PM Fraction | Lead (Pb) | Cadmium (Cd) | Chromium (Cr) | Nickel (Ni) | Primary Source |
|---|---|---|---|---|---|---|---|
| Nigeria | West | $PM_{2.5}$ | 50– 1,200 | 1 – 15 | 10 – 85 | 5 – 45 | Traffic/Dust |
| Ghana | West | $PM_{10}$ | 120– 3,500 | 5 – 60 | 15 – 110 | 10 – 70 | E-waste/Burning |
| South Africa | South | $PM_{2.5}$ | 10– 150 | 0.5 – 8 | 50 – 320 | 25 – 190 | Industry/Coal |
| Zambia | South | $PM_{10}$ | 200–4,800 | 2 – 25 | 10 – 50 | 5 – 30 | Mining/Smelting |
| Kenya | East | $PM_{2.5}$ | 15– 280 | 0.2 – 5 | 5 – 40 | 2 – 15 | Biomass/Traffic |
| WHO Limit | - | - | *500 (Annual)* | *5 (Annual)* | *N/A* | *20 (Annual))* | - |

*Note: Concentration ranges represent aggregated values synthesized from the 96 included studies (see Supplementary Data Matrix). Where multiple studies reported data for the same location, minimum–maximum ranges were derived. Variations reflect differences in sampling duration, seasonality, analytical techniques, and site classification (urban, industrial, or rural). Specific study-level references contributing to each range are provided in the supplementary material.*

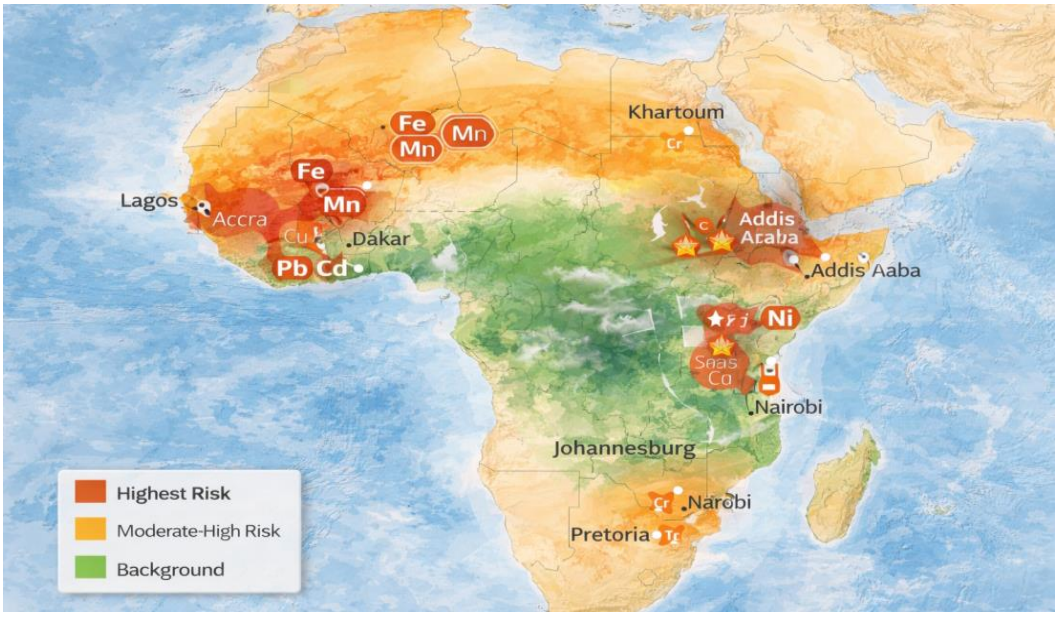


Figure 4: Schematic representation of regional hotspots based on synthesized literature data

This schema illustrates Toxic Hotspots across the subcontinent. Red zones (Highest Risk) are cantered on the Lagos-Accra urban corridor (Pb, Cd), the South African Highveld (Cr, Ni), and the Zambian Copper belt (Cu, Co, Pb). Orange zones (Moderate-High Risk) highlight the Sahelian belt during Harmattan (Fe, Mn + scavenged metals) and the East African Rift cities (Biomass tracers). Green zones (Background) are restricted to the sparsely populated central rainforests and remote desert regions, though even these show periodic influence from transboundary biomass smoke.

