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The initiatives against a swamp-invasive alien plant *Mimosa pigra*: Heavy metal uptake and wood charcoal feedstock

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ABSTRACT

Mimosa pigra, also called giant mimosa, is regarded as one of the most aggressive invasive alien plants due to its ability to grow extensively in various land types. The dominance of this species has been found in a swamp area located in Kutai Kartanegara, East Kalimantan, Indonesia, although the area contained various heavy metals, such as lead (Pb), iron (Fe), manganese (Mn), and mercury (Hg). Hence, it is of interest to point out the ability of *M. pigra* to absorb those metals for its potential application as a phytoremediation agent. Furthermore, the application of *M. pigra* wood as charcoal feedstock was also evaluated, as it can be used by rural societies for energy production. The presence of the evaluated metals was assessed using atomic absorption spectroscopy. The charcoal was produced in a drum-based kiln commonly used by local communities. Our investigation showed that almost all evaluated heavy metals were distributed across the various parts of the above-ground biomass of *M. pigra*, except for Pb. More importantly, it was found that *M. pigra* had the ability to hyperaccumulate Mn and Hg. The *M. pigra* charcoal also revealed desirable properties, indicating its market opportunity. Finally, this study suggested that its utilization as an agent of phytoremediation and wood charcoal feedstock could be one of the baneficial actions against the invasiveness of *M. pigra*.

Keywords: bioenergy, charcoal, invasive, *Mimosa pigra*, phytoremediation.

INTRODUCTION

Mimosa pigra L, commonly called giant mimosa, is considered one of the giant sensitive shrub species native to tropical America (Koodkaew et al., 2018). Due to its strong growth potential, it has been naturalized in many other countries beyond its native region, such as Australia, Eastern and Southern Africa, and South and Southeast Asia (Kato-Noguchi, 2023). This species belongs to the Fabaceae family. Its plantation has been first introduced, established, and proliferated as a cover crop, organic manure, and ornamental plant, even though its population has then invasively spread to various land types, including disturbed forests, floodplains, swamps, riparian areas, agricultural fields, and roadsides (Okonkwo et al., 2016). Although it is characterized as a shrub or small tree, the presence of *M. pigra* poses a serious threat to such habitats (Quy et al., 2023). Numerous studies also reported that *M. pigra* is characterized as a noxious weed, in which its seeds are able to remain dormant for a long period in nature and are easily distributed by animals, humans, and watercourses (Khang et al., 2023). Its seed production annually reaches more than 220,000 seeds per plant, whereas germination occurs when it receives enough moisture (Kato-Noguchi, 2023). Destruction of this species by moderate burning is ineffective, as it can regenerate from the stem base (Welgama et al., 2022). Furthermore, it has been found that secondary metabolites in the *M. pigra* leaves contain allelochemicals that provide a competitive benefit by inhibiting the germination of neighboring plants (Quy et al., 2023). Therefore, this evidence indicates that the invasion of *M. pigra* has a considerable negative impact on biodiversity conservation (Sungsukworn et al., 2021). Due to these characteristics, it has been noted that this species is known as one of the top 100 aggressive and invasive alien species in the world by the IUCN Invasive Species Specialist Group (Guyton et al., 2020).

Metals are defined as materials with a moderately high density relative to water (Razzaq et al., 2024). Heavy metals are currently considered elements that cause significant contributions to soil contamination, affecting the environment and posing health risks. Heavy metals and mineral oils constitute around 60% of the major causes of soil contamination (Touceda-Gonzales et al., 2015). The increase in heavy metal accumulation in soil has been found due to human activities such as intensive agriculture, industrial growth, and urbanization (Rodrigo et al., 2024). It is well known that some heavy metals are hazardous substances that can potentially harm the brain, kidneys, and neurological systems (Khan et al., 2016; Islam et al., 2024). Absorption by plants has emerged as a low-cost, effective method for removing heavy metal contamination (Ren et al., 2016; Tran et al., 2021). This technique is called phytoremediation. However, not all plant species are capable of this method, as metal uptake may affect physical and biological metabolism, reducing plant growth and biomass yield (Yang et al., 2021). Plants containing heavy metals are dangerous for food and food products (Ali et al., 2019). Hence, it is essential to find other applications of biomass harvested from plants utilized as phytoremediation agents.

