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TECHNICAL PAPER

Characterization of bottom ash from a medical waste incinerator and its potential environmental impacts: A case study of Kaloleni Hospital, Arusha, Tanzania

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ABSTRACT

Although incineration is a prevalent method for medical waste treatment in developing countries like Tanzania, the environmental safety of the resulting ash is often overlooked. This study aimed to present a detailed characterization of bottom ash from a medical waste incinerator at Kaloleni Hospital, Arusha, to assess its chemical composition, leaching potential, and environmental risk. Herein, source-segregated medical waste from three streams, including infectious waste (red bags), laboratory/pharmaceutical waste (yellow bags), and general waste (black bags), was analyzed. The findings revealed the distinct particle-size distributions, with the infectious waste (red bag) ash exhibited the highest fineness modulus (9.29) and the largest average particle size (2.35 mm), indicating greater potential for soil penetration and dust generation. Concentrations of heavy metals in the ash exceeded USEPA permissible limits for soil, including titanium (Ti) (3600–9884 mg/kg), iron (Fe) (3683–7789 mg/kg), zinc (Zn) (4020–7449 mg/kg), copper (Cu) (304–616 mg/kg), and mercury (Hg) (0.93–1.23 mg/kg). Notably, mercury predominated in infectious waste (red bag) ash, which was associated with thermometers. Leachate concentrations of critical metals such as lead (Pb) (1093 mg/L) and chromium (Cr) (601.1 mg/L) exceeded U.S. EPA regulatory limits by more than 200 and 120 times, respectively. Calcium sulfate ($CaSO_4$), silicon dioxide (SiO_2), and sodium chloride (NaCl) were the main crystalline phases. These findings demonstrate that the bottom ash poses a substantial risk of heavy metal leaching and environmental contamination. This underscores the urgent need for regulated disposal and pre-treatment of such ash at this hospital. This study recommends extending this investigation to other hospitals to fully assess and mitigate the regional risk to public and environmental health.

Implications: This study demonstrates that bottom ash from a typical medical waste incinerator in a low-resource setting poses a severe environmental threat. High concentrations of heavy metals (Pb, Cr, Hg, Zn) exceed regulatory limits, with leaching tests confirming alarming mobility, particularly for Pb and Cr. Particle size analysis indicates risks of atmospheric dispersion of fine particles and soil infiltration of coarser fragments. The established link between color-coded waste segregation and ash hazards provides critical insights. These findings necessitate integrated strategies, including optimized incinerator operation, mandatory pre-treatment (e.g., stabilization) of bottom ash, and context-specific regulatory frameworks to mitigate risks to air quality, soil, groundwater, and public health.

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Introduction

Medical wastes are hazardous materials, comprising solids, liquids, and laboratory waste (Jaber et al. 2021; Vashchenko et al. 2025). Medical waste is infectious and contains toxic chemicals and pathogenic organisms (Cook et al. 2023; Janik-Karpinska et al. 2023). If not handled properly, they can contaminate soil, groundwater, and surface water (William and Samwel 2024). The World Health Organization (WHO) has estimated that in 2000, injections with contaminated syringes caused 21 million hepatitis B infections, 2 million hepatitis C virus infections, and 260,000 HIV infections (Wajs et al. 2019). The rate of medical waste generation has been growing, with nearly 67% of the total medical waste generated being general waste, and about 31% being infectious and sharp (Singh et al. 2022). Therefore, the practical and responsible management of medical waste is crucial.

Incineration is a widely used method for treating medical waste, particularly for hazardous and infectious fractions (Attrah et al. 2022; Shaik et al. 2022). However, hospital waste incineration does not destroy the metallic components of the waste, but concentrates heavy metals

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into the bottom ash, creating a significant secondary waste stream (Wajs et al. 2019). In high-income countries, the management of incinerator bottom ash has evolved significantly, with standard practices including stabilization/solidification, thermal treatment (e.g., vitrification), and, following stringent pretreatment and testing, potential use in construction materials (Tait et al. 2020; Singh et al. 2022). These approaches are guided by robust regulatory frameworks that mandate characterization and limit leaching. In contrast, in many developing countries, including Tanzania, bottom ash from medical waste incinerators is often disposed of in open dumps or landfills without any pretreatment, posing direct risks of soil and groundwater pollution (Adama et al. 2016; de Titto and Savino 2019). This disparity highlights a critical gap between developed and developing countries.

Typically, a well-operated medical waste incinerator should maintain a combustion temperature of at least 850°C in the primary chamber and 1100°C in the secondary chamber with sufficient gas residence time to ensure complete combustion and minimize toxic emissions (Oumarou et al. 2018). However, many incinerators in developing countries, including Tanzania, are simply designed, operate at sub-optimal temperatures, and lack air pollution control systems, leading to incomplete combustion and the production of highly heterogeneous and contaminated bottom ash (Adama et al. 2016; William and Samwel 2024). Those ashes can contain large pieces of noncombustible material, indicating a poor combustion efficiency (Kocher 2024). These may result in severe environmental and health risks. They may contain harmful heavy metals like cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb) (Huber et al. 2020; Yang et al. 2025), which are toxic, persistent, and can bioaccumulate. Upon disposal, these metals can leach into groundwater or be dispersed as dust, leading to human exposure via inhalation, ingestion, or dermal contact (Suhani et al. 2021; Twagirayezu et al. 2022). Chronic exposure is linked to cancers, neurological damage, kidney failure, and respiratory diseases (Twagirayezu et al. 2023; Nguyen et al. 2024).

Despite the recognized dangers posed by medical waste incinerator bottom ash, a systematic scientific characterization of this waste stream specifically in relation to on-site source segregation practices remains severely lacking across sub-Saharan Africa. This study directly addresses that critical gap by providing a comprehensive, waste-stream-specific analysis of ash from a district hospital in Tanzania. The data generated here, which explicitly links bag-color segregation (red, yellow, black) to distinct ash properties and extreme heavy metal hazards, is an essential prerequisite for developing evidence-based, context-appropriate risk assessments and effective management policies in the region.

