

Research Article

Index of contamination/pollution factor, geo-accumulation and ecological risk in ex-gold mining soil contaminated with mercury

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Abstract

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Mercury is a hazardous contaminant, and it is necessary to clean up Hg contamination on an ongoing basis. However, Hg contamination and ecological risks have not become a particular concern in the community. As a first step, this study evaluated the environmental risk assessment of Hg contamination/pollution in ex-gold mining soil. The results showed that the average total Hg in ex-gold mining soil was 4.11 and 4.25 mg kg⁻¹ for depths 0-20 and 20-40 cm, respectively, greater than the threshold limit set nationally (0.3 mg kg⁻¹) and internationally (0.05-1 mg kg⁻¹). The index of contamination/pollution factor and geo-accumulation of Hg were 13.70 and 1.39 at a depth of 0-20 cm, and 14.16 and 1.47 at a depth of 20-40 cm. The prospective ecological risk index and risk quotient were 5.48E2 and 1.03E2 at a depth of 0-20 cm, and 5.66E2 and 1.06E2 at a depth of 20-40 cm. The contamination/ pollution factor and ecological risk index indicate high Hg contamination and pollution in the soil. Therefore, appropriate technology is needed for the remediation process of ex-gold mining soil that considers all elements to a user-friendly level, such as amelioration technology with heavy metal inactivation techniques.

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Introduction

Mercury is a heavy metal that can cause ecosystem pollution (Chen et al., 2022). Hg hurts ecosystems because of its biological toxicity. Mercury is among the more toxic metals (Wang et al., 2020). Mercury pollution and contamination in gold mining sites are caused by amalgamation activity. This can potentially damage the mining region environment in the former gold mining territory. Once discharged into water bodies, Hg precipitates in soil and accumulates in biological networks across the primary producers, posing ecological hazards (Yu et al., 2021). Assessing Hg concentration in soil is very important to determine the level and factors of contamination/ pollution to the ecosystem. This serves as a basis for determining and

evaluating past and current environmental contamination/pollution factors (Jafarabadi et al., 2020). Various methods, such as AAS, AFS, and ICP-related techniques, can be employed for Hg monitoring based on existing capacity. The AAS approach using cold steam may be applied to soil samples to detect Hg and assess Hg contents with excellent sensitivity (El Zrelli et al., 2021). Further clinical studies of Hg-polluted soil are required to properly assess the ecological risks and the efficiency of Hg pollution remediation initiatives, particularly in ex-gold mining regions.

Soil is a natural sorbent and a target of various contaminants, including Hg, it is important to study the assessment of geological, biological, and ecosystem consequences of Hg impact in soil, so it is important to

know the assessment of geo-accumulation and ecological risk. Hg concentrations in soil can provide fundamental information for determining the overall assessment. To acquire consistent findings, multiple indices depending on metal concentrations in the soil are determined (Luo et al., 2021), such as the index of contamination/ pollution factor (C_i/P_f) (Hoang et al., 2020; Chen et al., 2021; Paul et al. 2021) and index of geo-accumulation (I-geo) (Elsagh et al., 2021). As for ecological concerns, Hg concentrations may fluctuate regionally and seasonally. Some studies explain that the risk assessment code (RAC) is seen from the fraction of Hg accumulated and modified by the availability of soil organisms (Zhang et al., 2021). The determination of C_i/P_f index and toxicity response (Tr) values are also necessary for calculating potential ecological risks to anthropogenic Hg contamination and pollution in the soil (Li et al., 2020).