***Synthesis of Reliability and Data Gaps***

While the reported concentrations provide a clear picture of high risk, the data reliability is constrained by the lack of longitudinal studies. Most values in Table 3 are derived from campaigns lasting less than one year. Consequently, the average levels may not capture the true chronic exposure profile of the population. Furthermore, the significant variations in Pb levels across regions even after leaded fuel bans suggest that soil resuspension and artisanal activities are more dominant contributors to the SSA atmospheric burden than previously estimated by global emission models.

**Human Exposure Pathways**

The transition of particulate matter (PM)-bound heavy metals from atmospheric pollutants to physiological stressors is mediated through complex exposure pathways. In Sub-Saharan Africa (SSA), human exposure is intensified by unique urban morphologies, high levels of ambient dust, and a significant portion of the population residing in close proximity to unregulated emission sources. Understanding these pathways is critical for translating environmental concentrations into internal biological doses.

***Inhalation: The Primary Gateway***

Inhalation is the most direct and significant pathway for PM-bound heavy metals. The dose received via inhalation is fundamentally dictated by the aerodynamic diameter of the carrier particle. $PM_{10}$ particles are generally deposited in the extra-thoracic and tracheobronchial regions, where they may be cleared via mucociliary action and subsequently swallowed, transitioning to the ingestion pathway. However, the fine fraction ($PM_{2.5}$) and ultrafine particles (UFP) reach the alveolar region, where the thin air-blood barrier facilitates the systemic translocation of soluble metal species (Gaita *et al.,* 2014).

In the SSA context, the inhalation risk is exacerbated by the cocktail effect of multiple sources. For instance, commuters in Lagos or Nairobi are simultaneously exposed to fresh combustion aerosols (rich in Zn and Pb) and resuspended crustal dust (rich in Fe and Mn). The bioavailability of these metals in the lung environment specifically their solubility in lung surfactant determines the rate of absorption into the bloodstream (Kolawole *et al.,* 2026).

***Ingestion and Dermal Routes: The Dust-to-Gut Connection***

While inhalation is the primary focus of air quality research, the ingestion of resuspended PM is critically overlooked pathway in SSA. Due to the high prevalence of unpaved roads and the absence of green cover in many urban informal settlements, PM-bound metals rapidly deposit onto surfaces, soils, and outdoor foodstuffs.

The ingestion pathway becomes dominant for metals with low volatility, such as Lead (Pb) and Arsenic (As). Once deposited on the soil, these metals can be inadvertently ingested through hand-to-mouth contact or the consumption of street-vended foods exposed to ambient air. Dermal absorption, though generally considered a minor pathway for most metals, remains relevant for lipophilic metal compounds or in occupational settings such as artisanal mining in the Copperbelt or e-waste dismantling in Ghana where prolonged skin contact with metal-laden dust is common (Feldt *et al.,* 2014; Nkosi *et al.,* 2018).

***Vulnerable Populations and Socioeconomic Drivers***

Exposure is not uniformly distributed across the SSA population; it is sharply delineated by age, physiology and socioeconomic status.

*Children*: Paediatric populations are at the highest risk due to their higher metabolic rates and greater oxygen demand per unit of body weight, leading to a higher inhalation dose of PM. Behavioural factors, such as playing in proximity to the ground and frequent hand-to-mouth activity, significantly increase their ingestion dose. In mining-impacted regions of Zambia, this "multi-pathway" exposure has been linked to elevated blood lead levels (BLL) even when atmospheric concentrations appear moderate (Nkosi *et al.,* 2018).

*Low-Income Urban Residents*: Socioeconomic vulnerability in SSA often translates to proximity exposure. Residents of informal settlements like Kibera in Kenya or Makoko in Nigeria frequently live adjacent to major highways, open dumpsites, or artisanal workshops. These populations lack the protection of air-conditioned indoor environments and often spend significant portions of their day outdoors, leading to chronic, high-level exposure.