Materials and methods

Study site description

The study was conducted at Kaloleni Hospital, a government healthcare facility in Arusha, Tanzania. Based on hospital records and staff discussions, the total amount of medical waste generated is estimated at approximately 350 kg per week. All infectious and hazardous waste is incinerated on-site. The hospital employs a batch-fed dual-chamber incinerator. Waste is combusted in the primary chamber, with gases and particulates subsequently treated in a secondary chamber, which utilizes an auxiliary burner and a blower for enhanced combustion efficiency. During operation, the primary chamber is maintained at temperatures between 400°C and 700°C. The secondary chamber is designed to operate at temperatures between 800°C and 1200°C, with a target gas retention time of 2 sec. The incinerator is not equipped with advanced air pollution control devices (e.g., scrubbers or fabric filters); combustion gases are emitted directly via a stack. Furthermore, the bottom ash generated (estimated at approximately 50–110 kg/week based on waste input and observed residues) is currently collected and disposed of in an uncovered, designated area on the hospital grounds without any pretreatment. The schematic layout of the incinerator is presented in Figure 1 (Adu et al. 2022).

Collection of medical waste and ash

Medical waste at Kaloleni Hospital was collected from various departments by trained personnel, in accordance with strict protocols to ensure safety and traceability throughout handling. Comprehensive source segregation was implemented in accordance with the Tanzanian Medical Waste Management Guidelines, which prescribe a color-coded classification system. Accordingly, highly infectious, anatomical, and hazardous chemical waste is segregated into red bags; less infectious laboratory and pharmaceutical waste into yellow bags; and general, non-hazardous municipal-type waste into black bags. This practice minimizes cross-contamination, supports optimal combustion efficiency, and facilitates subsequent material characterization. Each waste bag retained its original category throughout the collection and transport phases until incineration, ensuring that each ash sample reflected a single waste stream. Red and yellow bags

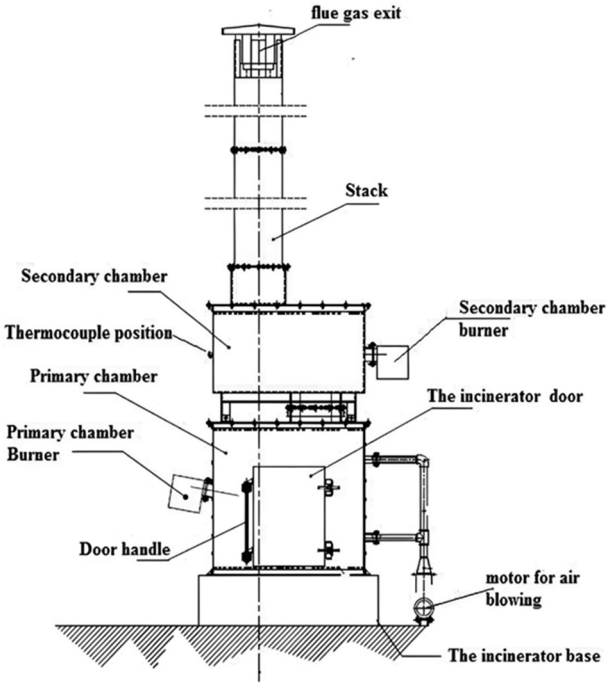

Figure 1. Kaloleni incinerator layout.

were fed directly into the incinerator without being opened, thereby limiting worker exposure to hazardous contaminants and pathogens. Each bag type was incinerated separately to prevent mixing of waste fractions and to enable precise assessment of the ash produced from each category. To account for potential daily variability in hospital waste composition, triplicate 100 g ash samples from each color category were collected over three consecutive days, yielding statistically robust and representative results. All samples were thoroughly dried at 105°C before subsequent testing to eliminate moisture variability and ensure standardized preparation. The details of waste types corresponding to each bag color are summarized in Table 1 to ensure an explicit mapping between waste sources and ash properties. Such standardized and meticulous segregation and sampling are critical for valid assessment of incinerator performance and the environmental impact of the resulting bottom ash.

Table 1. Types of waste received at the incinerator facility.

S/N	Color of bags	Waste received
1	Red	Gloves with blood, medical boxes, cotton with blood, plastic drips, placenta and microbiology waste, human body parts, thermometer, medical springs.
2	Yellow	Laboratory waste, instruments, and leaded glass bottles.
3	Black	Medical boxes, discarded plastic containers for medical injection boxes, syringes, papers, and food leftovers.

Sieve analysis

Particle size distribution was determined using standard sieve analysis procedures (Rahman and Shamsuddin 2016). Twelve sieves with mesh sizes ranging from 0.063 mm to 4 mm were arranged sequentially from top to bottom for the sieve analysis. A 100 g sample of the bottom ash was placed on the top sieve and subjected to mechanical shaking for at least 15 min to thoroughly separate particle sizes. Each sieve and the collection pan were weighed before and after sieving to determine the weight of ash retained on each sieve. Using the retained weights, cumulative weights were calculated, and the percentage of ash passing through each sieve was computed using eq 1.

$$\text{Cummulative \% retained} = \frac{\text{Cummulative mass retained (g)}}{\text{Total cummulative mass retained (g)}} \times 100 \quad (1)$$

To assess the distribution between fine particles (<2 µm) and coarser aggregates (>2 µm) relevant to soil impact, the fineness modulus (FM) was calculated. FM represents the sum of the percentages retained on each specified size divided by 100 (eq 2) and indicates particle coarseness.

$$\text{FM} = \frac{\sum P_{\text{retained}}}{100} \quad (2)$$

Additionally, the average particle size of the ash samples was computed using eq 3,

$$\text{Average particle size} = \frac{\sum_0^i W_i \bar{d}_i}{W_t} \quad (3)$$

where W_i is the weight retained on the sieve with mean diameter d_i, and W_t is the total mass of ash collected across all sieves and the pan.

Elemental analysis

X-ray fluorescence (XRF) spectroscopy was employed to analyze the elemental composition of bottom ash samples from each waste bag category. Approximately 4 g of each homogenized sample was thoroughly mixed with 0.9 g of a wax binder (CEREOX® BM-0002-1, FLUXANA® GmbH & Co. KG) and compressed at 15 bar to form solid pellets for analysis.

Morphological and mineralogical analysis

Mineralogical characterization was performed using X-ray powder diffraction (XRD) analysis, with a diffractometer (X'Pert MPD) operated at 20 kV, scanning angles between 10° and 90° (2θ) at 4° per minute. Morphological analysis and semi-quantitative elemental mapping were conducted using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX).