To effectively control anthropogenic Hg contamination and pollution in the soil through soil quality guidelines (SQG) and, at the same time, promote appropriate remediation technologies. Generally, Hg concentrations in soil should and must be at international and national threshold values of 0.05-1 mg kg⁻¹ (Chiroma et al., 2014; Horvart et al., 2019) and 0.3 mg kg⁻¹ (Alloway, 2012), respectively. If the concentration of Hg in the soil exceeds a certain threshold, ecological hazards should be recognized, and the need for remediation activities should be implemented as a remedial process for the use of SQG in Hg evaluation (Wang et al., 2020). Furthermore, numerous approaches for soil Hg cleanup have recently been studied (Palansooriya et al., 2020), such as amelioration technology with heavy metal inactivation techniques. However, the impact of remedial efforts on rising levels of Hg pollution and ecological danger at realistic contamination locations remains unknown. Therefore, it is important to conduct this study to evaluate and analyze Hg contamination, pollution, and environmental risks in ex-gold mining soil contaminated with Hg using several indices of contamination, pollution, and risk that can help in the future management of Hg.

Material and Methods

Study area

This study was conducted in Dharmasraya Regency and continued with soil analysis at the Soil Laboratory, Faculty of Agriculture, Andalas University. The research area was 100-131 m above sea level, with an annual mean precipitation of 2469 mm and a temperature of 27.5 °C (BMKG, 2022). This study was located at seven mine sites (Figure 1A). The location selection was based on the interpretation of satellite imagery data and historical land use from interviews with community leaders and local miners. All mine sites have a landscape extending from west to east. Each mine site is part of a micro-hydrological channel

that is connected to the Batanghari River. There is a potential for water flow and soil sediment containing mercury to enter the Batanghari river when it rains. The results of field observations showed that the ex-gold mining soil is generally sandy, and the soil surface contains gravel covered by shrubs and grasses (Figure 1B).

Soil sampling

A survey approach was used for this study. However, field soil sampling was conducted using a technique called purposive random sampling. This strategy was based on the diversity of former gold mining areas in each region with disturbed soil sampling at three to five replicates at each depth of 0-20 and 20-40 cm. A total of fifty-four (54) samples were collected.

Soil analysis

The prepared soil samples were analyzed in the laboratory. The CV-AAS technology was used to measure total Hg (Eviati and Sulaeman, 2012). Data were statistically evaluated and displayed in graphical form using SPSS software, including correlation test, mean, standard deviation, maximum, and minimum values. Maps were created using ArcGIS 10.8.

Evaluation of Hg contamination and pollution accumulation and risk in soil

SQG is used to categorize the amount of Hg contamination and pollution in soil. The soil quality requirement for Hg used in this study was 0.3 mg kg⁻¹ (Alloway, 2012), which is the threshold value set nationally for Hg contamination and pollution in soil. However, this exceeds the safe limit in agricultural soils according to WHO guidelines of 0.05 g kg⁻¹ (Chiroma et al., 2014), 0.08 g kg⁻¹ to the European Union (Horvart et al., 2019), and 1 g kg⁻¹ to the US EPA. The study also included indices for contamination and pollution factors and ecological risks listed in Tables 1, 2, 3 and 4 for additional risk assessment.

Index of contamination/ pollution factor

By dividing Hg in soil by the limit value, C_i/P_f (F.1) (Lacatusu, 2000) and I-geo (F.2) (Abdullah et al., 2020; Jaworska and Klimek, 2021; Gonçalves et al., 2022) was calculated as follows:

$$C_i/P_f = \frac{C_i}{c} \quad (\text{F.1})$$

where: C_i = Hg in the soil sample; C = Hg concentration within acceptable environmental limits (e.g., 0.3 mg kg⁻¹).

$$\text{I-geo} = \text{Log}_2 \left[\frac{C_i}{1.5 \cdot B_n} \right] \quad (\text{F.2})$$

where: C_i = Hg in the soil sample; B_n = the geochemical background value for Hg in the soil (1 mg kg⁻¹).

