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Evaluating the productivity of five forages for the phytoremediation of heavy metal-contaminated land

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Abstract: Post-tin mining land holds promise for cultivating forage crops, with the potential to address Pb metal contamination through plant-based phytoremediation. However, the presence of heavy metals and depleted soil fertility resulting from tin mining activities may pose challenges to plant productivity and contribute to residual heavy metal accumulation. This study aims to assess the productivity and phytoremediation capacity of Pb by various grass species on reclaimed mining land. Using a randomised block design with three replications, the study was conducted over a four-year period in a post-mining area in Central Bangka Regency, Indonesia. Three grass species: *Megathyrsus maximus* ('Riversdale' and 'Purple guinea'), *Pennisetum purpureum* ('Taiwan' and 'Mott'), and *Chrysopogon zizanioides* were evaluated for forage production, quality, digestibility, and heavy metal content. It was shown that 'Riversdale' and 'Purple guinea' cultivars had relatively stable production for over four years, with the crude protein content of all grass types remaining relatively low (<6%), apart from 'Mott' cultivar, which had a crude protein content of 10%. The Pb concentration in the plants remained below the permitted limits for ruminants. In the post-tin mining site, 'Riversdale' and 'Purple guinea' cultivars showed potential for development. It is concluded that mined land can be replanted with forage crops for phytoremediation purposes. 'Purple guinea' and 'Riversdale' cultivars emerge as potential livestock feed sources on ex-mining land due to their four-year productive stability and low lead (Pb) concentration in their shoots, which falls below the safe threshold for cattle.

Keywords: forage, heavy metal, post-tin mining land, ruminant feed

INTRODUCTION

Tin is mostly mined on the islands of Bangka Belitung in Indonesia, with such mining accounting for up to 27.6% of the total land area (Inounu, 2008). Tin mining land on Bangka Belitung Island covers a total area measuring 124,838 ha (Sukarman *et al*., 2016). Former tin land is a suboptimal land type, dominated by a sand fraction, with sand and loamy sand textures, meaning it has a low water holding capacity and a very low soil fertility status, with a soil pH value of 4.3–4.5, organic carbon (C) content 0.22–0.32%, and a very low cation exchange capacity (CEC) (Nurcholis, Wijayani and Widodo, 2013). Studies have shown that heavy metals such as Cd (Ariani *et al*., 2018), Zn, and Pb (Puttiwongrak *et al*., 2019) are present in former tin land. Moreover, Rahmat *et al*. (2022) detected As, Pb, Cu, Fe, Cd, Cr, Ni, and Zn in such soil. Heavy metals, such as Fe, Cu and Zn, are essential micronutrients for plants and animals, but excessive amounts can be toxic to plants. The toxic effect of heavy metals on plants can be both direct, through the inhibition of cytoplasmic enzymes and damage to cell structures caused by oxidative stress from high metal content (Bartkowiak *et al*., 2020), and indirect, through the loss of plant-beneficial microbes or interference with a key nutrient exchange in plant cation exchange processes (Taiz and Zeiger, 2002).

The former tin mining land in Central Bangka Regency has the potential for agricultural use through land reclamation and soil quality improvement (Asmarhansyah, 2016). However, land improvement entails significant expenses, as it involves the addition of organic matter and various nutrients. Cost reductions can be achieved through phytoremediation methods, as this approach employs plants to remove contaminants from the environment without the need for high energy or expensive chemicals (Wei *et al*., 2021). Phytoremediation has been employed to reduce contaminants such as heavy metals, explosives, petroleum hydrocarbons, and radioactive substances (Dixit *et al*., 2015; Tang, 2019). Research on phytoremediation has been extensive, particularly the identification of plant species capable of removing different contaminants from diverse environmental matrices (Ali *et al*., 2020; Tang, 2023). Research findings have demonstrated the accumulation of heavy metals such as As (Souza *et al*., 2019), Cd (Bastos *et al*., 2019; Li *et al*., 2021), hydrocarbons (Ekperusi *et al*., 2020), and 2,4,6-trinitrotoluene (TNT) in the soil (Aken van *et al*., 2011). Phytoremediation mechanisms have been extensively studied, with the most frequently cited approaches including phytoextraction, rhizofiltration, phytostabilisation, phytovolatilisation, phytodegradation and rhizodegradation (Cristaldi *et al*., 2020).