Charcoal is one of the renewable energy sources mainly derived from wood and other biomass. Charcoal is produced by carbonizing at high temperatures under limited or controlled oxygen, resulting in a solid, carbon-rich product. The global charcoal production reached 53 million tons, with the highest production coming from Africa (64%), followed by the Asia-Pacific regions (26%), and the remaining from Latin America and the Caribbean (Sangsuk et al., 2023). Some high-income countries, including Germany, France, the United Kingdom, the United States, and Japan, are top global charcoal importers, especially in the barbecue sector (Mencarelli et al., 2022). Charcoal is often used as an energy source for metallurgical processes, such as the iron and steel industry, since it has a high heating value (Getahun et al., 2024). In low- and middle-income countries, charcoal is an essential energy source for urban households and small industries (Rocci et al., 2023). It always plays a fundamental role in cooking and heating requirements (Kongprasert et al., 2019). In order to provide a good-performance charcoal product, the use of traditional earth kilns must be changed since they often release carbon-based products to the atmosphere, such as carbon dioxide (CO_2) and various incomplete combustion products, including carbon monoxide (CO) and methane (CH_4), which decrease the energy properties (Njenga et al., 2023). A previous study revealed that the use of a drum kiln revealed higher efficiency in the production of high-quality charcoal (Sudaryanto et al., 2023). Thus, this method will open the opportunity for its large-scale operation due to its simplicity to be applied in wide-ranging rural communities.

The adaptation of *M. pigra* under various metal stresses, including nickel (Ni), zinc (Zn), chromium (Cr), cadmium (Cd), and copper (Cu), had been reported earlier (Mahalel et al., 2021). The presence of specific heavy metals was probably why *M. pigra* was observed as the only species growing in certain areas, for instance, in some swamp areas located in Kutai Kartanegara, East Kalimantan, Indonesia. Therefore, the objective of the present study was to evaluate the possible heavy metals present in those areas and to analyze the adsorption potential of *M. pigra* as a future phytoremediation agent. Furthermore, the potential application of *M. pigra* woody biomass as charcoal feedstock using a simple modified drum kiln method was also evaluated in order to enhance its economic benefits, since it can be produced locally in rural communities.

METHODOLOGY

Study area

The present work was conducted in a swamp area located in Moehoeran Village, Kutai Kartanegara, East Kalimantan, Indonesia (Figure 1). The research location was selected since almost the entire area was covered by *M. pigra*. A total of four circular random sampling plots with a radius of 1 m from the central plot were made, according to Sutaryo (2009). The plants inside the plot were harvested, and each plant part, including leaf, flower, stem, and bark, was weighed separately. The total moisture content of each plant part was also gravimetrically evaluated by oven-drying at 105 ± 3 °C to calculate the biomass yield in dry condition. The pH measurement was applied to soil and water, while the COD analysis was only applied to water.

Heavy metals quantification

In this study, the presence of various heavy metals commonly found in a swamp area, including lead (Pb), iron (Fe), and manganese (Mn), was analyzed using a flame atomic absorption spectroscopy (AAS) instrument according to the SNI 6989-84:2019 standard. On the other hand, mercury (Hg) was evaluated using a cold vapor AAS instrument that followed the SNI 6989-78:2019 standard. The tested samples included water, soil, and *M. pigra* plant parts, including leaf, flower, stem, root, and bark. The water sample was filtered through a Whatman filter paper No. 42 prior to analysis. The soil sample was prepared by oven drying at 105 ± 3 °C, followed by sieving with a size of 60 mesh. Both soil and biomass samples were first destructively digested with 65% HNO_3 and 60% $HClO_4$ before measurement. The quantity of heavy metal found in the plant part was then combined with the data on biomass potential to estimate the heavy metal absorption by *M. pigra* per hectare. Furthermore, translocation factor (TF) and the biological accumulation coefficient (BAC) were calculated according to Tong et al. (2022) as follows:

$$TF = C_{above\ ground\ plant\ part}/C_{root} \quad (1)$$

The TF value of more than 1 shows its capability to effectively translocate heavy metals from the root to above-ground plant parts.