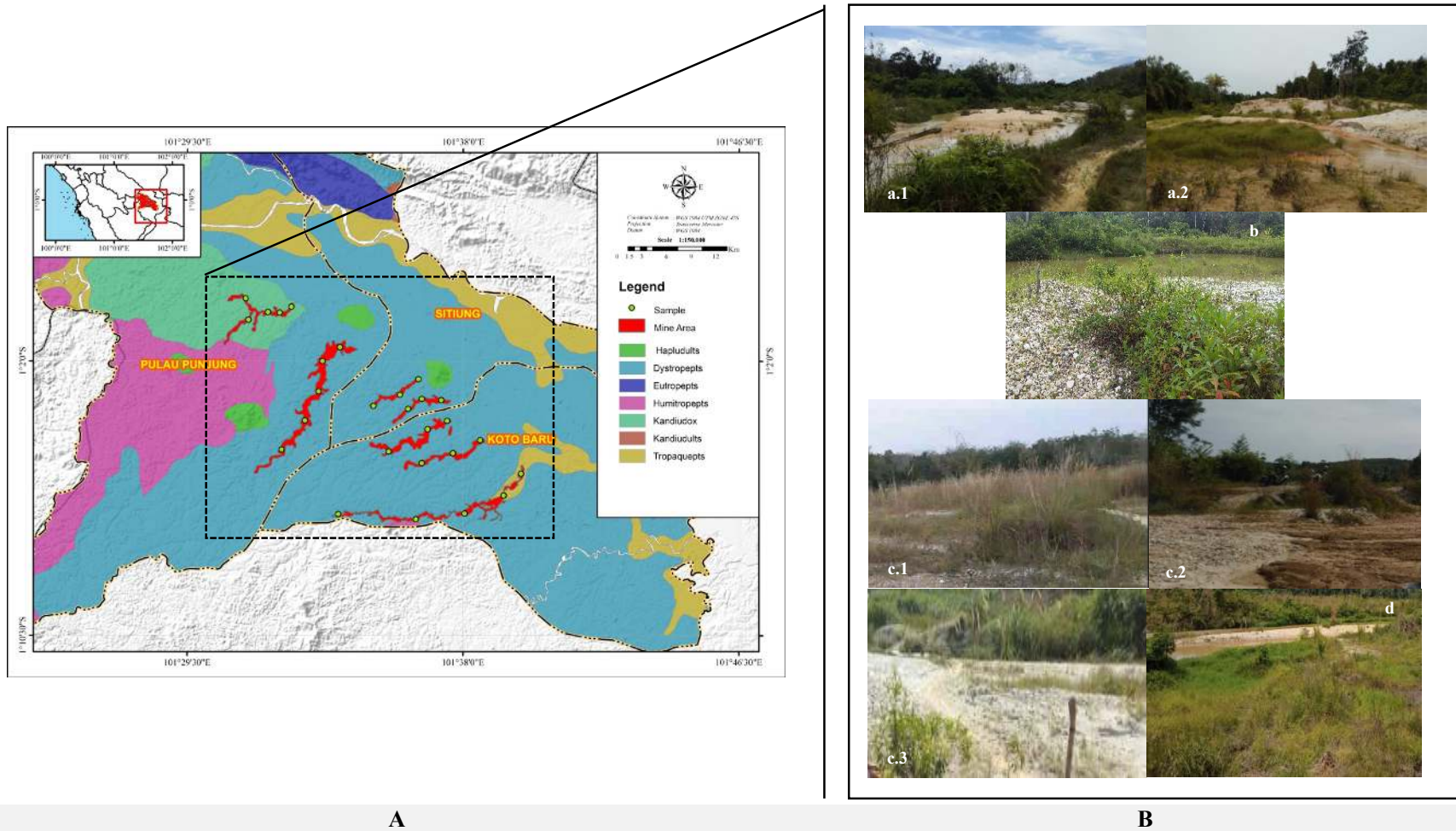


Figure 1. The study area of (A) soil sampling map and (B) appearance of ex-gold mining land in Dharmasraya: Pulau Punjung District in Tebing Tinggi at spot 1 (a.1) and spot 2 (a.2); and Sikabau (b); Sitiung District in Gunung Medan at spot 1 (c.1); spot 2 (c.2) and spot 3 (c.3); and Koto Baru District in Koto Padang (d).

