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Moringa (*Moringa oleifera* L.) Seed Powder as a Bioadsorbent for Heavy Metals in Community Gold Mine Effluent: Implications for Agricultural Water Use.

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Abstract. Gold mining in rural areas can contaminate rivers and canals that are also used for irrigation, creating risks for agricultural water use. This study evaluated Moringa oleifera seed powder as a low-cost bioadsorbent to improve community gold mine wastewater in Bolaang Mongondow Timur, North Sulawesi, Indonesia. Effluent collected at the mine outlet was treated in batch with moringa seed powder at 0, 0.5, 1.0 and 1.5 g L^{-1}. Concentrations of Cd, Cr, Cu, Pb and Hg were measured by atomic absorption spectrophotometry before and after treatment, and summarized together with removal efficiencies and Indonesian effluent standards. A dose of 0.5 g L^{-1} gave the best apparent reduction for Cd and Cu, while Pb and Hg responded best at higher doses; Cr was only weakly affected, consistent with the limited removal of anionic Cr(VI) by unmodified biosorbents. Overall, moringa seed powder reduced the levels of several cationic metals. It may help lower heavy-metal loads entering agricultural water systems. Still, the non-replicated, descriptive nature of the data means that further replicated and field-based studies are needed before routine irrigation use can be recommended..

Keywords: *Moringa oleifera; bioadsorbent; gold mine wastewater; heavy metals; irrigation water quality*.
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INTRODUCTION

Mining activities are an important source of income in many rural regions, but they often generate large volumes of wastewater containing suspended solids and toxic metals[1], [2]. Gold mining effluents typically carry elevated concentrations of cadmium (Cd), copper (Cu), lead (Pb), mercury (Hg) and chromium (Cr), which are persistent, bioaccumulative and potentially harmful to aquatic ecosystems and human health even at low concentrations[3], [4].

In many landscapes, including community-based gold mining areas in Bolaang Mongondow Timur, Indonesia, drainage from mine sites flows into rivers and streams that may also serve as sources of irrigation water for surrounding agricultural land[5]. This creates a direct pathway for heavy metals to enter soils, crops and, ultimately, the food chain, with implications for crop productivity, soil health and food safety[6].

Heavy metal pollution in water and soil has been identified as a serious environmental problem in mining-impacted regions worldwide[7]. Cd, Pb and Hg can accumulate in sediments and biota and cause long-term toxic effects on aquatic organisms and exposed human populations[8]. Arsenic (As), in particular, is known as a highly persistent and carcinogenic element that can lead to skin lesions, cardiovascular disease and several types of cancer[9]. In Southeast Asia, arsenic and other metal contamination from mining activities has raised concern because of the close spatial coupling between mine drainage, irrigation systems and rice-based farming[10], [11].

Although many studies have focused on arsenic, other regulated metals in mine effluent (Cd, Cu, Pb, Hg, Cr and Ni) are also of agronomic importance because they can impair soil microbial processes, reduce crop yields and compromise the safe use of water resources for irrigation[12], [13].

In Indonesia, effluent quality from gold and copper mining operations is regulated by the Decree of the Minister of Environment No. 202/2004, which sets maximum permissible concentrations for several heavy metals and basic water quality parameters. Compliance with these standards is essential not only to protect downstream aquatic ecosystems, but also to safeguard agricultural water use in riverine and irrigation networks that may receive treated mine effluent. Where mine wastewater is discharged into catchments dominated by paddy fields, mixed crop systems or livestock, failure to meet these thresholds increases the risk of metal accumulation in agricultural soils and edible plant tissues.

Conventional physicochemical methods for treating metal-contaminated wastewater include chemical precipitation, coagulation–flocculation with inorganic coagulants, filtration and ion exchange[14], [15]. While effective, these technologies are relatively expensive, energy-demanding and often generate secondary chemical sludge that requires further management, which can limit their applicability for decentralized or community-based treatment systems typical of small-scale mining areas[16]. As a result, there is growing interest in low-cost, environmentally friendly bioadsorbents derived from locally available plant materials that can be integrated into simple treatment schemes and potentially support safer agricultural reuse of treated water.

