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Mining impacts on air quality in the Copper-Cobalt Belt, Democratic Republic of Congo

First assessment of particulate matter and inhalable heavy metals in Lualaba's frontline communities • October 2025 sampling campaign

Province of Lualaba, DRC

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Executive summary

The Democratic Republic of Congo (DRC) produces more than 75% of the world's cobalt – an essential mineral for the global energy transition. As demand continues to rise, the environmental and public health toll of cobalt extraction on nearby communities remains poorly documented and insufficiently addressed.

In October 2025, Source International, in collaboration with RAID, Afrewatch, and the University of Lubumbashi, conducted a field campaign in Kolwezi and surrounding areas to investigate the environmental impacts of large-scale cobalt mining. Sampling focused on communities near active mining operations run by COMMUS (Kolwezi and Pierre Muteba II), MUMI (villages near Lake Kando), and TFM (Fungurume). This report presents the findings of our air quality assessment, focusing on particulate matter ($PM_{2.5}$ and PM_{10}) and heavy metal content in inhalable dust.

Particulate matter measurements revealed **persistent and widespread air quality issues across the study area**. Daily $PM_{2.5}$ and PM_{10} concentrations exceeded the WHO Air Quality Guidelines by 2–6 and 1.5–4 times, respectively, and at most sites were also above several international Air Quality Standards. Notably, **South African standards** – the jurisdiction most referenced by mining companies operating in the DRC – **were exceeded at 7 of 8 sites**, all located close to active mining areas. When translated into an Air Quality Index, **6 of 8 sites resulted "unhealthy for sensitive groups"** and one site in Kolwezi – located less than 500 m from COMMUS waste rock dump – was "unhealthy". Hourly PM data confirmed that **daily values reflected persistently elevated background concentrations**, not isolated events. Sites located near open pits and waste rock dumps showed additional evening spikes consistent with localized mine-related dust emissions. Because most measurements were taken after two intense rainfall events, **air quality during typical dry-season conditions is likely worse** than documented here. The **established link between particulate matter pollution and serious health impacts** – including respiratory illness and adverse birth outcomes, among others – combined with the increase in respiratory problems, reproductive issues, and other health conditions over the past 5–10 years, raises significant concerns on the health of frontline communities in Lualaba.

Multiple lines of evidence indicated **that inhalable dust in the area originated predominantly from the resuspension of mining residues**. First, all samples displayed a highly consistent metal fingerprint characterized by the ubiquitous presence of cobalt, copper, and manganese. Second, cobalt and copper were strongly enriched relative to the natural topsoil but depleted compared to the local unprocessed ore. Third, the enrichment compared to topsoil was highest at sites closest to waste rock dumps or active mining operations. Fourth, we found no markers of biomass burning or charcoal combustion, and only minor evidence of additional sources such as regular traffic. **Cobalt and copper also consistently exceeded precautionary screening values derived from occupational health benchmarks**. While these screening values are only indicative, inhalation of cobalt-rich dust and fumes is the primary exposure pathway for this metal and cobalt-rich dust and fumes are known to cause respiratory irritation and lung damage. Past biomonitoring studies in the

region have also documented concerning levels of cobalt in the urine of communities living near mining and smelting operations, identifying dust as a primary exposure pathway for children and artisanal miners.

Overall, **Kolwezi emerged as the most critical hotspot for particulate matter pollution**, particularly within 0.5–1 km of waste rock dumps and other mine-related facilities. **Especially alarming were the results recorded at the Galaxy school**, an educational facility serving approximately 1700 students and located immediately adjacent to COMMUS open pit, waste rock dump, and other mine-related activities. Based on the spatial patterns that emerged in our dataset, it is likely that other schools located near mining operations experience similarly elevated – or potentially worse – levels of air pollution.

Although this study did not assess health outcomes directly, **the documented air pollution levels are overall consistent with existing biomonitoring results and health records**. Our findings underscore the urgent need for a formal epidemiological study aimed at linking exposure to pollutants to specific health outcomes, together with the introduction of national air quality standards, strengthened monitoring, improved emission controls, and implementation of effective mitigation measures.

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Abbreviation list

AQI	Air Quality Index, a simple metric to express and communicate air pollution's health impacts
AQGs	Air Quality Guidelines (recommendations from authoritative institutions)
AQSs	Air Quality Standards (legally binding regulations set by individual states)
DRC	Democratic Republic of Congo
ECHA	European Chemical Agency
EF	Enrichment Factor, a parameter that helps identify the origin of metals in inhalable dust
EPA	United States' Environmental Protection Agency
EU	European Union
WHO	World Health Organization
NO_x	nitrogen oxides, including NO and NO_2
OELs	Occupational Exposure Limits
PM	particulate matter, including $PM_{2.5}$ and PM_{10}
$PM_{2.5}$	particulate matter with diameter below 2.5 µm
PM_{10}	particulate matter with diameter below 10 µm
SCOEL	Scientific Committee on Occupational Exposure Limits
SO_2	sulfur dioxide
US	United States

Introduction

The context

The city of Kolwezi and its surrounding communities lie at the heart of the Copper–Cobalt Belt in the southern Democratic Republic of Congo (DRC). This region has gained significant international attention in recent years due to its vast mineral reserves, which are strategic for the global green energy and technology transition. Indeed, **the DRC is currently the world's largest producer of cobalt**, a critical component of lithium-ion batteries used in electric vehicles and electronic devices.[1] **In 2024, the country supplied 76% of the cobalt extracted worldwide**, primarily through large industrial mines located in and around Kolwezi.[1,2] A small amount of DRC's cobalt is also supplied via artisanal mining.[2]

While the international community increasingly recognizes the urgency of phasing out fossil fuels, **the environmental and human rights impact of this green transition are still largely overlooked**. Several strategic minerals required for this transition are sourced from countries where basic human rights are frequently violated and environmental regulations are weak, absent, or poorly enforced. Cobalt is one of these cases. A recent study conducted by RAID and Afrewatch documented **severe human health and environmental consequences of cobalt extraction in the DRC's Copper-Cobalt Belt**.[3] Through more than 140 interviews with residents, the study identified widespread health issues – including, among others, respiratory complaints, reproductive health issues, and dermatological problems – alongside a general deterioration of living standards over the past decade.[3] Scientific studies and civil society reports have similarly reported extensive environmental damage, particularly heavy metal contamination in water bodies. Although the

Figure 1. Aerial view of the open pit located near the sampling area, property of the mining company COMMUS.

Chinese and European multinationals included in the study acknowledge these risks in their Environmental and Social Impact Assessment, pollution remains pervasive.[3]

This report

In 2025, Source International joined RAID, Afrewatch, and the University of Lubumbashi to strengthen the evidence base on environmental pollution and human rights abuses in the DRC's Copper-Cobalt Belt region. The first sampling campaign took place in October 2025, at the end of the dry season, with the objective of assessing particulate matter (PM) pollution and supporting ongoing scientific investigations into water and sediment contamination led by the University of Lubumbashi.

This report describes our assessment of air quality, including **real-time detection of particulate matter and the analysis of heavy metal content in inhalable dust** in Kolwezi, Pierre Muteba II, villages near Lake Kando, and Fungurume. The results of our water and sediment monitoring campaign are instead presented in a dedicated report.[4]

Particulate matter measurements relied on the use of real-time monitors, which provided daily and hourly concentrations of $PM_{2.5}$ and PM_{10} – i.e., particles less than 2.5 µm and 10 µm, respectively, in diameter (Figure 2; further details in the section Sampling and methods). We also collected inhalable particles (i.e., particles up to 100 µm in diameter, which can be inhaled via mouth and nose; Figure 2) and sent them to an accredited laboratory for heavy metal analyses. To the best of our knowledge, **this is the first systematic study of mine-related particulate matter pollution in frontline communities of the DRC's Copper-Cobalt Belt region.**

Figure 2. Overview of the parameters monitored in this study. The definition of "$PM_{2.5}$" and "PM_{10}" (top) is based on particle size, while "respirable" and "inhalable" (bottom) refer to particles' behavior in the respiratory system – the *inhalable* fraction get only into the mouth and nose, while the *respirable* fraction gets deep into the lungs. We measured PM_{10} and $PM_{2.5}$ with an Aeroqual, while inalable particles were collected with an active sampler and sent to an accredited laboratory for the quantification of heavy metals (more details in the section Sampling and methods).

Previous studies

Reliable peer-reviewed studies on air quality in the Lualaba region are scarce. At the time of writing, we are only aware of two that address this topic – although not covering the pollutants targeted in

our campaign. The first, by Martínez-Alonso et al.[5], used satellite observations to assess air quality over the Copper-Cobalt Belt in the DRC and Zambia, with a focus on nitrogen oxides (NO_x) and sulfur dioxide (SO_2). Their analysis identified clear NO_x emission hotspots over 4 large open-pit mines and 2 cities, including Kolwezi and Lubumbashi. In Kolwezi, the authors reported a correlation between the yearly copper production and NO_x emissions, which they attributed to gasoline combustion from trucks, crushers, and other mining equipment. Due to inherent methodological limitations, the investigation did not yield clear insights into SO_2 emissions.

The second study, by Banza et al.[6], investigated metal exposure through mining dust among artisanal miners in Kasulo, a suburb of Kolwezi where artisanal mining became popular after the discovery of near-surface cobalt-rich ore in the backyards of many households. The authors collected urine, blood, drinking water, and dust samples deposited in artisanal miners' households, and compared them with a control group from another area of the city. Deposited dust in Kasulo contained markedly higher cobalt concentrations than the control area (205–8140 vs. 6–41 µg/g). Biomonitoring results were consistent with these findings, showing significantly higher levels of cobalt in both urine and blood of Kasulo's residents. On this basis, the authors hypothesized that cobalt-rich dust constitutes a primary exposure pathway for this metal.

A small number of additional studies have also investigated particulate matter pollution in Kolwezi, Lubumbashi, and nearby areas.[7–9] However, methodological limitations and data reporting issues limited their comparability and suitability for use as references.

Adding to the academic literature, in March 2026 the Environmental Investigation Agency (EIA) US and Premi Congo released an independent study focused on SO_2 in Fungurume.[10] The report aimed at establishing a nexus between the increase in health issues and the construction of the TFM 30k mixed ore processing plant in 2023. Amid growing concerns in the local community, in 2024 TFM commissioned an air quality study to the Congolese firm Skyside. Using passive samplers deployed over several weeks, the campaign revealed no exceedances of Congolese regulatory limits for SO_2. In contrast, the expert commissioned by the EIA recorded frequent exceedances to the 10-minute WHO guideline of 0.2 ppm (500 µg/m^3) at all monitored points, with peaks as high as 0.6–0.8 ppm. Unlike Skyside, the EIA expert employed a portable real-time monitor capable of capturing short-term spikes in SO_2. Although TFM raised methodological concerns, the study prompted the mining company to acknowledge responsibility for the SO_2 emission spikes in 2023–2024 and led to the announcement of an upcoming government-led inspection.[11]

Reference: guidelines, standards, and other comparisons

To contextualize our findings, we refer to air quality guidelines from the World Health Organization (WHO), air quality legislation from selected countries, and specific metrics from authoritative scientific bodies and peer-reviewed literature. Given the different availability of reference parameters and norms, we cover separately bulk particulate matter (i.e., $PM_{2.5}$ and PM_{10}; first section) and heavy metals in inhalable dust (second section).

Table 1. Overview of references relevant for air quality evaluation. References include Air Quality Guidelines (AQGs, not legally binding), Air Quality Standards (AQSs, legally binding), and other norms (details in text). Links to the relevant documents are in the Table (n.d. = not defined). [a] To be attained by 01/01/2030.[14] [b] To be reduced to 25 µg/m³ by 01/01/2030.[15] [c] Values for Class 1 (special regions, including national parks).[16] [d] Likely a typo in the units of measure (i.e., µg/m³, not g/m³).

		Daily values (24-hour average)	
Country / organization	**Reference type**	**$PM_{2.5}$ (µg/m³)**	**PM_{10} (µg/m³)**
World Health Organization[13]	AQG	15	45
European Union[14,17]	AQS	n.d. (25[a])	50 (45[a])
Switzerland[18]	AQS	n.d.	50
United States[19]	AQS	35	150
South Africa[15,20]	AQS	40[b]	75
China[21]	AQS	75 (35[c])	150 (50[c])
Democratic Republic of Congo[22]	Max mining areas	n.d.	500'000'000[d]

Regarding legislation, we included countries with active mining activities in Lualaba (e.g., Switzerland and China), with automotive industries that are likely to use elements mined in this area (e.g., European Union and the United States), and South Africa, whose environmental legislation is often taken as reference by the Congolese mining industry. Whenever available, we also included standards and regulations from the DRC.