Table 1. Criteria of C_f/P_f index

Symbol	Index	Criteria
C_f	<0.1	Very slightly
	0.10-0.25	Slightly
	0.26-0.5	Pretty
	0.51-0.57	Heavily
	0.76-1	Very
P_f	1.1-2.0	Slightly
	2.0-4.0	Pretty
	4.1-8.0	Heavily
	8.1-16	Very
	≥ 16	Extremely

Table 2. Criteria of I-geo index.

Index	Criteria
≤ 0	Uncontaminated
0-1	Uncontaminated to medium
1-2	Medium
2-3	Medium to highly
3-4	Highly
4-5	Highly to extremely
≥ 5	Extremely

Index of ecological risk

The ecological risk (ER) potential of Hg in soil was assessed based on the index values of contamination factors in soil and pollutant toxicity (Tr) (F.3). Meanwhile, the risk index (RI) describes the ecological hazard value of the soil by Hg (F.4). A risk quotient (RQ) index was estimated to describe the possible hazard of Hg contaminants in the ecosystem, where the Hg concentration value was divided by the predicted no-effect concentration (PNEC) of Hg (0.04 mg kg^{-1}) (F.5) (X. Li et al., 2019; Shao et al., 2020; Su et al., 2021).

$$ER = Tr * C_f/P_f \quad (\text{F.3})$$

$$RI = \sum ER \quad (\text{F.4})$$

$$RQ = \frac{Ci}{PNEC} \quad (\text{F.5})$$

where: C_f/P_f = the previously indicated contamination/pollution in the soil sample, and Tr represents the toxic reaction factor (Tr for Hg = 40) and Ci = Hg in the soil sample.

Table 3. Criteria of potential ER.

Index	Criteria
≤ 40	Low
40-80	Moderate
80-160	Considerable
160-320	High
≥ 320	Very high

Table 4. Criteria of RI and RQ.

	Index	Criteria
RI	≤ 150	Low
	150-300	Moderate
	300-600	Considerable
	≥ 600	High
RQ	≤ 1	Low
	≥ 1	High

Results and Discussion

Descriptive statistics of ex-gold mining soil contaminated with total Hg in Dharmasraya are presented in Table 5. The average total Hg in ex-gold mining soil was 4.11 and 4.25 mg kg^{-1} at depths of 0-20 and 20-40 cm, respectively. This value explains that the Hg concentration is above the threshold limit issued by the WHO Standard of 0.05 mg kg^{-1} (Chiroma et al., 2014), the European Union of 0.08 mg kg^{-1} (Horvart et al., 2019), and while the US EPA sets the maximum Hg at 1 mg kg^{-1} and 0.3 mg kg^{-1} (Alloway, 2012). This confirms that Hg levels on ex-gold mining soil in Dharmasraya are 85 times higher than WHO standards, 53 times higher than European Union standards, and 14 times higher than national standards. The high levels of Hg in the soil are caused by artisanal small-scale gold mining activities or, in Indonesia, known as unlicensed gold mining, which uses Hg in the amalgamation process as one of the sources of Hg pollution, which is around 20-30% (Mantey et al., 2020). If former gold mine land is used for reforestation, Hg can accumulate in plant tissue which will accumulate in the food chain.

Investigating anthropogenic pollution sources and the interaction between them, pollutant distribution processes (route), and recipients are very important. The assessment of the C_f/P_f index in the former gold mining soil in Dharmasraya is 13.70 and 14.16 at a depth of 0-20 and 20-40 cm, respectively, which explains that Hg is at a very polluted level. The geo-accumulation index is 1.39 and 1.47, which confirms Hg contamination/pollution is at a moderately polluted level. The I-geo describes contamination and pollution levels of anthropogenic enrichment of Hg in the soil. The background Hg values are in the order of the base soil value (B_v), surface sediment control value (C_{vs}), and deep soil control value (C_{vd}). The I-geo values are likewise exclusively connected to total heavy metal concentrations depending on specified background values, and soil attributes have no effect. On the other hand, soil type and composition can affect Hg concentrations, thus influencing risk assessment (Liao et al., 2022). The RI and RQ indices on ex-gold mining soil in Dharmasraya at depths of 0-20 and 20-40 cm of $5.48E2$ and $1.03E2$; $5.66E2$ and $1.06E2$ (Table 5). Prospective ecological risk aims to identify ecological impacts and possible hazards of Hg exposure by elucidating ecological sensitivity and susceptibility to