Forage crops (FC) are potential candidates for phytoremediation, and their presence in former tin mining sites can also transform the surrounding area into a livestock hub, providing organic material for land improvement. The phytoremediation role of FC was reported by Khodijah *et al*. (2019), who categorised *Pennisetum purpureum* Schumach and *Chrysopogon zizanioides* (L.) Roberty as phytostabilisers and accumulators of lead (Pb) in former mining sites. *C. zizanioides* has demonstrated the capability to reduce total petroleum hydrocarbons (TPH) and total oil and fat in former mining lands (Nero, 2021). Furthermore, *C. zizanioides* has been shown to remove 88% of TNT from the soil within 12 days (Das *et al*., 2010). The phytoremediation potential of *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs grass has also been documented by Olatunji *et al*. (2014), who reported that this grass can accumulate heavy metals such as Pb, Cr, and Cd, making it a viable option for phytoremediation in heavy metal-contaminated soils.

The potential of FC, specifically *P. purpureum*, *C. zizanioides* and *M. maximus*, as phytoremediators in heavy metal-contaminated soils justifies the need for related research and development of these FC varieties in former tin mining areas in Central Bangka Regency. Such an investigation is expected to yield effective FP varieties for land reclamation in contaminated tin mining sites in the region. To date, planting FC as a phytoremediation approach using these FC types has also been relatively limited. Furthermore, related research spans several periods (years) in the observation of the long-term effects of such plants as phytoremediators. The novelty of this study lies in the discovery of a forage species with high productivity when cultivated on reclaimed mining land, without causing toxicity to livestock. The study's aim is to determine the productivity of forage grasses on reclaimed mining land as a ruminant feed source in Central Bangka Regency, Indonesia.

MATERIALS AND METHODS

STUDY AREA

The research was conducted over a four-year period (2017–2020) in Bukit Kijang Village, Namang District, Central Bangka Regency, Indonesia, located at 2°14'07.0" S, 106°11'41.0" E at an altitude of 26 m a.s.l. Rainfall ranged from 60.4 to 411.9 mm, 0 to 224 mm, 0 to 388.5 mm, and 0 to 372 mm between 2017 and 2020, respectively. Temperature ranged from 22.97 to 31.70°C, from 22.13 to 31.63°C, from 22.67 to 31.96°C, and from 23.89 to 31.32°C between 2017 and 2020, respectively (Indonesian Agency for Meteorological, Climatological and Geophysics, 2024).

The characteristics of sandy tailing piles from post-tin mining were assessed and evaluated as a basis for phytoremediation measures. Composite soil samples were collected from each soil layer on all sides of the profile, thoroughly mixed, and then subsampled (~1 kg) for chemical and heavy metal analyses.

EXPERIMENTAL DESIGN AND TREATMENTS

Seeds from cuttings and pols were directly planted into cultivated land in 20 m^2 plots with 50 cm × 50 cm spacing. At planting, an organic fertiliser dose of 40 $Mg \cdot ha^{-1} \cdot y^{-1}$ was applied. This was made by a mixture of ruminant manure, with sawdust, dry leaf litter, and water plants at a 2:1 ratio. The pH value and chemical composition of the organic fertiliser are presented in Table 1.

DATA COLLECTION AND MEASUREMENT OF FORAGE ON THE POST-TIN MINING LAND

The variables observed in the study were plant height, number of tillers, and fresh and dry mass of the forage production, with a cutting interval of 2 months over a period of four years (2017–2020). The forage data obtained were analysed statistically using the Gomez and Gomez (1983) method, while the chemical content of the forage was analysed at the end of the research.

Table 1. The pH value and chemical composition of organic fertiliser

Item	Unit	Value
pH H_2O	–	7.70
Chemical composition		
Water content	%	47.53
Other materials		0.00
C-organic		13.25
N-total		0.61
C:N ratio	–	21.72
P_2O_5-total	%	0.80
K_2O-total		1.84
Fe-total	ppm	6,468
Mn-total		166.00
Zn-total		32.00
Pb-total		10.00
Cd-total		nd
As-total		0.10
Hg-total		0.01
La-total		0
Ce-total		nd

Explanations: nd = not detected.
Source: own study.