Determination of heavy metal content

Oven-dried, homogenized ash (50 mg) subsamples were weighed into Teflon® vessels and digested using a microwave-assisted system (MARS 6, CEM Corporation, U.S.A.). Ash samples were digested with a mixture of 3 mL concentrated HNO_3 and 0.8 mL HF. The sealed vessels were then heated in an oven at 150°C for 48 h. After cooling, the clear digests were transferred from the Teflon® vessels, and 1 mL aliquots of H_2O_2 were added. The solutions were heated on a hot plate at 90°C for 1 h. Subsequently, 1 mL aliquots of HNO_3 were added successively three times for ash digests. Following this, 1 mL of HNO_3 and 3 mL of ultrapure water were added, and the mixtures were heated again in an oven at 150°C for 6 h. After a final cooling step, the resulting solutions were diluted to a fixed volume and passed through a 0.22 µm syringe filter. Heavy metal concentration in ash was determined using inductively coupled plasma optical emission spectrometry (ICP-OES).

Assessment of heavy metal leaching

The toxicity characteristics leaching procedure (TCLP) test was done based on (Su et al. 2014) is designed to assess the mobility of toxic elements in liquids, solids, or waste materials under conditions that stimulate those found in a landfill etc. TCLP tests were performed to quantify the heavy metal leachability in ash following USEPA Method 1311. Two different buffered acidic leaching extraction fluids were used for TCLP depending on the alkalinity and the buffering capacity of the wastes. Therefore, fluid 1 is used for the soils with pH < 5.00 while the fluid #2 is for the as with pH > 5.00. In our study, the extraction fluid #2 was used, which was 0.1 mol/L glacial acetic acid (CH_3CO_2H) with pH adjusted to 2.88. An aliquot of 2.00 g of each sample and 40 mL extraction reagent was transferred to 100-mL plastic vessels and agitated on a shaker for 18 hr at 25°C. They were then centrifuged at 3900 r/min for 10 min. The suspension was filtered by vacuum filtration through 0.45 µm-pore glass fiber filter paper. The filtrates were analyzed for heavy metal concentrations using inductively coupled plasma optical emission spectrometry (ICP-OES).

Statistical analysis

Statistical analyses were performed using OriginPro 2025 (OriginLab Corporation, Northampton, MA, U.S.A.) to evaluate the significance of observed differences in ash properties across the three waste stream categories (red, yellow, and black bags). Descriptive statistics, including means, standard deviations, and coefficients of variation, were calculated for key parameters such as average particle size, fineness modulus, heavy metal concentrations (from XRF and microwave digestion – ICP-OES), and TCLP leachate concentrations. To determine whether significant differences existed among the waste categories, one-way analysis of variance (ANOVA) was applied, followed by Tukey's honestly significant difference (HSD) post-hoc test for pairwise comparisons; results were considered statistically significant at $p < .05$.

Results and discussion

Ash particle size distribution

The particle-size distribution of bottom ash is a key physical property influencing its environmental behavior, including dust dispersion, infiltration into soil, and the leaching potential of toxic elements. In this study, sieve analysis was conducted on bottom ash collected from three different waste categories, red, black, and yellow bags, each representing specific waste types generated from the medical facility. The particle-size distribution data presented in Table 2 and in Supplementary Tables S1-S3 reveal significant variation among the waste bag categories. For instance, the red bag ash retained the highest mass fraction on the largest sieve size (4 mm), with approximately 48.31% of the ash particles exceeding this size. This indicates substantially coarser ash than in the black and yellow bag samples, which retained 8.58% and 31.40%, respectively, on the 4 mm sieve. This coarseness aligns with findings by William and Samwel (2024), who reported that incomplete combustion in low-temperature medical waste incinerators in Tanzania often yields bottom ash with large, unburnt fragments. Large particles in red bag ash can be linked to the waste type present, such as infectious materials containing blood and tissue fragments, which do not fully combust to fine ash particles.

Conversely, the black bag ash exhibited a predominance of finer particles, with a much higher fraction passing

Table 2. Average particle sizes of bags.

	Yellow bag		Black bag		Red bag	
MD d_i (mm)	MR W_i (g)	$\sum W_i d_i$	MR W_i (g)	$\sum W_i d_i$	MR W_i (g)	$\sum W_i d_i$
5.00	0.00	–	0.00	–	0.00	–
4.00	31.40	125.61	8.58	34.32	48.31	193.23
2.00	13.18	26.36	14.33	28.66	12.17	24.17
1.50	5.04	7.56	6.97	10.45	4.30	6.44
1.00	5.82	5.82	11.44	11.43	4.78	4.78
0.71	4.20	2.98	8.80	6.25	4.43	0.75*
0.50	5.81	3.00	10.43	5.21	4.65	2.32
0.355	4.02	1.42	10.52	3.73	3.36	1.19
0.250	4.88	1.21	15.53	3.88	3.96	0.98
0.180	3.06	0.55	8.80	1.32	2.43	0.43
0.125	3.80	0.47	3.50	0.43	2.48	0.30
0.090	3.05	0.27	0.95	0.08	1.56	0.13
0.063	4.25	0.15	0.06	0.003	0.42	0.02
Pan	11.36	–	0.07	–	7.06	–
W_t	99.87	–	99.99	–	99.89	–

Notes. MD d_i = mean diameter of sieve opening (mm); MR = mass retained on sieve; W_i = weight retained on sieve; $\sum W_i d_i$ = sum of (weight retained × mean diameter); W_t = total mass of ash; – = No value.

through the larger sieves and accumulating on the finer sieves, such as 0.25 and 0.125 mm. This texture is attributed to the presence of paper, plastic, and other combustibles, which typically produce finer ash residues. Similar dominance of fine fractions (<1 mm) in ash from combustible municipal-type waste has been documented, highlighting its high potential for dust generation (Huber et al. 2020). The yellow bag ash exhibited an intermediate particle-size distribution, reflecting the mixed waste types it contains, including laboratory waste and leaded glass. Previous studies from similar low-resource settings support these findings; for example, as study by Adama et al. (2016) reported that infectious waste fractions in Ghanaian hospitals produced significantly coarser ash (mean particle size 3.2 mm) compared to general waste fractions (1.4 mm), attributing this difference to incomplete combustion of high-moisture organic matter.