Hg toxicity and assessing overall ecological risk. Parameters are taken into account in this assessment, such as the type of target heavy metal (e.g. Hg),

observed concentrations, toxicity coefficients, and the susceptibility of water bodies to heavy metals (e.g. Hg).

Table 5. Descriptive statistics of the index of C_f/P_f , I-geo, and ER, RI, and RQ on ex-gold mining soil contaminated with Hg in Dharmasraya.

Analysis	N	Min	Max	Mean	Std. Error	Std. Deviation
A. Depth: 0-20 cm						
Total Hg	27	2.61	7.42	4.11	0.25	1.31
C_f/P_f		8.71	24.74	13.70	0.84	4.38
I-geo		0.80	2.31	1.39	0.08	0.43
ER and RI		348.29	989.41	5.48E2	33.69	175.09
RQ		65.31	185.51	1.03E2	6.32	32.83
B. Depth: 20-40 cm						
Total Hg	27	2.94	6.57	4.25	0.19	0.99
C_f/P_f		9.80	21.89	14.16	0.63	3.29
I-geo		0.97	2.13	1.47	0.06	0.33
ER and RI		391.83	875.61	5.66E2	25.30	131.48
RQ		73.47	164.18	1.06E2	4.74	24.65

The RI and RQ as indicators of Hg contamination and pollution based on background values that can represent the overall risk of Hg enlightenment (Huang et al., 2023). This confirms the Hg contamination and pollution of ex-gold mining soil in Dharmasraya at a depth of 20-40 cm > 0-20 cm.

Total mercury on ex-gold mining soil

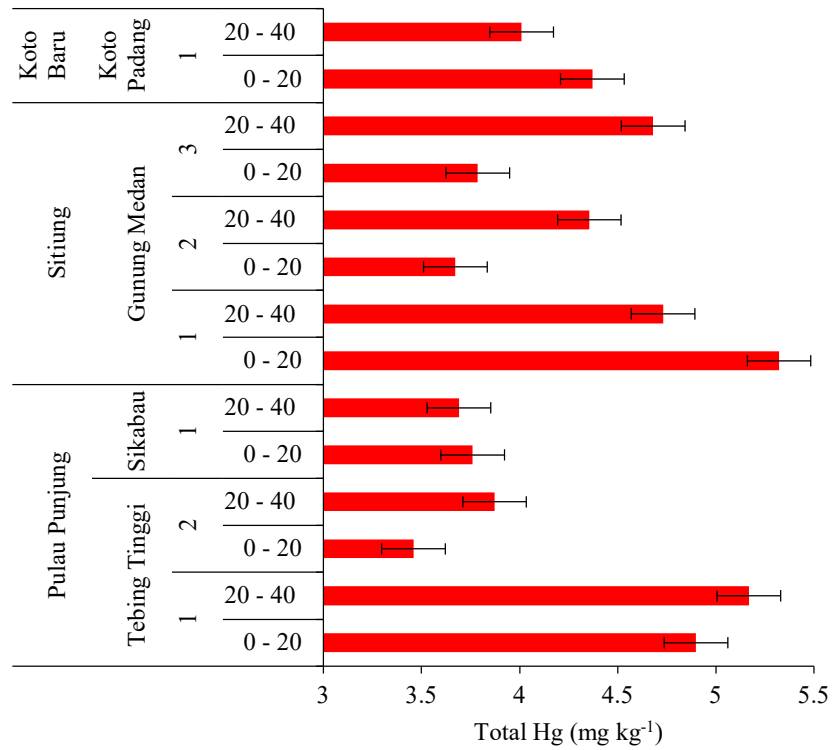
The high mercury content in the ex-gold mining soil in Dharmasraya can be seen clearly in the distribution of total Hg in the soil. The highest average total Hg was found on Gunung Medan at spot 1 at a depth of 0-20 cm, namely 5.23 mg kg⁻¹ and Tebing Tinggi at spot 1 at a depth of 20-40 cm, which was 5.17 mg kg⁻¹. However, the overall average total Hg was about 3-5 mg kg⁻¹ (Figure 2A). In comparison, the distribution of total Hg in each replicate in the former gold mine soil in Dharmasraya was around 2-7 mg kg⁻¹ (Figure 2B). This confirms that soil Hg is above the nationally and internationally established thresholds for soil (Alloway, 2012; Chiroma et al., 2014; Horvart et al., 2019). Based on field observations and community interviews, most of the gold mining locations are active mining areas, so the use of mercury by miners is still intensive. However, in some areas, the mining areas that lay were no longer active. Mining activities are carried out by dismantling the topsoil and washing the soil to separate the gold ore from the soil or rock, as a result of which the soil's physicochemical qualities are harmed. The use of Hg in gold-binding amalgamation activities has an impact on increasing the remaining Hg in the soil.