*The Elderly and Immunocompromised*: Reduced physiological clearance mechanisms and pre-existing respiratory or cardiovascular burdens make these groups highly susceptible to the acute oxidative stress induced by inhaled transition metals like Cr and Ni (Adimalla, 2020).

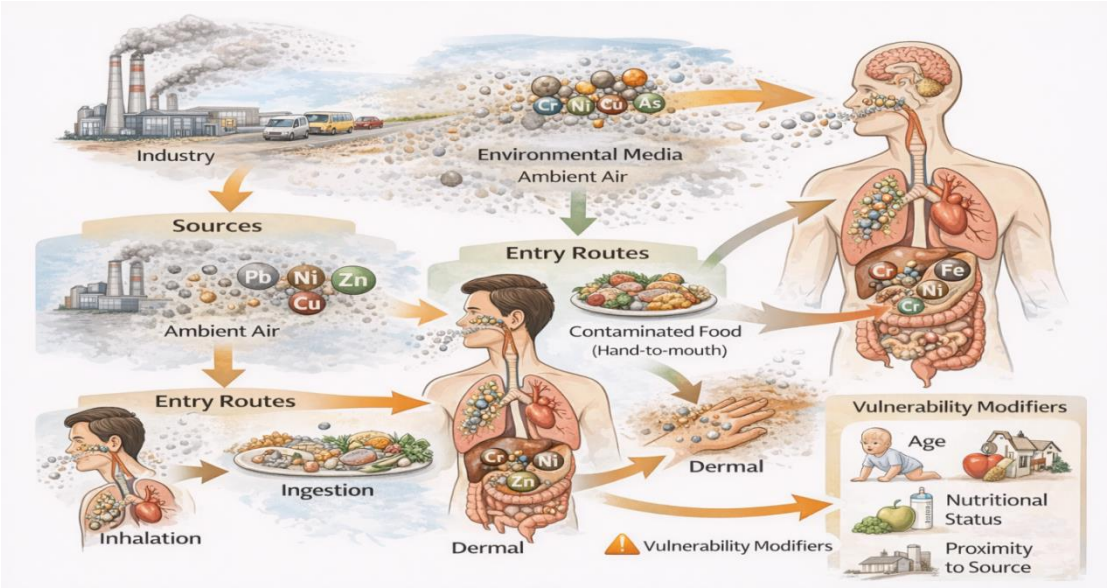


Figure 5: Conceptual Exposure Pathway Diagram: Source to Soma.

This figure illustrates the movement of PM-bound metals through the environment to the human body. (1) Sources: Industry, Traffic, Mining. (2) Environmental Media: Ambient Air and Resuspended Dust. (3) Entry Routes: Inhalation (lungs), Ingestion (GI tract via contaminated food/hand-to-mouth), and Dermal (skin contact). (4) Internal Dose: Bioavailability-driven translocation to target organs (Brain, Kidneys, Heart). (5) Vulnerability Modifiers: Age, Nutritional status, and Proximity to source.

***The Link between Bioavailability and Dose***

A critical distinction must be made between exposure (the amount of metal in the air) and the absorbed dose (the amount that crosses a biological membrane). The bioavailability of metals in SSA aerosols is often higher than in temperate regions due to atmospheric acid processing, which converts insoluble oxides into soluble sulphates (Kolawole *et al.*, 2026). Consequently, the actual public health risk in SSA may be higher than predicted by mass-concentration models alone, necessitating a transition toward risk assessments that incorporate bioaccessibility testing in simulated lung and gastric fluids.

**Toxicological Effects and Health Outcomes**

The deposition of particulate matter (PM)-bound heavy metals within the human respiratory tract initiates a cascade of biochemical alterations that extend far beyond localized pulmonary irritation. In the context of Sub-Saharan Africa (SSA), where ambient PM concentrations frequently exceed international safety limits, the toxicological burden is amplified by the presence of redox-active transition metals and potent carcinogens. The health outcomes associated with these pollutants are governed by the interplay between the chemical speciation of the metals, the site of deposition, and the physiological vulnerability of the exposed population.