The computed average particle sizes, based on the weighted mean of retained fractions on each sieve, augment this observation: 2.35 mm (red bag), 1.75 mm (yellow bag), and 1.05 mm (black bag). These measurements indicate that red bag ash particles are approximately twice as large as black bag ash particles. This size differential is consistent with combustion efficiency patterns documented in sub-Saharan African healthcare settings, where infectious waste heterogeneity consistently produces coarser residues than general waste streams (Adama et al. 2016; William and Samwel 2024), confirming that waste stream segregation directly influences particle morphology. Fineness Modulus (FM), a numerical index that expresses the mean size of aggregate particles, also reflects these size differences. The FM values for the red, black, and yellow bags were 9.29, 7.65, and 7.85, respectively, each exceeding the typical safe range of 2.3 to 3.1 for environmental applications (Chowdhury et al. 2019). These elevated FM values are substantially higher than those reported for medical waste incinerator ash in recent European studies with FM 3.8–5.2 (Bernasconi et al. 2022), underscoring the suboptimal combustion conditions prevalent in Tanzanian facilities. This elevated FM underscores the dominance of coarser fractions, especially in the red bag, potentially indicating inefficient combustion or incomplete breakdown of larger waste components during incineration. The high FM values observed across all ash types of contrast with findings from well-controlled incineration studies, where ash is often finer due to more complete combustion, underscoring the operational deficiencies in the studied system (Oumarou et al. 2018).

Figure 2 illustrates the mass fractions retained for each size across the three ash types. While all ash samples exhibited particle concentrations below 1 mm, posing significant health threats through inhalation, the red bag ash showed substantial retention of mesoscale particles, which may settle faster but could include contaminated fragments with entrapped heavy metals. Notably, the >90% fraction below 1 mm in black bag ash exceeds the 75–85% range reported by Singh et al. (2022) for modern incinerators with air pollution controls, suggesting that the lack of emission controls at Kaloleni Hospital may enhance fine particle formation through incomplete combustion cycles. This prevalence of fine, inhalable particles (<10 μm) is a major occupational health concern, as noted in studies on incinerator ash handling, which link it to respiratory ailments among workers (Groma et al. 2022). Detailed data from Table S1, S2 and S3 show cumulative percentages passing, for example, over 88% of red bag ash passes below 1 mm. However, a meaningful fraction remains coarser, thereby balancing dust-generation concerns with solid-waste management challenges. The black

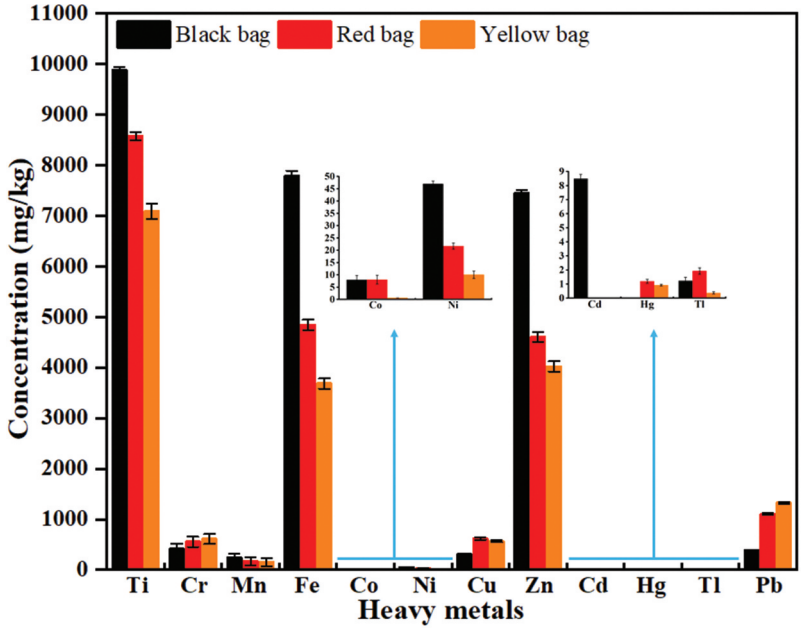

Figure 2. Percentage of materials retained against sieve size.

bag ash had over 90% passing the 1 mm sieve, indicating a greater fraction of highly respirable particles. From an environmental standpoint, smaller particles promote greater leachate generation and metal mobilization due to larger surface areas. Recent research conducted by Groma et al. (2022) demonstrated that ash particles <1 mm leached 3.5 times more Pb and Cr than coarser fractions under simulated landfill conditions, corroborating the heightened risk posed by Kaloleni's fine ash fractions. Finer ash increases the risks of atmospheric dust dispersion, which can be inhaled by workers and nearby residents, elevating acute and chronic health risks. Large, coarse particles, less likely to become airborne, pose hazards to soil penetration and groundwater contamination, particularly when they contain elevated concentrations of heavy metals.

The differences in particle size distribution among bag categories closely correlate with waste composition, as detailed in Table 1. Infectious waste in red bags, such as blood-contaminated materials and body parts, produces larger particle residues, which may be due to their heterogeneous, sometimes wet nature, which affects combustion dynamics. The black bag, composed mainly of paper, plastics, and debris, tends to combust more completely, producing smaller particulates. This combustion efficiency disparity mirrors findings by Tsakalou et al. (2018), who reported that moisture content exceeding 40% in infectious waste reduced combustion efficiency by 35% and increased residual particle size by 60% compared to dry general waste. The yellow bag contains laboratory waste and glass, contributing to intermediate physical characteristics.

The particle-size characteristics of ash were dominated by fine fractions and variable coarse-particle presence, underscoring the need for careful handling of wonderful ash from black bags, which is associated with health risks. The coarser red bag ash likewise requires attention to prevent heavy metal infiltration into soil systems. A study conducted by William and Samwel (2024) at Muhimbili Hospital in Tanzania reported similar particle size challenges, with 67% of ash samples <1 mm, and highlighted that local waste composition variations significantly affect residue characteristics across different healthcare facility tiers. These findings affirm that bottom ash management cannot adopt a one-size-fits-all approach; it must account for particle-size variability associated with waste types to mitigate environmental and occupational hazards effectively.

Average particle size

The average particle size of the bottom ash samples from the medical waste incinerator was calculated using the weighted mean diameter method, which considers the mass of ash retained on each sieve fraction. The results show notable differences in particle size distributions across the three waste categories represented by the red, yellow, and black bags (Table 2).