Index of contamination/ pollution factor

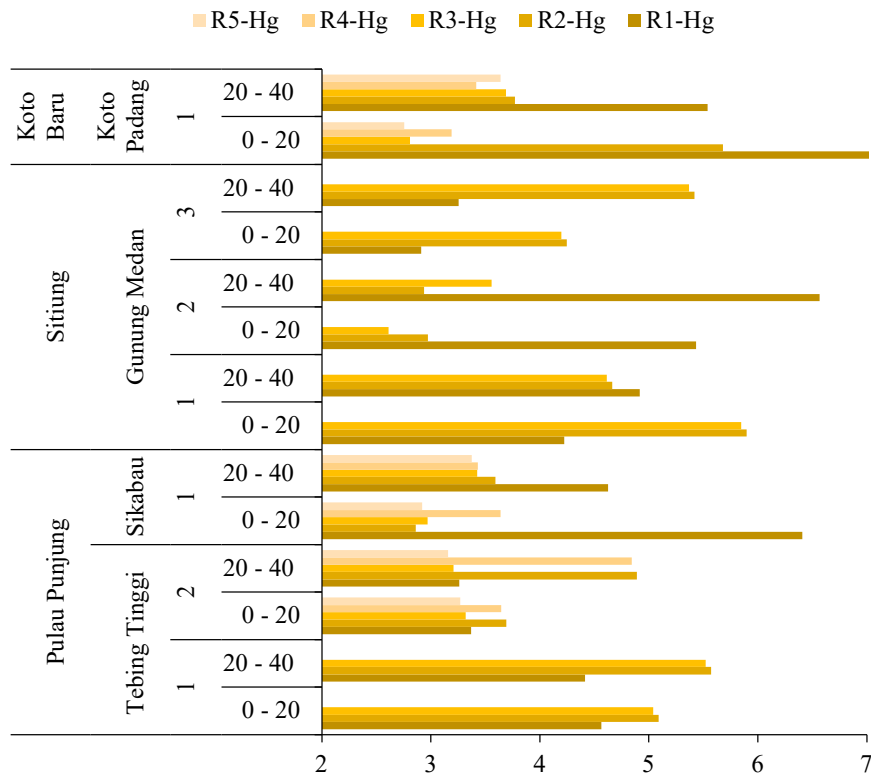
A location can be declared contaminated and polluted or not based on the assessment index, namely the C_f/P_f Index, which aims to determine and explain the status