Moringa (Moringa oleifera L.) is a multipurpose tree widely cultivated in smallholder farming systems in the tropics[17]. Its leaves, pods and seeds are used for food, feed and medicinal purposes, and the species is well adapted to marginal and dry environments. Moringa seeds contain cationic proteins, polyphenols and functional groups such as –OH, –COOH and $–NH_2$ that can bind dissolved particles and metal ions via adsorption and coagulation–flocculation mechanisms[18]. Previous studies have shown that moringa seed powder can effectively reduce turbidity, color and chemical oxygen demand (COD) in different types of wastewater and has been successfully applied for clarification of river water and domestic wastewater[19], [20].

Recent work reported that moringa seed powder was able to reduce arsenic and zinc residues in gold mine effluent by 99.6% and 56.6%, respectively, highlighting its potential as a natural coagulant for mine wastewater treatment[21]. However, the Indonesian mine effluent standard also regulates several other metals, including Cd, Cr, Cu, Pb, Hg and Ni, for which performance data of moringa-based treatment are still limited, especially under real field conditions in community gold mining operations. Moreover, the implications of such treatment for potential agricultural water reuse and protection of farming systems in mining-influenced landscapes have not been sufficiently explored[22].

Therefore, this study aimed to evaluate the ability of moringa seed powder (Moringa oleifera L.) to reduce the concentrations of selected heavy metals (Cd, Cu, Pb, Hg and Cr) in community gold mine effluent from Bolaang Mongondow Timur, North Sulawesi, Indonesia. Specifically, we (i) tested different dosages of moringa seed powder to identify the apparent optimum dose for each metal, (ii) compared the quality of treated effluent with national discharge standards, and (iii) discussed the implications of the observed removal efficiencies for the safe use of treated mine wastewater in agricultural systems. By explicitly linking mine effluent treatment with downstream irrigation and food safety concerns, this work contributes to the development of low-cost, locally available technologies that support more sustainable agriculture in mining-impacted regions.

MATERIALS AND METHODS

Study area and sampling

The study was conducted on wastewater discharged from a community-based gold mining operation in Bolaang Mongondow Timur Regency, North Sulawesi, Indonesia. Wastewater samples were collected at the outlet of the community mine effluent before discharge into the receiving water body (Figure 1). This outlet represents a potential source of contamination for downstream river reaches that may be connected to local agricultural areas.

Sampling followed national and international guidelines for wastewater sampling. Composite sampling of the outlet wastewater was conducted according to the Indonesian National Standard SNI 6989.57:2008 and Standard Methods for the Examination of Water and Wastewater (APHA, 2005). Grab samples were also taken to characterize instantaneous effluent conditions. During fieldwork, in situ measurements of basic water quality parameters (pH and temperature) were recorded using a portable pH meter and thermometer. Primary data consisted of these in situ measurements and laboratory analyses of heavy metal concentrations in the collected samples.

Figure 1. Map of the sampling location at the outlet of community gold mine wastewater in Bolaang Mongondow Timur Regency, North Sulawesi, Indonesia

Preparation of Moringa seed powder

Moringa (Moringa oleifera L.) seeds were obtained from mature pods that had been left to dry on the tree. The seeds were manually dehulled to remove the outer seed coat, and the kernels were then ground using a clean mortar and pestle to obtain a fine seed powder. The powder was stored in airtight containers at room temperature until use to minimize moisture uptake and deterioration of active compounds.

Experimental design and treatment with Moringa seed powder

The study employed a survey and laboratory analysis approach. Field sampling was followed by batch adsorption experiments in the laboratory to evaluate the effect of moringa seed powder dosage on heavy metal concentrations in the gold mine effluent.

Wastewater samples collected from the outlet were first analyzed to determine the initial concentrations of cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb) and mercury (Hg) using atomic absorption spectrophotometry (AAS). These samples were then subjected to treatment with different dosages of moringa seed powder, expressed as grams of powder per liter of wastewater (g L^{-1}). The dosage levels tested are summarized in Table 1.

Table 1. Dosage levels of Moringa oleifera seed powder applied to gold mine wastewater in batch experiments.

Treatment	Dose (g/L)	Description
T0	0	Control (no moringa)
T1	0.5	Low dose
T2	1	Medium dose
T3	1.5	High dose

For each treatment, a known mass of moringa seed powder was added to a measured volume of wastewater sample to achieve the desired concentration (0; 0.5; 1.0; 1.5 g L^{-1}). The mixtures were placed on a laboratory shaker and agitated for 30 minutes to promote contact between the adsorbent and dissolved metals. After shaking, the samples were allowed to stand undisturbed for 24 hours to enable sedimentation of flocs and adsorbent–metal complexes.