Particulate matter

Daily PM values. Particulate matter pollution is the second-leading risk factor for death globally,[12] and it is thus regulated in most countries. Here, we considered the most recent Air Quality Guidelines (AQGs) from the WHO[13] and selected international Air Quality Standards (AQSs). In 2021, the WHO updated its guidelines for several priority pollutants, including $PM_{2.5}$ and PM_{10}. The updated values for daily (i.e., 24-hour) averages are **15 µg/m³ for $PM_{2.5}$** and **45 µg/m³ for PM_{10}** (Table 1).[13]

The WHO guidelines are *recommendations* that prioritize human health protection and are not legally binding. Still, most countries used these guidelines to derive their AQSs, which consider both human health protection and economic interests. When available, daily PM standards range **25–75 µg/m³ for $PM_{2.5}$** and **50–150 µg/m³ for PM_{10}** (Table 1). To the best of our knowledge, **the DRC does not have enforceable AQSs for particulate matter.** We identified only a maximum 24-hour average value for PM_{10} to be attained outside mining areas (Mining Regulations, Decree No. 038/2003[22]; Table 1). This value is several orders of magnitude higher than typical AQSs, which we believe is due to a drafting error in the units of measure (i.e., 500 µg/m³, not 500 g/m³). For this reason, we did not include this value in our discussion. We note that **the absence of domestic AQSs leaves communities in the Copper-Cobalt Belt reliant on international frameworks**. Given the scale and intensity of industrial activity in the region, **there is an urgent need to establish realistic and enforceable national air quality standards in the DRC**.

Table 2. Simplified overview of US EPA's Air Quality Index (AQI) categories. The full health statement for each category is available in Appendix B of the 2024 *Guidance for Inhalation Exposures to Particulate Matter.*[23]

	Daily ranges (24-hour average)	
AQI category	**$PM_{2.5}$ (µg/m³)**	**PM_{10} (µg/m³)**
Good	0–9	0–54
Moderate	9.1–35.4	55–154
Unhealthy for sensitive groups	35.5–55.4	155–254
Unhealthy	55.5–125.4	255–354
Very unhealthy	125.5–225.4	355–424
Hazardous	>225.5	>425

Air Quality Index. Daily PM averages can also be used to compute the Air Quality Index (AQI), a simple metric that allows one to **directly link air pollutants' concentration to health outcomes**.[24,25] Although numerous AQIs exist (see the Air Quality Index Hub[24] for an overview), we selected the AQI from the United States' Environmental Protection Agency (EPA), which are recognized internationally and simple to compute. This version includes 5 priority pollutants – including $PM_{2.5}$ and PM_{10} – and classifies health risks into 6 classes (Table 2). Each class is associated with a color, a health statement, and simple recommendations.[23,25,26] The section Data analysis contains a more detailed explanation on how we derived the AQI from daily PM concentrations.

Hourly PM values. Air quality standards and guidelines are always referred to a specific averaging time: for PM, it is always 24 hours (daily average) or 365 days (yearly average).[a] Since no official indications exist for shorter intervals, the Agency for Toxic Substances and Disease Registry – a US public health agency – acknowledged the **possibility of comparing *hourly* averages with *daily* AQGs for $PM_{2.5}$ and PM_{10}** for screening and evaluation purposes.[23] The rationale builds on the 2019 Integrated Science Assessment from the US EPA, which found adverse health effects at or below the 24-hour $PM_{2.5}$ and PM_{10} guidelines.[23,27]

Heavy metals in inhalable dust

Legislation. Most countries – including the EU, Switzerland, the US, China, and South Africa – set limits for selected heavy metals in air in their air quality legislation. However, these values always refer to *yearly* concentrations in PM_{10}, which we could not determine with our setup and available time. Furthermore, they typically regulate only metals of high concern – i.e., arsenic, cadmium, hexavalent chromium, mercury, and lead. To the best of our knowledge, none of the selected countries sets AQSs for cobalt, copper, and manganese in particulate matter.

Better comparable to our measurement setup is the legislation on workplace exposure, which aims at protecting workers during a 40-hour work week.[28] Unlike AQSs, occupational exposure limits (OELs) directly refer to respirable and inhalable dust over 8 hours. They do not aim to protect the

[a] For other pollutants, the averaging time can be different: for example, for SO_2, the WHO sets guidelines for 10-minute and 24-hour averages.[13]

Table 3. Overview of occupational exposure limits and health-based recommendations for cobalt, copper, and manganese (8-hour average). Values for single countries are from the GESTIS database,[29] not the original legislation (n.d. = not defined). The health-based recommendations are from the EU's Scientific Committee on Occupational Exposure Limits (SCOEL).[31,32,34] [a] Inhalable fraction. [b] Respirable fraction. [c] 15-min average. [d] Indicative OEL.

	Occupational Exposure Limit (µg/m³, 8-hour average)		
Country / organization	**Cobalt**	**Copper**	**Manganese**
European Union	10[a]	n.d.	200[a,d]
Switzerland	50[a]	100[a,c]	200[a]
United States (NIOSH)	50	n.d.	1,000[c]
South Africa	40[a]	n.d.	200
China	50[c]	n.d.	n.d.
DRC	n.d.	n.d.	n.d.
SCOEL recommendations	*1[a]*	*10[b]*	*200[a]*

general population over their whole lifespan: for these reasons, they are always substantially higher than AQSs. For example, OELs for cobalt, copper, and manganese are between 10 and 1000 µg/m³ (Table 3).[28,29] In the guidance documents that set the base for the EU legislation, the Scientific Committee on Occupational Exposure Limits (SCOEL)[30] provided health-based values of 1 µg/m³ for cobalt,[31] 10 µg/m³ for copper,[32] 2000 µg/m³ for chromium,[33] 200 µg/m³ for manganese,[34] and 10 µg/m³ for nickel.[35] The SCOEL did not define values for tin.[36]

Although for screening purposes only, we used the SCOEL recommendations to derive **rough ambient screening values for the general population.** Using a precautionary scenario detailed in the section Data analysis, we estimated screening values of 0.03 µg/m³ for cobalt, 0.3 µg/m³ for copper, 67 µg/m³ for chromium, 7 µg/m³ for manganese, and 0.3 µg/m³ for nickel in inhalable dust.

Enrichment factors. We interpreted our findings also in terms of enrichment factors (EFs), a parameter commonly employed in the scientific literature to identify the origin of specific metals in particulate matter.[37,38] In general, if EFs are close to 1 (between 0.1 and 10), elements' concentrations are close to their natural abundance. On the other hand, EFs considerably larger than 10 or smaller than 0.1 are indicative of elements that are, respectively, enriched or depleted compared to natural conditions – thus, they spotlight anthropogenic disturbance. As reference, we used 2 different baselines: the median topsoil composition in Katanga from a recently released database[39] and the median chemical composition of heterogenite, the most abundant ore in Kolwezi.[6,40]

Sampling sites and methods

Sampling sites

Between October 10 and 20, 2025, we sampled air, water, and sediment in Kolwezi, Pierre Muteba II, 2 villages near Lake Kando, and Fungurume (Figure 3). For air quality, we obtained 16 real-time particulate matter datasets (8 of ≥ 24 hours) and collected 9 inhalable dust samples at locations identified in collaboration with Afrewatch and its local focal points – including several private homes, 2 health centers, a school, and a hotel (Table A1). Water and sediment sampling are detailed in a dedicated report.[4]

Sites were selected based on their proximity to potential mine-related sources and repeated concerns on air quality expressed by local communities. In Kolwezi (Figure 3A) and Pierre Muteba II (Figure 3B), we sampled 10 sites (3 of them twice) near waste rock dumps, open pits, and other mine-related activities operated by the Compagnie Minière de Musonoie Global SAS (COMMUS) and other companies, including Glencore.[3] In Mibanze and Rianda, approximately 5 km south of the Mutanda

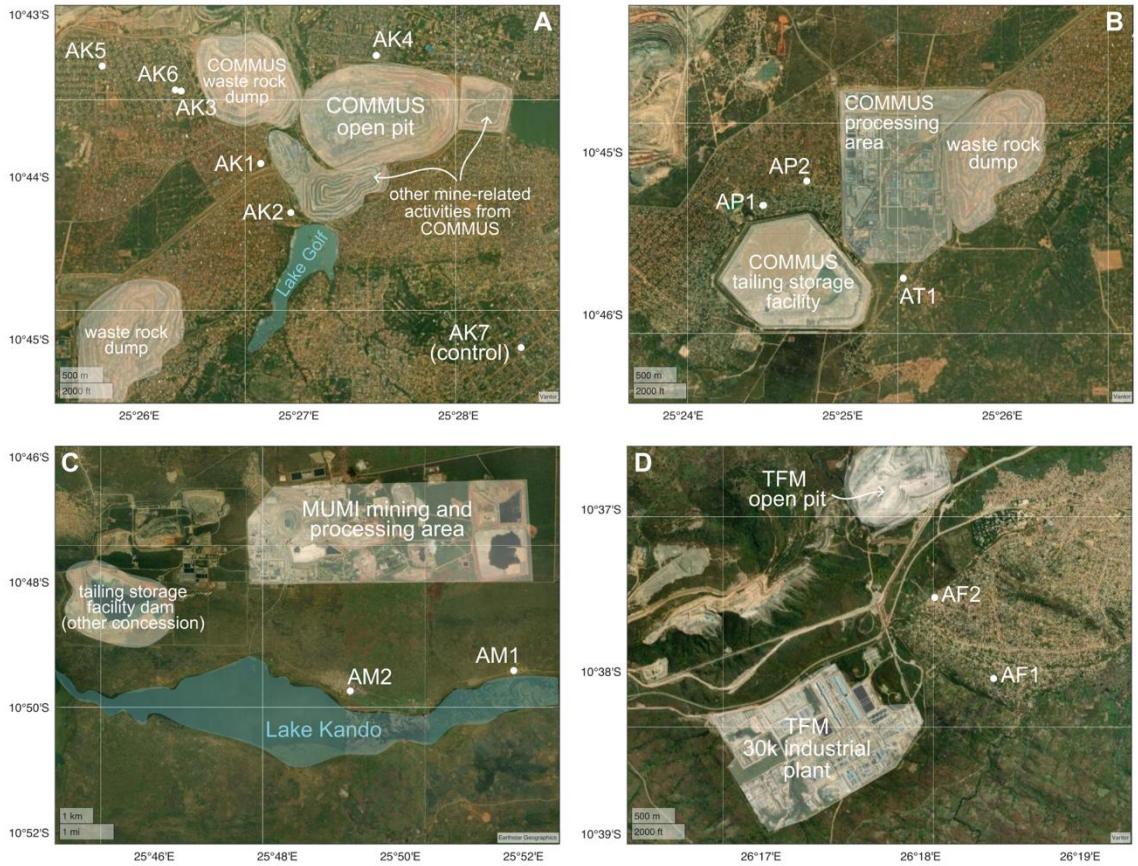

Figure 3. Overview of the sampling locations in Kolwezi (A), Pierre Muteba II and Tshizuza (B), Lake Kando and surrounding areas (C), and Fungurume (D). Companies operating in these areas include COMMUS (A, B), MUMI (C), and TFM (D), among others. The satellite images were plotted with Matlab and do not necessarily reflect the ground situation at the time of sampling. We primarily based out attribution of mining areas and facilities on data from OpenStreetMap[41] and the DRC Mining Cadastre Map Portal[42].

Mining SARL (MUMI) concession,[3] we sampled one site per village (Figure 3C). In Fungurume, we monitored 2 sites: one closer to the Tenke Fungurume Mining (TFM) 30k industrial plant and one nearer to TFM's open pit (Figure 3D).[3] The sites in Fungurume broadly overlap with the area that the Environmental Investigation Agency monitored in its recent study on SO_2 pollution.[10]

Most sampling activities took place after two intense rain events on the afternoons and nights of October 11 and 12, 2025, which may have alleviated air pollution in the remaining of the sampling campaign. After October 12, weather conditions were sunny to partially sunny, with generally absent to moderate winds.

General site characterization

At each site, we recorded general field data with ODK Collect[43], which was used to fill a questionnaire previously set up in KoboToolbox.[44] The questionnaire included date and time, sample ID, GPS location and altitude, parameters measured at the site, instruments ID, known pollution sources, weather conditions, and photographic evidence. For real-time air measurements, we also filled out a control questionnaire at the end of the deployment, recording sample ID and time of collection.

Real-time PM measurements

We obtained real-time $PM_{2.5}$ and PM_{10} data with 3 Aeroqual S500 instruments equipped with a particulate matter head. These sensors record $PM_{2.5}$ and PM_{10} data in real time, at a 1-min frequency and in units of mg/m^3 and were periodically recalibrated by the manufacturer. The error based on factory calibration accuracy was 5 $\mu g/m^3$ + 15% of the measured value.[45] Internal validation tests confirmed that all instruments performed consistently within the expected accuracy range.