IN VITRO PROCEDURE

Organic matter digestibility (*OMD*) and dry matter digestibility (*DMD*) were assessed *in vitro* using a technique by Tilley and Terry (1963). A 0.5 g. sample of forage, 40 mm^3 of McDougall buffer, and 10 mm of cattle rumen fluid were added into an *in vitro* tube. After being submerged in a shaker water bath, the tubes were incubated at 39°C for 48 hours. After 48 h of incubation, the residue was dried at 105°C for 24 h and then burned for 7 h at a steady 600°C to determine the digestibility of the organic matter.

CHEMICAL ANALYSES

Dry mass, crude protein, ash, calcium, and phosphor were measured using the AOAC (2005) method, while neutral detergent fibre (NDF) and acid detergent fibre (ADF) were measured using the Soest van *et al.* (1991) procedures. Measurement of the heavy metals was made based on Indonesian National Standard (Ind.: Standar Nasional Indonesia – SNI) 19-2896 (SNI, 1998) using an atomic absorption spectrophotometer (AAS) in relation to the determination of heavy metals Pb, Cd, Cr, Sn, Hg, Cu in soil and forage.

The heavy metal sample identification after preparation involved heating in a furnace at 400°C for 2 h to remove organic matter. The aqua regia extraction method was then used to determine the total metal content of each sample. This method consists of partially digesting (with HNO_3–HCl) 1 g of soil sample for 2 h at 90°C. Subsequently, the sample was diluted to 100 mm^3 with deionised water, allowed to stand for 3 hours, and then filtered. An atomic absorption spectrometer with a flame was used to analyse the heavy metal elements. All the results were measured in duplicate, and the average values were calculated.

The efficiency of Pb absorption by plants was calculated using Baker's efficiency formula (Baker, 1981).

$$Y_i\ (\%) = \frac{A_i}{B_i}\ 100\% \tag{1}$$

where: Y_i = absorption efficiency of Pb (%), A_i = Pb content in plant (mg·kg^{-1} DM), B_i = Pb content in the soil (mg·kg^{-1} DM), DM = dry mass.

STATISTICAL ANALYSIS

The data were analysed using analysis of variance (ANOVA), and any significant difference between treatments was compared with the least significant difference (*LSD*) test procedure at a significance level of 0.05% (Steel and Torrie, 1993) employing SAS 9.4 software.

RESULTS

The soil analysis results show that heavy metals such as Cu, Pb, and Hg were detected in all the soil samples (Tab. 2). However, their concentrations were very low. Specifically, the contents of

Table 2. The initial pH value, carbon, nitrogen and heavy metals of soil post-mining in Central Bangka Regency, Indonesia

Code	pH (H_2O)	C	N	P_2O_5	K_2O	Cu	Pb	Cd	Sn	Hg
		%		mg·100 g^{-1}		ppm				ppb
GA-01	4.70	0.60	0.04	7	1	0.67	22.90	nd	nd	nd
GA-03a	4.80	0.33	0.03	4	1	0.38	10.00	nd	nd	nd
GA-03b	4.90	0.37	0.03	5	1	0.48	15.10	nd	nd	39.80
GA-04	5.20	0.22	0.02	3	1	0.24	9.30	nd	nd	nd
GA-05	5.60	0.20	0.02	3	1	0.10	8.50	nd	nd	16.50
Average	5.04	0.34	0.028	4.4	1	0.374	13.14	–	–	11.26

Explanations: nd = not detected.
Source: own study.

Cu, Pb and Hg in the post-tin, mining soil were 0.374 ppm, 13.14 ppm and 11.26 ppb, respectively. Other heavy metals, such as Cd and Sn, were not detected. In addition, the available P_2O_5, K_2O and organic carbon and nitrogen content of the soil was detected at low concentrations. The initial available P_2O_5 and K_2O in the study were around 4.4 and 1 mg per 100 grams of soil, respectively. However, our findings indicate that these concentrations increased slightly after plantation with forage, together with an increase in the pH value, and carbon and nitrogen content (Tab. 3). The concentrations of carbon and nitrogen rose by almost 78 and 11%, respectively, in 2020, and more than doubled and increased fivefold in 2021 (Tab. 3).

