JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(9), 280–294
https://doi.org/10.12911/22998993/221878
ISSN 2299–8993, License CC-BY 4.0

Received: 2026.04.21
Accepted: 2026.07.15
Published: 2026.08.01

Water–soil–plant transfer of heavy metals in an active geothermal zone: the case of *Melastoma malabathricum* (L.) at Gunung Kembar, Aceh Province, Indonesia

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ABSTRACT

Geothermal manifestations can enrich the surrounding water and soil with trace metals, raising safety concerns for medicinal plants harvested from such areas. This study provides the first integrated assessment of Pb, Cd, Cu, Cr, Fe, and Zn in water, soil, and *Melastoma malabathricum* (L.) at two active hydrothermal sites within the Gunung Kembar geothermal zone, Aceh Province, Indonesia. Concentrations were determined by flame atomic absorption spectrometry (FAAS) using a validated external calibration method, and soil-to-plant transfer was evaluated through bioconcentration factors (BCF). Method validation confirmed analytical reliability for Pb (recovery 84.09%, within the AOAC concentration-dependent acceptance range of 80–110% applicable at the 0.1–1 mg/kg level), Cu (98.15%), and Fe (110.61%), while Cd, Zn, and Cr were treated as semi-quantitative because their recoveries fell outside any accepted range. Aqueous concentrations were two to three orders of magnitude lower than the corresponding solid-phase burdens, identifying soil as the principal long-term reservoir governing plant exposure. Pb in M. malabathricum reached 0.317–0.393 mg/kg, equivalent to 3.2–3.9% of the 10 mg/kg limit for Pb in natural medicines established by BPOM Regulation No. 29 of 2023. The estimated daily intake under a traditional-use scenario reached 6.55×10^{-2} µg/kg bw/day, or 4.4% of the EFSA $BMDL_{01}$ for effects on systolic blood pressure in adults (1.50 µg/kg bw/day) and 11.8% of the $BMDL_{01}$ for developmental neurotoxicity in a child scenario (0.50 µg/kg bw/day). The BCF values for Pb, Cu, and Fe (0.0016–0.0085) placed the species within the excluder category, rather than within the accumulator or hyperaccumulator ranges. The combination of demonstrably enriched geothermal Pb in the surrounding water and soil with excluder-range BCF and regulatorily compliant tissue Pb has not been documented for other Acehnese geothermal medicinal plants, and constitutes the novel, public-health-relevant contribution of this work: an evidence-based safety clearance for a widely harvested medicinal species growing in an active hydrothermal setting.. Pre-use contaminant screening is recommended before medicinal preparation.

Keywords: bioconcentration factor, geothermal manifestation, heavy metals, *Melastoma malabathricum* (L.), medicinal plant safety, lead (Pb).

INTRODUCTION

Heavy metal contamination remains a persistent environmental and public-health concern because elements such as lead (Pb), cadmium (Cd), copper (Cu), chromium (Cr), zinc (Zn), and iron (Fe), whether strictly toxic or essential at trace levels yet harmful in excess, are non-biodegradable, can remain bioavailable over long periods, and tend to accumulate in plants, animals, and humans through dietary and medicinal-use pathways (Jeyakumar et al., 2023; Khalef et al., 2022). Chronic exposure is linked to neurotoxicity, nephrotoxicity, and oxidative stress, making contamination of medicinal plants particularly relevant in the regions where natural and anthropogenic sources overlap. Although industrial activity and mining are widely recognized drivers of metal pollution, geothermal systems also act as natural sources of potentially toxic elements by releasing trace metals into surrounding waters, soils, and biota through hydrogeochemical processes (Abubakar et al., 2023). In such settings, high-temperature fluid circulation, mineral dissolution, steam separation, and mixing with shallow groundwater collectively alter pH, redox conditions, and complexation behavior, controlling whether metals remain dissolved, adsorb onto particulates, or precipitate into secondary phases, and ultimately producing heterogeneous zones of persistent metal exposure for nearby vegetation (Rajendiran, 2025; Xu et al., 2025).

This concern is especially pertinent in Indonesia, where active geothermal manifestations frequently occur in the landscapes used by local communities for water collection, agriculture, and harvesting of wild medicinal plants (Fakri et al., 2023; G.M. Idroes et al., 2025). In the Aceh Province, geothermal areas such as Seulawah exhibit fumaroles, hot springs, and altered ground indicative of active fluid circulation (Dharma et al., 2026; R. Idroes et al., 2019; Lala et al., 2024) and Tridax procumbens collected from the Ie-Seu'um geothermal area has been shown to contain detectable Cr, Pb, and Cd (Maulydia et al., 2024). Medicinal plants are particularly vulnerable, because they can absorb metals from both soil solution and contaminated water, with subsequent redistribution among roots, stems, and leaves depending on plant physiology and metal speciation (Asiminicesei et al., 2024; Hlihor et al., 2022). Because herbal remedies are often consumed repeatedly over extended periods, even moderate contamination can contribute to meaningful cumulative exposure, a concern amplified for Pb, which accumulates in bone and soft tissues, and for Cd, which causes progressive renal burden.

Melastoma malabathricum (L.) is widely used in traditional medicine for wound care, inflammation, and infection-related complaints owing to its anti-inflammatory and antioxidant properties (Neneng et al., 2025; Zheng et al., 2021). Its medicinal importance makes it a potentially significant exposure pathway when harvested from contaminated habitats, such as the Gunung Kembar geothermal zone, where hydrothermal inputs may enrich adjacent water and soil with Pb, Cd, Cu, Cr, Fe, and Zn. Despite a growing interest in geothermal contamination in Indonesia, site-specific evidence integrating water, soil, and medicinal plants within a single analytical framework remains scarce, particularly in Aceh (G.M. Idroes et al., 2024). To date, no study has specifically evaluated the heavy metal accumulation in *M. malabathricum* from Gunung Kembar while simultaneously characterizing the associated environmental matrices or directly benchmarking results against applicable medicinal safety thresholds.