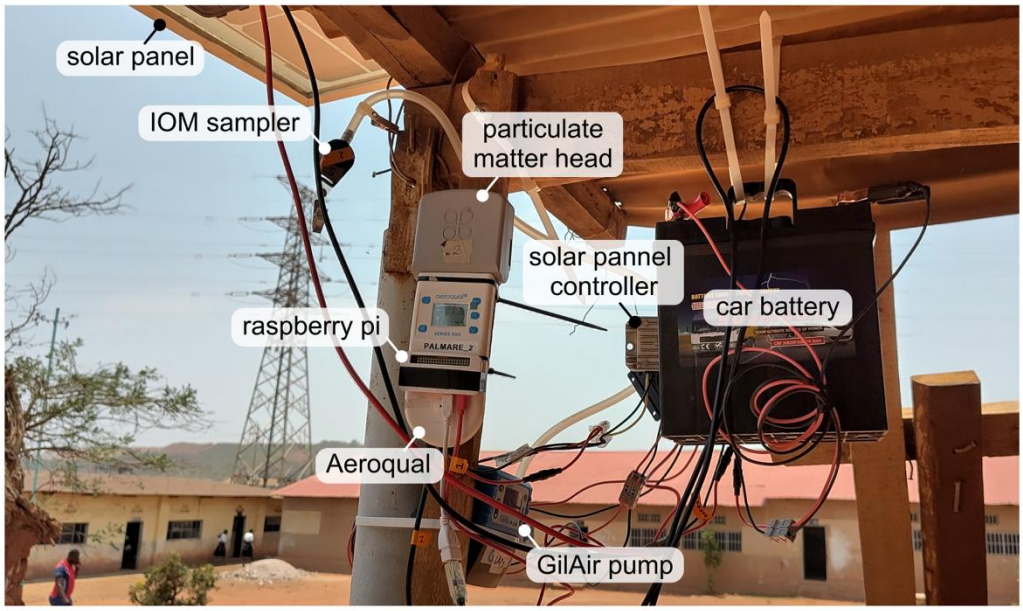

Figure 4. Key components of the air quality measurement setup, including the real-time PM detector (Aeroqual + raspberry pi) and the inhalable dust collector (GilAir pump + IOM sampler; more details in Figure 5). We also had a small solar panel and car battery to ensure energy self-sufficiency at all locations.

Furthermore, they *systematically underestimated* $PM_{2.5}$ and PM_{10} measurements obtained via a reference-grade instrument operated by the Italian Environmental Agency. On this basis, we are confident that the measurement uncertainty inherent to these instruments does not affect the overall conclusions of this study.

Each day, we deployed 2 or 3 instruments for several hours – ideally at least 24 – in locations previously identified by Afrewatch and its focal points. As most sites lacked continuous electricity, each Aeroqual was powered with an independent energy source supplied by a 40 or 60 W solar panel connected to an external battery through a solar charge controller (Figure 4). Each instrument was also supplied with a small computer (a Raspberry pi) equipped with a microSD and a custom-made program to increase its storage memory and allow wireless data download. The instruments were always placed 2–2.5 m from the ground in a shielded place (typically under a roof) away from direct PM emissions like traffic and cooking fires.

Collection of inhalable dust

At most locations, we also collected inhalable dust for heavy metal analyses. The setup included a small pump (GilAir Plus) equipped with a conductive plastic IOM sampler (Figure 4 and Figure 5). Before deployment, we loaded a pre-weighted 25-mm filter (mixed cellulose esters) into the IOM sampler using a clean metal tweezer. This step was always performed in a closed and protected space. We then placed the sampler outdoors and set the pump at 2.5 L/min in constant flow mode. We let the pump run until the filter clogged, which typically happened after 7–23 hours of deployment, depending on location. At the end of the daily PM measurement, we retrieved the Aeroqual, the pump, and the sampler, recorded the total pumped volume, and placed the filter back

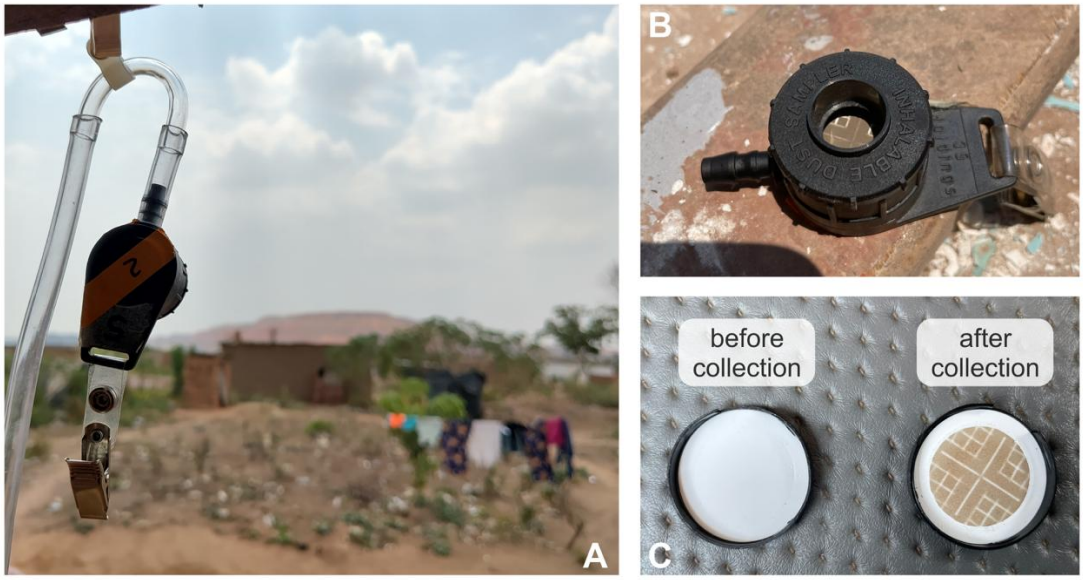

Figure 5. **Detail of the IOM sampler for the collection of inhalable dust.** We placed the sampler containing a clear filter facing potential dust sources (panel A). After collection, we retrieved it (panel B) and extracted the filter, which was always significantly darker than before collection (panel C).

into its plastic Petri dish. The Petri dish was labelled, closed with tape, and stored in the dark until shipping. Before switching off the pump, we noted the total pumped volume and time.

Chemical analyses

Heavy metal content in inhalable dust was determined by an Italian laboratory accredited by ACCREDIA. The procedure involved weighting the filters to obtain the total inhalable mass via the Italian Official Method (M.U.) 1998:13. The filter was then subjected to acid digestion (M.U. 723:1986) and the resulting solution was analyzed via inductively coupled plasma-mass spectrometry (EPA method 6020B 2014). The results were converted into µg/m^3 by dividing the aqueous concentrations by the total pumped volume. The laboratory's results for the 21 elements are in Table A2.

Data analysis

Particulate matter

We analyzed all data with Matlab (R2021b) and Excel. We used the real-time Aeroqual data to obtain daily and hourly $PM_{2.5}$ and PM_{10} values and to compute AQIs. For daily PM values, we discarded at least 7–10 data points at the beginning of each measurement (to account for the instrument's warmup time), averaged the following 1440 data, and multiplied the resulting value by 1000, yielding daily $PM_{2.5}$ and PM_{10} values in µg/m^3 (Table A2). To compute each site's AQI, we used the official US EPA online calculator[46] to obtain an individual AQI for each pollutant, then selected the highest value to obtain the overall AQI (Table A2).[26]

For hourly $PM_{2.5}$ and PM_{10} averages, we used only data points from the first available round hour until the last complete hour (e.g., from 12:00 to 16:59). In one case (AP1-bis), we discarded the dataset due to the clear interference of rain in the data. We ran a Matlab script that averaged groups of 60 subsequent data points. The results were multiplied by 1000 and reported in µg/m^3. As we observed a significant correlation between $PM_{2.5}$ and PM_{10} across all sites (Figure A1), and correlation between acute and sub-acute health impacts are better established for $PM_{2.5}$ than for PM_{10},[23] our discussion of hourly PM trends focuses on $PM_{2.5}$.

Inhalable dust

We used metal concentrations in inhalable dust to calculate enrichment factors (EF; Table A4). For each metal, we obtained its EF according to the following equation.[37,38]

$$\mathrm{EF} = \frac{[\mathrm{metal}]_{\mathrm{dust}}/[\mathrm{aluminum}]_{\mathrm{dust}}}{[\mathrm{metal}]_{\mathrm{ref}}/[\mathrm{aluminum}]_{\mathrm{ref}}}$$

where $[\mathrm{metal}]_{\mathrm{dust}}$ and $[\mathrm{aluminum}]_{\mathrm{dust}}$ are concentrations in the dust sample, while $[\mathrm{metal}]_{\mathrm{ref}}$ and $[\mathrm{aluminum}]_{\mathrm{ref}}$ are the concentrations of the same elements in the reference media, either Katanga's topsoil[39] or the local ore[40] (details in Section A1 of the Appendix). We used aluminum as metal reference due to its ubiquity and predominantly natural origin.[38] Control calculations using iron, another common reference,[37] provided comparable results.

Due to the absence of suitable international parameters for heavy metal content in inhalable dust, we used the recommended values from the EU's Scientific Committee on Occupational Exposure Limits (SCOEL; Table 3) to get a tentative screening value applicable to the general population. We obtained the value by first accounting for the difference in exposure time between workplaces (i.e., 8 hours for 5 days a week = 40 hours a week) and households (i.e., 24 hours for 7 days a week = 168 hours a week). We then assumed that sensitive individuals – like children, old people, and people with illnesses – are 3 to 10 more sensitive than the general population,[47] arriving at an average correction factor of ~ 30. Finally, we divided the SCOEL's recommended values by 30, yielding screening values applicable to the entire population. We stress that these numbers should be considered *precautionary* values for preliminary screening considerations only.

Results

General overview

Daily PM and Air Quality Index values

All daily particulate matter data exceeded the WHO's Air Quality Guidelines approximately 2- to 6-fold for $PM_{2.5}$ and 1.5- to 4-fold for PM_{10} (Figure 6 and Table A2), underscoring a **critical air quality issue in the whole study area. At 7 of the 8 monitoring sites**, **daily PM values also exceeded the South African Air Quality Standards** – the regulatory framework most frequently referred to by mining companies operating in the DRC. In addition, all sites except one (AF1, in Fungurume) exceeded the United States' AQS for $PM_{2.5}$, while daily PM_{10} values were above both the Swiss and the European AQSs at every site. Due to the substantially more permissive limits, only one location in Kolwezi (AK3, immediately adjacent to the COMMUS waste rock dump) was above the Chinese norm for both pollutants.

When converted to AQI values, **6 of 8 locations resulted unhealthy for sensitive groups** (AQI = 3), **one site was moderate** (AQI = 2; AF1, in Fungurume), **and one unhealthy** (AQI = 4; AK3, in Kolwezi). In all cases, the classification was driven by daily $PM_{2.5}$ values, not PM_{10}. According to the ATSDR,[23] an AQI of 3 is associated with "increased likelihood of respiratory symptoms in sensitive groups" (i.e., pregnant women, children, and elderly people) and "exacerbation of symptoms of or death from

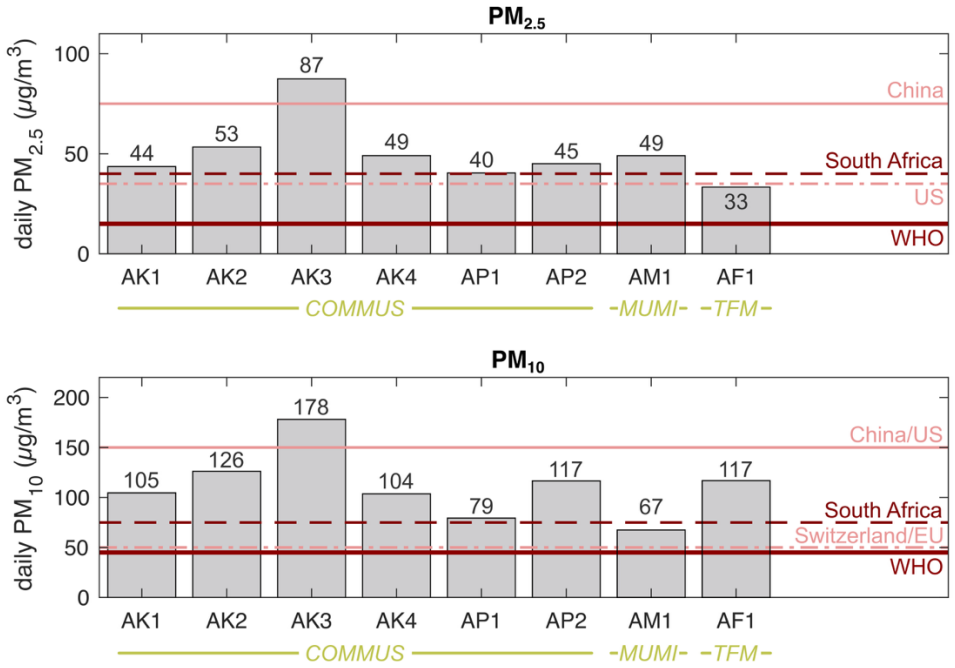

Figure 6. Daily particulate matter values at selected sites in Kolwezi (AK1 to AK4), Pierre Muteba II (AP1 and AP2), near Lake Kando (AM1), and Fungurume (AF1). The text in green indicates the relevant mining concession for each area. The daily averages are reported at the top of each bar and in Table A2. The continuous red line denotes the WHO's Air Quality Guideline, the dashed red line indicates the South African Air Quality Standard, while the pink lines are Air Quality Standards from other selected countries (Table 1).

