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Heavy metal tracing from gold mining soil to vinasse in the downstreaming process of sweet sorghum to bioethanol

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ABSTRACT

Soils in gold mining areas have the potential to contain heavy metals from rock weathering. Such soil was planted with sweet sorghum to increase land productivity in Boto Village, Wonogiri Regency, Central Java during the dry season. The harvested crop was not used for food, but processed into biofuels through fermentation and distillation. Accordingly, the aim of this research was to trace the presence of several heavy metals in vinasse, a by-product of sweet sorghum stem juice fermentation process, from plants grown on soil in a community of gold mining area. Two varieties of sweet sorghum, Samurai 1 and Samurai 2, were cultivated on this soil. Then, they were harvested and the sorghum stem extract was fermented to produce ethanol. Distillation process was carried out on the fermented juice to increase the ethanol concentration, leaving behind vinasse. Chemical analysis was carried out on the chemical properties of the soil (pH, CEC, Organic-C, total-N, available-K, and potential-P), and content of the heavy metals of Fe, Mn, Pb, and Cu in the soil, juice, and vinasse. The soil exhibits a neutral reaction, low salinity, organic-C, total-N, available P and CEC. The levels of Fe, Mn, Pb, and Cu in soil are 7.8%, 0.1%, 76.00 ppm, 23.81 ppm. In the juice, these concentrations were 9.66, 21.14, 1.49, 1.64 in ppm. In the vinasse, they were 5.29, 28.15, 1.05, 0.73 ppm, respectively. These results indicate that heavy metals in soils could be absorbed by sorghum crops and they were absorbed in the stems of Samurai 1 and 2 sweet sorghum varieties, extracted into the juice, and partially remained in the vinasse.

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1. INTRODUCTION

Gold mining environments are often at risk of heavy metal contamination, which can affect the quality of the surrounding soil. Source rocks containing heavy metals such as arsenic (As), lead (Pb), or mercury (Hg) can cause contamination if these rocks undergo weathering processes. The presence and type of heavy metal-bearing minerals in gold mining areas depend largely on the type of rock, as reviewed by Rivera-Parra et al. (2021) in various artisanal gold mining regions of Ecuador. These heavy metals can be released into the environment, contaminating both soil and water (Ouambeti-Wickon et al., 2025; Wu et al., 2025). When source rocks containing heavy metals undergo weathering, these metals can be released into the soil as a result of the pedogenesis process (Surour et al., 2025). For example, in the weathering process of argillaceous sand, the migration of heavy metals, namely Hg, Tl, As, and Sb, migrates from the inner to the outer layers due to changes in hydrophilic functional groups like -OH and -C=O (Wen et al., 2021). This weathering process can accelerate the spread of heavy metals in the soil. Released heavy metals can accumulate in the soil and persist for long periods of time, depending on the chemical properties of the soil and the climate. Research on

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heavy metal levels in soil in the gold mining environment in Wonogiri showed an increase in the levels of Fe, Mn, Pb, Cu, and Hg metals in the soil close to the mining location (Nurcholis et al., 2017).

Many plant species are capable of absorbing heavy metals from the soil, functioning as agents of phytoremediation. The accumulation of heavy metals in wild or forest plants has been investigated in previous studies (Du et al., 2024). Sorghum as a cereal crop type can be used in the soil cleaning process to reduce the concentration of heavy metals in contaminated soil. Sweet sorghum plants generally have tall stems and high sugar content, as indicated by a Brix value ranging from 15 to 23%. They also have the ability to absorb heavy metals, such as cadmium (Cd) and chromium (Cr) (Xiao et al., 2021). This makes sweet sorghum a promising, environmentally friendly option for reducing pollution without relying on costly technology. However, the accumulation of heavy metals in sorghum plants poses negative impacts on human and animal health if the plants are consumed directly or used as animal feed. In general, sorghum has the potential to absorb and store heavy metals from the soil, but its effectiveness depends on various factors, including soil conditions and the characteristics of the sorghum species or variety. Commonly absorbed heavy metals include lead (Pb), cadmium (Cd), arsenic (As), and zinc (Zn). The extent of absorption is influenced by the concentration of heavy metals in the soil, soil pH, and various chemical properties of the soil.

Sweet sorghum has a high sugar content in its stems, mainly in the form of sucrose, glucose, and fructose. This sugar content is the main raw material in bioethanol production through the fermentation process (Nurcholis et al., 2021). Sweet sorghum is capable of growing in marginal soils with suboptimal conditions, such as limited water availability or dryness. As an archipelago, Indonesia includes many small islands that have many constraints on fuel supply. In particular, the Nusa Tenggara Islands experience prolonged dry seasons each year, making sweet sorghum a promising alternative energy crop for the development of the bioethanol industry. Likewise, other islands could also consider sweet sorghum for bioethanol production. In addition, sorghum shows potential for cultivation on marginal lands along the Opak Fault in Bantul Regency, where soils are derived from Tertiary-aged breccia and tuff rocks. The main limitations in this region include shallow soil depth, steep slopes, and the absence of irrigation water sources (Nurcholis et al., 2023). However, even without increasing soil pH, sorghum plants can still possible to grow and produce when clay and organic materials are added to the soil.