$$BAC = C_{root}/C_{soil},\ C_{stem}/C_{soil},\ C_{bark}/C_{soil},\ C_{leaf}/C_{soil},\ C_{flower}/C_{soil} \quad (2)$$

where: C_{root}, C_{stem}, C_{bark}, C_{leaf}, and C_{flower} – the concentrations of heavy metals present in the root, stem, bark, leaf, and flower, respectively; C_{soil} – the concentration of heavy metals found in the soil.

The BCF value of ≤ 1 suggests that the observed plant is only able to absorb, and the value of > 1 indicates the ability of the plant to accumulate metal.

Charcoal Production

The production of charcoal from *M. pigra* woody biomass followed a procedure outlined by Sudaryanto et al. (2023). The debarked wood was cut to a size of approximately 10 cm. It was then air-conditioned until the moisture content reached less than 15%. The sample was then placed into the modified retort, which is commonly used by rural communities, created from a 200-liter residual oil drum, equipped with a small funnel to connect the syngas into the fuel room to minimize the amount of fuel wood needed. The heating reaction was set at around 4 hours, with a wood and charcoal feedstock ratio of 1:2 (dry condition). The charcoal yield was calculated on the following day as a black solid residue produced from the process. The performance of the obtained charcoal, including calorific value, proximate, and ultimate analyses, was assessed according to the ASTM standards (Haqiqi et al., 2018; Yuliansyah et al., 2019; Mukhdlor et al., 2021; Haqiqi et al., 2022).

RESULTS AND DISCUSSION

Heavy metals in soil and water

The contamination of heavy metals in the soil and water is a serious environmental problem that

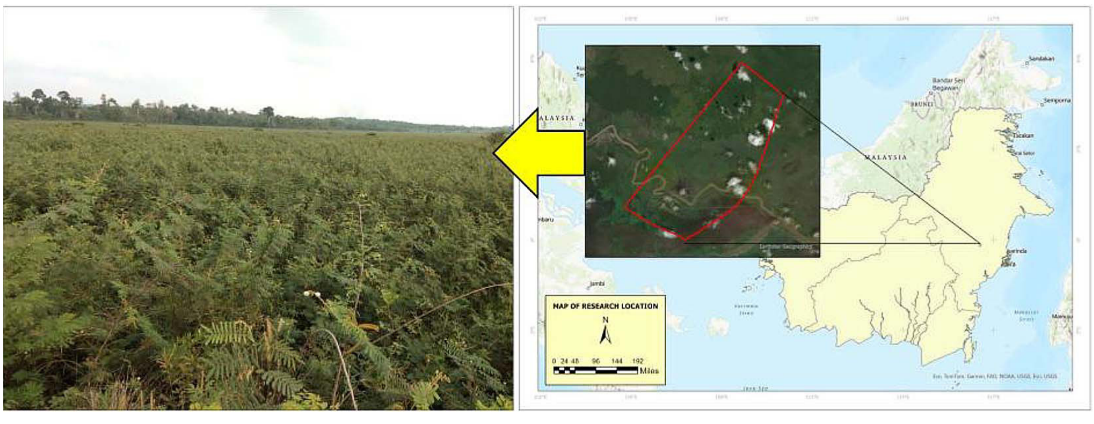

Figure 1. Research location in the swamp area in Moehoeran village, Kutai Kartanegara, East Kalimantan, Indonesia, which is highly covered by *Mimosa pigra*