The red bag ash exhibited the largest average particle size, measuring approximately 2.35 mm. This higher average is consistent with previous observations of higher coarse-particle fractions in this category. The composition of red bags, primarily infectious waste such as gloves with blood, human tissue, and solid

medical residues, likely contributes to these relatively coarse ash particles. The larger particle size indicates incomplete combustion of the bulky material, resulting in larger residue fragments. This phenomenon is consistent with reports from other developing regions, where inadequate incinerator temperatures lead to poor degradation of organic-infectious waste, yielding ash with a larger mean particle diameter (Adama et al. 2016). For instance, a study of Adama et al. (2016) documented coarser residues from infectious waste in Ghana, while a study of William and Samwel (2024) identified similar incomplete combustion in Tanzanian hospital incinerators operating at suboptimal temperatures (400–700°C), confirming that batch-feeding systems and temperature fluctuations directly influence ash morphology.

The black bag ashes exhibited the smallest average particle size, approximately 1.05 mm. This finer particle size corresponds to the predominance of noninfectious waste, such as paper, discarded syringes, and plastic containers. These materials combust more completely, resulting in finer ash particles that are more readily transported by wind and have a larger reactive surface area, thereby intensifying potential environmental risks associated with dust inhalation and leachate formation. This finding is corroborated with the results of Freslyn Mae et al. (2025), who reported that plastic-rich medical waste fractions produce ash with 40–60% higher surface area compared to organic-rich fractions, substantially increasing metal leaching potential.

The yellow bag ash had an intermediate particle size, approximately 1.75 mm, reflecting its mixed waste composition, including laboratory waste and leaded glass materials. The presence of glass and chemical residues may result in intermediate combustion conditions and ash particle sizes. These average particle sizes have crucial implications: Ash particles smaller than 1 mm, found in significant proportions across all ash types, especially black and yellow bags, pose substantial risks of respirable dust generation, which can affect workers' and nearby populations' respiratory health. A meta-analysis by Tait et al. (2020) found that incinerator workers exposed to ash particles <1 mm exhibited a 2.3-fold increased risk of respiratory morbidity compared to controls, with particulate matter concentrations 8 times higher near facilities lacking emission controls. Finer particle sizes exhibit higher surface areas, increasing the propensity for heavy metals to leach into soil and groundwater systems, exacerbating environmental contamination.

Previous study done by Yang et al. (2025) demonstrated that nanowire-like carbonate structures on fine ash particles enhance heavy metal immobilization, but these beneficial features require combustion temperatures above 1000°C conditions not met at Kaloleni, explaining the heightened leaching observed in our study. Larger particles, as abundant in the red bag ash, although less prone to airborne dispersion, may pose challenges for landfill stability and long-term heavy metal retention. Differences in particle size further underscore the importance of source segregation and proper incinerator operation, as waste type and combustion efficiency directly influence the physical characteristics of residual ash. Managing these ashes requires tailored approaches to minimize health and environmental risks, including dust control measures and stabilization treatments for fine particles prone to leaching (Chowdhury et al. 2019; Groma et al. 2022).

Elemental composition

The elemental composition of the bottom ash samples from the medical waste incinerator was analyzed using X-ray fluorescence (XRF), providing critical insights into the types and concentrations of heavy metals present. Table 3 summarizes the concentrations of key elements detected in ash from the red, black, and yellow bags, alongside the regulatory limits set by the U.S. Environmental Protection Agency (USEPA) for soil quality. The results reveal that titanium (Ti), iron (Fe), and zinc (Zn) are the predominant metals across all samples, with maximum concentrations of 9,883 mg/kg, 7,789 mg/kg, and 7,449 mg/kg, respectively, generally following the order Ti > Fe > Zn. These elevated levels are primarily attributable to the incinerator's construction materials (e.g., clay bricks, which contribute Ti and Fe) and to the presence of metal components in medical devices and packaging materials.

Previous study done by Huber et al. (2020) on biomedical waste incinerators in Austria reported similar Ti and Fe enrichment (Ti: 8,200–11,500 mg/kg; Fe: 6,800–9,100 mg/kg), confirming that incinerator construction materials are universal contributors regardless of facility sophistication. For instance, Zn and Ti often originate from metal alloys used in hospital equipment. Other metals detected include Cr, copper (Cu), nickel (Ni), Pb, Cd, Hg, cobalt (Co), manganese (Mn), thallium (Tl), and thorium (Th). Notably, many of these exceed international guideline values for soil contamination. Pb concentrations were particularly high in all ashes, with the yellow bag containing 1322 mg/kg and the red bag 1101 mg/kg, both above typical soil limits (200 mg/kg). These Pb levels are alarmingly consistent with recent findings from a study of Adama et al. (2016) in Ghana, who reported 1280 mg/kg near hospital ash dumpsites, and significantly exceed the 420 mg/kg

Table 3. Heavy metals detected in medical waste bottom ash and the commonly known permissible limit of heavy metal concentration in soil.

Element	Waste bags (mg/kg)			Permissible limit of heavy metal concentration in soils (mg/kg)
	Black bag	Red bag	Yellow bag	
Titanium	9883.93 ± 20	8578.60 ± 24	7085.93 ± 18	NA
Chromium	415.13 ± 15	551.90 ± 12	605.67 ± 8	10–1000
Manganese	238.73 ± 7	167.00 ± 10	144.80 ± 8	20–3000
Iron	7789.80 ± 24	4840.30 ± 19	3682.57 ± 15	4.0
Cobalt	8.00 ± 0.8	8.07 ± 0.6	0.67 ± 0.04	20–3000
Nickel	47.00 ± 2	21.73 ± 1.4	10.07 ± 0.8	4.0
Copper	304.33 ± 12	616.10 ± 14	564.23 ± 13	2–100
Zinc	7449.80 ± 16	4602.77 ± 14	4019.57 ± 16	10–300
Cadmium	8.50 ± 0.6	0.00	0.00	0.01–0.7
Mercury	0.00	1.20 ± 0.06	0.93 ± 0.02	0.005
Thallium	1.23 ± 0.04	1.93 ± 0.06	0.37 ± 0.07	NA
Lead	377.57 ± 16	1101.77 ± 14	1322.70 ± 17	2–2000

Notes. NA = not available or not regulated. Values are mean ± standard deviation. Permissible limits are based on USEPA soil quality guidelines.

average documented by Ramesh Kumar et al. (2021) in India, suggesting that African medical waste streams may contain higher Pb concentrations from outdated medical equipment and leaded glass. This may be due to the concentrating effect of uncontrolled medical waste incineration (Singh et al. 2022).