of Hg contamination and pollution in the soil (Lacatusu, 2000). The understanding of soil contamination and pollution is based on the level of Hg measured in the soil that will have a direct or indirect negative effect on the ecosystem. Meanwhile, soil pollution is based on the range of Hg levels measured in the soil that are detrimental to some or all ecosystems. The assessment of the C_f/P_f index on former gold mine land in Dharmasraya is shown in Figure 3. The concentration of Hg on the index of C_f/P_f of all ex-gold mining soil in Dharmasraya is in the very polluted to extremely polluted criteria. The index of C_f/P_f at the extremely polluted level is in the Gunung Medan (spot 1 at a depth of 0-20 cm) and Tebing Tinggi (spot 1 at a depth of 20-40 cm) because it corresponds to a very high identified Total Hg concentration (average >5 mg kg). This confirms that efforts are needed to reduce Hg levels in the soil so that it does not pollute the environment and does not accumulate in the food chain, especially if the reforestation process is carried out at ex-gold mining land in Dharmasraya.

Heavy metals are produced by human activities in the environment through direct and indirect anthropogenic activities and are stored in the soil as residues of heavy metals (Moldovan et al., 2022). The I-geo was established to evaluate and explain the status of Hg contamination and pollution in the soil and its background. The determination of I-geo is calculated from a factor of 1.5 and the possible variation of the background value (Bn) for the type of heavy metal (e.g. Hg) (Monjardin et al., 2022). The I-geo assessment of ex-gold mining soil contaminated with Hg in Dharmasraya of 1-2, which was identified as moderate contamination and pollution. Fluctuations in the I-geo index value in each ex-gold mining soil in Dharmasraya are shown in Figure 3.



A



B

Figure 2. Average of total Hg (A) and total Hg per replication (B) on ex-gold mining soil in Dharmasraya.

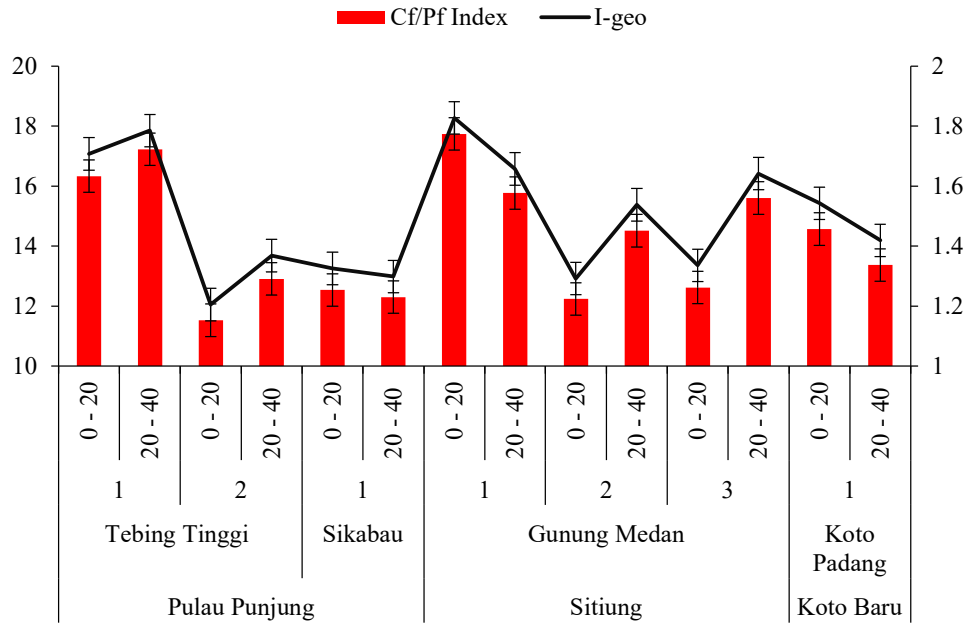


Figure 3. Index of C_f/P_f and I-geo on ex-gold mining soil contaminated with Hg in Dharmasraya

The fluctuations are strongly influenced by the distribution of total Hg concentrations in ex-gold mining land, which is very high, and the influence of alteration processes (geogenic) and supported by mining and gold processing activities with amalgamation (anthropogenic) activities. While establishing soil quality requirements, the value of the geochemical background index must be considered. According to soil quality standards, established quality criteria for soil detect abnormally high pollutant concentrations that derive only from anthropogenic sources. Inadequate environmental legal standards can lead to issues in the future.