Sweet sorghum is known for its high productivity and its ability to grow in various climatic and soil conditions (Khalil et al., 2015). These characteristics make it a good alternative raw material for bioethanol production, especially in areas with limited land and water resources. Accordingly, this research aimed to identify the presence of various heavy metals in vinasse, a by-product from the downstream processing of sweet sorghum stem juice when cultivated in soils within gold mining community areas.

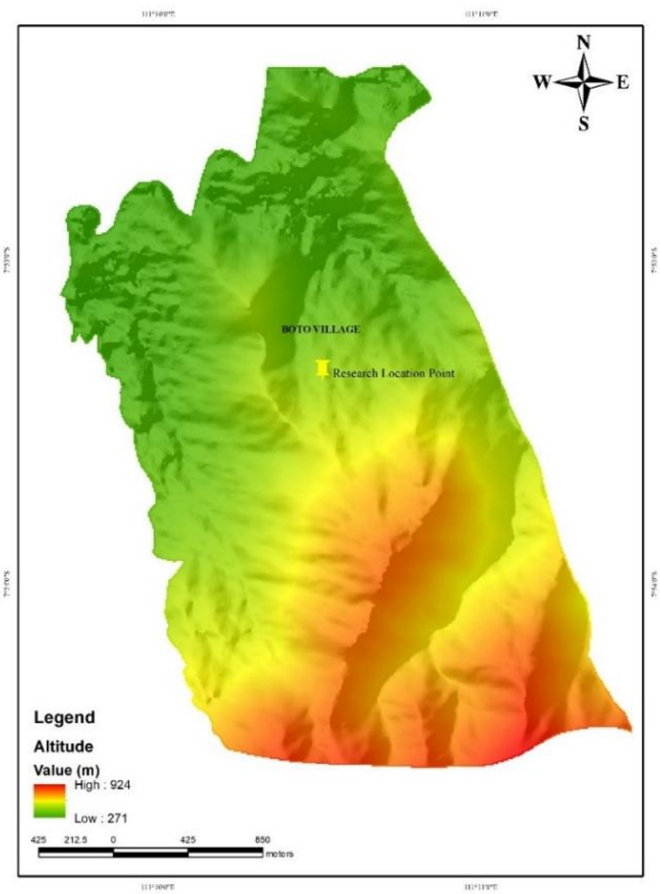

Figure 1. Location of Gunungmas, Wonogiri Regency, Central Java Province

2. MATERIAL AND METHODS

Research on the tracing of heavy metals from soil to vinasse of the by-products of agroindustry aspect, was conducted on the artisanal gold mining area in Gunungmas, Wonogiri Regency, Central Java Province (Fig. 1). The experiment was conducted by plotting the area to grow sweet sorghum crop as bioethanol-producing material in soils from gold mining community known to be contaminated with heavy metals (Nurcholis et al., 2017). A completely randomized design (CRD) with three replications was used for the experimental setup. There were two varieties of sweet sorghum, Samurai-1 and Samurai-2, which were mutant cultivars developed and released by Indonesia's National Nuclear Agency. There were three sites of land that lay on the slope land area of the gold mining: upper, middle, and lower slopes. The experiment was conducted on terraced steep, sloping land with a total area of 200 m^2.

The plotting location of the gold mining land for growing sweet sorghum took place at the beginning of the dry season. Soil was plowed and prepared, and the sweet sorghum seeds (Samurai 1 and Samurai 2 varieties) were sown on the land affected by heavy metals contamination and limited water availability (Fig. 2). Throughout the growing period, irrigation, fertilization, and pest control were caried out to support plant growth until the crops reached 60 days of age. However, due to the lack of irrigation water, the cultivation was discontinued before the crops reached full maturity (Fig. 2). Once the plants reached maturity, the sorghum was harvested, and the weight of stalks and seeds was measured. The sorghum stalks were then pressed using a horizontal sorghum stem-pressing machine to extract the stem juice, which was subsequently fermented using yeast to produce ethanol.

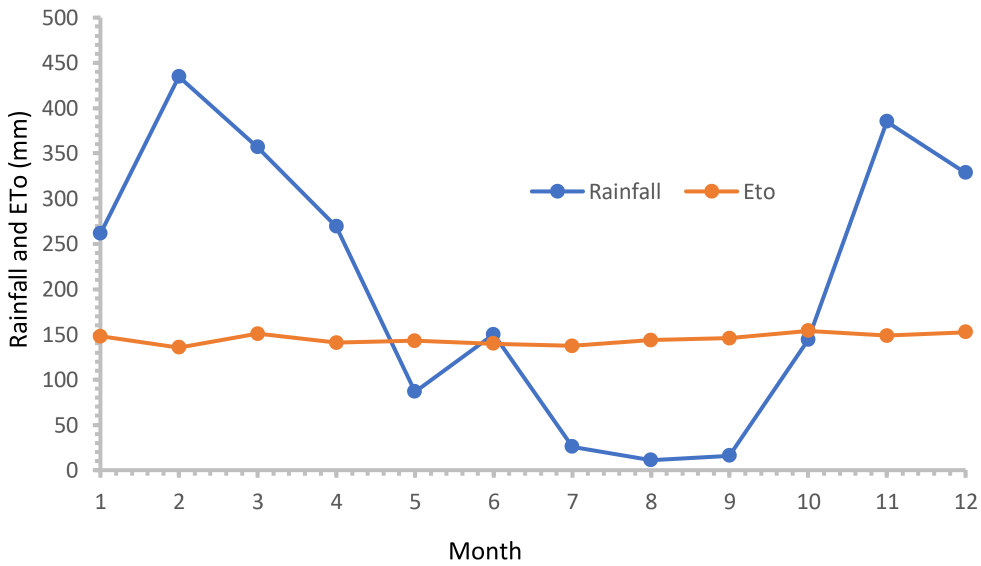

Figure 2. Water budget in Jatiroto District, Wonogiri Regency.