endangers humans, animals, and microbes. In the research site, the presence of some heavy metals was identified, including lead (Pb), iron (Fe), manganese (Mn), and mercury (Hg). According to Sharma et al., (2026), they were characterized as heavy metals, since they possessed an atomic density of more than 4 g cm^{-3} or five times higher than that of water. The results are displayed in Table 1. The first observed parameter was the chemical oxygen demand (COD) of the water, which recorded 70.77 mg L^{-1}. According to Bhuyan et al. (2018), this value indicated moderate pollution, as it remained below the maximum COD limit of 200 mg L^{-1}. The pH values of the water and soil samples were 6.55 (slightly acidic to neutral) and 5.65 (moderately acidic), respectively. It is well-known that a decrease in pH from neutral to acidic conditions raises the solubility and mobility of cationic heavy metals (Wan et al., 2024). Consequently, the moderately acidic soil condition in this study facilitated higher cationic heavy metal bioavailability (Pb, Fe, Mn, and Hg), particularly in the soil sample. The average concentrations of Pb, Fe, Mn, and Hg in the soil were 22.93 mg kg^{-1}, 1,755.49 mg kg^{-1}, 941.27 mg kg^{-1}, and 0.0002 mg kg^{-1}, respectively. These findings indicated that the concentrations of Pb, Fe, and Hg were within low to normal thresholds, whereas the Mn level was significantly elevated. It has been previously reported that the concentration of Mn in uncontaminated soils was around 488 mg kg^{-1} (Kravchenko et al., 2025). Mn is an essential nutrient for plant growth, but its accumulation in high quantities could induce phytotoxicity and could harm other living organisms (Dey et al., 2023).

Heavy metal absorption by *Mimosa pigra*

M. pigra is identified as the dominant woody species growing in the swamp area of the research site. Although the soil was highly contaminated with Mn, this species unexpectedly exhibited remarkable adaptation. To understand this issue, the accumulation and distribution of various metals within specific plant organs were investigated. The plants capable of efficiently transporting heavy metals from the roots to their aboveground biomass could be a great potential as phytoremediation agents via translocation (Eben et al., 2024). The distribution of Fe, Mn, Pb, and Hg detected in each *M. pigra* biomass part could be seen in Figure 2. Nearly all evaluated metals were present across all plant parts, except for Pb, which was found restricted entirely to the root part (0.86 mg kg^{-1}). This information suggests that *M. pigra* lacked the capacity to translocate Pb from its roots to the aboveground tissue. The concentration of Fe in the roots (1,340.00 mg kg^{-1}) was significantly higher than in other plant parts. This pattern demonstrated that the plant strictly regulated its internal Fe allocation to meet its physiological demands, which was closely linked to the role of Fe as an essential micronutrient. The Mn concentration in *M. pigra* biomass showed substantial variation. The lowest accumulation was observed from the stem (6.74 mg kg^{-1}), followed by a high increase in the flower (43.57 mg kg^{-1}) and bark (84.78 mg kg^{-1}), respectively. Among all plant parts, the leaf reached the highest Mn content with the value of 140.69 mg kg^{-1}. On the other hand, the Hg concentration was relatively comparable to those of all *M. pigra* parts (0.010 – 0.012 mg kg^{-1}).

The translocation factor (TF) is an essential parameter for evaluating heavy metal transfer from soil to plant organs (Kumar et al., 2022). A TF value greater than 1.0 demonstrates that the plant has the capacity to accumulate metals. The TF values in this study are presented in Figure 3. The TF value of Pb was zero, which aligned with the previous discussion, indicating that *M. pigra* lacked the ability to accumulate Pb. The TF value of Fe was low (0.52). Surprisingly, high TF values were obtained for Mn (4.12) and Hg (4.60). The fact that this plant adapted well to areas with high Mn content, coupled with its significant TF value, indicated that *M. pigra*

Table 1. General characteristics of soil, water, and heavy metal concentrations

Sample	COD (mg L^{-1})	pH	Heavy metal concentration (mg kg^{-1})			
			Pb	Fe	Mn	Hg
Water	70.77 ± 5.96	6.55 ± 0.02	0.04 ± 0.02	0.02 ± 0.01	0.10 ± 0.11	0.0002 ± 0.00
Soil	nd	5.65 ± 0.10	22.93 ± 2.62	1755.49 ± 76.92	941.27 ± 216.74	0.0002 ± 0.00

Note: nd : not detected.