Table 3. Physical and chemical characteristics of soil post-tin mining after planting

Parameter		Unit	Year	
			2020	2021
Texture	sand	–	76	72
	dust		18	20
	clay		6	8
pH	H_2O	–	5.30	5.80
	KCl		4.60	5.10
Organic matter	C-organic	%	0.38	0.72
	N		0.05	0.10
	C:N ratio	–	8.00	7.00
Extract HCl 25%	P_2O_5	$mg \cdot 100\ g^{-1}$	12.00	18.00
	K_2O		4.00	5.00
P_2O_5 (Bray–1)		–	21.00	16.00
Alkaline cation	Ca	$cmol \cdot kg^{-1}$	0.32	0.85
	Mg		0.18	0.31
	K		0.09	0.10
	Na		0.03	0.02
	total		0.62	1.28
CEC			2.76	5.20
Al, KCl 1N			0	0
H, KCl 1N			0.10	0.15
Base saturation		%	22.00	24.60
Al saturation			0	0

Explanations: *CEC* = cation exchange capacity.
Source: own study.

The fresh mass of forage production in this study differed ($p < 0.05$) between the three forage species (Tab. 4). *C. zizanioides* had the highest fresh mass in the first to third years of the growing seasons, whereas in the fourth year, *M. maximus* 'Purple guinea' grass had the highest fresh mass. The fresh mass production of *M. maximus* 'Riversdale' and *P. purpureum* 'Taiwan' grasses gradually increased each year over the four-year period. However, the fresh mass production of *M. maximus* 'Purple guinea', *C. zizanioides* and *P. purpureum* 'Mott' grasses varied. The dry mass of forage production also differed ($p < 0.05$) among the three forage species in the fourth year of the study (Tab. 5), with *M. maximus* 'Purple guinea' grass having the highest dry mass. The dry mass production of all types of grass observed varied over the four years. The number of tillers correlated directly with the fresh and dry forage mass, as seen from the high fresh and dry forage mass of *C. zizanioides* during the first to third years of the growing seasons and of *M. maximus* 'Purple guinea' grass in the fourth year (Tab. 6).

Table 4. Fresh mass of five types of grass (three species) on post-tin mining land

Forage species	Fresh mass ($Mg \cdot ha^{-1}$)			
	year 1	year 2	year 3	year 4
Megathyrsus maximus 'Riversdale'	14.28^{bc}	17.25^{b}	18.14^{b}	21.05^{ab}
Pennisetum purpureum 'Taiwan'	12.16^{c}	14.13^{b}	15.43^{b}	17.26^{bc}
Pennisetum purpureum 'Mott'	19.24^{ab}	27.66^{ab}	23.26^{ab}	14.02^{c}
Chrysopogon zizanioides	21.61^{a}	39.02^{a}	30.18^{a}	17.03^{bc}
Megathyrsus maximus 'Purple guinea'	11.99^{c}	20.21^{b}	19.22^{b}	22.55^{a}
LSD ($p < 0.05$)	5.10	4.89	5.10	6.01

Explanations: different letters in the same column indicate a statistically significant difference based on the least significant difference (*LSD*) test ($p < 0.05$).
Source: own study.

Table 5. Dry mass of five types of grass (three species) on post-tin mining land

Forage species	Dry mass ($Mg\ DM \cdot ha^{-1}$)			
	year 1	year 2	year 3	year 4
Megathyrsus maximus 'Riversdale'	5.99	5.69	5.45	$6{,}95^{b}$
Pennisetum purpureum 'Taiwan'	5.23	5.28	5.43	$6{,}44^{b}$
Pennisetum purpureum 'Mott'	6.06	6.27	5.27	$3{,}69^{c}$
Chrysopogon zizanioides	7.35	8.45	6.54	$3{,}18^{c}$
Megathyrsus maximus 'Purple guinea'	4.19	7.88	7.49	$8{,}79^{a}$
LSD ($p < 0.05$)	ns	ns	ns	2.47

Explanations: ns = non-significant, DM = dry mass, other as in Tab. 4.
Source: own study.