Table 1. Soil properties for growing sweet sorghum

Parameter	Soil for growing sorghum crops					
	Samurai 1			Samurai 2		
	Ma	Mt	Mb	Pa	Pt	Pb
Sand (%)	29.00	31.00	26.00	32.00	30.00	28.50
silt (%)	43.00	45.30	40.00	45.00	.43.00	41.50
Clay (%)	28.00	30.10	25.00	29.00	27.00	26.50
pH	7.00	7.20	6.60	7.10	6.80	6.30
EC 1:5 (mS/cm)	48.00	49.00	45.00	39.70	39.00	37.50
Organic C (%)	0.88	1.08	0.68	1.03	1.01	0.91
Total-N	0.07	0.27	0.07	0.12	0.06	-0.34
C/N Ratio	12.57	13.87	10.57	18.93	16.83	15.33
Available K	61.00	63.40	58.00	60.32	58.00	56.50
Available P2O2	4.00	6.00	1.00	2.30	1.00	0.97
CEC (cmol(+)/Kg	5.77	8.17	2.77	15.51	13.31	11.81
Fe (ppm)	89,492.00	79,188.00	77,116.00	79,737.00	71,998.00	70,220.00
Mn (ppm)	1,110.00	1,114.00	946.00	1,028.00	903.00	882.00
Pb (ppm)	80.90	72.60	80.80	60.20	84.90	76.60
Cu (ppm)	22.45	18.68	23.33	29.89	14.94	33.57

Notes: S1: soil with samurai 1 sorghum variety, while S2: soil with samurai 2 sorghum variety; on upper plot (a), middle plot (t), and lower plot (b)

Figure 3. Sorghum grown on land (left) and ready to harvest (right)

Ethanol distillation was conducted to increase the bioethanol concentration, with the goal of producing a renewable energy source. Soil samples were collected from each plot cultivated with sweet sorghum varieties, Samurai 1 and Samurai 2. The experimental areas consisted of three levels of bench terraces plots of high, medium, and low, resulting in six soil samples. For each plot, soil was sampled from three locations and composited into a representative sample. The following parameters for soil were analyzed for the soil samples: (1) pH – measured from a 1:5 soil to water extract using pH meter; (2) Electrical Conductivity (EC) – measured from 1:5 extract using EC meter; (3) Cation Exchange capacity (CEC) – determined using 1N NH_4OAc at pH 7.0, followed by washing with 80% ethanol and extraction of absorbed NH_4^+ using NaOH; (4) Organic Carbon (organic-C) – analyzed using Walkley and Black method; (5) Total Nitrogen (total-N) – measured using Kejhdahl method; (6) Available Potassium (K) – extracted with 1N NH_4OAc at pH 7.0 and measured by flame photometer; (7) Available Phosphorus (P) – determined using Bray-1 extraction and measured with a visible light spectrophotometer; (8) Soil texture – analyzed through a mechanical separation and pipette method; (9) Total heavy metals of Fe, Mn, Cu, and Pb – measured using X-ray fluorescence (XRF). The concentration of Fe, Mn, Cu, and Pb in the sorghum stem juice and vinasse (a by-product of ethanol distillation) was analyzed using an atomic absorption spectrophotometer (AAS). The results of these analyses were used to trace the presence and movement of heavy metals from soils into sorghum stem juice and vinasse. Based on the findings, potential sustainable applications for both bioethanol dan vinasse were evaluated.

3. RESULTS

3.1. Field condition of the research area

The area experienced water deficit from July to October, spanning approximately four months or more than 90 cumulative days in one year (Fig. 2). According to Soil Survey Staff (2014), areas with water deficit exceeding 90 cumulative days fall under the ustic soil moisture regime, while areas with deficits under 45 cumulative days fall under the Udic moisture regime. Based on this classification, the soil in the study area belongs to the ustic moisture regime. Field observations confirm that beginning in August, annual plants are difficult to grow, except for drought-tolerant species. Sweet sorghum plants, known for their adaptability to dry conditions, demonstrated strong growth and development in these challenging circumstances (Fig. 3).

The extended dry period from June to October did not support the availability of soil moisture. During this time, soil moisture tends to decrease drastically. This condition hinders both the establishment and maintenance of many annual crops. Therefore, it is necessary to select types of annual plants that are drought-tolerant or better suited for local agro-climatic conditions to increase the likelihood of success. In the present research area, during the dry season, most annual plants are difficult to grow. However, sorghum plants can grow and produce on dry climate land and low soil chemical fertility, as shown by the chemical properties of the soil (Table 1). Figure 2 shows that sweet sorghum plants of the Samurai 1 and Samurai 2 varieties were able to grow and produce under these conditions.