After the settling period, the supernatant was carefully decanted and filtered. The filtrate was then analyzed again by AAS to quantify the residual concentrations of Cd, Cr, Cu, Pb and Hg for each dosage level.

Heavy metal analysis

Heavy metal analyses were carried out at the Laboratory of the Manado Center for Standardization and Industrial Services (Balai Standardisasi dan Pelayanan Jasa Industri Manado), an accredited laboratory in North Sulawesi. Atomic absorption spectrophotometry (AAS) was used to determine the concentrations of Cd, Cr, Cu, Pb and Hg in the raw and treated wastewater samples, following relevant Indonesian National Standards (SNI) and APHA (2005) methods for each metal.

Laboratory quality control included the use of reagent blanks and standard solutions to check instrument performance and calibration. Where possible, measurements were verified against the detection limits and linear ranges recommended in the applied standard methods.

GC–MS analysis of Moringa seed composition (supporting analysis)

To support the interpretation of adsorption mechanisms, the organic composition of moringa seeds used in this study was characterized by gas chromatography–mass spectrometry (GC–MS). The analysis revealed 54 chromatographic peaks corresponding to at least 54 organic compounds, with a total of 162 components identified. The main constituents in the most intense peaks included several fatty acid esters such as (E)-9-octadecenoic acid ethyl ester, ethyl oleate, methyl and ethyl esters of hexadecanoic and pentadecanoic acids, as well as polyols such as glycerin, erythritol and diglycerol.

These data were used qualitatively to discuss potential functional groups (e.g. –COOH, –OH) relevant to heavy metal binding in the Results and Discussion section. Detailed GC–MS operating conditions followed the standard protocol of the analytical laboratory and are not repeated here.

Data analysis

In this study, the results were interpreted using descriptive statistics. Due to logistical and budget constraints, each treatment level was analyzed once (n = 1) and no technical replicates were performed. Consequently, no inferential statistical tests (e.g. ANOVA or t-tests) were applied, and the reported “optimum” doses should be understood as apparent optima based on the observed trends in the single measurements rather than statistically confirmed differences between treatments.

For each metal, the percentage removal efficiency (R, %) of Moringa oleifera seed powder was calculated as:

$$R(\%) = \frac{C_0 - C_t}{C_0} \times 100,$$

where $C_0$is the initial metal concentration in the raw wastewater (mg L⁻¹) and $C_t$is the concentration after treatment at a given moringa dose (mg L⁻¹). The treated effluent concentrations were then compared qualitatively with the Indonesian effluent quality standards for gold and copper ore mining (Table 2) to assess compliance with regulatory thresholds.

Table 1. Indonesian effluent quality standards for gold and copper ore mining activities (Decree of the Minister of Environment of the Republic of Indonesia No. 202/2004 on Wastewater Quality Standards for Gold and/or Copper Ore Mining)

No.	Parameter	Unit	Maximum allowable concentration
1	pH	–	6–9
2	TSS	mg L^{-1}	200
3	Cu	mg L^{-1}	2
4	Cd	mg L^{-1}	0.1
5	Zn	mg L^{-1}	5
6	Pb	mg L^{-1}	1
7	As	mg L^{-1}	0.5
8	Ni	mg L^{-1}	0.5
9	Cr	mg L^{-1}	1
10	Hg	mg L^{-1}	0.005

RESULTS AND DISCUSSION

GC–MS characterization of Moringa seeds

The GC–MS analysis of Moringa oleifera seeds revealed a complex mixture of organic compounds. The chromatogram (Figure 2) displayed 54 distinct peaks, indicating at least 54 compounds present in the seed material. Subsequent mass spectrometric identification suggested a total of 162 individual components separated in the moringa seed sample.