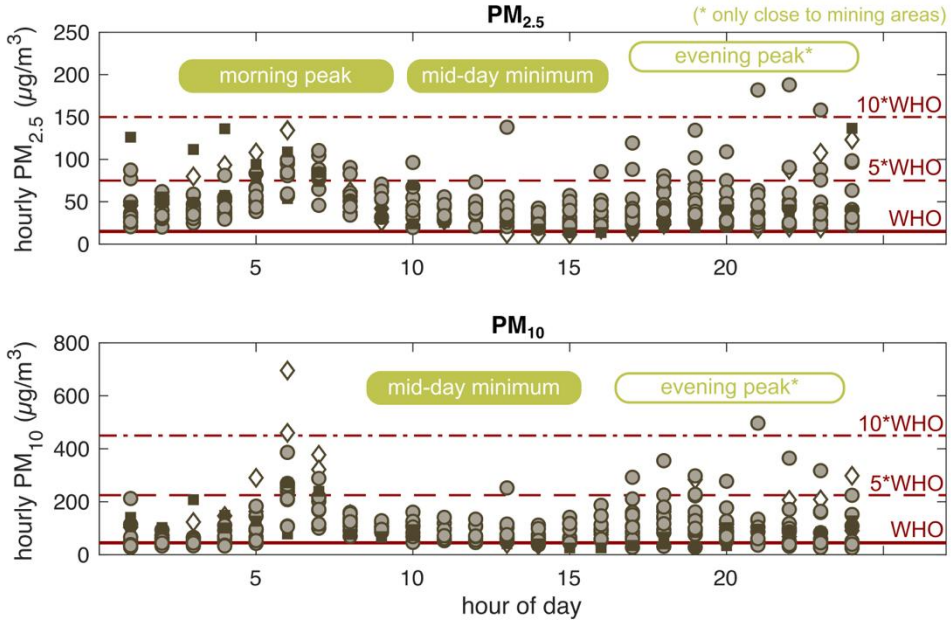

Figure 7. Combined daily trends of hourly PM data in Kolwezi and Pierre Muteba II (filled circles; near COMMUS), near Lake Kando (filled squares; near MUMI), and Fungurume (open diamonds; near TFM). The red lines are the WHO Air Quality Guidelines (bold continuous lines) and indicative values corresponding to 5 times (dashed lines) and 10 times (dash-dot lines) these guidelines. This figure is meant to show only similarities and differences across sites; hourly trends for each area are discussed in more detail in the following sections.

pre-existing cardiopulmonary disease". An AQI of 4 is also associated with an "increased likelihood of respiratory effects to the general public".

Hourly PM values

Across all sites, 98% of hourly $PM_{2.5}$ values and 84% of hourly PM_{10} values were above the WHO guidelines (Figure 7). For $PM_{2.5}$, 18% of the hourly data were also above 75 µg/m³ (i.e., 5 times the AQG), and 1% exceeded 150 µg/m³ (i.e., 10 times the AQG). Likewise, for PM_{10}, 8% of the data were above 255 µg/m³ and only 1% of the data was above 450 µg/m³ (i.e., 5 and 10 times the WHO guidelines, respectively). These observations indicate that the **daily averages are not driven by isolated spikes of pollution but reflect a constantly high background of particulate matter.**

All sites displayed similar diurnal trends overlayed with site-specific features. This behavior was particularly evident for $PM_{2.5}$, which always showed a peak early in the morning (approximately from 3:00 to 10:00 AM) followed by a minimum that persisted for several hours (Figure 7, top). Given the regularity of these features among sites and sampling days, we believe that this trend largely reflects a local natural phenomenon, most likely a variation in the thickness of the boundary layer caused by the day-night shift.[b] Adding to this feature, $PM_{2.5}$ data recorded in close vicinity to waste rock dumps, stockpiles, and open-pits had a second peak in the late afternoon and evening

[b] The boundary layer is a portion of the atmosphere in direct contact with the Earth's surface. Its thickness increases during the day and decreases at night in response to temperature changes. A reduction in the height of the boundary layer limits vertical mixing and concentrates pollutants near the surface, leading to increased observed concentrations even in the absence of active emissions.

(between 17:00 and 24:00). This peak was absent during rain and was not observed in Pierre Muteba II and at a control site close to Kolwezi's airport. While we do not have enough data to accurately pinpoint its causes, **these observations hint at the presence of a highly localized pollution source** (explained more in detail in the section Air quality in Kolwezi). Although with less pronounced peaks, hourly PM_{10} data showed overall a behavior similar to $PM_{2.5}$ (Figure 7, bottom).

While we expect the general population to be most active between 7:00 and 17:00 – largely coinciding with the mid-day minima – **hourly values recorded during these minima also systematically exceeded the WHO guidelines**, for both $PM_{2.5}$ and PM_{10}.

Heavy metals in inhalable dust

Inhalable dust samples had a highly homogeneous metal composition (Table A3). Aluminum, cobalt, iron, manganese, and copper were the only elements detected in 100% of the filters above their limits of detection, irrespective of the sampling location. Barium was detected at 7 sites (of 9, 78%), chromium was observed only in Fungurume (AF1 and AF2), while nickel and tin were above their detection limits only at 1 site each (AF2 and AK6, respectively). Overall, these metals contributed only to a small fraction of the total mass collected on filters (3–10%), in agreement with typical observations for $PM_{2.5}$ and PM_{10}.[37]

While aluminum and iron have predominantly natural sources, the other metals can derive at least in part from anthropogenic sources (Table 4).[37,38,48] For example, barium and manganese can have both natural and anthropogenic origin (e.g., traffic and coal combustion). Likewise, copper, together with barium and zinc, is common in vehicle emissions. On the other hand, **cobalt is not commonly detected in particulate matter**.[37] In a study on PM_{10}, Fomba et al.[48] attributed particulate cobalt to road dust resuspension, as this metal is often used in additives for road painting. However, roads in our study area were predominantly unpaved and, when asphalted, they typically had no paintings. Thus, the ubiquitous presence of cobalt must be linked to other causes.

Table 4. Simplified overview of typical metals associated with particulate matter. This non-exhaustive overview is based on peer-reviewed articles on $PM_{2.5}$ and PM_{10}.[37,38,48,49] Elements considered established biomarkers are highlighted. Values in parentheses are reported only by one author or are associated to specific scenarios (e.g., cobalt in vehicular traffic; see text). [a] K = potassium, Cd = cadmium, Ni = nickel, Pb = lead, Se = selenium, Rb = rubidium, V = vanadium.

	Aluminum	**Barium**	**Cobalt**	**Chromium**	**Iron**	**Manganese**	**Copper**	**Nickel**	**Tin**	**Zinc**	**Others [a]**
Earth's crust	**x**	x			x	x					
Biomass burning										x	**K**, Rb
Coal combustion		(x)		x		x					**As**, Cd, **Se**, Pb
Vehicular traffic		(x)	(x)	x	(x)		x	x	x	x	As, Cd, Pb, **Sb**
Oil fuel combustion						x	x	x		x	Pb, **V**
Industrial activities				x	(x)	x		x		x	As, Cd, Pb
Observed	**x**	**(x)**	**x**	**(x)**	**x**	**x**	**x**	**(x)**	**(x)**		

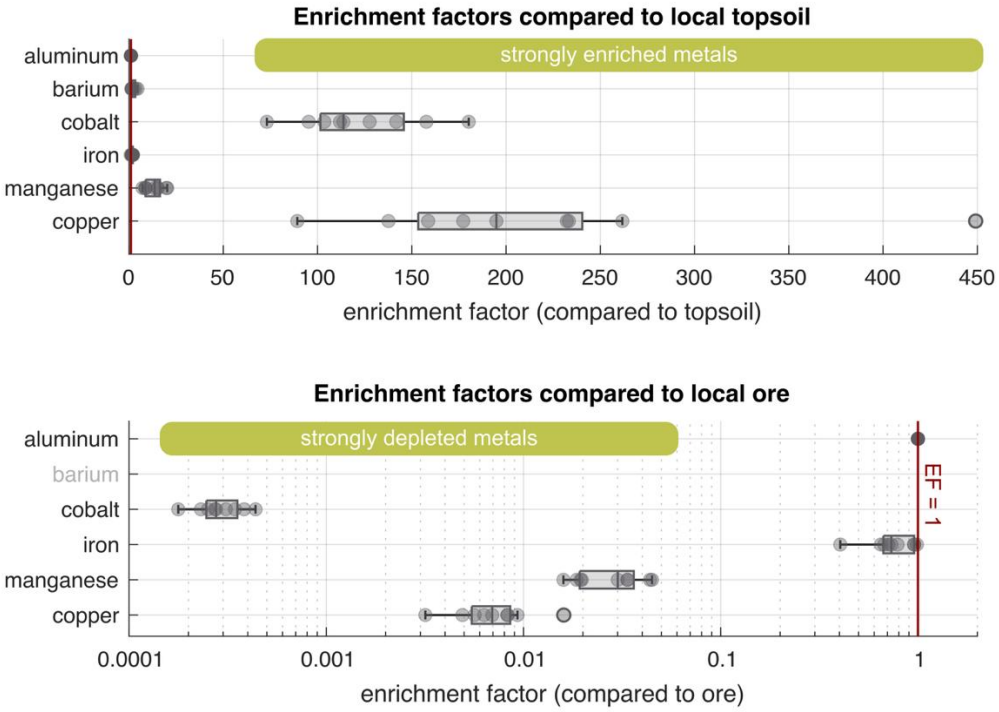

Figure 8. Overview of enrichment factors of key heavy metals in inhalable dust collected in Kolwezi, Pierre Muteba 2, and Fungurume. EFs around 1 (0.1 – 10, dark red like) denote metals with predominantly natural sources, while EFs above 10 or below 0.1 indicate metals that are, respectively, enriched at least 10 times or depleted at least 10 times compared to their natural abundance – thus, they are indicative of anthropogenic impacts. For clarity, the bottom plot is indicated in logarithmic scale. Raw data are in Table A4.

The **lack of biomass-specific markers suggests that wood and charcoal burning are minor sources of metals in our dust samples** (Table 4). Biomass burning typically emits particles rich in potassium, rubidium, and zinc.[37,48,49] Although potassium and rubidium were not included in our analysis, zinc was among the metals constantly below detection. A caveat of this analysis is that metal content varies based on particulate matter size:[37,38,48] thus, some metals are likely to have a different distribution in inhalable dust compared to $PM_{2.5}$ and PM_{10}. However, the *systematic absence of all source-specific metals* makes us confident of our conclusions.

To gain better insights into the origin of inhalable dust, we calculated the enrichment factor (EF) of the most common metals within the dataset (Figure 8 and Table A4). First, we used as reference the median topsoil composition in Katanga from a recently published dataset.[39] Overall, we found no or minimal enrichment for iron and barium, indicative of predominantly natural sources (median EF of 1.2 and 2.0, respectively). On the other hand, manganese was slightly enriched (median EF of 13), while **copper and cobalt were strongly enriched compared to the local topsoil** (median EF of 108 and 126, respectively). The sites with the largest enrichment factors were AK1, AK3, and AK4, all located near the COMMUS open pit and waste rock dump (more details in the section Air quality in Kolwezi). We then ran a second calculation using as reference the median ore composition in the Katanga Cobalt-Copper Belt from Decrée et al.[40] and found virtually no enrichment in iron (median EF of 0.7) and a strong depletion in cobalt, copper, and manganese (median EF of 0.0003, 0.007, and 0.03, respectively). Although heterogenite composition may vary also within a short radius,[40] these elements were *strongly depleted* compared to the ore (i.e., more than 100- to 10,000-times): the large

orders-of-magnitude difference gives confidence to our findings. Taken together, these results strongly suggest that **inhalable dust** is richer in cobalt, copper, and manganese than the topsoil but contains less of these elements than the unprocessed ore: thus, it **most likely originates from the resuspension of residual material from mining activities, including waste rock, low-grade ore, and processed ore residues**, with only minor and localized additional contributions (see section Air quality in Fungurume).

Although a direct comparison with legally binding AQSs and occupational exposure limits was not possible, we used the health-based OELs from the SCOEL (Table 3) to derive order-of-magnitude screening values for metals in inhalable dust that may be protective for the general population. Based on this approach, **cobalt and copper concentrations appear concerning.** Cobalt was 0.05–0.32 µg/m^3, consistently exceeding the screening value of 0.03 µg/m^3. Likewise, copper concentrations (0.2–1.8 µg/m^3) were above the precautionary threshold of 0.3 µg/m^3 in 8 of 9 samples. In contrast, manganese and chromium remained well below their estimated screening values of 7 and 67 µg/m^3 (Table A3). Although this analysis should not be considered definitive evidence for harm, the systematic exceedances in copper and cobalt highlight the need for an in-depth toxicological assessment in the general population.

Air quality in Kolwezi

Figure 9. Overview of the most polluted sites in Kolwezi. Sites AK3 (panel A), AK6 (panel C), and AK4 (panel D) were in various *cellule*s of the Musonoie *quartier*, in Kolwezi. The Galaxy school (site AK1, see Figure 12) was also nearby. All sites were less than a kilometer away from the large COMMUS waste rock dump in panel B. Site AK4 (panel E) was in the *quartier* Gecamines Kolwezi, near the open pit that starts at the end of the road.