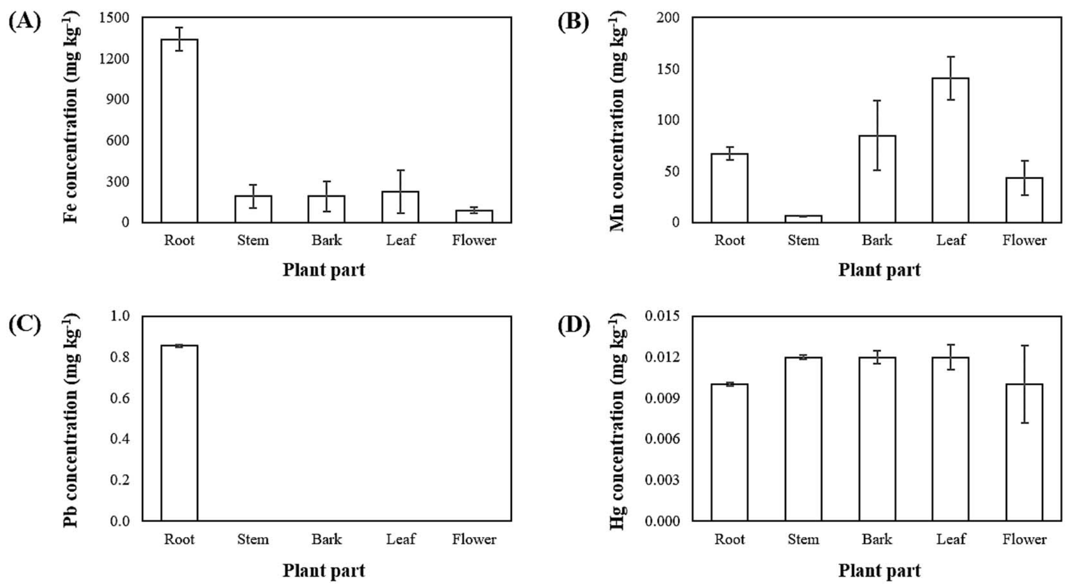

Figure 2. Concentration of heavy metals in the biomass of *Mimosa pigra*: Fe (A), Mn (B), Pb (C), and Hg (D)

was an Mn hyperaccumulator. Consequently, it could be highly suitable for phytoextraction in Mn-contaminated lands. Numerous plant species have been reported as efficient hyperaccumulators capable of extracting and tolerating high concentrations of specific heavy metals in their shoots. For instance, *Noccaea caerulescens* was noted a primary model for understanding the molecular mechanisms of Zn and Cd hyperaccumulation (Morina et al., 2023). In tropical ecosystems, *Phyllanthus rufuschaneyi* has demonstrated remarkable capacities for nickel (Ni) hyperaccumulation, translocation, and foliar storage (Tisserand et al., 2021). Regarding Mn, recent characterizations of plants such as *Gossia bidwillii* and *Phaseolus vulgaris* have verified their ability to accumulate Mn concentrations (Fernando et al., 2010). Li et al. (2023) reported differential heavy metal accumulation among roots, stems, and leaves of dominant woody plants in iron and lead–zinc tailing areas in Jiangxi, Southeast China, confirming tissue-specific uptake patterns. These plants demonstrated the diverse physiological mechanisms to adapt to metalliferous soils, providing a contemporary benchmark for evaluating the phytoremediation potential.

The biological accumulation coefficient (BAC) of *M. pigra* reflected its metal accumulation capacity (Figure 4), showing a similar trend to the total heavy metal accumulation profile that appeared in Figure 3. Only the BAC value of Hg exceeded the threshold of 1.0, reaching a remarkably high average value of more than 50. Although the concentration of Hg in the soil was within normal limits, its accumulation in the shoot was severalfold higher, indicating the strong capacity of this plant as a hyperaccumulator for Hg. However, since this plant was at a juvenile stage (characterized by an average stem diameter of 1.08 cm, an average height of 1.80 m, and a stand density of 62,000 plants ha^{-1}), it was stated that the bioaccumulation capacity for other metals, particularly Mn and Fe, did not yet reflect its ultimate potential. Metal accumulation in plants highly depends on plant age and seasonal variations (Matei et al., 2025).