The nutrient content of the grass, such as crude protein, calcium and potassium, varied ($p < 0.05$) by species across the four years, as shown in Table 7. The results reveal that *P. purpureum* 'Mott' had the highest crude protein (*CP*) content ($p < 0.05$), at approximately 10%. On the other hand, the other types of grass (*M. maximus* 'Riversdale', *P. purpureum* 'Taiwan', *C. zizanioides*, and *M. maximus* 'Purple guinea') contained crude protein levels of less than 6%. In addition, the potassium (K) content of *M. maximus* 'Riversdale' grass was the highest, at around 4%, whereas the calcium (Ca) content of *C. zizanioides* and *M. maximus* 'Purple guinea' grasses was higher than that of the other grasses. The phosphorus content and *in vitro*

Table 6. Number of the tiller of five types of grass (three species) in post-tin mining land

Forage species	Tiller (pcs)			
	year 1	year 2	year 3	year 4
Megathyrsus maximus 'Riversdale'	63.89[a]	85.59[ab]	52.53[a]	58.90[a]
Pennisetum purpureum 'Taiwan'	12.56[b]	15.56[c]	6.07[c]	4.08[c]
Pennisetum purpureum 'Mott'	16.33[b]	17.74[c]	9.93[c]	7.86[c]
Chrysopogon zizanioides	66.55[a]	105.37[a]	60.53[a]	45.80[b]
Megathyrsus maximus 'Purple guinea'	57.00[a]	69.37[b]	25.72[b]	56.87[a]
LSD ($p < 0.05$)	22.22	24.03	60.26	10.22

Explanations: as in Tab. 4.
Source: own study.

Table 8. Heavy metal content in five types of grass (three species) in post-tin mining land (% DM)

Forage species	Pb (ppm)	Cd	Cr	Sn	Hg	Cu
Megathyrsus maximus 'Riversdale'	0.67[a]	nd	nd	nd	nd	nd
Pennisetum purpureum 'Taiwan'	0.33[b]	nd	nd	nd	nd	nd
Pennisetum purpureum 'Mott'	0.33[b]	nd	nd	nd	nd	nd
Chrysopogon zizanioides	0.47[ab]	nd	nd	nd	nd	nd
Megathyrsus maximus 'Purple guinea'	0.50[ab]	nd	nd	nd	nd	nd
LSD ($p < 0.05$)	0.22					

Explanations: nd = not detected, other as in Tab. 4.
Source: own study.

Table 7. Nutrient content and digestibility of five types of grass (three species) on post-tin mining land (% DM)

Forage species	*CP*	K	P	Ca	*DMD*	*OMD*
	%					
Megathyrsus maximus 'Riversdale'	5.44[b]	4.32[a]	0.17	0.35[ab]	68.98	56.21
Pennisetum purpureum 'Taiwan'	4.13[b]	2.78[b]	0.13	0.33[ab]	73.58	72.72
Pennisetum purpureum 'Mott'	10.19[a]	2.85[b]	0.16	0.21[b]	73.56	72.14
Chrysopogon zizanioides	5.65[b]	3.15[ab]	0.15	0.38[a]	61.99	63.77
Megathyrsus maximus 'Purple guinea'	5.58[b]	3.23[ab]	0.16	0.43[a]	54.31	52.28
LSD ($p < 0.05$)	7.11	10.38	ns	ns	ns	ns

Explanations: *CP* = crude protein, *DMD* = dry matter digestibility, *OMD* = organic matter digestibility, ns = non-significant, other as in Tab. 4.
Source: own study.

digestibility of both dry and organic matter were not affected by forage species ($p > 0.05$).

The content of heavy metals in the five types of grass (three species) during the four years of the growing seasons is presented in Table 8. The results show that among the five types of grass examined, Cd, Cr, Sn, Hg and Cu were not detected. The only heavy metal detected in the studied grasses was Pb, with the highest concentration found in *M. maximus* 'Riversdale' grass (0.67 ppm) and the lowest in *P. purpureum* 'Taiwan' and 'Mott' grasses (0.33 ppm).

Morphological characteristics were measured at the end of the study. Plant height, stem length, leaf width, and internode length differed among the three species (Tab. 9). Plant height, stem length and leaf length were the highest in *P. purpureum* 'Taiwan' grass ($p < 0.05$), while the internode length of *M. maximus* 'Riversdale' grass was longer than that of the other grasses ($p < 0.05$). Morphological characteristics may contribute to the mass of leaves and stems (Tab. 10). Leaf mass and stem mass were significantly different ($p < 0.05$) among the five types of grass (three species), however, the ratio of leaf to stem was not different ($p > 0.05$) (Tab. 10). *P. purpureum* 'Taiwan' grass had the highest leaf and stem mass, at 821 g and 526 g, respectively. The leaf to stem ratio ranged from 0.57 to 0.67%.