In Kolwezi, we visited 7 sites, 6 of which located 100 m to 1.5 km from the COMMUS open pit and waste rock dump, plus other activities directly or indirectly associated with mining (Figure 9). These included the Galaxy school (AK1; described in more detail in the following section) and a site sampled on October 12, 2025, during one of the rain events (AK5). The seventh site (AK7) served as a control, as it was located near Kolwezi's airport and city center but at least 5 km away from any mine-related pollution sources.

Kolwezi was the most polluted site in terms of air quality, with the area near the COMMUS open pit and waste rock dump being the most critical one (Figure 9). All daily $PM_{2.5}$ and PM_{10} data exceeded the WHO air quality guidelines, the South African standards, and at least another international standard (Figure 5). The highest values – 87 and 178 µg/m³ for $PM_{2.5}$ and PM_{10}, respectively – were always recorded at site AK3, within 500 meters of the COMMUS waste rock dump. Overall, the 4 sites in Kolwezi with daily PM values had an Air Quality Index between 3 ("unhealthy for sensitive people") and 4 ("unhealthy").

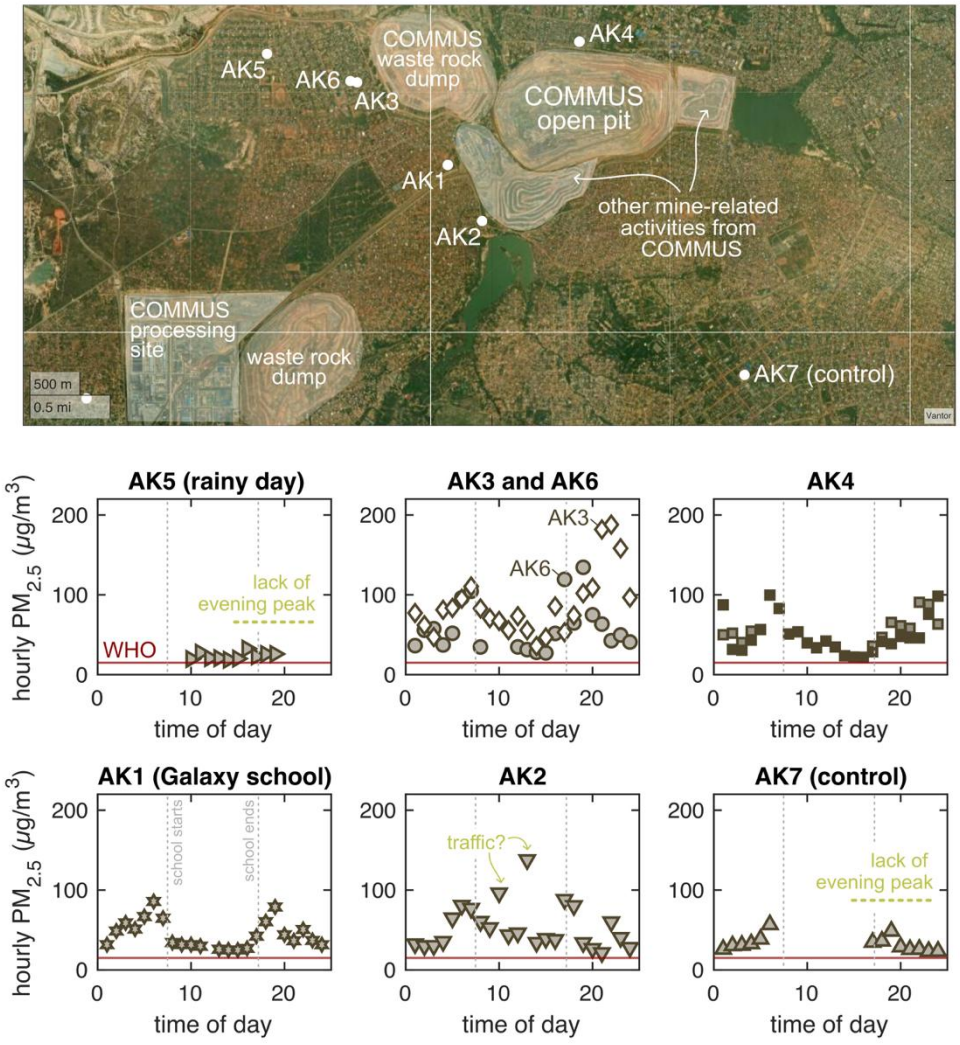

Figure 10. Details of sampling sites and hourly $PM_{2.5}$ trends in Kolwezi. In each plot, the red horizontal line shows the WHO guideline of 15 µg/m³, while the grey vertical lines are the starting and ending school times at the Galaxy school (AK1, see also Figure 13). Site AK4 includes hourly data for amost 2 days, while AK5, AK6, and AK7 had incomplete datasets.

The sites around the COMMUS open pit and waste rock dump had also the most concerning values for hourly $PM_{2.5}$, showing the highest mid-day minima and a recurring late afternoon/evening peak (Figure 10). Sites AK3 and AK6, immediately adjacent to the waste rock dump, had the most evident evening peaks across the dataset, reaching values as high as 180 µg/m^3. Following were AK4, near the Gecamines, and AK1, the Galaxy school. The sensor at AK2, close to Lake Golf and near a busy road, may have detected combined PM emissions from mine-related activities and traffic – in particular, we suspect urban traffic is responsible for the peaks observed in the middle of the day. Unfortunately, we did not collect inhalable dust at this site, and we are thus unable to confirm or disprove this hypothesis. Only 2 sites did not show the evening $PM_{2.5}$ peak. The first was AK5, relatively close to AK6 but visited during the rain event of October 10, 2025. Rain is well known to clean the atmosphere from particles: the low PM levels reflect this natural phenomenon. The second was AK7, a control site close to Kolwezi's airport and regular traffic but away from major mine-related activities.

In Kolwezi, we collected inhalable dust only at 4 sites – AK1, AK3, AK4, and AK6 –, which were all located around the COMMUS open pit and waste rock dump. These were also the most polluted sites based on real-time PM data (Figure 6 and Table A2). All inhalable dust samples contained aluminum, cobalt, iron, manganese, and copper. One sample did not contain barium (AK4), and one had 0.21 µg/m^3 of tin (AK6; Table A3). A statistical test (details in the figure caption) showed that **inhalable dust in Kolwezi was significantly enriched in manganese and iron as compared to Fungurume and Pierre Muteba II** (Figure 11). While not statistically significant, copper and cobalt were also higher in Kolwezi. Although based on a small dataset, this result suggests that resuspended dust has a unique site-specific fingerprint despite the common origin from mine-related activities.

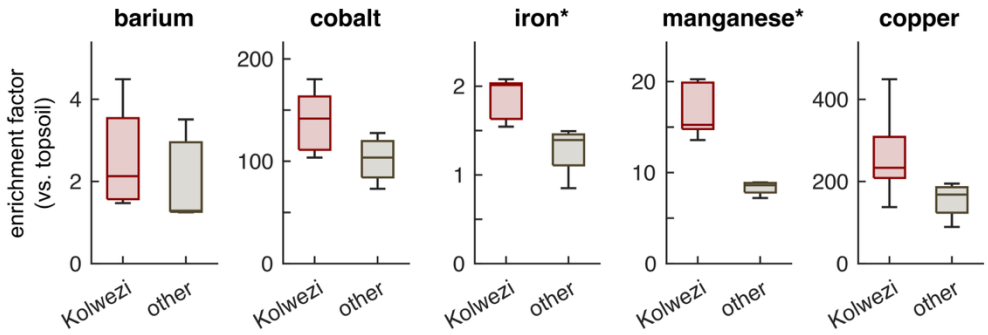

Figure 11. Comparison between enrichment factors in Kolwezi (red box) **and other sampling sites** (Pierre Muteba II and Fungurume). A Mann-Whitney U test showed that iron and manganese were significantly different in the 2 areas (p = 0.016 in both cases), while the difference for copper and cobalt was smaller (p = 0.11 in both cases). Raw data are in Table A4.

Air quality at the Galaxy school

A key sampling site in Kolwezi was the Galaxy school (AK1), which serves approximately 1700 students from primary to secondary education. The school is located in the *cellule* Kabila (Musonoie), near the COMMUS open pit, waste rock dump, and other mining-related activities (Figure 12). According to residents, the area is characterized by frequent explosions and near-

Figure 12. Aerial view of the stockpile visible from the yard of the Galaxy school. The map on the upper right shows the location of the school (site AK1) with respect to relevant mine-related activities. The waste rock dump is the same as in Figure 9B.

constant movement of trucks transporting ore and mining residues – observations that we confirmed during our campaign. These activities generate substantial noise and mobilize large amounts of dust, particularly during the dry season. Although this was the only educational facility included in the October 2025 campaign, several other institutes lay within 0.5–1 km from COMMUS operations in Kolwezi. Based on our results, we expect these facilities to experience air quality issues comparable to – or worse than – the Galaxy school.

We visited this site twice. On October 14, 2025, we collected a complete PM dataset and one inhalable dust sample; on October 17, we obtained a second dust sample. In both cases, we installed the instruments inside the school yard, above the professors' room.

The real-time monitor revealed a **concerning level of particulate matter pollution**, consistent with observations at other sites in Kolwezi located near mining operations. The daily concentration of $PM_{2.5}$ was 44 µg/m^3 – almost 3 times the WHO guideline and above legally binding standards from South Africa and the United States (Figure 6 and Table A2). Similarly, daily PM_{10} was 105 µg/m^3, exceeding by more than a factor of 2 the WHO guideline as well as the South African, European, and Swiss AQSs (Figure 6). These concentrations corresponded to an **AQI of 3 (unhealthy for sensitive groups)**, associated with an "increased likelihood of respiratory symptoms in sensitive groups (e.g., children), exacerbation of symptoms of or death from pre-existing cardiopulmonary disease, and increased likelihood of respiratory effects in the general population".[23]

Hourly PM data further indicate that **children attending this school experience higher PM exposure than students in institutes further away from mine-related activities.** Figure 13 reveals a clear overlap between the morning and evening PM peak and the school's starting and ending time. While the morning peak was observed across the entire study area, the evening spike was limited to sites within 0.5–1 km from waste rock dumps and other mining-related activities (Figure 7 and Figure 10). Notably, we detected no PM spikes during the scheduled school breaks

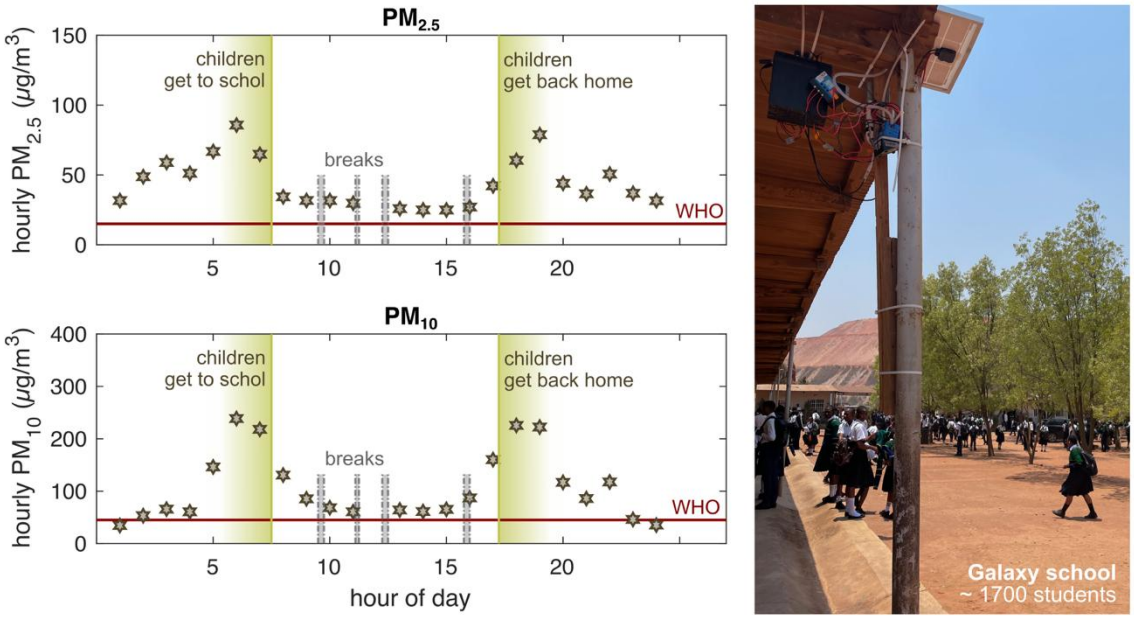

Figure 13. Daily trends of hourly $PM_{2.5}$ and PM_{10} at the Galaxy school. The grey areas during the mid-day minimum are the break times of the primary school. The red lines are the WHO air quality guidelines. The photo on the right shows the location of our measuring setup during the lunch break (around 12:30), with the stockpile visible nearby.

(Figure 12), demonstrating that the instruments detected ambient pollution rather than particles suspended by the children's movement.