Accordingly, the present study investigated the concentrations of Pb, Cd, Cu, Cr, Fe, and Zn in *M. malabathricum* and in the associated water and soil of the Gunung Kembar geothermal zone, addressing three questions: (i) whether geothermal influence corresponds to detectable metal enrichment across local environmental matrices; (ii) whether *M. malabathricum* exhibits element-specific accumulation patterns under geothermal exposure; and (iii) whether the measured concentrations, particularly for Pb, raise concern for medicinal use relative to applicable safety benchmarks. The study was grounded in the hypothesis that the geothermal activity at Gunung Kembar enhances metal availability in surrounding water and soil, that *M. malabathricum* accumulates these metals with element-dependent efficiencies, and that at least some tissue concentrations may approach or exceed the levels relevant to safe traditional use. The novelty of this work lies in (i) targeting a previously unexamined plant–site combination, (ii) applying a multi-matrix approach that jointly evaluates water, soil, and plant samples, and (iii) generating data through a validated atomic absorption spectroscopy method that can be interpreted within both environmental and public-health frameworks.

MATERIALS AND METHODS

Study area and sampling sites

Field sampling for this study was carried out in February 2025 within the Gunung Kembar geothermal manifestation zone, located in Aceh Province, Indonesia. Two active geothermal sites were chosen as sampling locations, designated Gunung Kembar 1 (GK1; 3°45’02” N, 97°37’35” E) and Gunung Kembar 2 (GK2; 3°45’03” N, 97°37’37” E) (Figure 1). These locations were selected, because both exhibit active hydrothermal features and allow simultaneous collection of geothermal water, surrounding soil, and naturally occurring *Melastoma malabathricum* (L.) specimens within the same area. Because a non-geothermal reference site was not incorporated into the sampling design, the interpretation of metal concentrations was confined to comparisons between the two geothermal locations and to benchmarking against applicable regulatory limits and values reported in the literature.

Procedure

Reagents and instrumentation

Analytical-grade reagents were employed throughout the study. Concentrated nitric acid (HNO_3, 65%) and perchloric acid ($HClO_4$) served as the digestion media, while certified single-element standard solutions of Pb, Cd, Cu, Cr, Zn, and Fe (Merck, Darmstadt, Germany) were used to prepare calibration curves. Quantification of heavy metal concentrations was performed on a Thermo Scientific iCE 3000 Series flame atomic absorption spectrometer (FAAS). Ancillary apparatus comprised an analytical balance, a hot plate, a drying oven, calibrated volumetric glassware, Whatman No. 42 filter paper, a 2-mm stainless-steel sieve for soil preparation, and acid-washed polyethylene containers for sample collection and storage (Irnawati et al., 2021).

Sample collection

Water, soil, and plant samples were collected from the immediate surroundings of the geothermal manifestations at GK1 and GK2. The water samples were collected using clean plastic scoops and transferred into acid-washed polyethylene bottles. The bottles were pre-rinsed with dilute nitric acid and then rinsed three times with sample water before use. Immediately after collection, samples were acidified to pH < 2 with HNO_3 and stored at 2–6 °C until analysis. The soil samples were collected from a depth of 0–30 cm at the same locations as the water and plant samples, placed in clean sealed plastic bags, and transported to the laboratory. The plant samples of *M. malabathricum* (L.) in Figure 2 were collected from the same geothermal area. Leaves were selected as the target organ for three reasons: they are the plant part most commonly used in traditional preparations, whether as a decoction or a poultice, and are therefore the most relevant to exposure assessment; they represent the terminal organ of metal translocation through the transpiration stream as well as the receptor of atmospheric deposition, so that their concentrations integrate both root uptake and surface deposition; and they were available in

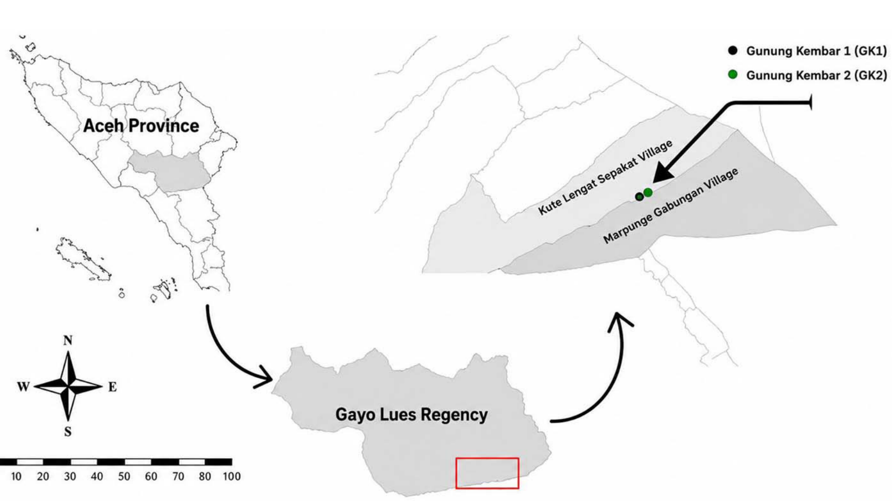

Figure 1. Location of the sampling points (GK1 and GK2) within the Gunung Kembar geothermal manifestation zone, Gayo Lues Regency, Aceh Province, Indonesia.

Figure 2. *Melastoma malabathricum* (L.) specimens collected from the two geothermal sampling sites: GK1 (left) and GK2 (right)

sufficient biomass at both sites to permit equivalent comparison. Adhering particles were removed by washing the plant material thoroughly prior to drying and digestion (Andrews 2004; BSN, 2004; Shojaei et al., 2021; Wang and Cheng, 2023).

Sample preparation

The water samples were filtered through a Whatman No. 42 filter paper to remove suspended particulates and subsequently transferred into calibrated volumetric flasks for analysis (Tesfaye et al., 2024). The soil samples were air-dried, homogenized, and sieved through a 2 mm mesh, after which a 0.5 g aliquot was digested with concentrated HNO_3 on a hot plate; the digest was then cooled, filtered when necessary, and made up to volume with deionized water prior to FAAS analysis (Singh et al., 2023). Because acidification preceded filtration, and because the 2.5 µm filter used is coarser than the 0.45 µm cut-off conventionally applied to dissolved metals, the aqueous results represent an operationally defined acid-extractable fraction rather than a strictly dissolved fraction. For plant analysis, harvested specimens were rinsed with deionized water, oven-dried to constant weight, and ground into a fine powder; a 0.5 g portion of the dried material was subsequently digested in a mixture of HNO_3 and $HClO_4$ until a clear solution was obtained, cooled, filtered as required, and brought to a defined volume with deionized water before FAAS measurement. It should be noted that heavy metals in the present study were quantified directly from acid-digested plant tissue rather than from phytochemical extracts, as maceration and rotary evaporation are not appropriate procedures for total metal determination and would likely introduce losses or alterations of the target analytes (Akinkpelumi et al., 2025).