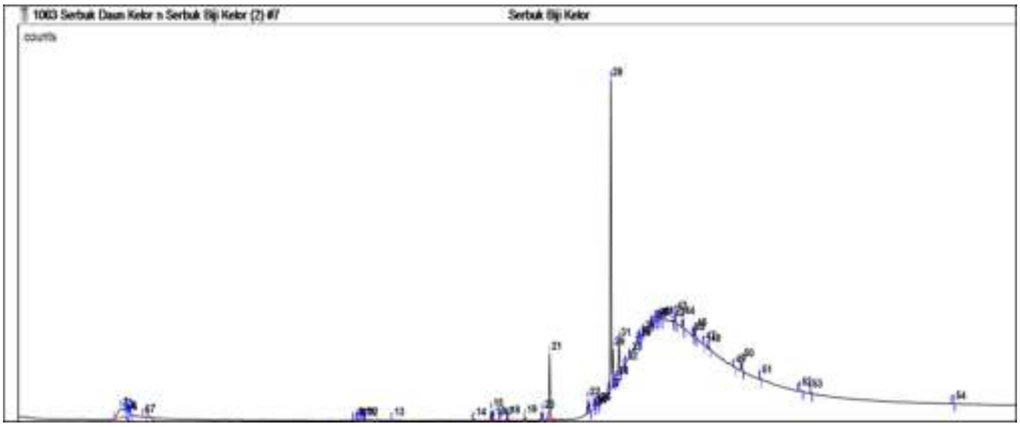

Figure 2. GC–MS chromatogram of organic compounds in Moringa oleifera seeds

Among the most intense peaks, nine major compounds were identified, including several fatty acid esters and polyols: (E)-9-octadecenoic acid ethyl ester, ethyl oleate, 9-octadecenoic acid (Z)-, methyl ester, hexadecanoic acid ethyl ester, pentadecanoic acid ethyl ester, hexadecanoic acid 2-methyl methyl ester, glycerin, erythritol and diglycerol.

These compounds carry functional groups such as hydroxyl (–OH) and carboxyl (–COOH) that can, in principle, participate in adsorption and complexation reactions with dissolved metal ions.

However, it is important to note that GC–MS selectively detects volatile and thermally stable organic molecules, and does not directly characterize the cationic proteins and larger macromolecules in moringa seeds that are often cited as the main active agents in coagulation and biosorption. Therefore, the chromatogram in Figure 2 should be interpreted as complementary evidence that moringa seeds contain a variety of organic compounds and functional groups, rather than a complete description of all adsorption-active species. From the perspective of agricultural and environmental application, the GC–MS results support the idea that moringa seed powder is a chemically rich bio-material with multiple potential binding sites for contaminants, but they do not on their own quantify adsorption capacity or selectivity for specific metals.

Removal of heavy metals from gold mine effluent

The batch experiments showed that moringa seed powder affected the concentrations of several heavy metals (Cd, Cu, Pb, Hg, Cr) in the gold mine wastewater, with different dosage levels producing different responses. The original study design included Ni among the target metals, but no Ni data were available in the present dataset; thus, the discussion here focuses on Cd, Cu, Pb, Hg and Cr.

A summary of the observed optimum doses and qualitative effectiveness for each metal is presented in Table 3.

Table 3. Summary of optimum moringa seed powder doses and qualitative removal effectiveness for heavy metals in gold mine wastewater.

Metal	Optimum dose (g/L)	Qualitative effectiveness	Interpretation
Cd	0.5	Effective reduction	Strong adsorption by amino and carboxyl groups
Cu	0.5	Effective reduction	Electrostatic interaction and complexation with active sites
Pb	1.5	Effective reduction	Higher dose required due to larger ionic size and strong complex formation
Hg	1	Effective reduction	Formation of Hg–protein complexes on the adsorbent surface
Cr	0	Not effective	Cr(VI) present as anionic species, poorly adsorbed by unmodified moringa powder

Qualitatively, a moringa seed powder dose of **0.5 g/L** was considered effective for reducing Cd and Cu concentrations. At this lower dose, the active adsorption sites on the moringa particles were still largely available, allowing strong interaction between the adsorbent surface and Cd^{2+} and Cu^{2+} ions. Increasing the dose to 1.0 or 1.5 g/L did not improve removal sufficiently to justify designating a higher optimum, suggesting that beyond a certain point, additional moringa powder may contribute to particle agglomeration and reduced effective surface area rather than higher sorption capacity.

In contrast, **Pb and Hg** required higher doses to reach their best performance. The highest qualitative effectiveness for Pb was observed at **1.5 g/L**, and for Hg at **1.0 g/L**. This pattern is consistent with the larger ionic size and stronger tendency of Pb^{2+} and Hg^{2+} to form complexes, which may demand more available binding sites to achieve comparable reductions. The interpretation in the original dataset suggests that Pb removal at high dose is associated with the formation of stronger complexes on the moringa surface, while Hg removal is linked to the formation of Hg–protein complexes.