The soil in the study area, predominantly clay-textured with low levels of organic carbon (C), total nitrogen (N), and a C/N ratio below 20%. In addition, the cation exchange capacity (CEC) is low (Table 1). These characteristics collectively indicate that the soil has low chemical fertility.

3.2. Soil reaction (pH) and electrical conductivity (EC)

The studied soil planted with sorghum is slightly acidic in nature, with a soil pH of approximately 5 (Fig. 4a). Soil with this pH level is generally considered moderately acidic. In terms of soil development, such acidity suggests the presence of various pedogenic processes that have occurred over time. Soils developed in the environment of the Old Lawu Volcano exhibit variability in parent materials, landform morphology, and pedogenic processes (Nurcholis et al., 2019). These soils provide evidence that the composition and mineral types within the sand fraction, particularly in soils formed from hydrothermally altered parent materials, are characterized by the presence of leucophoenicite and ribbeite minerals. A pH of 5 typically allows for moderate biological and chemical activity in the soil, supporting the growth of various plant types. This level of acidity can facilitate nutrient availability while limiting the potential for toxic elements to reach harmful concentrations.

The electrical conductivity value of soil with 1:5 extract varies from 0.05 to 0.3 mS/cm based on the classification made by Liu (2015) has the characteristic of non-saline to low-saline (Fig. 4b). Electrical conductivity (EC) is a measurement of soil's ability to conduct electricity (Venturin et al., 2025), which is directly related to the concentration of ions or dissolved salts in the soil solution. The higher the EC value, the higher the salt concentration in the soil. Overall, soil with an EC between 0.05 and 0.3 mS/cm in a 1:5 soil extract is an indication that the soil is in a safe range, suggesting that salt levels are not high enough to inhibit plant growth. A decrease in soil moisture can lead to salt accumulation on soil colloids, potentially affecting EC readings.

The variation in EC values observed across different plots (Fig. 4b) may be attributed to the formation of salt traps or microtopographic features that influence surface water retention and salt distribution.

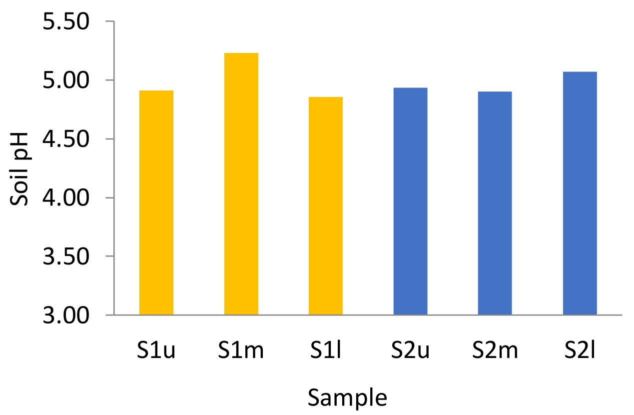

Figure 4a. pH of the studied soil, with M: soil with S1: soil with samurai 1 sorghum variety, while S2: soil with samurai 2 sorghum variety; on upper plot (u), middle plot (m), and lower plot (l)

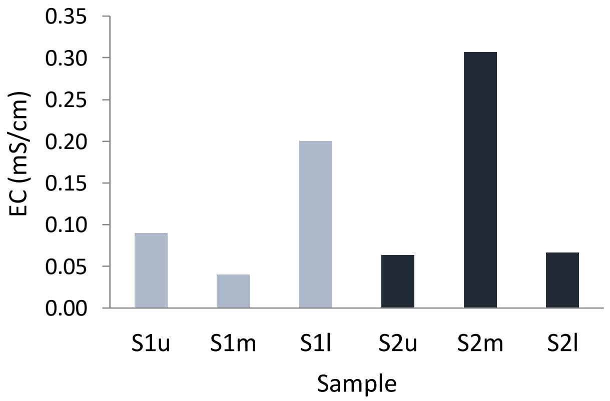

Figure 4b. Electrical conductivity (EC) of the studied soil, with S1: soil with samurai 1 sorghum variety, while S2: soil with samurai 2 sorghum variety; on upper plot (u), middle plot (m), and lower plot (l)

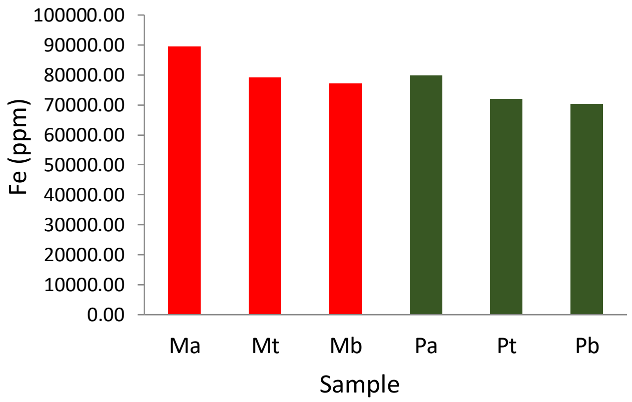

Figure 5a. Fe content of the studied soil, with M: soil with samurai 1 sorghum variety, while P: soil with samurai 2 sorghum variety; on upper plot (a), middle plot (t), and lower plot (b)