The 2 dust samples had a comparable chemical composition, with a typical fingerprint of residual material from local mining activities. In both samples, we detected only aluminum, barium, cobalt, copper, iron, and manganese (Table A3). **Copper and cobalt** had the second- and third-highest concentrations of the entire dataset and **exceeded the estimated precautionary limit by a factor greater than 4** (i.e., copper: 1.64–1.03 µg/m³ vs. a limit of 0.3 µg/m³; cobalt: 0.16 µg/m³ vs. a limit of 0.03 µg/m³). Although these limits are only indicative, this finding is concerning – especially when read in the context of previous biomonitoring studies in the area, which identified contaminated dust as a primary exposure pathway for cobalt in children.[6,50]

In line with observations from other sites in Kolwezi, the enrichment factor analysis showed that **inhalable dust bears the chemical fingerprint of residual mining material, hinting at the nearby waste rock dump as the most likely source.** Indeed, EFs compared to topsoil were 142–158 for cobalt, 262–449 for copper, and 14–20 for manganese (Table A4), indicating moderate to strong enrichment compared to dust generated from the resuspension of local soil. On the other hand, EFs relative to the unprocessed local ore were 100 to 10000 times below 1, indicating significant depletion (Table A4). Like at other sites, **we did not detect chemical markers of biomass burning** (e.g., zinc) and other common anthropogenic sources (Table 4), strongly indicating a secondary contribution to the detected metals.

Air quality in Pierre Muteba II

In Pierre Muteba II, we deployed our instruments at a private home (AP1) and a health center (AP2). The area is located west of the COMMUS processing plant, near a large tailing storage facility, and close to a second stockpile not belonging to COMMUS (Figure 14). At both locations, we collected at least one complete PM dataset and one inhalable dust sample.

Particulate pollution in Pierre Muteba II was generally lower than in Kolwezi – yet PM levels still exceeded several international guidelines and air quality standards (Figure 6 and Table A2). Daily $PM_{2.5}$ concentrations reached 40 and 45 µg/m³ at AP1 and AP2, respectively, exceeding the WHO guideline as well as the South African and the United States AQSs. Likewise, daily PM_{10} were 79 and 117 µg/m³, above the WHO guideline and the South African, European, and Swiss standards. At both sites, these concentrations corresponded to an **AQI of 3**, classified as "unhealthy for sensitive groups".

The hourly PM trends consistently lacked the evening peak (Figure 14), similarly to patterns recorded in areas of Kolwezi located more than 1 km away from waste rock dumps, pits, and other mine-related activities. The characteristic morning peak and subsequent mid-day minimum were instead consistently observed at both sites. At AP2, 43 hours of continuous monitoring confirmed the day-to-day reproducibility of this pattern. An additional incomplete dataset collected at Tshizuza (AT1), southeast of the tailing storage facility and further away from waste rock dumps, showed

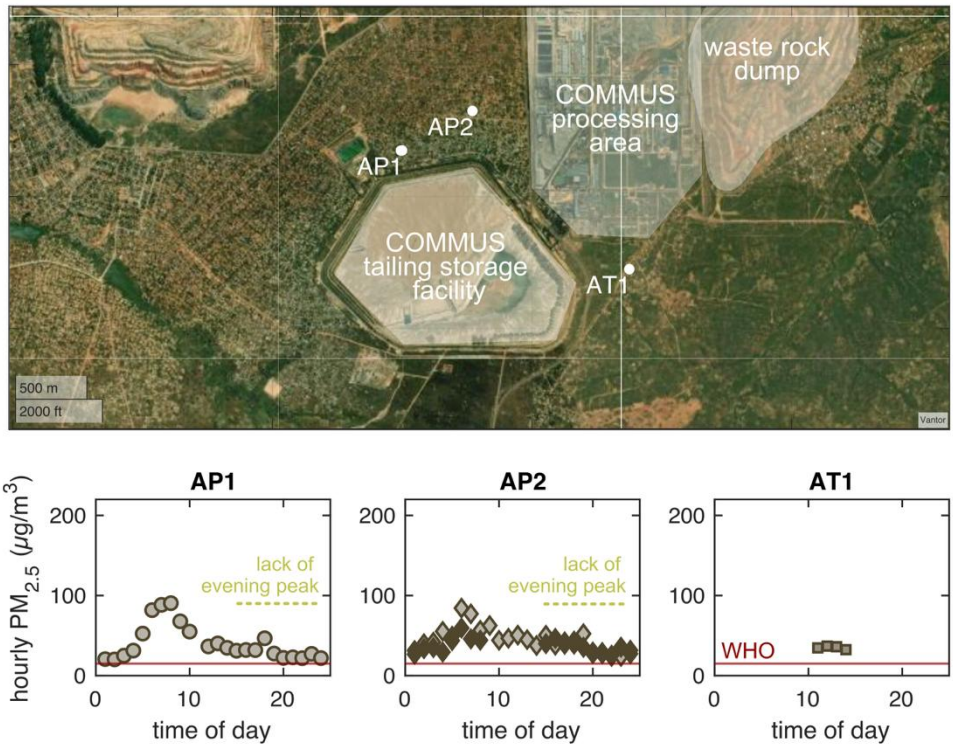

Figure 14. Details of sampling sites and hourly $PM_{2.5}$ trends in Pierre Muteba II. The red line in each plot shows the WHO guideline of 15 µg/m³. Site AP2 includes hourly data for almost 2 days. The waste rock dump on the upper left edge of the map does not belong to COMMUS.

hourly $PM_{2.5}$ concentrations of 32–37 µg/m³, within the typical range of mid-day minimum values across all sites (Figure 14).

Inhalable dust samples were qualitatively similar to those collected in Kolwezi but contained lower concentrations of metals, especially cobalt, copper, and barium (the latter below detection limit at AP1; Table A3). Despite these lower concentrations, **cobalt and copper exceeded their estimated precautionary limit** (copper: 0.49–0.73 µg/m³ vs. a limit of 0.30 µg/m³; cobalt: 0.096–0.109 µg/m³ vs. a limit of 0.030 µg/m³). **The enrichment factor analysis confirmed a major contribution of residual material from local mining activities**, although the relative enrichment was lower compared to Kolwezi (Figure 15 and Table A4), possibly reflecting the significantly larger distance from major waste rock dumps. This behavior fits with what is known on particles' behavior in the atmosphere: the larger the particle, the smaller the distance it can travel.[51]

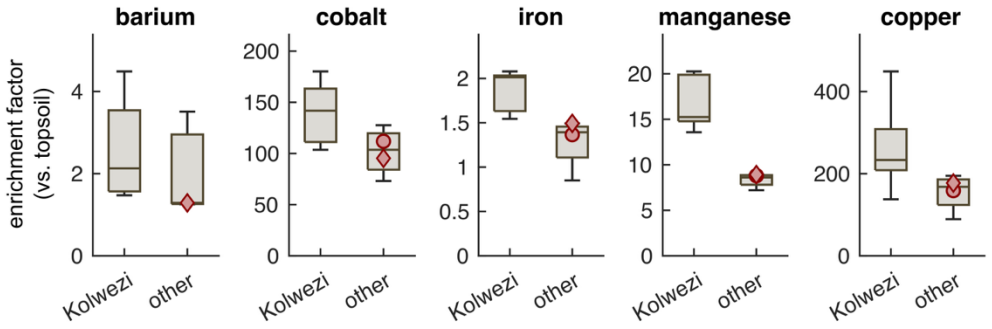

Figure 15. Enrichment factors in Pierre Muteba II (red symbols; circle: AP1; diamond: AP2) **compared to other sampling sites**. Raw data are in Table A4.

Air quality near Lake Kando

Further east in the Mutshatsha Territory, we visited Mibanze and Rianda, rural villages located on the shores of Lake Kando, south of the MUMI concession area (Figure 16). We placed our PM sensors at 2 private homes but failed to collect inhalable dust samples due to unforeseeable delays.

Particulate matter pollution at these villages was broadly comparable to the rest of the study area. In Mibanze (AM1), we measured daily $PM_{2.5}$ and PM_{10} values of 49 and 67 µg/m³, exceeding the WHO guidelines and several legally binding standards, including those from South Africa (Figure 6 and Table A2). These values translated to an **AQI of 3**, classified as "unhealthy for sensitive groups".

Although in Rianda we collected only 23 hours of data, **hourly trends at the two villages were fully comparable** – showing a morning peak and a mid-day minimum that persisted until the evening, with only a moderate increase during the last hours of the day (Figure 16). This pattern mirrored well the trends observed in Pierre Muteba II and other sites in Kolwezi located more than 1 km away from mine-related dust sources (Figure 9 and Figure 14). Indeed, both villages were at least 5 km away from MUMI's active mining and processing area and other facilities not belonging to MUMI. While

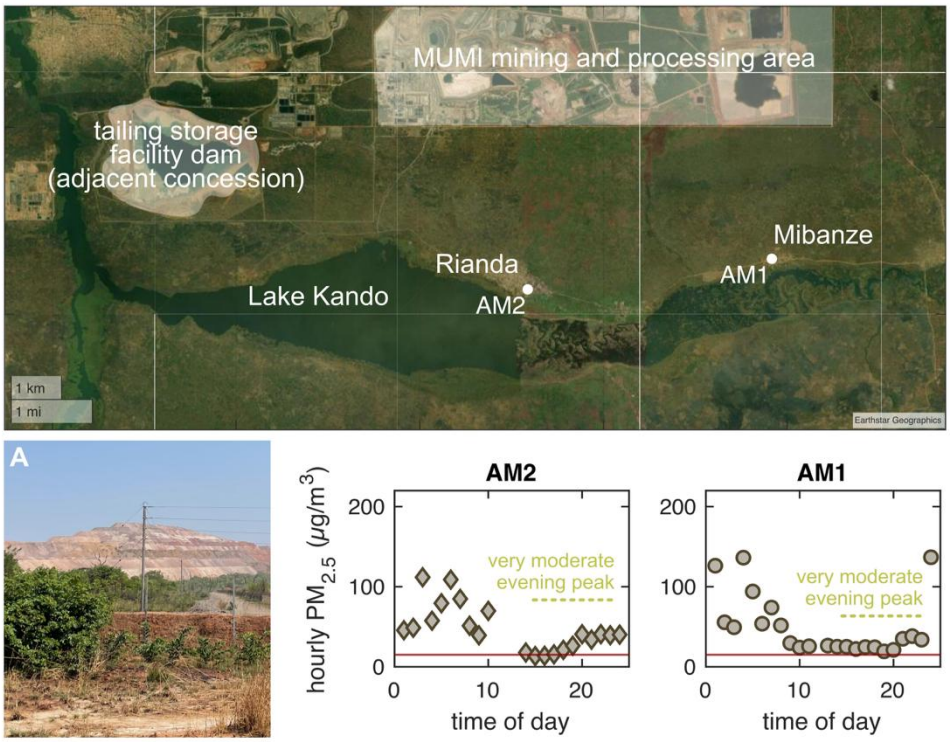

Figure 16. Details of sampling sites and hourly $PM_{2.5}$ trends near Lake Kando. The red line in each plot shows the WHO guideline of 15 µg/m³. Panel A shows the tailing storage facility dam visible from the route from Kisenda to Rianda and belonging to the Société Minière de Deziwa SAS (attribution based on OpenStreetMap[41]). Site AM2 had an incomplete dataset.

driving near the tailing storage facility dam (not belonging to MUMI; Figure 16A), we also noticed water trucks wetting the streets, which likely contributed to lower dust resuspension in the area.

Air quality in Fungurume

In Fungurume, we collected 2 particulate matter datasets and 2 inhalable dust samples from private homes located southeast of the TFM mining and processing area. These measurements differ from the rest of the dataset in that they were collected on October 10, prior to a 2-day perturbation that contributed to at least partial atmospheric cleansing.

Particulate matter pollution was overall comparable to other study sites. At AF1, daily $PM_{2.5}$ and PM_{10} were, respectively, 33 µg/m³ and 117 µg/m³, exceeding more than twice the WHO guidelines and, for PM_{10}, the European, Swiss, and South African AQS. Due to the relatively low $PM_{2.5}$ value, **we obtained an AQI of 2 ("moderate"), the lowest of the dataset**. A comparison of daily trends hints that **site AF2 experienced stronger particulate matter pollution than AF1**, placing it closer to the median of our dataset. While both locations showed the typical morning peak and mid-day minimum, AF2 showed a pronounced evening increase in $PM_{2.5}$ (Figure 17), in analogy to the most polluted sites in Kolwezi. Notably, AF2 was closer to the TFM open pit than AF1, which instead was nearer to 30k industrial plant.