***Core Toxicological Mechanisms: The Role of Oxidative Stress***

The primary mechanism through which PM-bound heavy metals exert toxicity is the induction of oxidative stress. Transition metals sequestered on the surface of PM, such as iron (Fe), copper (Cu), vanadium (V), and chromium (Cr), act as catalysts in Fenton-like and Haber-Weiss reactions. These reactions facilitate the reduction of hydrogen peroxide and the subsequent generation of highly reactive hydroxyl radicals (OH·) and other Reactive Oxygen Species (ROS).

When the production of ROS overwhelms the bodies endogenous antioxidant defences like glutathione, superoxide dismutase, it leads to widespread cellular damage. Key pathways include:

1. Lipid Peroxidation: ROS attack the polyunsaturated fatty acids in cell membranes, compromising membrane integrity and leading to cell death (Adimalla, 2020).
2. Protein Carbonylation: Oxidative modification of proteins alters enzyme functions and signaling pathways.
3. Genotoxicity: Heavy metals such as Arsenic (As), Cadmium (Cd), and Nickel (Ni) can induce DNA strand breaks, cross-linking, and the inhibition of DNA repair enzymes. These epigenetic and genetic modifications are precursors to the high carcinogenic risks observed in industrial SSA corridors (Kolawole *et al.*, 2026).

Furthermore, the presence of these metals triggers a systemic inflammatory response. The interaction between PM-bound metals and alveolar macrophages stimulates

the release of pro-inflammatory cytokines, such as Interleukin-6 (IL-6) and Tumour Necrosis Factor-alpha (TNF-α), which can translocate into the systemic circulation, driving multi-organ pathology.

***Systemic Health Outcomes***

The health implications of chronic exposure to PM-bound metals in SSA are multifaceted, spanning respiratory, cardiovascular, and neurological domains.

*Respiratory Disorders*: Direct contact between metal-laden PM and the lung epithelium causes chronic inflammation, leading to an increased incidence of chronic obstructive pulmonary disease (COPD), asthma exacerbations, and reduced lung function. In regions like the Niger Delta or the South African Highveld, high concentrations of Ni and Cr are strongly associated with pulmonary fibrosis and lung cancer (Tshehla & Wright, 2019).

*Cardiovascular Effects*: Fine PM ($PM_{2.5}$) can carry metals across the alveolar-capillary membrane into the bloodstream. This promotes atherosclerosis through the oxidation of low-density lipoproteins (LDL) and induces autonomic nervous system imbalances, increasing the risk of hypertension, myocardial infarction, and stroke.

*Neurological and Developmental Impact*: Perhaps the most critical concern in SSA is the neurotoxicity of Lead (Pb) and Manganese (Mn). Lead is a potent neurotoxin that interferes with neurotransmitter release and calcium signaling. In mining regions such as the Copperbelt in Zambia, pediatric exposure to Pb-rich dust has been linked to irreversible cognitive impairments, lower IQ scores, and behavioral disorders (Nkosi *et al.,* 2018).

***Metal-Specific Toxicological Profiles***

The unique industrial and environmental landscape of SSA creates specific risks associated with individual elements:

*Lead (Pb)*: Classified by the IARC as a Group 2A carcinogen, Pb affects the hematopoietic system by inhibiting heme synthesis, leading to anaemia which is a condition already prevalent in many SSA paediatric cohorts due to nutritional deficiencies.

*Cadmium (Cd)*: Often released during e-waste burning in hubs like Agbogbloshie, Cd is a Group 1 carcinogen with a biological half-life of 10–30 years. It bioaccumulates primarily in the kidneys, leading to nephrotoxicity and renal tubular dysfunction (Feldt *et al.,* 2014).

*Chromium (Cr)*: While Cr(III) is an essential nutrient, hexavalent chromium [Cr(VI)], frequently found in SSA industrial plumes, is highly soluble and toxic. It easily penetrates cellular membranes, where it is reduced, generating ROS and causing severe DNA damage.