Hg was detected mainly in the red bag ashes at 1.20 mg/kg, significantly above the permissible limit of 0.005 mg/kg. The preferential concentration of Hg in infectious waste ash mirrors results of Tsakalou et al. (2018), who found 1.5 mg/kg Hg in clinical waste residues, attributing it to thermometers, sphygmomanometers, and fluorescent lamps that are frequently co-disposed in infectious waste streams in developing countries. The volatility and toxicity of Hg pose serious health risks, particularly through inhalation of vapor. Cd was found only in the yellow bag, at levels (8.5 mg/kg) exceeding the safe soil limit of 0.01 mg/kg, likely linked to the plastic and chemical waste components. This Cd enrichment pattern aligns with that in the study of Freslyn Mae et al. (2025), who demonstrated that laboratory waste plastics contain 5–12 mg/kg Cd from stabilizers and pigments, confirming that yellow bag segregation concentrates this highly toxic metal. Cr and Cu were also present at elevated concentrations, ranging from 415 to 605 mg/kg and 304 to 616 mg/kg, respectively, across bag types, both exceeding typical soil quality thresholds. These findings underscore the potential environmental and health hazards associated with the direct disposal of untreated incinerator bottom ash. The heavy metals in the ash could accumulate in the soil and subsequently enter the food chain via plants and animals, or leach into groundwater, thereby creating a pathway for widespread exposure.

Figure 3 shows the comparative elemental distribution in the ash samples, highlighting the dominance of Ti, Fe, and Zn and the elevated Hg levels, particularly in the red bag. Comparative analysis reveals that the Zn concentrations (4,020–7,449 mg/kg) are substantially higher than those reported by Singh et al. (2022) in their global review of medical waste incineration (Zn: 1200–3,400 mg/kg), suggesting that Tanzanian medical waste contains elevated Zn from galvanized containers and medical instrument alloys. The presence of these metals reflects the variable composition of the original waste streams, emphasizing the need for strict segregation of medical wastes at the source to limit heavy metal dispersion. Particularly concerning is the detection of Th (0.37–1.93 mg/kg), which, though not regulated, exceeds background soil concentrations by 10- to 50-fold and correlates with recent reports by Nguyen et al. (2024) on radioactive hotspot formation in Vietnamese incinerator ash from diagnostic imaging waste. The study of Bernasconi et al. (2022) and Chuai et al. (2022) found similar heavy metal enrichment in incineration residues worldwide. Given the carcinogenic and toxic nature of several metals (e.g., Cd, Pb, Cr, and Hg), their high concentrations in bottom ash necessitate careful monitoring and the implementation of appropriate disposal or stabilization techniques to mitigate environmental contamination and public health risks (Honest et al. 2020; Freslyn Mae et al. 2025).

Mineralogy

The mineralogical composition of the bottom ash samples from the medical waste incinerator was characterized using X-ray diffraction (XRD) analysis, which identifies crystalline phases present in the ash and provides insight into their potential environmental behavior and stability. As shown in Figure 4, the XRD patterns reveal that the dominant crystalline phases within the ashes are calcium sulfate ($CaSO_4$), silicon dioxide (SiO_2), and sodium chloride (NaCl), consistent across all samples from the red, black, and yellow waste bags. $CaSO_4$ and NaCl likely originate from the

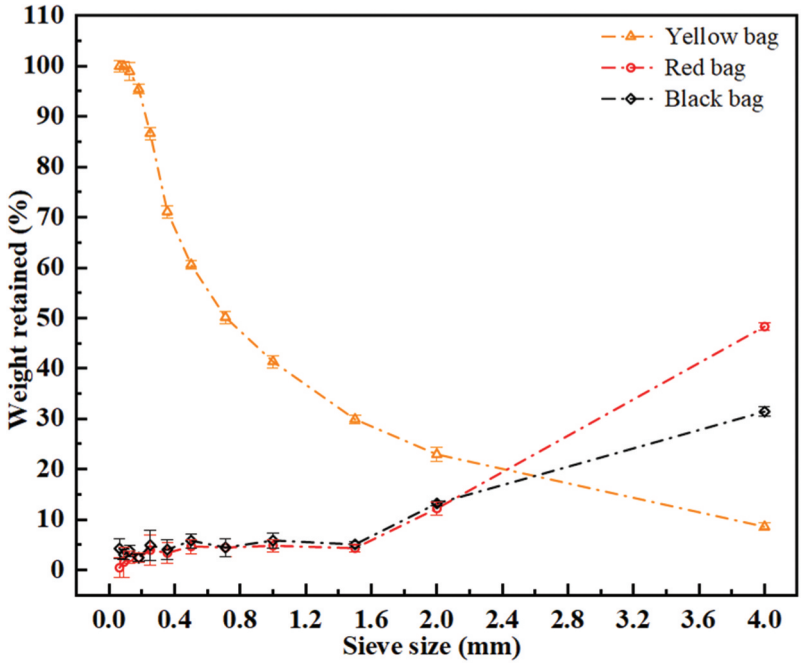

Figure 3. XRF results of elemental composition in all bags.