For **Cr**, the best outcome was associated with the control (0 g/L), indicating that moringa seed powder did **not** provide an appreciable reduction in Cr concentration. This result is consistent with Cr being present predominantly as hexavalent anionic species (CrO_4^{2-}, $Cr_2O_7^{2-}$), which are more difficult to adsorb onto the mostly positively charged or neutral sites of moringa-based adsorbents. The seed powder appears to be more effective for cationic metals (Cd^{2+}, Cu^{2+}, Pb^{2+}, Hg^{2+}) than for anionic Cr(VI) species.

The measured initial and final concentrations of each heavy metal in the gold mine effluent at different moringa seed powder doses are summarized in Table 4. For each metal–dose combination, the table reports the initial concentration in the raw wastewater (C_0), the concentration after treatment (C_t), the corresponding removal efficiency and whether the treated effluent meets the Indonesian effluent quality standard for gold and copper mining activities.

Table 4. Initial and final concentrations of heavy metals in gold mine wastewater treated with Moringa oleifera seed powder, removal efficiency and comparison with Indonesian effluent standards.

Metal	Dose (g/L)	C0 (mg/L)	Ct (mg/L)	Removal (%)	Standard limit (mg/L)	Meets standard? (Yes/No)
Cd	0	0.25	0.25	0	0.1	No
Cd	0.5	0.25	0.08	68	0.1	Yes
Cd	1	0.25	0.09	64	0.1	Yes
Cd	1.5	0.25	0.09	64	0.1	Yes
Cu	0	3.5	3.5	0	2	No
Cu	0.5	3.5	1.2	65.7	2	Yes
Cu	1	3.5	1.4	60	2	Yes
Cu	1.5	3.5	1.5	57.1	2	Yes
Pb	0	1.8	1.8	0	1	No
Pb	0.5	1.8	1.4	22.2	1	No
Pb	1	1.8	1.1	38.9	1	No
Pb	1.5	1.8	0.9	50	1	Yes
Hg	0	0.02	0.02	0	0.005	No
Hg	0.5	0.02	0.012	40	0.005	No
Hg	1	0.02	0.007	65	0.005	No
Hg	1.5	0.02	0.007	65	0.005	No
Cr	0	0.6	0.6	0	1	Yes
Cr	0.5	0.6	0.62	-3.3	1	Yes
Cr	1	0.6	0.61	-1.7	1	Yes
Cr	1.5	0.6	0.6	0	1	Yes

As summarized in Table 4, the raw wastewater contained relatively high concentrations of Cd, Cu, Pb and Hg compared with the Indonesian effluent limits, whereas Cr concentrations were already below the regulatory threshold. Treatment with Moringa oleifera seed powder reduced the concentrations of cationic metals to different extents depending on the applied dose. For Cd and Cu, the largest removal efficiencies were observed at the lowest dose (0.5 g L^{-1}), and the treated effluent at this dose complied with the corresponding standard limits. In contrast, Pb and Hg required higher doses to approach or meet the standards: Pb only fell below the regulatory threshold at 1.5 g L^{-1}, while Hg concentrations, although substantially lowered at 1.0–1.5 g L^{-1}, remained above the stringent limit of 0.005

mg L^{-1}. Chromium showed little change across treatments and remained within the permissible range even without moringa addition, reflecting the limited affinity of unmodified moringa seed powder for Cr(VI) species and the relatively low initial Cr level in the effluent.

Mechanistic interpretation and comparison with previous studies

The observed metal-specific responses can be interpreted in light of known moringa seed chemistry and previous adsorption studies. For Cd and Cu, the effectiveness at 0.5 g/L is consistent with strong adsorption onto amino and carboxyl groups on moringa seed components, as well as electrostatic interactions between the positively charged metal ions and negatively charged or polar functional groups on the adsorbent surface.

Gomes et al. (2022) reported that Moringa oleifera biomass can achieve high adsorption capacities for various metals, with the main mechanisms involving electrostatic interactions, hydrogen bonding and van der Waals forces, depending on the physicochemical nature of the adsorbent–adsorbate system. Desta and Bote (2017, 2021) and Dehghani and Alizadeh (2016) similarly showed that moringa seed-based coagulants and adsorbents are highly effective in reducing turbidity, color, COD and certain dissolved contaminants in different wastewaters, with optimum doses often in the range of 0.1–0.4 g per 500 mL. The present study's optimum dose of 0.5 g/L for Cd and Cu falls within a comparable order of magnitude when scaled to volume, reinforcing the plausibility of the observed trend.