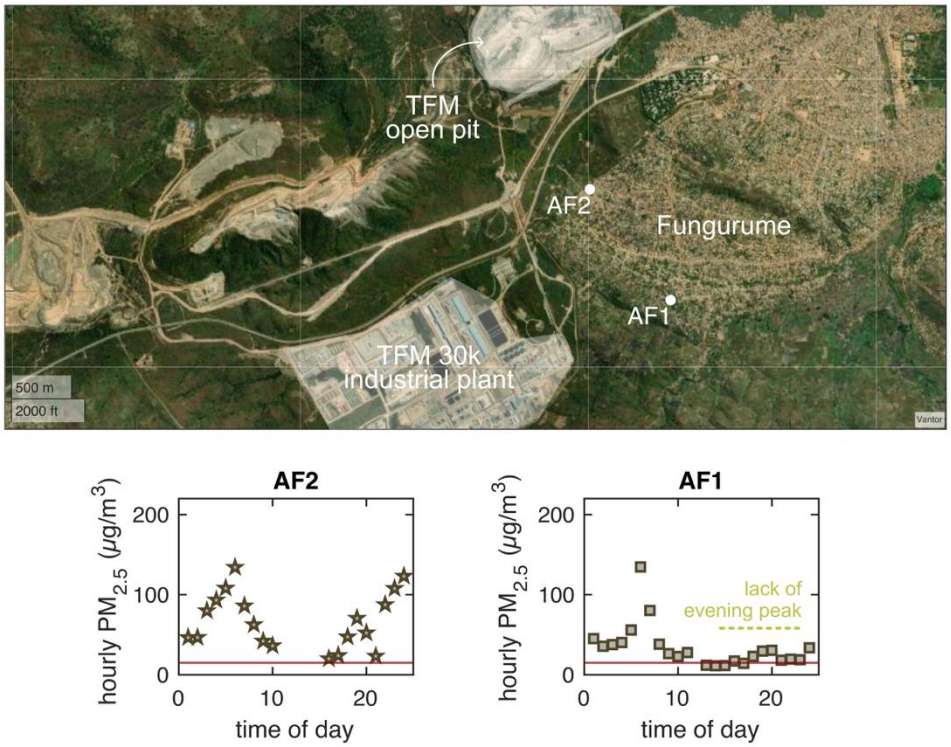

Figure 17. Details of sampling sites and hourly $PM_{2.5}$ trends in Fungurume. The red line in each plot shows the WHO guideline of 15 µg/m³. Site AF2 had an incomplete dataset.

Site AF2 also appeared more impacted in terms of metal content in inhalable dust. While both samples contained aluminum, barium, cobalt, chromium, copper, iron, and manganese, concentrations at site AF2 were substantially higher than at AF1 (Table A3). Cobalt (0.091 at AF1 vs. 0.32 µg/m³ at AF2), chromium (0.018 vs. 0.29 µg/m³), and copper (0.4 vs. 1.7 µg/m³) were the metals that better showed this difference. AF2 was also the only location where we detected nickel (0.4 µg/m³). Although chromium concentrations remained well below the estimated screening value (0.02–0.3 µg/m³ vs. a reference value of 67 µg/m³), **copper, cobalt, and nickel were close to or exceeded their precautionary screening values** – a finding that warrants further investigations.

Enrichment factors indicated that aluminum, barium, iron, and chromium were predominantly of natural origin, with abundances comparable to the regional topsoil (Table A4). Cobalt, copper, and manganese were enriched relative to the topsoil but remained within the low-end range of EF across the dataset. At AF2, nickel showed enrichment compared to the topsoil (EF of 63) but had an abundance consistent with *unprocessed* ore (EF of 0.2; Table A4) – suggesting that ore processing does not impact the concentration of this element in inhalable dust. While particulate nickel can also originate from vehicular traffic, oil combustion, or industrial activities (Table 4), the presence of small amounts of nickel in the local ore[40] and lack of other source-specific tracers (i.e., zinc, lead, and cadmium) suggests that these non-mining contributions, if present, are minor. Taken together, these findings indicate that, **also in Fungurume, metals in inhalable dust derive primarily from residual material from local mining activities.**

Key findings

Particulate matter

Daily $PM_{2.5}$ and PM_{10} concentrations measured across multiple days and locations systematically exceeded the WHO Air Quality Guidelines and several legally binding air quality standards (Figure 6 and Table A2). Notably, 7 of 8 sites exceeded the South African standards – the normative framework widely adopted by mining companies operating in the DRC – for both $PM_{2.5}$ and PM_{10}. **The highest PM levels were systematically recorded in Kolwezi** near the COMMUS waste rock dump, open pit, and other mining-related dust sources.

Consistent with these exceedances, **6 of 8 locations had an Air Quality Index of 3**, corresponding to "unhealthy for sensitive groups", **and one site had an AQI of 4** ("unhealthy"; Table A2). According to the ATSDR,[23] an AQI of 3 is associated with an increased likelihood of respiratory symptoms in vulnerable populations (including children, pregnant women, and the elderly) and exacerbation of cardiopulmonary disease, while an AQI of 4 further encompasses increased likelihood of respiratory effects for the general public.

The hourly PM data reinforce this picture. Across the study area, dry days exhibited a reproducible diurnal pattern characterized by a morning peak and mid-day minimum (Figure 7), consistent with typical atmospheric dynamics in continental areas. Superimposed on this background, **sites located within approximately 0.5–1 km of waste rock dumps and/or active mining operations displayed pronounced late-afternoon or evening peaks**, in some cases reaching concentrations up to 10 times the WHO guidelines (Figure 7). The Galaxy school – the only educational facility included in our study, though not the only one located near mining operations – was among the sites exhibiting this late-afternoon peak. Even when excluding these extremes, **98% of hourly $PM_{2.5}$ values and 84% of hourly PM_{10} values exceeded the WHO guidelines**. Importantly, **most monitoring was conducted shortly after two intense rainfall events** that have most likely attenuated air quality issues. Thus, typical dry-season conditions are likely more severe than revealed by our measurements.

Expected impacts on health

The health implications of these findings are substantial. **Air pollution is currently the second-leading global risk factor for mortality**; in 2021 alone, it contributed to an estimated 8.1 million deaths worldwide, **the vast majority** (i.e., 90%) **of which attributable to $PM_{2.5}$ exposure**.[12] Both $PM_{2.5}$ and PM_{10} are associated with increased all-cause mortality, cardiovascular disease, respiratory illness, adverse birth outcomes, and impaired neurological development in children.[13,23,52] The International Agency for Research on Cancer (IARC) further classified particulate matter in outdoor air pollution as a Group 1 carcinogen (i.e., certain to cause cancer in humans).[53] Given the lack of studies on PM pollution in the area, these findings represent an important contribution to the

evidence base, underscoring the **urgent need to introduce national Air Quality Standards in the country and ensure their compliance, especially near mining areas**.

Inhalable dust

All inhalable dust samples exhibited a clear fingerprint of residual material from local mining activities (Figure 8, Table A3, and Table A4). While minor differences among sites likely reflect variations in meteorological conditions, local geology, and specific mine-related activities, the overall pattern was robust. The strong enrichment of cobalt, copper, and manganese relative to local topsoil combined with their depletion compared to raw ore strongly suggests that **inhalable dust predominantly originated from the resuspension of material from barren waste rock dumps, stockpiles, and open pits** – as hypothesized in previous work[6]. The ubiquitous presence of cobalt, which is not associated with common anthropogenic disturbance (Table 4), and the observation of the highest enrichment factors near waste rock dumps and active mining operations further strengthen this hypothesis.

We detected no chemical markers indicative of biomass burning, suggesting minor contributions of wood and charcoal burning across the study area (Table 4). Consistent with this finding, daily PM dynamics did not show patterns characteristic of cooking or other domestic burning activities (Figure 7); patterns attributable to traffic emissions were observed only at one site immediately adjacent to a main road (AK2; Figure 10). Taken together, these observations support the idea that **particulate pollution in the area is driven – directly or indirectly – by mining activities rather than household fuel use or general urban traffic**.

Order-of-magnitude screening suggests that cobalt and copper concentrations in inhalable dust represent a health concern for local communities (Table A3). Although the lack of standards for direct comparisons prevents a definitive risk assessment, cobalt and copper exceeded their screening values in 88–100% of the samples (Table A3). Cobalt has recently attracted increased scrutiny at the European level, as the green and digital transition is expected to drive higher occupational exposure while toxicological and epidemiological evidence remains limited.[54] **Inhalation of cobalt-rich dust and fumes is the primary exposure pathway for this metal in occupational settings**.[31] Previous investigations in the DRC's Cobalt-Copper Belt unraveled significantly higher levels of cobalt in the urine of communities living close to mining areas, with children being disproportionately more affected than adults.[6,50,55] While dietary uptake appeared predominant in the general adult population,[50] exposure to cobalt-rich dust was identified as the main exposure pathway for children and artisanal miners.[6,55]

Expected impacts on health

Cobalt is an essential trace element (it is a component of vitamin B_{12}) but inhalation of cobalt-rich dust and fumes can have adverse health effects. Breathing cobalt-rich particles may cause respiratory irritation, reduced lung function, and respiratory sensitization, including asthma.[31,56] Animal studies showed an increased incidence of lung tumors following inhalation, and several cobalt compounds are classified as carcinogenic or suspected carcinogenic.[31,57] Elevated oral

exposure has also been associated with adverse effects on the blood and thyroid.[56] Reflecting these concerns, the **ATSDR advises that children avoid playing in areas where cobalt-rich soil or dust may be present**[56] – an ubiquitous situation across our study area, especially at the Galaxy school and, potentially, other educational facilities less than a kilometer away from waste rock dumps, open pits, and other dust-generating mining activities.

Copper is another essential element that may become harmful at high exposure levels. Inhalation of copper-containing dust or aerosols can irritate the nose and throat and has been associated with symptoms such as headaches and dizziness.[58] High oral intake has, in severe cases, resulted in serious poisoning.[58] Like cobalt, copper exposure occurs through multiple pathways, including through contaminated water and food.[50,58]

Air quality and human health in Lualaba's frontline communities

The data presented in this report provide important evidence to help establish a link between mine-related pollution and human health impacts in the Lualaba province.

The grey literature has documented worsening health conditions in the area following the recent mining boom. In 2024, RAID and Afrewatch interviewed healthcare professionals in Kolwezi, who reported a **marked increase in specific diseases over the last 5–10 years, coinciding with an intensification in mining activity in the region**.[3] The most commonly reported conditions included skin and eye problems, respiratory issues, and, among women, gynecological and reproductive problems, such as miscarriages and birth defects. Although many of these outcomes have been anecdotally linked to poor water quality,[3] **several are also broadly consistent with exposure to air pollution**. For example, $PM_{2.5}$ and PM_{10} have been associated with eye irritation, respiratory illnesses, and adverse birth outcomes, among other things.[13,23,52,59] Inhalation of cobalt- and copper-rich particles can also cause respiratory problems.[31,56,58] Given the complex scenario, it is unlikely that a single pollutant explains the observed patterns. However, **the consistently elevated levels of $PM_{2.5}$, PM_{10}, and selected metals in inhalable dust align, at least in part, with the spectrum of conditions reported in Kolwezi and nearby communities**.

Recent work by the EIA US and Premi Congo also identified a link between SO_2, an air pollutant not included in this study, and ore processing in Fungurume.[10] Health issues that have increased dramatically in the area since 2023 – construction year of the 30k mixed ore processing plant[60] – included nosebleeds, coughing blood, respiratory infections, and adverse maternity outcomes. While exposure to elevated levels of SO_2 may be limited to the immediate surroundings of ore processing sites, this finding reinforces the idea that **communities in Lualaba are exposed to multiple pollutants through various environmental media, potentially leading to cumulative health effects** (e.g., see also our assessment on water and sediment quality[4]).

There is also solid evidence showing that **communities within kilometers of mining or smelting operations** in Lubumbashi, Likasi, and surrounding areas **have higher concentrations of heavy metals in their urine** than control populations.[50,55] Similar findings were reported in a suburb of Kolwezi with intense artisanal mining.[6] Indeed, Banza et al.[55] found that communities within 3 km of

mining or smelting operations had the highest urinary concentrations of cobalt ever recorded in the general population (at the time of writing), with 87% of the children exceeding occupational exposure thresholds for this metal. Across studies, children were consistently more affected than adults,[6,50,55,61] reflecting a well-established pattern of heightened vulnerability of youths to environmental pollutants.[59,62] Cheyns et al.[50] further showed that food was the predominant exposure pathway for cobalt in adults (see our report on water and sediment quality[4]), whereas contaminated dust dominated in children.

Despite the caveats – these studies are relatively old, only partially overlap with our sampling area, and considered deposited rather than inhalable dust –, **the proposed mechanism for cobalt exposure in children is broadly consistent with our findings on inhalable dust**, reinforcing our concern for the school-age population. Although Cheyns et al.[50] focused on hand-to-mouth ingestion of *deposited* dust as a possible cobalt exposure mechanism, the occupational literature identifies inhalation as the major pathway,[31] hinting that both may be relevant.

At present, the lack of a formal epidemiological study directly linking exposure to air pollutants to specific health outcomes in Lualaba represents a critical gap that this report alone cannot fill. An urgent, independent health assessment is thus warranted.

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Appendix

Section A1 Reference values for enrichment factor calculation.

Table A1 Overview of sites for particulate matter measurements and collection of inhalable dust samples.

Table A2 Overview of daily $PM_{2.5}$, daily PM_{10}, and US EPA's Air Quality Index values in comparison with international air quality guidelines and standards.

Table A3 Chemical composition of inhalable dust in comparison with relevant reference.

Table A4 Enrichment factors of metals in inhalable dust compared to local topsoil and ore.

Figure A1 Correlation between hourly $PM_{2.5}$ and hourly PM_{10} across the dataset.

Section A1. Reference values for enrichment factor calculation.