Heavy metal determination

The concentrations of Pb, Cd, Cu, Cr, Zn, and Fe in water, soil, and plant samples were quantified by FAAS using external calibration. For each element, a seven-point calibration curve was constructed from certified stock standards, covering a concentration range appropriate to the expected levels in the three matrices. Every prepared sample solution was analyzed in triplicate, and the final concentrations were reported in mg/L for water samples and in mg/kg dry weight for soil and plant tissues (Kassim et al., 2022; Nava et al., 2022).

Method validation and quality control

The analytical method was validated in accordance with established guidelines for linearity, precision, recovery, limit of detection (LoD), and limit of quantification (LoQ). Linearity was evaluated from seven-point calibration curves, with acceptance set at a coefficient of determination (R^2) of at least 0.99. Precision was assessed by performing six replicate measurements of standard solutions and expressed as the relative standard deviation (RSD). Recovery was determined through the analysis of spiked samples and calculated as the ratio between the measured increment and the known spiked concentration. LoD and LoQ were derived from the calibration-curve statistics by multiplying the ratio of the intercept standard deviation to the slope by factors of 3.3 and 10, respectively. All samples were analyzed in triplicate, and overall quality control was maintained through the use of certified calibration standards, routine inspection of calibration-curve parameters, and repeatability of verification across runs. Procedural blanks were carried through the full digestion sequence in every batch, and all reported concentrations are blank-corrected. Concentrations are reported without correction for recovery; applying the measured Pb recovery of 84.09% would raise the highest tissue value from 0.393 to 0.467 mg/kg, which does not alter the compliance conclusion drawn against the 10 mg/kg limit (Hossain et al., 2022; G.M. Idroes et al., 2024; Kassim et al., 2022).

Estimation of concentration uncertainty

The uncertainty associated with each analytical result was evaluated through linear regression of the calibration data using the LINEST function in Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). This function returned the slope and intercept of the calibration line, the standard deviations of both parameters, the coefficient of determination, and the standard deviation of the regression, which together characterize the sensitivity and goodness-of-fit of the calibration model. The standard deviation of concentration was then calculated and reported alongside each measured value as the analytical uncertainty interval. This quantity was obtained by taking the ratio of the regression standard deviation to the calibration slope, and then scaling it by a dimensionless term that accounts for the number of replicate sample measurements, the number of calibration points, and the deviation between the measured sample signal and the centroid of the calibration range. As a result, sample concentrations located near the middle of the calibrated range carried lower uncertainty than those falling closer to either extreme, which provided a statistically robust estimate of confidence for every heavy metal concentration reported across water, soil, and plant matrices (Skoog et al., 2021). The quantity Sc reported in Table 4 is the calibration-derived standard deviation of concentration at a

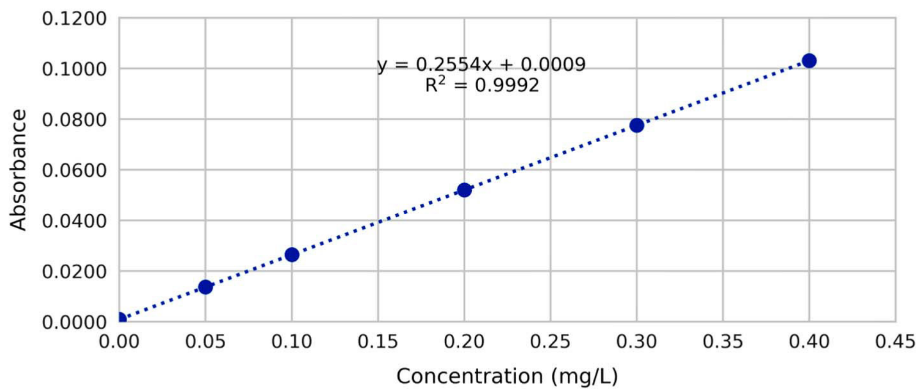

Figure 3. Representative seven-point external calibration curve for Cd, prepared from certified standard solutions and applied to the plant digests

Table 1. Linearity and uncertainty parameters of the calibration curves for the six heavy metals

Parameter	Pb	Cd	Cu	Cr	Zn	Fe
Slope (m)	0.0335	0.2554	0.0999	0.0266	0.2891	0.0477
Intercept (b)	0.0009	0.0009	−0.0003	−0.0008	−0.0008	0.00004
SD of slope (Sm)	0.0008	0.0036	0.0009	0.0003	0.0020	0.0008
SD of intercept (Sb)	0.0002	0.0008	0.0002	0.0001	0.0004	0.0002
R^2	0.9978	0.9992	0.9997	0.9994	0.9998	0.9994
SD of regression (Sr)	0.0003	0.0012	0.0003	0.0001	0.0007	0.0003
SS regression	0.0001	0.0075	0.0012	0.0001	0.0096	0.0003
SS residual	3×10^{-7}	1×10^{-5}	3×10^{-7}	1×10^{-7}	2×10^{-6}	3×10^{-7}

coverage factor of k = 1. Expanded uncertainties (U = 2uc) were additionally computed in accordance with Eurachem/CITAC Guide CG4. Where the distance between a measured mean and a regulatory threshold is smaller than U, the result is reported as not resolvable and no compliance statement is made.

Bioconcentration factor

The transfer of heavy metals from soil into plant tissue was quantified through the bioconcentration factor (BCF), calculated as the ratio between the metal concentration in the plant tissue and that in the corresponding soil, with both matrices expressed in mg/kg on a dry-weight basis. Following established interpretive criteria, BCF values lower than 1 reflect restricted uptake or excluder behavior, values ranging from 1 to 10 denote accumulator behavior, and values exceeding 10 are indicative of hyperaccumulation (Aziz et al., 2023; Tong et al., 2022). Because the water concentrations were reported in mg/L and therefore do not share the same dimensional basis as the soil and plant data, water-to-plant comparisons were regarded as descriptive observations only and were not interpreted as a formal bioconcentration coefficient.