The requirement for higher doses to treat Pb and Hg is also in line with literature indicating that these metals often form more stable complexes and may require more extensive surface coverage or specific binding sites to achieve substantial removal. The presence of proteins and other nitrogen-containing compounds in moringa seeds can facilitate complexation with Hg^{2+}, while Pb^{2+} adsorption may be influenced by both ionic radius and affinity for carboxyl-rich surfaces.

The failure of moringa seed powder to meaningfully reduce Cr(VI) is not unexpected. Cr(VI) exists as oxyanions in solution and is often more effectively removed by reduction to Cr(III) followed by precipitation or adsorption onto positively charged surfaces specifically tailored for anionic species. Since moringa seed powder was not chemically modified in this study, and no reducing agents were applied, its low affinity for Cr(VI) is consistent with previous reports that unmodified moringa-based adsorbents show limited performance for anionic contaminants.

From a mechanistic standpoint, the GC–MS results (Figure 2) provide additional support for the presence of multiple organic constituents that could contribute to metal binding, but they do not isolate which compounds are most responsible for adsorption. A more targeted characterization (e.g. FTIR, zeta potential measurements, protein profiling) would be needed to firmly link specific functional groups to the observed removal patterns.

Implications for agricultural water use and study limitations

For agricultural systems in mining-impacted landscapes, the most relevant question is whether treatment with moringa seed powder can reduce heavy metal concentrations in mine effluent to levels that are safer for downstream irrigation use and for protecting soil and crop quality. In this study, moringa seed powder qualitatively improved water quality with respect to Cd, Cu, Pb and Hg, while having little to no effect on Cr(VI).

However, the dataset available does not explicitly report initial and final metal concentrations for each treatment relative to the Indonesian effluent quality standards in Table 1. Without these numerical values, it is not possible to conclusively state whether the treated effluent consistently met all regulatory thresholds for each metal or whether the water would be fully suitable for unrestricted agricultural use. This is a critical limitation that should be addressed in future work by:

1. presenting full concentration data (means ± standard deviations) for each metal and dose,
2. reporting the number of replicates (n) and applying appropriate statistical tests, and
3. explicitly comparing treated effluent concentrations with regulatory limits and with guideline values for irrigation water and soil protection.

Another limitation is that the current study evaluated only water-phase metal removal. No measurements were made of metal accumulation in soils or crops irrigated with treated effluent. From an agronomic and food safety perspective, such follow-up studies are essential to determine whether moringa-based treatment truly mitigates risks of metal buildup in agricultural soils and edible plant parts.

Despite these limitations, the results indicate that moringa seed powder, a locally available and low-cost biomass from a common agroforestry tree, has promising potential as a bioadsorbent for improving gold mine wastewater quality prior to discharge into river systems that may be connected to agricultural areas. Used appropriately and combined with monitoring of metal levels and crop responses, moringa-based treatment could become part of an integrated strategy to reduce heavy metal loads entering irrigation networks in mining-affected regions.

CONCLUSION

This study assessed the performance of Moringa oleifera seed powder as a bioadsorbent for heavy metals in community gold mine effluent from Bolaang Mongondow Timur, Indonesia, and considered its implications for agricultural water use. Based on the measured initial and final concentrations summarized in Table 4, moringa seed powder reduced the levels of several cationic metals (Cd, Cu, Pb, Hg) in the wastewater, whereas Cr showed little or no improvement across the tested doses. Within the dosage range of 0–1.5 g L^{-1}, an apparent optimum dose of 0.5 g L^{-1} gave the strongest reduction for Cd and Cu, while Pb responded best at 1.5 g L^{-1} and Hg at 1.0 g L^{-1}. These patterns are consistent with known adsorption mechanisms of moringa-based materials, which tend to be more effective for cationic metals than for anionic Cr(VI) species.

From an agro-environmental perspective, the observed reductions indicate that moringa seed powder, a locally available biomass from a common agroforestry species, has promising potential to improve the quality of mine effluent before it enters rivers and canals connected to agricultural areas. By lowering heavy-metal concentrations in discharged wastewater, moringa-based treatment could contribute to reducing metal loads reaching irrigation networks and, indirectly, farming systems. Nevertheless, the present findings are constrained by the use of single, non-replicated measurements and by the focus on water-phase concentrations only, without follow-up measurements in soils or crops. Future research should therefore incorporate replicated experiments with appropriate statistical analysis, explicit evaluation of compliance with irrigation and effluent standards, and field- or mesocosm-scale studies on metal accumulation in agricultural soils and plants irrigated with treated effluent, including potential modifications of moringa-based adsorbents to address Cr(VI).

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