*Arsenic (As)*: Found in emissions from coal combustion and gold mining, As interferes with cellular respiration and is a multi-organ carcinogen affecting the lungs, skin, and bladder.

**Table 4: Summary of PM-Bound Heavy Metals and Associated Health Effects**

| Metal | Primary SSA Source | IARC Class | Target Organs/Systems | Key Health Outcomes |
|---|---|---|---|---|
| Lead (Pb) | Traffic, Mining, Paint | 2A | Central Nervous System, Blood | Neurodevelopmental delays, Anemia, Hypertension |
| Cadmium (Cd) | E-waste, Fertilizers | 1 | Kidneys, Lungs, Bone | Renal failure, Lung cancer, Osteosteoporosis |
| Chromium (VI) | Industry, Steelwork | 1 | Respiratory System | Lung cancer, Asthma, Dermatitis |
| Nickel (Ni) | Industry, Coal Power | 1 | Lungs, Immune System | Nasal/Lung cancer, Contact dermatitis |
| Arsenic (As) | Mining, Coal, Biomass | 1 | Skin, Lungs, Bladder | Carcinogenesis, Skin lesions, Cardiovascular disease |
| Manganese (Mn) | Dust, Mining | - | Brain (Basal ganglia) | Manganism (Parkinson-like symptoms), Cognitive deficit |
| Zinc (Zn) | Tire wear, Incineration | - | Respiratory System | Metal fume fever (acute), Oxidative stress (chronic) |

***The Interaction of Co-exposure and Bioaccumulation***

A critical synthesis of SSA health data suggests that the risk is rarely driven by a single metal. The synergistic toxicity of multiple metals such as the combined impact of Cd and Pb on renal and neurological health remains an area of profound concern but limited empirical study in the region. Furthermore, because many of these metals bioaccumulate (notably Pb in bone and Cd in the kidney), current health risk assessments that rely on short-term atmospheric measurements likely underestimate the lifetime burden of NCDs (Non-Communicable Diseases) in the African population. The convergence of high pollution levels, high infectious disease prevalence, and limited access to specialized healthcare makes the toxicological impact of PM-bound metals in Sub-Saharan Africa a

primary driver of the region's shifting epidemiological profile from communicable to chronic diseases.

**Human Health Risk Assessment**

Human Health Risk Assessment (HHRA) serves as the quantitative link between environmental chemistry and public health policy. In the context of Sub-Saharan Africa (SSA), HHRA provides a standardized framework to translate the mass concentrations of PM-bound heavy metals into deterministic and probabilistic estimates of health risk. Regional studies predominantly follow the United States Environmental Protection Agency (US EPA) risk assessment paradigm, which integrates exposure modelling with toxicological dose-response relationships to characterize both non-carcinogenic and carcinogenic hazards.

***Exposure Assessment Modelling***

The first step in HHRA is estimating the Chronic Daily Intake (CDI) or Average Daily Dose (ADD) for specific exposure pathways. In SSA, while inhalation is often the primary focus, high dust loading and outdoor lifestyles necessitate a multi-pathway approach, including ingestion of resuspended particles and dermal absorption. The conceptual model for calculating dose (D) generally follows:

$$D = \frac{(C \times IR \times EF \times ED)}{(BW \times AT)}$$

Where:

C = metal concentration in the PM fraction
IR = intake rate (inhalation or ingestion)
EF = exposure frequency
ED = exposure duration
BW = average body weight
AT = averaging time

A common observation in SSA literature is the reliance on US EPA default values for BW such as 70 kg for adults and IR. However, studies in Nigeria and Ethiopia suggest these defaults may not reflect local physiological profiles and higher inhalation rates, potentially underestimating internal dose (Kolawole *et al.*, 2026; Owoade *et al.,* 2015).

*Non-Carcinogenic Risk: Hazard Quotient (HQ) and Hazard Index (HI)*

Non-carcinogenic risk is expressed through the Hazard Quotient (HQ), defined as the ratio of estimated dose to a Reference Dose (RfD), which represents the maximum daily exposure unlikely to cause adverse effects:

$$HQ = \frac{ADD}{RfD}$$

For multiple heavy metals, the individual HQs are summed to obtain the Hazard Index (HI). An HI > 1.0 indicates potential non-carcinogenic health risk. In industrial zones of South Africa and mining towns in Zambia, paediatric populations frequently show HI values exceeding unity, largely driven by Pb, Mn, and Cd (Nkosi *et al.,* 2018; Tshehla & Wright, 2019).