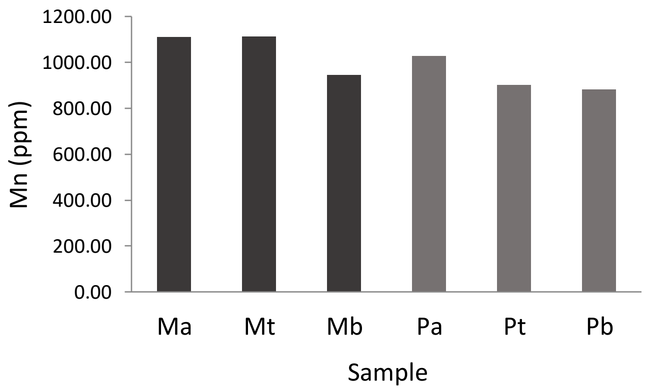

Figure 5b. Mn content of the studied soil, with M: soil with samurai 1 sorghum variety, while P: soil with samurai 2 sorghum variety; on upper plot (a), middle plot (t), and lower plot (b)

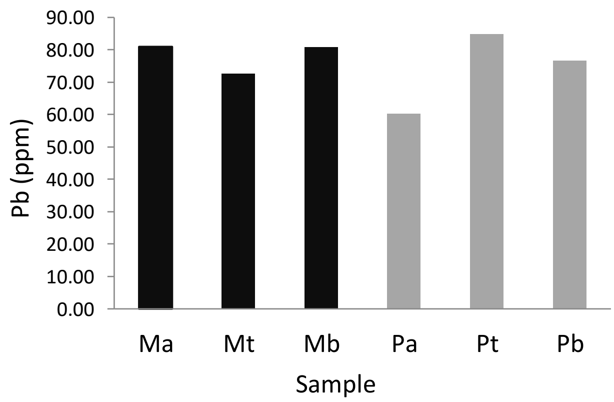

Figure 5c. Pb content of the studied soil, with M: soil with samurai 1 sorghum variety, while P: soil with samurai 2 sorghum variety; on upper plot (a), middle plot (t), and lower plot (b)

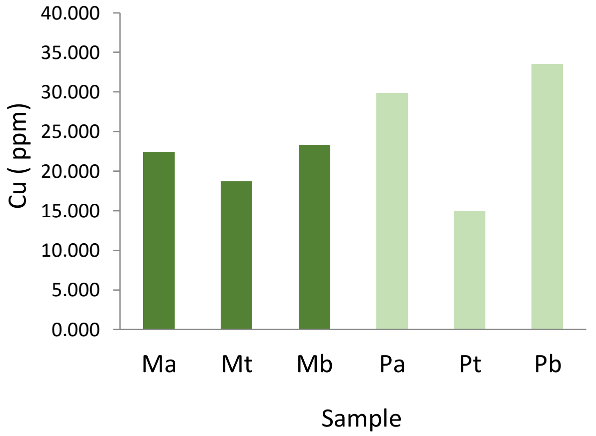

Figure 5d. Cu content of the studied soil, with M: soil with samurai 1 sorghum variety, while P: soil with samurai 2 sorghum variety; on upper plot (a), middle plot (t), and lower plot (b)

3.3. Heavy metal content in soil

The total Fe content in the soil is very high, on average around 7% (Fig. 5a). The high Fe content in the soil is one of the characteristics of advanced soil development in the research area. At this stage of soil development, other elements have mostly been dissolved and leached out of the soil's solum. The steep slopes in the area also contribute to the lateral movement of base cations, which results in reduced exchangeable base content. As a result, Fe in the form of oxides becomes the dominant mineral, giving the soil a characteristic red color. High levels of Fe have been reported to reduce the germination rate of crops such as soybean (Timotiwu et al., 2023), suggesting that its potential effects on sweet sorghum seed germination warrant further investigation.

The total manganese (Mn) content of the soil is also high, which is above 800 ppm (Fig. 5b). In general, like Fe, Mn remains in the soil as a residual element. The presence of Mn and Fe oxides can influence the fixation of other heavy metals in the soil. During the formation of Fe oxide minerals such as schwertmannite, jarosite, ferrihydrite, goethite, hematite, and magnetite, heavy metals can co-precipitate with Fe in the solution phase and become integrated into oxide mineral structures (Shi et al., 2021). In a gold mining environment, the presence of these oxides is often associated with elevated concentrations of various heavy metals. In this study, the analysis of heavy metal levels was done using X-ray Fluorescence (XRF), a reliable technique capable of detecting the presence and content of heavy metals at high levels or in percent (%) to small content or in ppm. The Pb element in the gold mining soil presents as it comes from metal sulfide minerals (PbS), minerals commonly found in gold mining environments (D. Wang et al., 2022). XRF provides accurate and comprehensive information on the presence of heavy metals in soil samples. This technique allows identification and measurement of the concentration of heavy elements in soil samples with high accuracy, both in percent and parts per million (ppm). With XRF, detailed information about the concentration of lead (Pb) and other heavy metal elements in soil samples is obtained.