RESULTS AND DISCUSSION

Analytical performance of the method

The analytical performance of the flame atomic absorption spectrometry (FAAS) procedure was evaluated prior to any environmental or toxicological interpretation, because the reliability of downstream inferences depends critically on the linearity, sensitivity, and accuracy of the calibration model applied to each element. Linearity, limits of detection (LoD) and quantification (LoQ), precision, and recovery were therefore examined in sequence to establish which of the six target metals, Pb, Cd, Cu, Cr, Zn, and Fe, could support quantitative interpretation and which had to be treated as semi-quantitative (G.M. Idroes et al., 2024). A representative calibration curve for cadmium in the plant matrix is shown in Figure 3 as an illustrative example, while the complete calibration parameters for all six metals are summarized in Table 1, and the derived LoD and LoQ values are compiled in Table 2.

Precision was uniformly high across all six elements, with RSD values ranging from 0.25% for Cu to 0.89% for Pb, indicating that the FAAS measurements were highly reproducible and not compromised by random error. Recovery performance differed markedly among elements. Acceptance was evaluated against the concentration-dependent criteria of AOAC International, which specify a recovery range of 80–110% at analyte levels of 0.1–1 mg/kg. On that basis Pb (84.09%), Cu (98.15%) and Fe (110.61%) were acceptable, whereas Cd (22.06%), Zn (15.45%) and Cr (205.05%) fell far outside any accepted range. This pattern of pronounced under-recovery for Cd and Zn, coupled with substantial over-recovery for Cr, is a well-documented signature of matrix interference in FAAS analysis of geothermal-derived samples, in which high background concentrations of Fe, Ca, and dissolved silicates can suppress atomization efficiency for volatile elements such as Cd and Zn while enhancing

Table 2. Limits of detection (LoD) and quantification (LoQ) of the FAAS method for each heavy metal

Metal	LoD (mg/L)	LoQ (mg/L)
Pb	0.0175	0.0530
Cd	0.0103	0.0313
Cu	0.0064	0.0195
Cr	0.0119	0.0360
Zn	0.0050	0.0152
Fe	0.0121	0.0366

Table 3. Precision (RSD) and accuracy (recovery) of the FAAS method, with indication of analytical reliability

Metal	Recovery (%)	RSD (%)	Analytical reliability
Pb	84.09	0.89	Reliable
Cd	22.06	0.48	Semi-quantitative (under-recovery)
Cu	98.15	0.25	Reliable
Cr	205.05	0.81	Semi-quantitative (over-recovery)
Zn	15.45	0.62	Semi-quantitative (under-recovery)
Fe	110.61	0.32	Reliable

the apparent signal for Cr through non-specific background absorption and spectral interference (Xing et al., 2022).

Because the external calibration approach adopted here does not correct for such sample-specific interferences, the quantitative values reported for Cd, Zn, and Cr must be regarded as semi-quantitative only, and the environmental and toxicological interpretation developed in the following sections is therefore anchored on the three elements with reliable recovery, namely Pb, Cu, and Fe. The data for Cd, Zn, and Cr are retained in the tables for completeness, but are explicitly flagged as provisional throughout, a conservative analytical framing that mitigates the recovery-related concerns that were acknowledged during the method-validation exercise (G.M. Idroes et al., 2024). The magnitude of the deviations observed here, particularly the 15.45% recovery for Zn, exceeds what matrix suppression alone would ordinarily produce and cannot be excluded as arising from an error in spiking, dilution or calibration. The direction and approximate magnitude of the resulting bias should therefore be borne in mind when reading the tables: Zn concentrations may be underestimated by a factor of roughly six, Cd by a factor of roughly four, and Cr overestimated by a factor of roughly two.

Heavy metal distribution across water, soil, and plant matrices

Having established the analytical reliability of the FAAS procedure, the concentrations of the six target metals were determined in geothermal water, surrounding soil, and co-located *Melastoma malabathricum* (L.) tissue at the two Gunung Kembar sampling sites (GK1 and GK2). Because the three matrices differ in character and in the exposure pathway they represent, the benchmarks applied to each are correspondingly different: aqueous concentrations are compared with drinking-water and Class I surface-water standards, soil concentrations with national and international soil quality guidelines, and plant tissue with the contamination limits set for natural medicines, each of which is identified explicitly. The resulting dataset, together with the BPOM Regulation No. 29 of 2023 (BPOM, 2023) medicinal-plant thresholds used as the principal regulatory benchmark, is presented in Table 4.

Heavy metals were detected in all three matrices at both GK1 and GK2, and the dataset reveals a consistent matrix-dependent concentration gradient in which values were lowest in water, highest in soil, and intermediate in plant tissue. In water, Pb ranged from 0.122 to 0.140 mg/L, followed by Fe (0.026–0.066 mg/L) and Cu (0.009–0.012 mg/L). Soil concentrations were several orders of magnitude higher, with Cu reaching 100.10 mg/kg, Pb 84.33 mg/kg, Zn 72.49 mg/kg, Fe 51.42 mg/kg, and Cr 12.98 mg/kg, indicating substantial accumulation of metals within the solid phase. Plant tissue concentrations were lower than those in soil, but clearly confirmed measurable uptake for every element analyzed, with Pb values of 0.317 mg/kg at GK1 and 0.393 mg/kg at GK2 and Cu values of 0.308 mg/kg at GK1 and 0.162 mg/kg at GK2.