Table 9. Plant growth of five types of grass (three species) on post-tin mining land

Forage species	Plant height (cm)	Stem length (cm)	Leaves length (cm)	Leaf width (mm)	Inter-nodes (cm)
Megathyrsus maximus 'Riversdale'	149.93[b]	22.40[b]	63.93[b]	13.60[c]	13.80[a]
Pennisetum purpureum 'Taiwan'	233.60[a]	42.93[a]	107.67[a]	42.60[a]	9.27[ab]
Pennisetum purpureum 'Mott'	100.47[b]	20.40[b]	55.73[b]	31.27[b]	2.27[c]
Chrysopogon zizanioides	146.40[b]	9.73[c]	108.53[a]	8.33[c]	7.20[bc]
Megathyrsus maximus 'Purple guinea'	144.60[b]	15.13[c]	59.13[b]	14.00[c]	11.60[ab]
LSD ($p < 0.05$)	49.88	10.16	19.32	7.47	6.24

Explanations: as in Tab. 4.
Source: own study.

Table 10. Trait-productivity relationships of five types of grass (three species) on post-tin mining land

Forage species	Stem mass (g)*	Number of tillers (pcs)	Leaf mass (g)*	Ratio (leaf:stem)
Megathyrsus maximus 'Riversdale'	487.00[bc]	52.53[a]	328.33[bc]	0.67
Pennisetum purpureum 'Taiwan'	821.30[a]	6.07[c]	526.00[a]	0.64
Pennisetum purpureum 'Mott'	607.00[ab]	9.93[c]	420.33[ab]	0.69
Chrysopogon zizanioides	322.30[c]	60.53[a]	207.67[c]	0.64
Megathyrsus maximus 'Purple guinea'	333.30[c]	26.33[b]	188.67[c]	0.57
LSD ($p < 0.05$)	241.88	10.12	181.09	ns

Explanations: * = fresh mass, other as in Tab. 4.
Source: own study.

DISCUSSION

LAND CONDITIONS AND HEAVY METAL CONTENT

Previous studies have reported on the types of heavy metals found in post-tin mining areas, particularly in Bangka Belitung (Sukarman and Gani, 2017). In this study, the content of Cu, Pb and Hg in soil was still below the standards set by several countries, such as the US, Canada and Australia, for agricultural land (He *et al.*, 2015). The pH values found in ex-tin mining land ranged from 4.7 to 5.6, which falls within the common condition range (Agus *et al.*, 2017; Sukarman *et al.*, 2020; Wulandari *et al.*, 2022). Anda *et al.* (2022) reported that ex-tin mining ground had a pH range of 5.2 to 6.3, which was higher than the original parent soil due to the reduced Al exchange rate. The sandy nature of ex-mines reduces the capacity to retain aluminium. Arsyad (2010) reported that after tin mining in Malaysia, the soil fraction consisted of 95% sand and gravel, while Anda *et al.* (2022) reported that the sand percentage increased to 82–96% compared to the original soil, which contained just 69% sand. The texture of sand in former tin-mining soil suggests that it has a very low water-holding capacity; in addition, the soil temperature can rise during the day, which can be a factor limiting plant growth.

The low level of organic matter is the result of mining activity, which removes organic matter from the soil (Hamid *et al.*, 2017; Anda *et al.*, 2022). Therefore, improving the low organic N and C values is essential for cultivating high-yielding plants, including forage crops. Improving soil fertility can be achieved by applying soil amendments, utilising organic fertilisers, or employing plants for phytoremediation purposes. In this study, these concentrations of N and C slightly increased after planting with grasses. The pH value and concentration of P_2O_5 and K_2O also increased. Additionally, the proportion of sandy texture soil fell from 76 to 72%. This suggests that the addition of organic material from grasses can improve soil texture after tin mining. Such an improvement results in a more friable texture, neutralises soil acidity, and can enhance yield, quality and stress resistance, together with promoting growth (Hou *et al.*, 2013).