Index of ecological risk

The exposure of the amalgamation activities of gold mining to Hg contaminants in the soil was estimated from effect concentrations considered to be representative environmental concentrations for safe screening controls. The ER and RI indices were developed to evaluate and explain the amount of heavy metal (e.g. Hg) contamination and pollution in the soil based on toxicity and environmental reactions (Radomirović et al., 2020; He et al., 2021; Rong et al., 2022). The species sensitivity distribution approach was used to calculate the biological hazard potential of Hg in the soil (Figure 4).

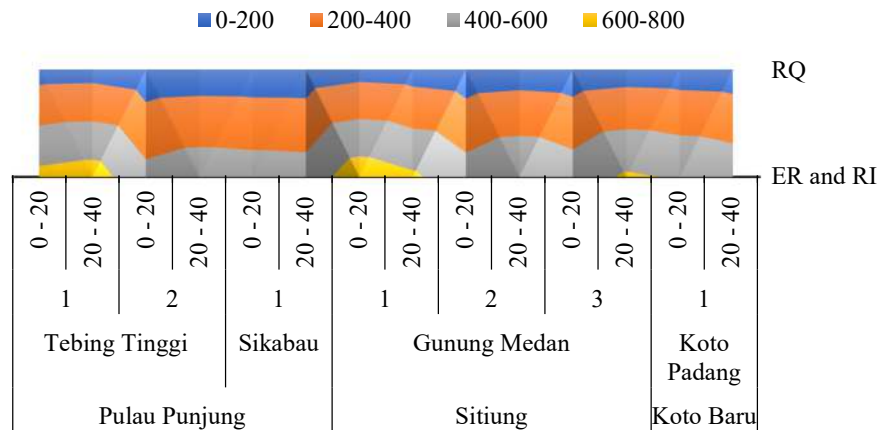


Figure 4. Index of ER, RI, and RQ on ex-gold mining soil contaminated with Hg in Dharmasraya.

Areas with the highest ecological risk are the Mount Medan area (ER and RI = 709.66) and Tebing Tinggi (ER and RI = 689.12). Hg contamination in soil from gold mining activities has an impact on the environment and ecosystems around mining. Relatively high values of $ER \geq 320$ (very high), $RI \geq 600$ (high), and $RQ > 1$ (high) on ex-gold mining soil in Dharmasraya (Figure 4). This risk shows a different pattern of fluctuating Hg concentration levels around the mining area. The ER, RI, and RQ values indicated greater Hg levels in Gunung Medan and Tebing Tinggi than in other regions (Sikabau and Koto Padang). This signifies that the entire sample poses a significant ER. The risk assessment results showed efforts to reduce Hg concentrations in ecosystems, especially in plants. If ex-gold mining soil contaminated with Hg will be used as productive land, many stages may be suggested for building a risk management plan. Developing amelioration technology with heavy metal inactivation techniques in the mining area is suggested.

Conclusion

This study found a high accumulation of total Hg (2-7 mg kg⁻¹) in ex-gold mining soil in Dharmasraya. Indicators of contamination, pollution, and risk factors such as C/P_f (≥ 16 : extreme), I-geo (1-2: moderate), ER (≥ 320 : very high), and RI (≥ 600 : high), and RQ (≥ 1 : high) in very high Hg contaminated and polluted in the soil. Mining activities pose a severe ER and cause significant C/P_f in the soil. It is necessary to take corrective action in reducing Hg pollution in the soil as offered, namely amelioration technology with inactivation techniques for heavy metals. These corrective activities must be carried out to reduce the degree of risk in all sectors to a level appropriate to users (society and government).

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