Median topsoil composition in Katanga. We obtained the median topsoil composition by taking the median of all available values of the database[39] (*N* = 394) for the metals of interest (tin was not available). The calculation yielded median topsoil concentrations of 59,450 ppm (5.9%) for aluminum, 190 ppm for barium, 10 ppm for cobalt, 36 ppm for copper, 248 ppm for chromium, and 50,350 ppm (5.0%) for iron, 192 ppm for manganese, and 25 ppm for nickel.

Median ore composition in Katanga. We obtained the median heterogenite composition in the Cobalt-Copper Belt in Katanga by taking the median chemical composition from Decrée et al.[40] (Supplementary Table 2). The study reports the composition in weight percent of metal *oxides*, which we converted to weight percent *of metals* using simple correction factors obtained as the ratio of molecular weights of the oxide and the metal alone. For example, for cobalt oxide (CoO), the correction factor was 0.787, obtained as the ratio of the atomic weight of cobalt (58.93 g/mol) to that of cobalt oxide (74.93 g/mol). Thus, the median weight percent of cobalt oxide (32.6%) corresponded to a weight percent of 25.6% of cobalt (i.e., 32.6% * 0.787). Following this approach, we obtained a median value of 0.37% for aluminum, 0.66% for iron, 0.54% for manganese, 25.6% for cobalt, and 6.3% for copper. Nickel was reported directly in ppm of metal; we calculated the median and converted it into percent dividing by 10,000, yielding 0.046%. Barium, chromium, and nickel were not included in the study.

Table A1. **Overview of sites for particulate matter (PM) measurements and collection of inhalable dust.** We discarded sample CKA05 because the specific location of the PM monitor did not allow us to distinguish between particles and rain droplets – thus, we are not confident enough of this data to use it. The initial sampling time has been rounded.

Report ID	Field ID	Starting time of sampling	Area / Town	Closest relevant concession	Site type	PM dataset (* if < 24 h)	Inhalable dust sample	Latitude	Longitude	Comments
AK1	CKA08	14/10/25 12:00	Kolwezi	COMMUS	Public school	Yes	Yes	-10.73192	25.44596	
AK1-bis	CKA13	17/10/25 09:10	Kolwezi	COMMUS	Public school	No	Yes	-10.73194	25.44593	
AK2	CKA10	15/10/25 13:50	Kolwezi	COMMUS	Private home	Yes	No	-10.73697	25.44909	
AK3	CKA11	16/10/25 12:40	Kolwezi	COMMUS	Private home	Yes	Yes	-10.72450	25.43764	
AK4	CKA17	19/10/25 10:10	Kolwezi	COMMUS	Private home	Yes	Yes	-10.72085	25.45799	
AK4-bis	CKA12	16/10/25 16:40	Kolwezi	COMMUS	Private home	Yes*	No	-10.72083	25.45803	
AK5	CKA04	12/10/25 09:10	Kolwezi	COMMUS	Health center	Yes*	No	-10.72193	25.42938	Interrupted because of rain
AK6	CKA07	14/10/25 11:00	Kolwezi	COMMUS	Private home	Yes*	Yes	-10.72438	25.43702	
AK7	CKA15	17/10/25 16:40	Kolwezi	COMMUS	Hotel	Yes*	No	-10.75082	25.47314	
AP1	CKA9	15/10/25 11:00	Pierre Muteba II	COMMUS	Private home	Yes	Yes	-10.75542	25.40832	
~~AP1-bis~~	~~CKA05~~	~~12/10/25 12:30~~	~~Pierre Muteba II~~	~~COMMUS~~	~~Private home~~	~~Yes*~~	~~No~~	~~-10.75543~~	~~25.40825~~	Interrupted because of rain
AP2	CKA14	17/10/25 14:30	Pierre Muteba II	COMMUS	Health center	Yes	Yes	-10.75293	25.41284	
AT1	CKA06	12/10/25 10:50	Tshizuza	COMMUS	Private home	Yes*	No	-10.76291	25.42291	Interrupted because of rain
AM1	CKA16	18/10/25 12:20	Mibanza	MUMI	Private home	Yes	No	-10.82345	25.86387	
AM2	CKA18	19/10/25 13:20	Rianda	MUMI	Private home	Yes*	No	-10.82889	25.81958	
AF1	CKA01	10/10/25 12:20	Fungurume	TFM	Private home	Yes	Yes	-10.63401	26.30756	Prior to rain events
AF2	CKA02	10/10/25 15:10	Fungurume	TFM	Private home	Yes*	Yes	-10.62570	26.30139	Prior to rain events

Table A2. Overview of daily $PM_{2.5}$, daily PM_{10}, and US EPA's Air Quality Index (AQI) values and comparison with international air quality guidelines (AQG) and standards (AQS). Samples with incomplete or no PM datasets were omitted.

Report ID	Closest relevant concession	Area / Town	Site type	Starting time	Daily $PM_{2.5}$ ($\mu g/m^3$)	Daily PM_{10} ($\mu g/m^3$)	AQI	AQI explained[26]	Other comments
AK1	COMMUS	Kolwezi	Public school	14/10/25 12:10	44	105	3	Unhealthy for sensitive groups	
AK2	COMMUS	Kolwezi	Private home	15/10/25 14:00	53	126	3	Unhealthy for sensitive groups	
AK3	COMMUS	Kolwezi	Private home	16/10/25 12:40	87	178	4	Unhealthy	
AK4	COMMUS	Kolwezi	Private home	19/10/25 10:00	49	104	3	Unhealthy for sensitive groups	
AP1	COMMUS	Pierre Muteba II	Private home	15/10/25 11:10	40	79	3	Unhealthy for sensitive groups	
AP2	COMMUS	Pierre Muteba II	Health center	17/10/25 14:30	45	117	3	Unhealthy for sensitive groups	
AM1	MUMI	Mibanza	Private home	18/10/25 12:15	49	67	3	Unhealthy for sensitive groups	
AF1	TFM	Fungurume	Private home	10/10/25 12:10	33	117	2	Moderate	Prior to rain
WHO AQG					15	45			
South Africa AQS					40	75			
EU and Swiss AQS					n.a.	50			
US AQS					35	150			
China AQS					75	150			

Table A3. Chemical composition of inhalable dust in comparison with relevant references. All concentrations are in µg/m³. References at the bottom of the table include the range of Occupational Exposure Limits (OELs) for selected countries (Table 3; values for chromium, nickel, and tin were not included [n.i.]) and estimated screening values applicable to the general population obtained as described in the Data analysis section (the value for tin could not be calculated due to lack of recommended OEL). Cells highlighted in grey and bold are above the estimated screening values for the general population. Values and elements in grey text were below the detection limit. The second column in red shows the closest relevant mining concession (more details in the text and in Table A1). * Site AK1 is the Galaxy school.

Sample ID	Relevant concession	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Copper	Selenium	Tin	Thallium	Vanadium	Zinc
AK1*	COMMUS	6.0	<0.025	<0.05	0.050	<0.005	<1	<0.05	**0.160**	<0.025	5.9	0.145	<0.0049	<0.012	<0.025	<0.025	**0.49**	<0.025	<0.025	<0.012	<0.049	<0.12
AK1-bis*	COMMUS	6.5	<0.011	<0.021	0.0306	<0.021	<0.43	<0.021	**0.155**	<0.021	8.5	0.285	<0.0043	<0.011	<0.021	<0.021	**1.03**	<0.021	<0.021	<0.011	<0.043	<0.11
AK3	COMMUS	6.4	<0.010	<0.021	0.034	<0.021	<0.41	<0.021	**0.194**	<0.021	9.0	0.314	<0.0041	<0.010	<0.021	<0.021	**0.90**	<0.021	<0.021	<0.010	<0.041	<0.10
AK4	COMMUS	2.6	<0.012	<0.024	<0.024	<0.024	<0.49	<0.024	**0.046**	<0.024	4.5	0.130	<0.0049	<0.012	<0.024	<0.024	0.22	<0.024	<0.024	<0.012	<0.049	<0.12
AK6	COMMUS	4.6	<0.018	<0.035	0.066	<0.035	<0.71	<0.035	**0.088**	<0.035	8.1	0.301	<0.0070	<0.018	<0.035	<0.035	**0.65**	<0.035	0.213	<0.018	<0.070	<0.18
AP1	COMMUS	5.1	<0.012	<0.025	<0.025	<0.025	<0.49	<0.025	**0.096**	<0.025	5.9	0.145	<0.0049	<0.012	<0.025	<0.025	**0.49**	<0.025	<0.025	<0.012	<0.049	<0.12
AP2	COMMUS	6.8	<0.012	<0.025	0.028	<0.025	<0.50	<0.025	**0.109**	<0.025	8.6	0.196	<0.0050	<0.012	<0.025	<0.025	**0.73**	<0.025	<0.025	<0.012	<0.050	<0.12
AF1	TFM	7.4	<0.007	<0.014	0.083	<0.0014	<0.28	<0.014	**0.091**	0.018	8.9	0.201	<0.0028	<0.0070	<0.014	<0.014	**0.40**	<0.014	<0.014	<0.0070	<0.028	<0.070
AF2	TFM	15	<0.018	<0.035	0.060	<0.035	<0.71	<0.035	**0.322**	0.287	10.8	0.349	<0.0071	<0.018	0.4	<0.035	**1.77**	<0.035	<0.035	<0.018	<0.071	<0.18
OELs range									1–50	n.i.		200–1000			n.i.		10–100		n.i.			
Screening values									0.03	67		7			0.3		0.3		n.a.			

Table A4. Enrichment factors of metals in inhalable dust compared to local topsoil (left) and ore (right). For some elements, we did not calculate enrichment factors because they were not detected in the samples (n.d., not detected) or reference values were not available (n.a., not available). Tin was detected in AK6 but had no reference values for topsoil nor ore.

		Compared to topsoil							Compared to ore						
Report ID	Closest relevant concession	Barium	Cobalt	Copper	Chromium	Iron	Manganese	Nickel	Barium	Cobalt	Copper	Chromium	Iron	Manganese	Nickel
AK1	COMMUS	3	158	449	n.d.	2.0	20	n.d.	n.a.	0.0004	0.016	n.d.	1.0	0.04	n.d.
AK1-bis	COMMUS	1	142	262	n.d.	1.5	14	n.d.	n.a.	0.0003	0.009	n.d.	0.7	0.03	n.d.
AK3	COMMUS	2	180	232	n.d.	1.7	15	n.d.	n.a.	0.0004	0.008	n.d.	0.8	0.03	n.d.
AK4	COMMUS	n.d.	104	138	n.d.	2.0	15	n.d.	n.d.	0.0003	0.005	n.d.	1.0	0.03	n.d.
AK6	COMMUS	4	114	233	n.d.	2.1	20	n.d.	n.a.	0.0003	0.008	n.d.	1.0	0.04	n.d.
AP1	COMMUS	n.d.	112	159	n.d.	1.4	9	n.d.	n.d.	0.0003	0.006	n.d.	0.6	0.02	n.d.
AP2	COMMUS	1	95	177	n.d.	1.5	9	n.d.	n.a.	0.0002	0.006	n.d.	0.7	0.02	n.d.
AF1	TFM	4	73	89	0.6	1.4	8	n.d.	n.a.	0.0002	0.003	n.a.	0.7	0.02	n.d.
AF2	TFM	1	128	195	4.6	0.9	7	63	n.a.	0.0003	0.007	n.a.	0.4	0.02	0.2

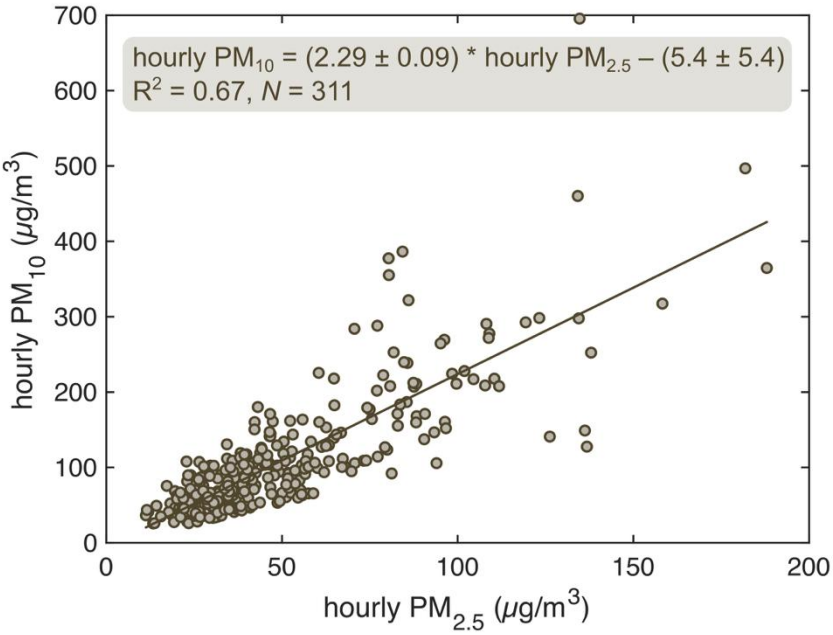

Figure A1. Correlation between hourly $PM_{2.5}$ and hourly PM_{10} across the dataset (311 observations).