PRODUCTIVITY OF FORAGE CROPS

In the fourth year, *M. maximus* 'Purple guinea' grass produced the highest amount of forage. The type of grass did not influence its dry mass from the first to the third year, and there were no significant differences observed in dry mass production among all types of grass. However, in the fourth year, the type of grass did affect the dry mass output, with *M. maximus* 'Purple guinea' grass producing more than other types. It is suggested that the fall in soil lead content, as a result of the addition of organic matter (fertiliser) and the accumulation of lead in the plant roots, contributed to the increased forage production in the fourth year.

Compared to optimal land, the research found that the production of fresh forage was relatively lower, which is thought to be due to the presence of Pb in the soil (Syam, Hasan and Rusdy, 2021). Amin *et al.* (2018) reported that such presence at levels of 100–1000 mg·kg^{-1} led to reduced fresh and dry production of forage and roots in *Cyamopsis tetragonoloba* L. and *Sesamum indicum* L. Pb exposure was also shown to cause a reduction in the plant height, leaf number and dry mass production of sunflowers (Hung *et al.*, 2014). Nascimento *et al.* (2014) observed reduced forage production in various grass species including *Brachiaria decumbens* 'Balsilisk', *Brachiaria brizantha* 'Xaraes' and 'Marandu', *M. maximus* 'Aruana' and 'Tanzania', *B. decumbens*, and *Chloris gayana*, as a result of Pb exposure. These reductions in forage biomass were attributed to disturbances in metabolic activity and nutrient absorption in plants growing in Pb-contaminated soil.

DRY MASS AND NUMBER OF TILLERS

M. maximus 'Riversdale', *C. zizanioides*, and *M. maximus* 'Purple guinea' grasses showed the highest number of tillers compared to other types. During the first growing season, *M. maximus* 'Riversdale', *C. zizanioides* and *M. maximus* 'Purple guinea' grasses produced the most tillers, while in the second and third growing seasons, it was just *C. zizanioides* and *M. maximus* 'Riversdale' grasses that produced the greatest number of tillers. By the fourth year, *M. maximus* 'Riversdale' and 'Purple guinea' grasses produced the most. Generally, the number of tillers is proportional to the mass of the forage produced (Fanindi *et al.*, 2022). The quantity of fresh and dry forage produced from each grass type is directly proportional to the number of tillers it produces. *P. purpureum* 'Taiwan' and 'Mott' showed an extremely low number of tillers, likely due to their growth in areas of old tin mining contaminated with Pb. Such contamination can negatively affect root growth, elongation and proliferation, and reduce photosynthesis and leaf number, including tillers (Vasile *et al.*, 2021).

NUTRIENT CONTENT

In the fourth year of the study, the nutritional content of each grass type was evaluated. The analysis revealed that *P. purpureum* 'Mott' grass had the highest crude protein (*CP*) content of 10%. This *CP* value was comparable to that of the same grass grown in optimal soil conditions. However, *P. purpureum* 'Mott' grass intercropped with sweet potato had a lower *CP* content (Widjajanto *et al.*, 2022). The crude protein content of the various grass types ranged from 4 to 5% (Tab. 5). The low *CP* value of grass is believed to be a result of the low N content in ex-tin mining soil (Tab. 3); the N content of the soil has a positive effect on leaf N content (Núñez *et al.*, 2022). Sajimin *et al.* (2021) also reported a low *CP* value in leguminous plants grown on ex-tin mining land. Such a low value in grass can also be attributed to the Pb content in the soil (Tab. 2). Pb in the soil can decrease the absorption and translocation of nutrients in plants, resulting in oxidative stress and genotoxic effects, inhibition of chlorophyll synthesis, and disruption to water balance and membrane integrity (Venkatachalam *et al.*, 2017).

The value of K is influenced by the type of grass, with the highest value obtained by the *M. maximus* 'Riversdale' type. Similarly, the value of Ca is also affected by the type of grass, with *C. zizanioides* and *M. maximus* 'Purple guinea' grass having higher Ca values than the others. Mineral uptake in plants is affected by Pb, and the research results indicate that an increase in Pb content in the growing medium decreases the mineral content, such as Ca, P, K, Mg, and Fe in wheat and spinach plants (Lamhamdi *et al.*, 2013), as well as in *Picea abies* L. (Rout and Das, 2003). The decrease in mineral content was also observed in *P. purpureum* 'Taiwan' grass, with its Ca content falling from the optimal soil condition of around 0.33–4.34% (Mohammed *et al.*, 2015) (Tab. 2). This reduction in minerals is a common effect that occurs in plants exposed to Pb (Lamhamdi *et al.*, 2013). The rates of *DMD* and *OMD* in the grass are influenced by the type of grass, with *P. purpureum* 'Taiwan' and 'Mott' grasses having the greatest values.