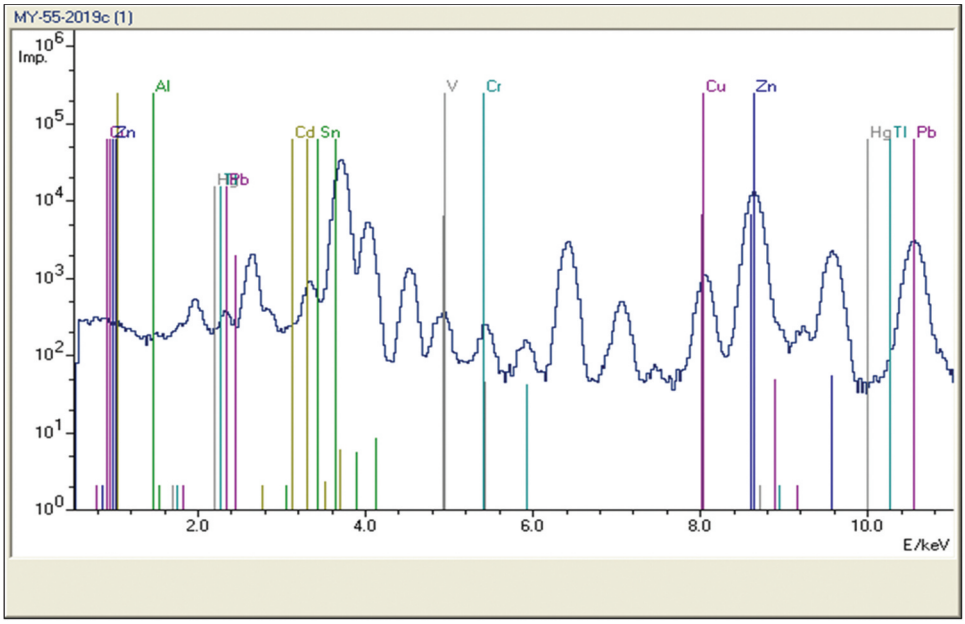

Figure 4. XRD peaks of bottom ash sample.

chemical constituents of waste and combustion reactions. At the same time, SiO_2 is a common mineral residue formed during the incineration of silica-rich materials, such as paper, plastics, and soil contaminants, in waste. Recent XRD investigations done by Chuai et al. (2022) on medical waste incinerator residues in China identified identical dominant phases ($CaSO_4$, SiO_2, NaCl), confirming that these mineral assemblages are characteristic of medical waste combustion regardless of geographic location. The presence of these stable crystalline minerals suggests that a significant portion of the ash matrix comprises inorganic salts and silicates, which influence the physical stability and pollutant immobilization capacity of the residues (Chuai et al. 2022). Comparison of XRD patterns before and after the Toxicity Characteristic Leaching Procedure (TCLP) revealed noticeable changes in peak intensities, indicating alterations in mineral phases due to leaching. Such

changes highlight the reactivity of the ash components and the potential release of certain metals under environmental conditions, such as landfill leachate. This phase instability under acidic conditions corroborates findings of Bernasconi et al. (2022), who reported 40–60% dissolution of $CaSO_4$ matrices during TCLP testing, which subsequently released encapsulated heavy metals. Understanding mineralogy is critical because it affects the speciation and mobility of hazardous elements within the ash. For example, metals bound within mineral phases, such as calcium sulfate, may be less bioavailable and less prone to leaching, whereas elements associated with more soluble components (e.g., NaCl) may pose greater environmental risks (Bernasconi et al. 2022; Chuai et al. 2022).

Furthermore, the formation of mineral phases such as $CaSO_4$, which is relatively insoluble under neutral to alkaline conditions, can be advantageous for immobilizing heavy metals, reducing their bioavailability and mobility. However, recent thermodynamic modeling by Yang et al. (2025) demonstrated that in chloride-rich environments like Kaloleni ash (NaCl presence), $CaSO_4$ stability decreases significantly, promoting metal mobilization under mildly acidic conditions (pH 5–7) typical of Tanzanian soils. However, the presence of salts such as sodium chloride can enhance solubility and facilitate metal transport when ash is disposed of in the environment. This is particularly concerning given that study has documented that enhanced heavy metal uptake in maize crops grown on soil amended with NaCl-rich incinerator residues, with Cd translocation factors increasing threefold compared to chloride-free ash amendments (Novák et al. 2025). These findings emphasize the importance of detailed mineralogical characterization for assessing the environmental fate of bottom ash and for designing effective management and treatment strategies to mitigate potential contamination pathways.

Leaching test

Table 4 presents the concentrations of selected heavy metals detected in the leachates of the bottom ash samples. The results reveal that critical metals such as Pb and Cr leached at concentrations that dramatically exceeded the U.S. EPA TCLP regulatory limits, indicating a significant risk of environmental contamination if the ash is disposed of without treatment. Specifically, Pb was leached at 1093 mg/L, which is more than 200 times the regulatory threshold of 5.0 mg/L, whereas Cr was detected at 601.1 mg/L, exceeding the limit by more than 120 times. These exceedance factors are substantially higher than those reported in recent study (Singh et al. 2022) compiled data showing typical exceedances of 50–80 times for Pb and 20–40 times for Cr in medical waste ash from middle-income countries, suggesting that Kaloleni's suboptimal combustion conditions (400–700°C) create exceptionally mobile heavy metal species. These elevated leachate concentrations indicate that these metals are highly mobile under landfill-like acidic conditions, posing significant risks to soil and groundwater quality.

Table 4. TCLP results of bottom ashes.

Metals	Bottom ashes (mg/l)	EPA TCLP regulatory limits
Cd	0.46 ± 0.02	1.0
Pb	1093 ± 26	5.0
Cr	601.1 ± 12	5.0
Zn	7449.80 ± 24	NA
Ni	14.13 ± 1	NA
Cu	555.67 ± 8	NA

Notes. NA: No regulatory limits available. TCLP = toxicity characteristic leaching procedure. Values are mean ± standard deviation. NA = not available or not regulated by EPA TCLP.

Heavy metals, including Zn, Ni, and Cu, were also present in the leachates at substantial concentrations of 7449.8 mg/L, 14.13 mg/L, and 555.67 mg/L, respectively. However, those values exceed the EPA values, which are Zn (100 mg/L), Ni (5 mg/L), Cu (100 mg/L) and exceed other regions. Zn leachate concentration (7,449.8 mg/L) is particularly alarming, exceeding the 1200 mg/L reported by (Phoungthong et al. 2016) in Thailand and the 2800 mg/L documented by (Ramesh Kumar et al. 2021) in India by factors of 6.2 and 2.7, respectively, indicating unprecedented Zn mobility that may be attributed to high chloride-mediated complexation. These indicate a potential environmental hazard, particularly given their toxicity and bioaccumulation.

Cd was detected at 0.46 mg/L, which are below the regulatory limit of 1.0 mg/L; however, its toxicity and persistence still warrant attention. While below TCLP limits, this Cd concentration exceeds the 0.15 mg/L reported by Tsakalou et al. (2018) for vitrified medical waste ash and approaches the 0.62 mg/L from untreated ash in their study, confirming that even "compliant" metals pose ecological risks. The release of these metals during the leaching tests highlights the urgent need for careful management and effective treatment methods to immobilize heavy metals and prevent their migration into the ecosystem. These findings align with other studies reporting the leachability and environmental hazard of heavy metals from medical waste incinerator residues (Tsakalou et al. 2018; Ramesh Kumar et al. 2021). Critical comparisons reveal that the Pb:Cr leaching ratio (1.82:1) in Kaloleni ash differs markedly from the 3.5:1 ratio reported by Chuai et al. (2022), suggesting distinct heavy metal speciation patterns possibly linked to alkaline battery waste in yellow bags, as evidenced by

the high Mn content (238.7 mg/kg) in our elemental analysis.