*Carcinogenic Risk (CR) and Lifetime Exposure*

For known or suspected carcinogens (e.g., Cr(VI), As, Cd, Ni), the Incremental Lifetime Cancer Risk (ILCR) is calculated as:

$$CR = \frac{ADD}{SF}$$

Where SF is the Slope Factor, converting daily intake to lifetime cancer probability. The US EPA considers CR values between $1 \times 10^{-6}$ and $1 \times 10^{-4}$ as acceptable. However, SSA studies often report values exceeding $1 \times 10^{-4}$, particularly near coal-fired power plants and e-waste sites, signaling urgent regulatory attention (Feldt *et al.,* 2014; Tshehla & Wright, 2019).

***Critical Assumptions and Uncertainties***

Total vs. Bioaccessible Concentrations: Most studies assume 100% bioavailability, which may overestimate risk. However, atmospheric acid processing can increase metal solubility, enhancing bioreactivity (Kolawole *et al.*, 2026).

Averaging Time and Exposure Duration: Rapid migration and informal housing can alter actual exposure periods. Age-Dependent Adjustment Factors (ADAFs) are rarely applied.

Synergistic Toxicity: The additive HI model assumes independent effects of metals, ignoring potential synergistic toxicity, e.g., co-exposure of Pb and Cd exacerbating renal damage (Adimalla, 2020). Health risk metrics and threshold benchmarks are summarized in Table 5.

**Table 5: Summary of Health Risk Indices and Thresholds in SSA Studies**

| Index | Definition / Formula Concept | Threshold of Concern | Significance in SSA Context |
|---|---|---|---|
| ADD/CDI | Daily intake per kg of body weight | N/A | Essential for calculating HQ and CR |
| HQ | ADD / RfD | >1.0 | High for Pb and Mn in mining/traffic zones |
| HI | ΣHQ (for multiple metals) | >1.0 | Indicates cumulative non-cancer threat |
| CR/ILCR | ADD × Slope Factor | $>1 \times 10^{-4}$ | Critical for Cr(VI) and Ni in industrial cities |

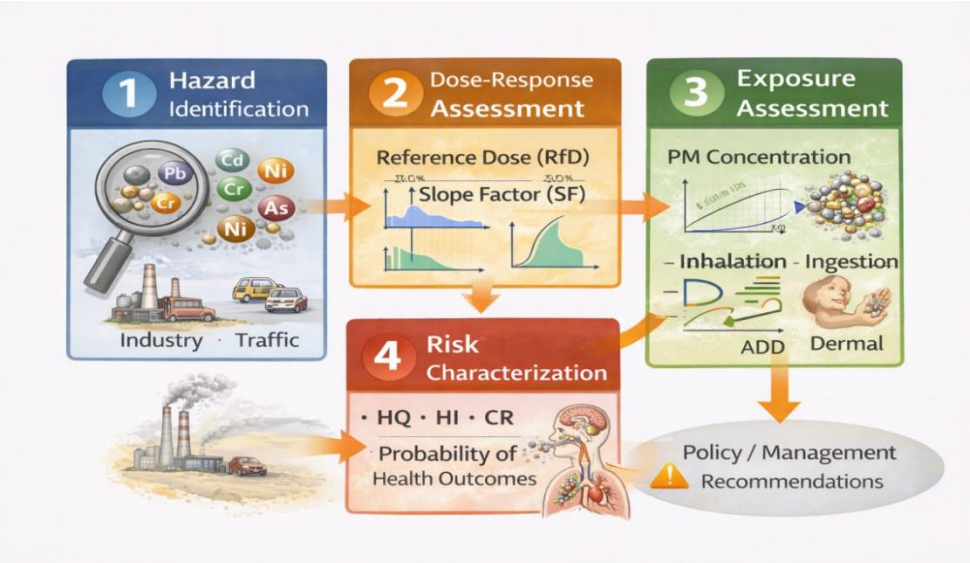


Figure 6: Integrated Human Health Risk Assessment Framework, Adapted from standard HHRA frameworks ( USEPA, 1989; 2001)