The observed distribution, in which aqueous concentrations are far lower than the solid-phase burdens and plant tissue is intermediate, reflects a pattern commonly documented for trace metals in geothermal-influenced terrains. Because the aqueous data are expressed per unit volume and the solid-phase data per unit mass, this ordering is presented as an approximate comparison rather than a quantitative partitioning coefficient. Dissolved species transported upward by hydrothermal fluids tend to be captured by the soil compartment through a combination of pH-controlled

Table 4. Heavy metal concentrations in geothermal water, soil, and Melastoma malabathricum L. tissue at GK1 and GK2, compared with BPOM Regulation No. 29 of 2023 for natural medicines

Element	Water GK1 (mg/L)	Water GK2 (mg/L)	Soil (mg/kg)	Plant GK1 (mg/kg)	Plant GK2 (mg/kg)	BPOM limit
Pb	0.122 ± 0.152	0.140 ± 0.178	84.33 ± 2.417	0.317 ± 0.220	0.393 ± 0.273	≤ 10 mg/kg
Cd*	0.007 ± 0.007	0.012 ± 0.007	1.232 ± 0.006	0.021 ± 0.004	0.012 ± 0.004	≤ 0.3 mg/kg
Cu	0.009 ± 0.009	0.012 ± 0.009	100.10 ± 0.212	0.308 ± 0.025	0.162 ± 0.013	Not regulated
Cr*	0.036 ± 0.004	0.042 ± 0.004	12.98 ± 0.024	0.972 ± 0.430	0.978 ± 0.433	Not regulated
Fe	0.026 ± 0.009	0.066 ± 0.012	51.42 ± 0.247	0.439 ± 0.218	0.339 ± 0.167	Not regulated
Zn*	0.023 ± 0.012	0.035 ± 0.012	72.49 ± 0.609	0.156 ± 0.003	0.276 ± 0.006	Not regulated

Note: *Cd, Cr, and Zn are reported as semi-quantitative due to spike recoveries outside the 85–115% acceptance window (see Table 3). Values are mean ± analytical uncertainty (S_c).

precipitation, sorption onto iron and manganese (oxy)hydroxide surfaces, and co-precipitation with neoformed mineral phases, processes that together transform the soil into the dominant long-term sink controlling metal availability to vegetation (Allahkarami and Allahkarami, 2025; Rajendiran, 2025). The reddish, hydrothermally altered soils observed at both sites indicate abundant pedogenic Fe (oxy)hydroxide phases, which constitute an effective sorbent matrix for coexisting divalent trace metals, a behaviour previously documented in other active geothermal manifestations within Aceh Province (Dharma et al., 2026; Idroes et al., 2019). The HNO_3-extractable Fe reported here (51.42 mg/kg) captures only a minor, operationally defined fraction of total soil Fe and should not be read as a measure of Fe abundance. This same soil-buffering process likely accounts for the finding that plant tissue concentrations, although smaller in magnitude than those in the soil matrix, consistently exceeded the corresponding aqueous values; root uptake effectively integrates metals accumulated in the soil over long periods rather than mirroring the transient chemistry of hydrothermal discharge at any given moment (Eliana, 2024).

Comparison with environmental and health-based benchmarks

Because no non-geothermal reference site was sampled in the present design, the magnitude of contamination cannot be expressed through formal enrichment factors and must instead be assessed indirectly, by contextualising the measured concentrations against established regulatory thresholds and typical crustal background values. The comparison is summarized in Table 5, which places each measured value alongside the relevant World Health Organization drinking-water guideline, the Indonesian Class I surface-water standard under Government Regulation No. 22 of 2021, the Dutch soil screening values, and the BPOM Regulation No. 29 of 2023 (BPOM, 2023) medicinal-plant limits (WHO, 2022).

For water, Pb concentrations of 0.122–0.140 mg/L exceed the WHO provisional drinking-water guideline of 0.01 mg/L by approximately an order of magnitude and also surpass the Indonesian Class I surface-water standard of 0.03 mg/L, which confirms that the geothermal discharge at Gunung Kembar cannot be considered suitable for direct drinking use, in agreement with earlier geochemical assessments of other Acehnese geothermal manifestations (G.M. Idroes et al., 2024). Aqueous Cu and Fe were at or below the quantification limit of the method at one or both sites and are therefore reported as not quantifiable rather than as compliant; no drinking-water conclusion can be drawn for these two elements from the present dataset. Cadmium likewise fell at or below the detection limit at both sites; although the semi-quantitative values obtained lie in the same range as the 0.003 mg/L limit of the Indonesian environmental health standard, no compliance statement can be made, and cadmium in this discharge warrants targeted re-measurement by a technique with a lower detection limit. For soil, Pb at 84.33 mg/kg lies close to the Dutch soil target value of 85 mg/kg and represents approximately fourfold enrichment over the typical crustal background of ~20 mg/kg, whereas Cu at 100.10 mg/kg exceeds the Dutch target of 36 mg/kg by almost a factor of three; these levels are indicative of moderate to elevated metal loading in the geothermal soil matrix (Rajendiran, 2025; Xu et al., 2025). Fe in soil (51.42 mg/kg) is well below typical crustal abundance and

Table 5. Comparison of measured concentrations with Indonesian national standards and international guidelines

Matrix	Element	Measured	Benchmark	Status
Water	Pb	0.122–0.140 mg/L	WHO DW 0.01; PP 22/2021 Class I 0.03 mg/L	Exceeds both
Water	Cu	0.009–0.012 mg/L	WHO 2.0; PP 22/2021 Class I 0.02 mg/L	Below
Water	Fe	0.026–0.066 mg/L	WHO 0.3; PP 22/2021 Class I 0.3 mg/L	Below
Soil	Pb	84.33 mg/kg	Crustal ~20; Dutch target 85 mg/kg	~4× crustal; near Dutch target
Soil	Cu	100.10 mg/kg	Crustal ~55; Dutch target 36 mg/kg	~2× crustal; exceeds Dutch
Soil	Zn*	72.49 mg/kg	Crustal ~70; Dutch target 140 mg/kg	Near crustal
Soil	Fe	51.42 mg/kg	Crustal ~56 mg/kg	Within normal range
Plant	Pb	0.317–0.393 mg/kg	BPOM Regulation No. 29 of 2023: 0.3 mg/kg	Exceeds
Plant	Cu	0.162–0.308 mg/kg	BPOM Regulation No. 29 of 2023: 10 mg/kg	Below

Note: *Semi-quantitative value. DW = drinking water; WHO = World Health Organization; PP = Peraturan Pemerintah (Government Regulation); BPOM = Badan Pengawas Obat dan Makanan.

therefore does not indicate enrichment on a mass basis, although the pedogenic Fe phases present are the most likely scavengers of the coexisting trace metals (Reijneveld and Oenema, 2025).