These elevated concentrations of Pb and Cr in leachates underscore the need for regulated disposal practices, such as stabilization, solidification, or vitrification, to mitigate potential impacts on surrounding populations and natural resources. A study of Tsakalou et al. (2018) demonstrated that vitrification reduced TCLP leachability by over 90% for Pb and Cr in medical waste ash, whereas Ramesh Kumar et al. (2021) reported that solidification with cement-based binders decreased heavy metal mobility by 85–95%, confirming that effective treatment options exist for mitigating such hazards. The leaching test confirms that the bottom ash produced at Kaloleni Hospital contains environmentally hazardous concentrations of heavy metals that can leach into groundwater under typical landfill conditions, underscoring the imperative for stringent control measures to safeguard public health and the environment.

Elemental distribution

Elemental analysis by EDX revealed that the ashes were enriched in chlorine (Cl), silicon (Si), sodium (Na), calcium (Ca), and sulfur (S). The approximate composition, expressed in weight percent (wt%), was Ca (31.2%), Cl (5.8%), Na (3.4%), Si (3.4%), and S (0.4%). These weight percentages are remarkably similar to EDX results reported by (Chuai et al. 2022) for Chinese medical waste ash (Ca: 28–34%, Cl: 4.2–7.1%, Na: 2.8–4.5%), validating that combustion chemistry produces consistent elemental signatures regardless of geographic location. The dominant presence of Na, Si, and Cl indicates substantial amounts of NaCl in the ash matrix, a salt typically formed by combustion reactions involving chlorinated plastics and other chloride-containing materials. Calcium co-occurring with sulfur indicates the presence of $CaSO_4$, a common combustion residue formed from sulfurous compounds in the waste. The co-location of calcium with chlorine suggests $CaCl_2$ is also present in the ash. These mineralogical insights from EDX are consistent with the XRD results, confirming that NaCl, $CaSO_4$, and $CaCl_2$ are key ash constituents. The coexistence of soluble salts like sodium chloride potentially enhances the mobility of metals, increasing leachability under certain environmental conditions (Bernasconi et al. 2022; Chuai et al. 2022). The high chloride content (5.8 wt% Cl) in Kaloleni ash suggests enhanced metal complexation, consistent with documented mechanisms where chloride ions facilitate heavy metal transport in landfill leachate (Tsakalou et al. 2018). The EDX-derived elemental mapping corroborates the XRF data, providing visual confirmation of the co-localization of heavy metals with these soluble salt phases, which is a critical factor for predicting environmental fate (Bernasconi et al. 2022).

Understanding elemental distribution is crucial for assessing the potential environmental impacts of bottom ash and guiding treatment and disposal strategies. For example, the presence of soluble mineral phases underscores the need for stabilization treatments to reduce heavy metal mobility and prevent groundwater contamination when the ash is disposed of in landfill sites.

Conclusion and recommendations

This study provided a comprehensive physicochemical, mineralogical, morphological, and leaching characterization of bottom ash generated from a medical waste incinerator at Kaloleni Hospital in Tanzania. The results reveal significant variations in ash properties across waste streams, with red bag (infectious waste) ash exhibiting the highest fineness modulus (9.29) and largest average particle size (2.35 mm), reflecting incomplete combustion of heterogeneous, moisture rich waste. In contrast, black bag (general waste) ash was predominantly fine (<1 mm), posing heightened risks of dust generation and respirable particulate exposure.

Elemental analysis confirmed elevated concentrations of heavy metals including Ti, Fe, Zn, Cu, Pb, Cr, Hg, and Cd exceeding USEPA soil quality limits across all ash types. Hg was notably enriched in red bag ash, linked to thermometers and clinical devices, while Cd was isolated in yellow bag ash from laboratory and pharmaceutical waste. Leaching tests demonstrated extreme mobility of toxic metals, with Pb (1093 mg/L) and Cr (601.1 mg/L) exceeding U.S. EPA TCLP limits by more than 200 and 120-fold, respectively. Mineralogical analysis identified dominant crystalline phases ($CaSO_4$, SiO_2, NaCl) that influence ash stability and metal mobility, with chloride rich phases likely enhancing metal leachability.

The findings underscore that bottom ash from inadequately operated medical waste incinerators in resource limited settings represents a severe, yet overlooked, environmental and public health hazard. Without pretreatment or regulated disposal, such ash can contaminate soil, groundwater, and air, posing acute and chronic risks to nearby communities and ecosystems. To address these risks, the following evidence-based recommendations are proposed:

- Immediate operational improvements: Kaloleni Hospital should prioritize incinerator maintenance and operational training to ensure combustion temperatures meet WHO guidelines (≥850°C

primary, ≥1100°C secondary). Implementing basic emission controls and ash handling protocols, such as wetting ash to suppress dust, can reduce immediate exposure risks.

- Ash pretreatment and stabilization: Before disposal, ash should undergo stabilization using locally available materials, for example, lime, cement, or pozzolanic additives, to immobilize heavy metals. Low-cost solidification techniques should be piloted and assessed for effectiveness under local conditions.
- Enhanced waste segregation and monitoring: Strengthening at source segregation practices, particularly separating Hg containing devices and laboratory chemicals, can reduce toxic metal loading in ash. Routine monitoring of ash composition and leachability should be integrated into hospital waste management protocols.
- Policy and regulatory action: Tanzanian environmental and health authorities should develop and enforce guidelines for medical waste ash management, informed by locally generated data. Policies should mandate ash characterization, pretreatment standards, and safe disposal practices, supported by capacity building for healthcare facilities.
- Further research and regional assessment: This study should be expanded to other healthcare facilities across Tanzania and similar regions to assess variability in ash hazards. Research into low-cost treatment technologies, such as ash reuse in construction materials or phytoremediation, should be encouraged to support sustainable and context appropriate solutions.

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Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

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