The total Pb content in the soil ranges from 60 to 80 ppm (Fig. 5c). The presence of Pb in the soil in the mining environment is very reasonable. This is consistent with the findings of Nurcholis et al. (2017) reported that the average concentrations of heavy metals in the soil were 83.76 ppm for Hg, 79.45 ppm for Pb, and 32.00 ppm for As. The concentration of Fe, Cd, Pb, and As in soil samples significantly contributed to gold mining activities in Tanzania (Akoto et al., 2023). The presence of types and concentrations of heavy metals is greatly influenced by the indigenous minerals and rocks that make up the mining area. The results of the current study indicate that the heavy metals in the soil that dominate in the mining area are Fe, Mn, Pb, and Cu.

The soil studied also has a high Cu content, which is between 15,000 to 35,000 ppm (Fig. 5d). The high levels of Cu in gold mining soil are usually in the form of chalcopyrite ($CuFeS_2$) minerals. This mineral is a form of copper-iron sulfide that has a copper content of around 34.6%. This mineral is also one of the most common copper minerals and is often the main source of copper in copper ore.

3.4. Heavy metals content in stem juice and vinasse

Figure 6a, 6b, 6c, and 6d show the heavy metals in stem juice and vinasse. Sweet sorghum plants as heavy metals accumulators can absorb high Fe, Mn, Pb, and Cu from the soil. The Fe content in stem juice in the Samurai 1 variety is around 9,000 ppm, and in the Samurai-2 variety around 11,000 ppm (Fig. 6a). The microelement iron (Fe) is a nutrient that is needed by plants in small amounts, but it is particularly important. Iron (Fe) plays a crucial role in the synthesis of chlorophyll, which is an important green pigment in the process of photosynthesis in plants. Iron is needed for the synthesis of several enzymes involved in chlorophyll production. Fe levels decreased in vinasse for both sorghum varieties of Samurai 1 and Samurai 2, which means that the bioethanol from the distillation also contains Fe. Excessive Fe levels in plants can generally cause plant quality disorders. However, this process did not occur in sorghum plants.

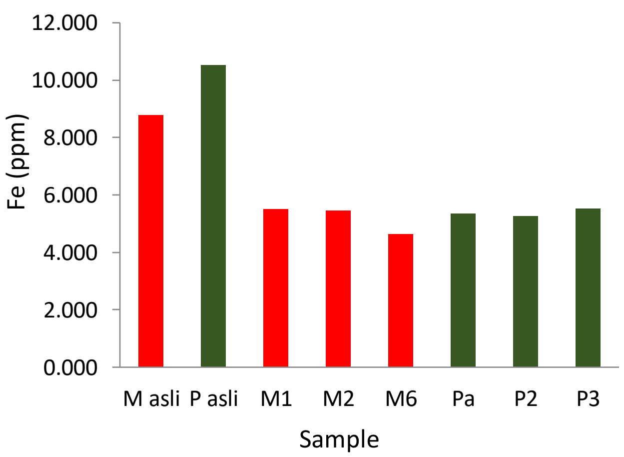

Figure 6a. Fe content of the stem juice and vinasse, with M asli: juice of the sorghum stem of the Samurai 1, and P asli of the Samurai 2; M: vinasse from bioethanol distillation of the sorghum stem of the Samurai 1, and P from Samurai 2. While 1,2,6, a, 2, and 3 are replications

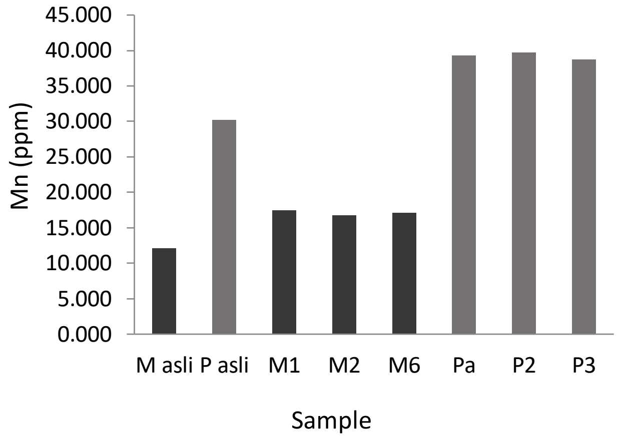

Figure 6b. Mn content of the stem juice and vinasse, with M asli: juice of the sorghum stem of the Samurai 1, and P asli of the Samurai 2; M: vinasse from bioethanol distillation of the sorghum stem of the Samurai 1, and P from Samurai 2. While 1,2,6, a, 2, and 3 are replications