The figure 6 above shows the process flow diagram as it illustrates the four-stage framework applied in PM-bound metal research: (1) Hazard Identification: Selecting toxic metals (Pb, Cd, Cr, etc.) and identifying sources. (2) Dose-Response Assessment: Utilizing established RfD and SF values. (3) Exposure Assessment: Measuring PM concentrations and modelling ADD for inhalation, ingestion, and dermal routes. (4) Risk Characterization: Calculating HQ, HI, and CR to determine the probability of health outcomes, leading to Policy/Management recommendations.

***Conclusions for Risk Management***

HHRA in SSA consistently indicates disproportionate risk for children and low-socioeconomic populations. While African aerosols have high geogenic backgrounds, anthropogenic enrichment drives Hazard Index and Cancer Risk above safe thresholds. Future studies should adopt probabilistic techniques (e.g., Monte Carlo simulations) to better capture variability in African exposure scenarios.

**Policy and Mitigation Strategies**

The mitigation of airborne heavy metal pollution in Sub-Saharan Africa (SSA) requires a transition from reactive, mass-based monitoring to proactive, composition-oriented governance. While scientific evidence regarding the toxicity of PM-bound metals continues to mount, the regional regulatory landscape remains characterized by a governance gap which is a misalignment between ambitious international health guidelines and the localized realities of industrial expansion and institutional capacity.

***Regulatory Frameworks: WHO Guidelines vs. Regional Standards***

The World Health Organization (WHO) provides the global benchmark for air quality; however, most SSA nations struggle to harmonize local standards with the stringent 2021 WHO Global Air Quality Guidelines. A critical deficiency in regional policy is the focus on PM mass concentration ($PM_{2.5}$ and $PM_{10}$) without specific statutory limits for its metallic components, with the notable exception of Lead (Pb).

As shown in Table 6, even when standards exist, they are often significantly more lenient than WHO recommendations. For instance, while the WHO sets a clear annual limit for Pb, many SSA countries lack specific ambient air quality standards for Group 1 carcinogens such as Cadmium (Cd), Nickel (Ni), and Arsenic (As). This regulatory inertia effectively creates a permissible environment for high-intensity emissions from the mining and energy sectors (Tshehla & Wright, 2019).

**Table 6: Comparison of Annual Ambient Air Quality Standards (µg/m³)**

| Pollutant | WHO (2021/Global) | South Africa (NAAQS) | Nigeria (NESREA) | Ghana (EPA-Ghana) |
|---|---|---|---|---|
| $PM_{2.5}$ | 5 | 20 | 15 | 15 |
| $PM_{10}$ | 15 | 40 | 50 | 70 |
| Lead (Pb) | 0.5 | 0.5 | 1.0 | 2.5 |
| Cadmium (Cd) | 0.005 | N/S* | N/S | N/S |
| Nickel (Ni) | 0.02 (EU) | N/S | N/S | N/S |

*(N/S: Not Specified in general ambient standards; *EU values used as proxy for metals where WHO lacks specific ambient guidelines.)*

***Challenges in Enforcement and Implementation***

The primary obstacle to effective mitigation in SSA is not necessarily the absence of law, but the implementation-enforcement gap. Several factors contribute to this:

1. Monitoring Infrastructure: Robust enforcement requires real-time, high-precision data. However, many SSA nations possess limited active monitoring stations, often relying on sporadic, filter-based sampling for academic research rather than systematic regulatory oversight (Owoade *et al.,* 2015).
2. Economic Trade-offs: There is often a perceived conflict between stringent environmental regulation and the need for rapid industrialization. Governments may hesitate to impose heavy penalties on mining or manufacturing sectors that are primary drivers of GDP.
3. The Informal Sector: A significant portion of metal emissions such as those from artisanal mining or informal e-waste recycling operates outside the reach of formal regulatory frameworks. Managing these diffuse sources requires community-based interventions rather than traditional top-down enforcement (Feldt *et al.,* 2014).