For plant tissue, the most consequential finding is that Pb at 0.317–0.393 mg/kg exceeds the BPOM Regulation No. 9 of 2022 medicinal-plant threshold of 0.3 mg/kg at both sampling sites, whereas Cu at 0.162–0.308 mg/kg remains approximately two orders of magnitude below its 10 mg/kg threshold (BPOM, 2023). Because no local non-geothermal background was sampled, this benchmark-based comparison should be interpreted as plausible rather than definitive evidence of geothermal enrichment, and paired background–geothermal sampling is recommended in future work.

Pb as the principal toxicological concern

Among the six target metals, Pb in plant tissue emerged as the most robust and consequential finding and was therefore selected for a targeted exposure-risk evaluation. Pb concentrations in M. malabathricum reached 0.317 mg/kg at GK1 and 0.393 mg/kg at GK2, corresponding to only 3.2–3.9% of the 10 mg/kg limit for Pb in natural medicines under BPOM Regulation No. 29 of 2023, and also below the 0.3 mg/kg limit that the same regulation applies to the more toxic cadmium. Benchmarked instead against the 0.3 mg/kg maximum level applied to leafy vegetables as foodstuffs, the measured values lie marginally above that level; given analytical uncertainties of ±0.220 to ±0.273 mg/kg this marginal difference is not statistically resolvable and is reported here only as a precautionary observation. Because Pb recovery met the AOAC acceptance range applicable at this concentration level, this interpretation rests on the most reliable portion of the dataset and is defensible independently of the recovery limitations affecting Cd, Zn, and Cr (Hossain et al., 2022; Lata and Ansari, 2024).

To translate these tissue concentrations into an indicative exposure estimate, an estimated daily intake (EDI) was calculated under a traditional-use scenario in which a 60 kg adult consumes 10 g of dried *M. malabathricum* leaves per day, a value consistent with typical herbal-decoction practices documented for *Melastomataceae* species in Southeast Asia (Kamsani et al., 2019; Ulloa et al., 2022). Using the higher observed Pb concentration (0.393 mg/kg), the resulting EDI is 6.55×10^{-2} µg/kg bw/day. The EFSA CONTAM Panel (2010) derived three reference points for dietary lead: a BMDL01 of 0.50 µg/kg bw/day for developmental neurotoxicity in children up to seven years of age, a BMDL01 of 1.50 µg/kg bw/day for effects on systolic blood pressure in adults, and a BMDL10 of 0.63 µg/kg bw/day for chronic kidney disease in adults; JECFA subsequently withdrew the former provisional tolerable weekly intake of 25 µg/kg bw. The adult EDI derived here corresponds to 4.4% of the cardiovascular BMDL01 and 10.4% of the renal BMDL10, giving a margin of exposure of 22.9 for the cardiovascular endpoint. For a 20 kg child consuming 3 g of dried leaves per day the EDI is 5.90×10^{-2} µg/kg bw/day. Although lower than the adult value in absolute terms, this scenario carries the narrower margin, amounting to 11.8% of the developmental-neurotoxicity BMDL01, because the applicable reference point is threefold lower and because gastrointestinal absorption of lead is substantially higher in children than in adults.

Two further considerations strengthen the Pb-related health-risk signal. First, medicinal-plant use is typically repetitive and sustained over weeks to months, so chronic exposure integrates the daily intake over extended periods, and the 13% margin relative to BMDL01 narrows rapidly when prolonged consumption is considered. Second, Pb from *M. malabathricum* acts as an incremental burden that adds to dietary Pb from rice, drinking water, and staple vegetables, so the medicinal source cannot be evaluated in isolation from background dietary exposure (Collin et al., 2022; Mlangeni et al., 2023). Together, these considerations indicate that Pb in *M. malabathricum* harvested from the Gunung Kembar geothermal zone constitutes the principal toxicological concern identified by this study and warrants pre-use contaminant screening before any medicinal application.

Soil-to-plant transfer and apparent accumulation behavior

To characterize the efficiency with which *M. malabathricum* transfers metals from the soil reservoir into its leaf tissue, bioconcentration factors (BCF) were calculated as the ratio of plant tissue concentration to corresponding soil concentration, with both matrices expressed in mg/kg on a dry-weight basis. Apparent plant-to-water ratios R(T/A) were also derived as descriptive observations, although, as noted in the Methods, these ratios do not share the same dimensional basis as

Table 6. Plant-to-water ratios (L/kg) and bioconcentration factors (BCF; dimensionless) for heavy metals in *M. malabathricum* (L.) at Gunung Kembar

Metal	R(T/A) GK1 (L/kg)	R(T/A) GK2 (L/kg)	BCF GK1	BCF GK2	Interpretation
Pb	2.60	2.81	0.0038	0.0047	Excluder
Cu	32.08	12.89	0.0031	0.0016	Excluder (essential element)
Fe	16.57	5.12	0.0085	0.0066	Excluder
Cd*	2.96	0.98	0.0170	0.0097	Provisional
Cr*	26.86	23.30	0.0749	0.0753	Provisional
Zn*	6.68	7.82	0.0022	0.0038	Provisional

Note: *Provisional values, based on semi-quantitative concentrations for Cd, Cr, and Zn (Table 3). BCF interpretive categories: <1 = excluder; 1–10 = accumulator; >10 = hyperaccumulator.

BCF and are therefore not interpreted as a formal bioconcentration coefficient. The results are summarized in Table 6.

For the three analytically reliable elements, BCF values were 0.0038–0.0047 for Pb, 0.0016–0.0031 for Cu, and 0.0066–0.0085 for Fe, all well below unity. Interpreted against the standard categorization in which BCF < 1 denotes excluder behavior, 1 < BCF ≤ 10 denotes accumulator behavior, and BCF > 10 denotes hyperaccumulation, these values place *M. malabathricum* at Gunung Kembar firmly within the excluder category for Pb, Cu, and Fe, rather than within accumulator or hyperaccumulator ranges (Saberi et al., 2024; Yap and Al-Mutairi, 2023). The higher BCF values observed for Cr (0.0749–0.0753) and Cd (0.0097–0.0170), although numerically larger, cannot be interpreted mechanistically because of the recovery limitations that affect these elements and are therefore reported only as provisional observations.