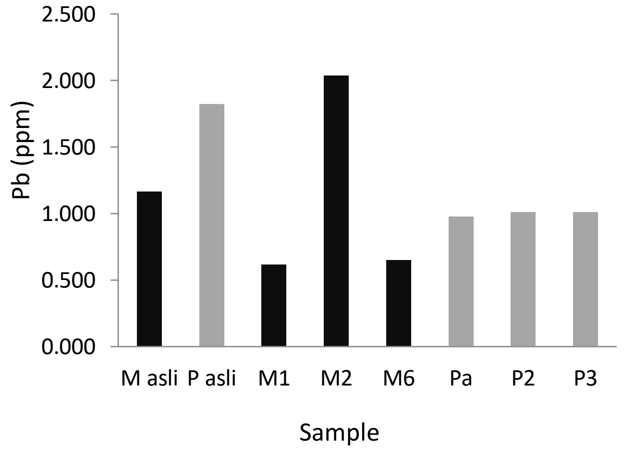

Figure 6c. Pb content of the stem juice and vinasse. with M asli: juice of the sorghum stem of the Samurai 1, and P asli of the Samurai 2; M: vinasse from bioethanol distillation of the sorghum stem of the Samurai 1, and P from Samurai 2. While 1,2,6, a, 2, and 3 are replications

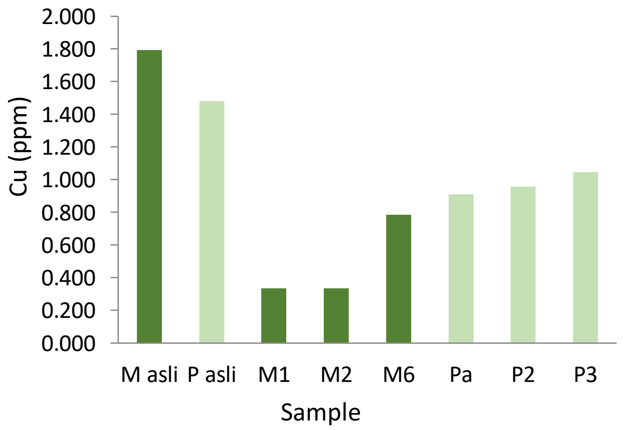

Figure 6d. Cu content of the stem juice and vinasse. with M asli: juice of the sorghum stem of the Samurai 1, and P asli of the Samurai 2; M: vinasse from bioethanol distillation of the sorghum stem of the Samurai 1, and P from Samurai 2. While 1,2,6, a, 2, and 3 are replications

Figure 6b shows the Mn content in stem juice and in vinasse of both sorghum varieties, Samurai 1 and Samurai 2. Manganese (Mn), another essential micronutrient, is involved in photosynthesis, root and leaf development, carbohydrate metabolism, and disease resistance. Mn levels in stem juice were high, and interestingly, levels increased in vinasse after distillation—an opposite trend to Fe. This may suggest that Mn is less likely to be carried into the ethanol phase or more concentrated in the distillation residue. Despite elevated Mn concentrations, neither Samurai-1 nor Samurai-2 showed physiological symptoms of toxicity.

Figure 6c displays (Pb) concentrations revealing lower levels of stem juice in Samurai 1 compared to Samurai. Then, the Pb content in vinasse was lower than in stem juice or decreased. This means that there is a part of Pb included in bioethanol. In general, the absorption of large amounts of Pb can cause poisoning in plants. Even though sweet sorghum Samurai-1 and Samurai-2, absorb large amounts of Pb, they did not experience this symptom.

Figure 6d illustrates Cu concentration in both stem juice and vinasse. The high levels of Cu in stem juice indicate the high absorption of Cu by the sorghum plants. The plants studied also did not experience interference with the high absorption of Cu in plants. In this study, it can be concluded that sweet sorghum plants are able to absorb heavy metals Fe, Pb, Mn, and Cu from the soil with high content of these metals.

4. DISCUSSION

In the context of gold mining, the presence of lead and other heavy metals is important not only to evaluate soil and environmental quality, but also to assess potential health risks for workers and surrounding communities. In a gold mining environment, heavy metals such as Fe, Mn, Pb, Hg, As, and Co contaminate the Soil (Akoto et al., 2023; Nurcholis et al., 2017; Wan et al., 2024). Mercury (Hg), in particular, has also been detected in vegetable crops such as chili, a commonly consumed spice in Indonesia, generally (Lazare et al., 2021; Yudiantoro et al., 2018). Therefore, regular monitoring and analysis using techniques such as XRF is an important step to manage and reduce the negative impacts of the presence of heavy metals. In this study, heavy metal tracing was conducted to analyze their presence in soil and their uptake by sweet sorghum plants (varieties Samurai 1 and Samurai 2). The sweet sorghum stems were squeezed with a press machine, producing juice or sap, which was fermented to produce bioethanol, highlighting the crop potential as a renewable biofuel source, as stated by Sathya et al. (2016).

Sorghum variety of Samurai 1 can be used as raw material for bioethanol production, as the content of sugar in the stem, with a brix value, of 12 or higher, and grain productivity reaching 6.1 tons per hectare (Human et al., 2020). However, further research is required to develop sweet sorghum varieties with higher biomass and sugar concentrations to improve ethanol yield. For example, the SS-301 variety of sweet sorghum is estimated to produce up to 2,585 liters of ethanol per feddan (approximately 6,155 litters per hectare), based on an ethanol concentration of 251 mL per litter of juice and a juice yield of 10,300 litters per feddan (or 24,253 litters per hectare) (Khalil et al., 2015).