The metal concentration patterns in the biomass of *M. pigra* varied among plant tissues, indicating tissue-specific uptake and translocation. We further evaluated its absorption capacity (Table 2). The stem accumulated the highest Fe content (4,023 g ha^{-1}), followed by bark (762.77 g ha^{-1}), leaf (524.28 g ha^{-1}), and flower (203.89 g ha^{-1}). Mn was primarily concentrated in bark and leaf tissues (339.10 g ha^{-1} and 327.82 g ha^{-1}, respectively), with lower amounts in stem and flower (142.38 g ha^{-1} and 101.53 g ha^{-1}). Hg were absorbed in smaller quantities, detected only in trace amounts totalling 0.35 g ha^{-1}. The absence of the Pb in the above-ground biomass suggested that *M. pigra* selectively translocated Fe, Mn, and Hg from the roots to the shoots. Regarding the effectiveness of woody invasive species for heavy metal uptake, Miletić et al. (2026) reported that invasive plants commonly accumulate heavy

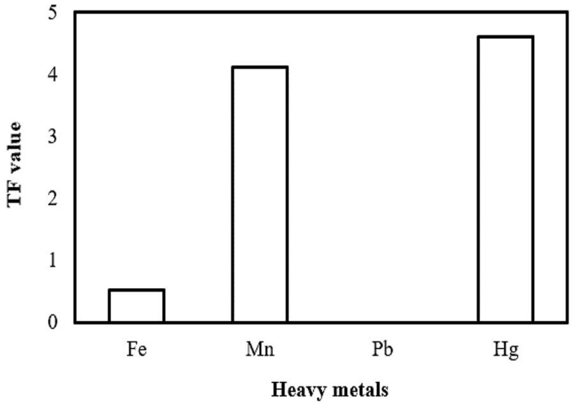

Figure 3. Translocation factor of the evaluated heavy metals by *Mimosa pigra*

metals in a tissue-specific manner, reflecting their adaptability to contaminated environments. Furthermore, Khan et al. (2023) highlighted that both invasive and perennial woody species could serve as phytoremediation agents while providing biomass for energy production. Such a dual benefit will create a win-win scenario, given that *M. pigra* produces rapid and abundant woody biomass that can be readily harvested as a sustainable energy source.

Woody biomass of *Mimosa pigra* as charcoal feedstock

The woody biomass of *M. pigra* represents a sustainable and potential material for charcoal production (Table 3). It is well-known that charcoal can be effectively produced by charcoal kilns from modified recycled drums, a method highly accessible for local communities that typically yields a charcoal recovery rate of approximately 30% based on the weight of raw material. The estimation of charcoal production from *M. pigra* was 6.34 tons ha^{-1}. The charcoal exhibited a high calorific value of 6,478.92 kcal kg^{-1}, surpassing the minimum national standard (Yuniarti et al., 2025) and confirming its viability for domestic commercialization. The fixed carbon, volatile matter, moisture, and ash contents were determined to be 60.28%, 30.22%, 6.34%, and 3.16%, respectively. The calorific value was strongly driven by the fixed carbon content. Hence, process optimization is still necessary to reach international export benchmarks, where the fixed carbon fraction must be elevated to reach approximately 70% (Mencarelli et al., 2022). A low ash content of *M. pigra* charcoal (<5%) is a key market requirement for commercial products (Oke et al., 2022). The physicochemical properties of this charcoal were further shown by ultimate analysis. The relatively high oxygen content (20.51%) indicated that the woody biomass was not completely carbonized. However, this implies that *M. pigra* charcoal can be further upgraded to meet export-quality standards by employing more efficient carbonization methods.