The low BCF values for Pb and Cu are environmentally plausible and consistent with established mechanisms of metal partitioning at the soil–plant interface. Pb is known to be strongly retained in soils through adsorption onto clay minerals, Fe (oxy)hydroxides, and soil organic matter, and tends to precipitate as insoluble phosphate and carbonate phases that are poorly bioavailable; as a result, even when soil Pb is markedly elevated, root uptake is typically restricted and the majority of absorbed Pb is immobilized in the root apoplast and cell walls rather than translocated to aboveground tissues (Aziz et al., 2023; Rahman et al., 2024). Cu, although relatively abundant in the soil at this site, is an essential micronutrient the uptake of which is tightly regulated by physiological homeostasis through transporter-mediated control, and Cu^{2+} in the soil solution further interacts with root exudates and soil organic matter, reducing free-ion activity and limiting excessive accumulation (Akhtar et al., 2025; E. Xu et al., 2024). The mobility of Fe in circumneutral, well-oxygenated soils is similarly constrained by the rapid formation of Fe(III) (oxy)hydroxides, which explains the excluder-range BCF observed for Fe despite moderate soil concentrations (Kim et al., 2025)

Soil and plant physiological processes provide a coherent mechanistic frame for the overall pattern observed: the bioavailability of trace metals is governed by soil pH, cation exchange capacity, and the presence of competing cations, and is further modulated by root exudates and mycorrhizal associations that generally restrict the apparent uptake of non-essential metals, such as Pb (Asare et al., 2023). Soil pH, organic matter content and cation exchange capacity were not measured in the present study, however, so the attribution remains inferential. These mechanisms collectively account for the BCF values below unity observed for all reliably quantified elements (Pb, Cu, and Fe) and argue against interpreting *M. malabathricum* as a hyperaccumulator in this environment. It should be emphasised that excluder behaviour here is element-specific rather than a property of the species as a whole. M. malabathricum is well known as an aluminium accumulator, and Saberi et al. (2024) reported element-dependent accumulation across Malaysian populations of the same species in relation to soil edaphic factors. The sub-unity BCF values obtained at Gunung Kembar for Pb, Cu and Fe are therefore consistent with the wider literature and should not be read as indicating that the species excludes all metals uniformly A more accurate characterization is that the species functions as a limited accumulator that nevertheless takes up sufficient Pb to exceed the medicinal-safety threshold, and it is precisely this combination of restricted uptake and low but regulatorily significant tissue Pb concentrations that constitutes the principal public-health relevance of the present dataset (Hurseresht and Jalali, 2026).

Environmental interpretation of the geothermal system

The contrast between the low aqueous concentrations and the substantially higher soil concentrations observed at Gunung Kembar identifies the soil compartment as the dominant long-term reservoir controlling plant exposure. In active geothermal systems, metals released into hydrothermal fluids at depth are progressively redistributed during ascent through cooling, dilution, adsorption onto suspended particulates, and precipitation as secondary mineral phases as the fluids mix with shallow groundwater and discharge to the surface (Rotich et al., 2024). Once retained in the soil matrix, particularly on Fe (oxy)hydroxides and clay–organic complexes, these metals remain available for gradual root uptake over years to decades, consistent with the characterization of geothermal soils as long-term metal reservoirs (Mensah and Amoakwah, 2024). The apparently high plant-to-water ratios reported in Table 6, reaching 32.1 L/kg for Cu and 26.9 L/kg for Cr, should not be read as evidence of efficient uptake from the aqueous phase. They arise principally because the aqueous concentrations forming the denominator are extremely low, in several cases at or below the quantification limit of the method. Accumulation behaviour is therefore assessed here on the soil-to-plant bioconcentration factor alone, and the plant-to-water ratios are retained only as descriptive observations.

M. malabathricum specimens at Gunung Kembar were observed growing within meters of hot-spring drainage channels, where surface runoff periodically delivers hydrothermal fluid onto rooting soils. This hydrological configuration supports a soil-mediated exposure pathway in which episodic aqueous inputs from hot-spring water are first sequestered into the soil phase and then slowly released to plant roots through exchange, dissolution, and colloidal transport (Van Kranendonk et al., 2026). The available evidence does not, however, establish geothermal activity as the sole enrichment driver, because the absence of a paired non-geothermal control site precludes formal calculation of enrichment factors; this limitation, together with three additional analytical constraints.

Comparison with previous geothermal plant studies

To contextualize the present findings, the heavy metal profile observed in *M. malabathricum* at Gunung Kembar was compared with the previously published data for two other medicinal species sampled from geothermal manifestation zones of the Seulawah Agam volcanic complex in Aceh Province, namely *Tridax procumbens* L. from Ie-Seu'um (Maulydia et al., 2024) and *Chromolaena odorata* L. from Ie-Suum, Ie-Jue, and Ie-Brouk (Abubakar et al., 2023). The present study and Maulydia et al. (2024) both employed FAAS for the six target metals, whereas Abubakar et al. (2023) employed FAAS for Pb and Cd and graphite-furnace AAS (GFAAS) for As and Hg, a distinction that should be borne in mind when comparing analytical sensitivity across the three datasets. All values are nonetheless expressed on a dry-weight basis, which enables a direct element-by-element comparison of concentrations in the matrices analyzed. The comparison is summarized in Table 7, together with the regulatory reference limits established by BPOM Regulation No. 29 of 2023 for medicinal plant materials.

Three patterns emerge. *Tridax procumbens* from Ie-Seu'um shows markedly higher tissue Pb (6.42 mg/kg), Cr (13.81 mg/kg), and Cd (0.91 mg/kg). Benchmarked against BPOM Regulation No. 29 of 2023, which regulates only Pb, Cd, As and Hg in natural medicines, its Pb remains below the 10 mg/kg limit while its Cd exceeds the 0.3 mg/kg limit approximately threefold; Cr is not subject to a BPOM limit and is reported here for comparison only (Maulydia et al., 2024). *Chromolaena odorata* from the Ie-Suum, Ie-Jue, and Ie-Brouk hot springs shows the opposite profile: Pb remains well below the BPOM threshold (0.022–0.067 mg/kg), yet Cd reaches 1.147 mg/kg in ethanolic extracts, exceeding the 0.30 mg/kg limit nearly fourfold, a divergence attributed to the differing solubility of Pb and Cd species in ethanol (Abubakar et al., 2023). In contrast, *M. malabathricum* at Gunung Kembar occupies an intermediate position (Pb 0.317–0.393 mg/kg) yet still breaches the BPOM threshold at both sites.