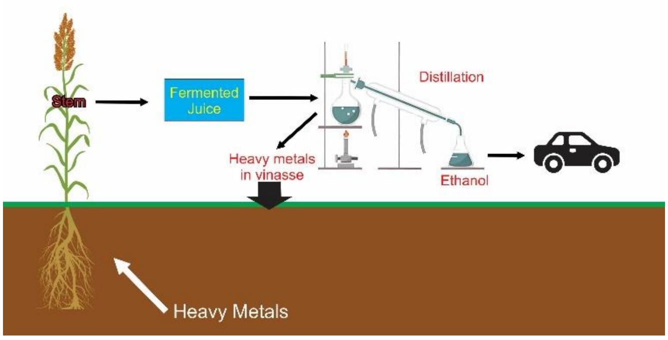

Figure 7. Tracing model for heavy metals content in the soil, stem juice and vinasse

This study was attempted to integrate several important aspects in soil management and plant utilization in the context of the presence of heavy metals. Analysis of heavy metals in soil planted with sweet sorghum is an important step in understanding the levels of heavy metal contamination in the environment. This includes measuring the total concentration of Fe, Mn, Pb, Cu in the soil detected using the XRF technique. Sweet sorghum plants (Sorghum bicolor) as heavy metals accumulator crops have the ability to absorb heavy metals from the soil (Ofori-Agyemang et al., 2024). Examining the concentration of heavy metals in the sorghum stems can trace the extent of heavy metals absorbed by plants, determine the portion present in the stem juice, and assess the remaining amounts in the vinasse.

Sweet sorghum grown on soil contaminated with heavy metals necessitates careful evaluation of how these metals affect the quality of the extracted juice, the produced ethanol and resulting vinasse. Management of this contamination is part of an effort to ensure that the biofuel produced is safe and effective. To assess this, it is necessary to trace presence of the heavy metals from the soil, to their absorption by the plants, and finally to their accumulation in the sorghum stems (Fig. 7). The sorghum stems were pressed to extract juice, which was then fermented to produce bioethanol with initial ethanol concentration of approximately 10%. This fermented juice is subsequently distilled to increase ethanol concentration for use of biofuel. Ethanol intended for engine fuel must reach a purity level of 99.9%, while ethanol used dor cooking stoves typically requires a concentration of 80 to 90%. Distillation produces vinasse as a by-product. Given that the ethanol yield from fermented juice is only about 10%, approximately 90% of the volume remains as vinasse. For every liter of ethanol produced, around 12 liters of vinasse are generated. With Brazil's annual bioethanol production reaching 30 million m³, this results in an estimated 360 billion liters of vinasse each year (Marafon et al., 2020). This substantial volume of vinasse must be properly managed to prevent environmental issues. Although vinasse is rich in nutrients and can enhance soil fertility, the potential presence of heavy metals—originating from contaminated sorghum—poses a risk. Therefore, its application as irrigation water, liquid organic fertilizer, or through fertigation must be carefully evaluated (Fig. 7). As an organic by-product, vinasse contributes significantly to soil fertility (Vyatrisa et al., 2017), and understanding the impact of different organic fertilizers enables farmers to choose the best approach to improve crop yield and quality. Aligned with circular economy principles, valorizing vinasse as a useful agricultural input—especially in the ethanol production industry—is a promising strategy (Carpanez et al., 2022). However, the development of organo-mineral fertilizers from vinasse requires thorough empirical validation. In addition, both the agronomic and economic viability of vinasse use must be assessed through comparative studies of fertigation versus organo-mineral fertilizer application.

The use of vinasse, a by-product of the sugarcane industry, as a soil amendment in sugarcane fields provides several sustainability benefits, including the reduction of greenhouse gas (GHG) emissions (Vasconcelos et al., 2022). However, when vinasse contains heavy metals, its return to the soil can lead to the accumulation of these contaminants. Despite this concern, sweet sorghum cultivation for ethanol production presents a potential closed-loop system—from cultivation to biofuel production—where vinasse is reused only within that specific cycle (Fig. 7). In such a system, environmental risks can be contained. This approach requires careful evaluation of both the benefits and the potential risks associated with cultivating sweet sorghum in contaminated environments. While sweet sorghum has phytoremediation potential—helping remove heavy metals from soil—it also poses a risk of transferring those metals into juice, ethanol, and vinasse. A study by F. Wang et al. (2022) found that growing sorghum on soil amended with 1% hydroxyapatite effectively supported plant growth, enhanced Phyto stabilization of cadmium (Cd), lead (Pb), and zinc (Zn), and promoted phytoextraction of cadmium.

5. CONCLUSION

According to the results of the present research, there several kinds of paths for Fe, Mn, Pb, and Cu from soil, sorghum stem juice, and vinasse, in a gold mining environment. There is a potential of contamination of heavy metals such as Fe, Mn, Pb and Cu heavy metals in soils. Sweet sorghum cultivars, Samurai 1 and Samurai 2, demonstrated the ability to absorb these heavy metals from contaminated soils. When the stems are processed into juice, the metals are transferred into the liquid. Subsequent fermentation and distillation processes further distribute these metals into both the ethanol and vinasse by-products. Therefore, the application of vinasse as fertigation should be restricted to sorghum cultivation intended solely for bioethanol production, ensuring that the system remains contained and does not extend contamination risks to food or broader agricultural systems.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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