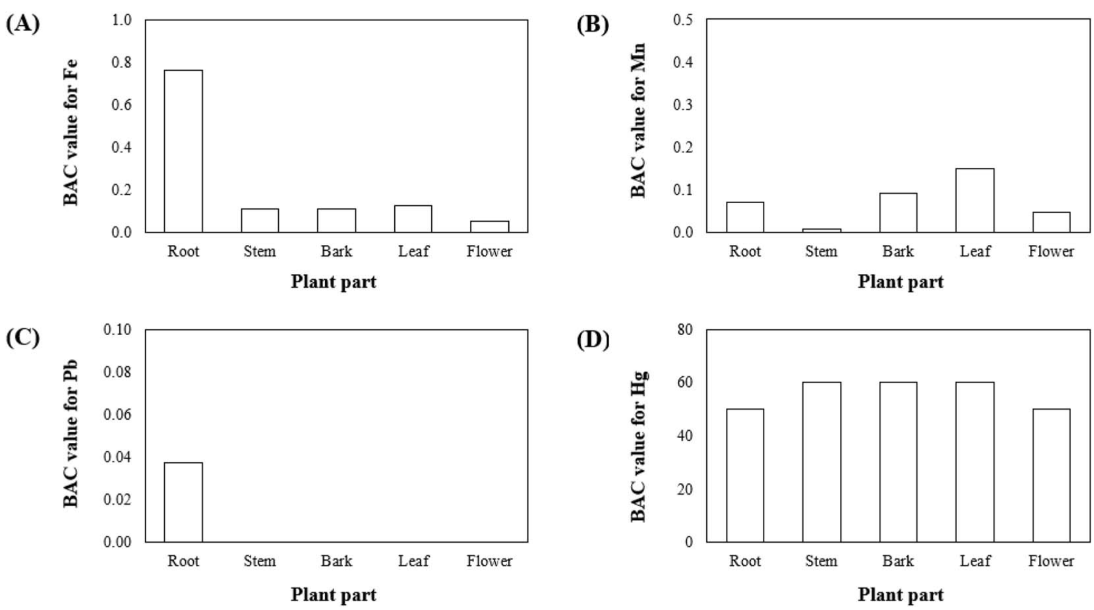

Figure 4. Biological accumulation coefficient based on each plant part of *Mimosa pigra*: Fe (A), Mn (B), Pb (C), and Hg (D)

Table 2. Total heavy metals accumulated in the above-ground biomass of *Mimosa pigra*

No	Plant part	Biomass (ton ha^{-1})	Total heavy metals absorbed by plant (g ha^{-1})			
			Fe	Mn	Pb	Hg
1	Stem	21.14	4,023.08	142.38	nd	0.25
2	Bark	4.00	762.77	339.10	nd	0.05
3	Leaf	2.33	524.28	327.82	nd	0.03
4	Flower	2.33	203.89	101.53	nd	0.02
5	Total above ground plant part	29.80	5,514.02	910.82	nd	0.35

Note: nd : not detected.

Table 3. Properties of charcoal produced from *Mimosa pigra* woody biomass

No	Analysis	Value
1	Calorific value (kcal kg^{-1})	6,478.92
	Proximate	
2	Fixed carbon (%)	60.28
3	Volatile matter (%)	30.22
4	Moisture content (%)	6.34
5	Ash (%)	3.16
	Ultimate	
6	C (%)	71.04
7	O (%)	20.51
8	H (%)	4.86
9	N (%)	0.38
10	S (%)	0.03

CONCLUSIONS

Finally, the obtained findings suggested that the high Mn contamination might explain why *M. pigra* was the exclusive species growing at the study site with high domination. Interestingly, almost all evaluated heavy metals were distributed throughout the biomass of this species. The capacity of *M. pigra* as a hyperaccumulator of both Mn and Hg could potentially expand its application for the phytoremediation of lands heavily contaminated with these specific metals. The high woody biomass availability of *M. pigra* makes it a highly advantageous feedstock for generating a high-quality charcoal product. It was predicted that achieving a comparable biomass yield to that observed in this study would require two to three harvesting cycles per year, confirming the rapid growth of this invasive species. In some cases, while invasive plant species commonly disrupt native biodiversity or commercial biomass plantations under normal conditions, their high adaptability to heavy metal-contaminated marginal lands offers a distinct advantage for utilization in non-food sectors, such as premium charcoal production. Hence, the development of this concept will foster long-term sustainability within rural communities, catalyzing a circular economy that will enhance local energy security while simultaneously generating new income streams.

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