Together, these comparisons show that the heavy metal uptake in geothermal-influenced medicinal plants is species, matrix, and site-specific, varying by more than an order of magnitude even within the same volcanic complex, so that findings from one plant–site combination cannot be

Table 7. Comparison of heavy metal concentrations in medicinal plants reported from geothermal areas (mg/kg dry weight)

Species	Location	Leaf tissue	Pb	Cd	Cu	Cr	Zn	Fe	As	Reference
M. malabathricum (L.)	Gunung Kembar, Aceh	Whole-plant tissue	0.317–0.393	0.012–0.021*	0.162–0.308	0.972–0.978*	0.156–0.276*	0.339–0.439	n.a.	This study
Tridax procumbens L.	Ie-Seu'um (Seulawah Agam), Aceh	Ethanolic extract of aerial parts	6.42 ± 0.05	0.91 ± 0.03	n.d.	13.81 ± 0.07	3.50 ± 0.03	4.65 ± 0.02	n.a.	(Maulydia et al., 2024)
Chromolaena odorata L.	Ie-Suum, Ie-Jue, Ie-Brouk (Seulawah Agam), Aceh	Ethanolic leaf extract	0.022–0.067	0.022–1.147	n.r.	n.r.	n.r.	n.r.	n.d.–0.064	(Abubakar et al., 2023)
BPOM Reg. No. 29 of 2023	Regulatory limit (medicinal plant materials)	-	0.30	0.30	10	2	-	-	5	(BPOM, 2023)

Note: *semi-quantitative; n.r. = not reported.; n.a. = not analysed.

extrapolated without direct verification. The combination of tissue Pb exceeding the BPOM threshold while BCF values remain within the excluder range, documented here for M. malabathricum at Gunung Kembar, is not replicated in the other two Acehnese geothermal species and constitutes the novel, public-health-relevant contribution of this work.

Study limitations

First, this study sampled only the geothermal zone and did not include a non-geothermal reference site. Without such a reference, enrichment factors cannot be calculated, and the link between geothermal activity and the observed metal loads remains plausible but not definitive. Earlier geochemical assessments of Acehnese geothermal systems have likewise highlighted this gap, and paired background–geothermal sampling is recommended for future work. Second, recovery values for Cd, Zn, and Cr fell outside the 85–115% analytical acceptance window, reflecting matrix interference in the FAAS measurements for these elements; accordingly, the principal environmental and toxicological conclusions of this study have been restricted to Pb, Cu, and Fe, while the data for Cd, Zn, and Cr are retained for completeness but are consistently flagged as semi-quantitative throughout (Balali-Mood et al., 2021). Third, plant material was processed as a composite of aboveground and belowground tissue, so root-to-shoot translocation factors could not be calculated, and organ-specific uptake patterns remain to be characterized in future sampling designs (Tang et al., 2025). Fourth, biomass inventories and co-occurring species were not documented, so the present dataset cannot support quantitative claims regarding phytoremediation capacity (Keith et al., 2024). In light of these limitations, *M. malabathricum* at Gunung Kembar is characterized here as a limited accumulator with medicinal-safety implications driven primarily by Pb, rather than as a hyperaccumulator or phytoremediator.

CONCLUSIONS

This study provided the first integrated assessment of heavy metal distribution in water, soil, and *Melastoma malabathricum* (L.) within the Gunung Kembar geothermal zone of Aceh Province, Indonesia, and addressed the three research questions that motivated the work. First, geothermal influence coincides with detectable metal enrichment across environmental matrices, with aqueous Pb exceeding the WHO drinking-water guideline (0.01 mg/L) and the Indonesian Class I surface-water standard (0.03 mg/L), and soil Cu (100.10 mg/kg) exceeding both the Indonesian and the Canadian soil guidelines, while soil Pb (84.33 mg/kg) complies with the Indonesian limit but exceeds the more conservative Canadian agricultural guideline. Second, *M. malabathricum* exhibits element-specific uptake behavior: for the three analytically reliable elements (Pb, Cu, Fe), bioconcentration factors remained well below unity (0.0016–0.0085), placing the species within the excluder category rather than within accumulator or hyperaccumulator ranges. Third, the measured Pb concentrations (0.317–0.393 mg/kg) comply with the 10 mg/kg limit for natural medicines under BPOM Regulation No. 29 of 2023, representing 3.2–3.9% of that limit, while approaching the stricter 0.3 mg/kg level applied to leafy vegetables as foodstuffs. The estimated daily intake under a traditional-use scenario reaches 4.4% of the EFSA BMDL01 for adult cardiovascular effects and 11.8% of the BMDL01 for developmental neurotoxicity in a child scenario —margins that narrow appreciably once chronic herbal consumption and background dietary lead are taken into account.

The principal contribution of this work is the demonstration that, within a hydrothermal zone where aqueous Pb exceeds drinking-water guidance and soil Cu exceeds national and international soil guidelines, M. malabathricum nonetheless functions as an excluder and retains tissue Pb within the applicable natural-medicine limit a profile not previously documented for Tridax procumbens or Chromolaena odorata in the Seulawah Agam volcanic complex, and one that supports continued but monitored traditional use rather than avoidance. The findings support three practical recommendations: pre-use contaminant screening should accompany medicinal preparation of *M. malabathricum* harvested from geothermal areas; harvesting should preferentially target plants beyond the immediate drainage of hot-spring discharge; and future studies should pair geothermal and non-geothermal reference sites, incorporate organ-level and biomass measurements, resolve matrix interferences for Cd, Zn, and Cr through standard-addition or ICP-MS analysis, and extend the present dataset into a quantitative human-health risk assessment that integrates dietary and medicinal exposure pathways.

Acknowledgements

This study was funded by Direktorat Riset, Teknologi, dan Pengabdian Kepada Masyarakat, Direktorat Jenderal Pendidikan Tinggi, Riset, dan Teknologi, Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi and Universitas Syiah Kuala through ”Penelitian Fundamental – Reguler” scheme with grant number: 094/E5/PG.02.00.PL/2024.

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