***Technological and Policy Interventions***

Mitigation strategies must be multi-sectorial and source-specific.

1. Fuel and Vehicle Standards: Transitioning to Euro 4/IV equivalent fuel standards (such as the AFRI-4 initiative) is essential to reduce vehicular emissions of Zn, Cu, and Pb.
2. Formalizing Waste Management: Implementing Extended Producer Responsibility (EPR) frameworks can redirect e-waste from open-air burning pits to formal recycling facilities, drastically reducing atmospheric Cd and Cr pulses (Feldt *et al.,* 2014).
3. Industrial Controls: Mandating the installation of electrostatic precipitators (ESPs) and bag house filters in smelters and coal-fired power plants is a proven technological intervention that has yet to be universally enforced across the Southern African industrial belt (Tshehla & Wright, 2019).

***The Role of Green Chemistry and Sustainability***

The long-term solution lies in the integration of Green Chemistry principles into African industrialization. This involves moving toward benign-by-design manufacturing processes that minimize the use and emission of toxic heavy metals. For instance, the promotion of bio-based stabilizers in tire manufacturing could reduce Zn emissions, while the shift toward renewable energy (SDG 7) would eliminate the primary source of Cr and Hg from coal combustion. Furthermore, urban sustainability requires Green Buffering which is the use of specific vegetation belts to intercept and filter PM-bound metals before they reach residential zones. This nature based solution is particularly viable in tropical SSA regions where rapid plant growth can provide a low-cost supplemental barrier to atmospheric pollution (Adimalla, 2020).

***Actionable Policy Insights***

To safeguard public health, SSA nations must transition toward Risk-Based Air Quality Management. This involves: (i) establishing statutory limits for carcinogenic metals (As, Cd, Cr, Ni); (ii) investing in regional Centre of Excellence laboratories for elemental analysis; and (iii) linking air quality data with public health surveillance to quantify the economic burden of inaction.

**CONCLUSION**

It is the purpose of this study to compile heterogeneous data into a cohesive regional risk framework and thereby provides a comprehensive summary of PM-bound heavy metal contamination throughout sub-Saharan Africa. We discovered that some regions contain elevated concentrations of toxicants-in particular Pb, Cd and Cr-with an accompanying level of health risk that exceeds internationally recognized safe standards. Large spatiotemporal variation is revealed through this investigation with the west of SSA containing both the greatest pollution burden and thus, health risks. However, important gaps remain: analytical methods are inconsistent; data quality procedures are absent; monitoring does not extend to the long term. An urgent need for a standardized monitoring framework, the introduction of stronger legislative instruments and a broadened environment monitoring apparatus has become apparent. We believe this article establishes a base upon which to build evidence-based initiatives aimed at minimizing air pollution, and in so doing protecting public health across sub-Saharan Africa; thereby strengthening progress toward SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) through improved air quality governance, closing the gap between science and policy. It is time for a fundamental shift in air quality management across Africa.

**RECOMMENDATIONS**

Efforts must move from mass-centric monitoring and toward composition-centric governance where the most bioreactive metallic species are actively managed. In this context we argue for the following: (i) statutory ambient limits for carcinogenic trace metals to be adopted, (ii) a formalization process for the e-waste and artisanal mining sectors to mitigate diffuse emissions, and (iii) the deployment of low-cost, high-accuracy sensor networks for greater spatiotemporal resolution. In the final analysis, a transition towards meeting the SDGs in SSA is dependent upon integrating Green Chemistry and sustainable city

planning in such a manner as to prevent the economy from dictating the emission of toxicants into the atmosphere. This silent pandemic of airborne heavy metals cannot be ignored if long term public health is to be secured throughout SSA. Future research should focus on the development of harmonized, multi-country longitudinal monitoring frameworks integrating atmospheric chemistry, health outcome data, and real-time sensor technologies to enable predictive risk modelling across sub-Saharan Africa.

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