HEAVY METAL CONTENT

The European Union has established a permissible level of 10 ppm for lead in feed ingredients, while the National Research Council (NRC) has set the Pb threshold for cattle and sheep at 100 ppm and for pigs and poultry at 10 ppm (Dai *et al.*, 2016). However, it is still essential to closely monitor its accumulation, as it can have negative impacts on human health. The Pb concentration in the tested grass was comparable to that reported in previous studies (Miranda *et al.*, 2012) on *B. decumbens* and *B. brizantha* grass but lower than that reported in a study by Nascimento *et al.* (2014) on *B. decumbens* grass. The difference in Pb concentration among the grass species is thought to be due to differences in their metabolism and anatomy.

The percentage of Pb absorption varied among the five grass types, with *M. maximus* 'Riversdale', *P. purpureum* 'Taiwan' and 'Mott', *C. zizanioides*, and *M. maximus* 'Purple guinea' absorbing Pb at rates of 5.10, 2.51, 2.51, 3.58, and 3.80%, respectively. The low absorption of Pb from soil to shoot is due to the fact that some metals, especially Pb, are insoluble and cannot move freely in the plant vascular system because this toxic element can be immobilised in the apoplastic and symplastic compartments with the formation of sulphate, carbonate, and phosphate deposits (Raskin, Smith and Salt, 1997). Additionally, Pb is generally present as a Pb^{2+} ion (Kabata-Pendias, 2010), which explains the low mobility of Pb in the soil through the formation of stable complexes between the metal and inorganic (Cl^-, CO_3^{2-}) or organic ligands (humic and fulvic acids) present in the soil (Zhang *et al.*, 2013). High accumulation of Pb usually occurs in roots rather than in shoots, indicating that Pb mobility in plants is relatively low. Martin *et al.* (2006) showed that there was no translocation of Pb from roots to shoots in chives (*Allium schoenoprasum* L.), lettuce (*Lactuca sativa* L.), beans (*Phaseolus vulgaris*), and Japanese spinach (*Spinacia oleracea* L.). Low translocation also occurred in the grasses *B. decumbens*, *B. brizantha*, and *M. maximus* (Zhang *et al.*, 2013).

The low translocation of Pb to the shoots of the research grass, as well as its values still being below the permissible threshold for cattle, indicate that the forage crops grown on former tin mining land will not be harmful when given to livestock. Further research should focus on studying the productivity of these grasses on former mining land for several years. Research has shown that *M. maximus* 'Purple guinea' and 'Riversdale' can be good cultivars to be grown on former mining land in Central Bangka. The selection of these cultivars is based on their stable productivity, even tending to increase over four years.

PRECIPITATION AT THE SITE OF RESEARCH

According to Figure 1, it can be seen that in 2017 and 2018, the precipitation in February reached 400 mm compared to January, but dropped dramatically to 150 mm in March before increasing again in April, and then fluctuating downwards. Almost the same trend occurred in 2019 and 2020, although there is a variation in 2020, with rainfall from August decreasing to below 50 mm despite the absence of precipitation from September to December. In 2018, precipitation in the research area began at 200 mm in January, fluctuated until July, and then became rain-free. However, it increased to 130 mm by the end of the period. In 2019 and 2020, a similar trend was observed, although there was some variation in 2020. Rainfall in August decreased to below 50 mm, despite the absence of precipitation from September to December. The annual precipitation decreased from 2,206.05 mm in 2017 to 1,574 mm in 2020. This information is comparable to data from the BMKG station Depati Amir, Bangka Belitung, which recorded a total of 1,534.70 mm and 163 rainy days (Statistics Indonesia, 2017). Additionally, Oldeman, Las and Muladi (1980) classified a month as wet if monthly precipitation was greater than 200 mm and as dry if it was less than 100 mm. Insufficient precipitation affects plant water requirements, which ultimately impacts plant growth and productivity in the area of study.

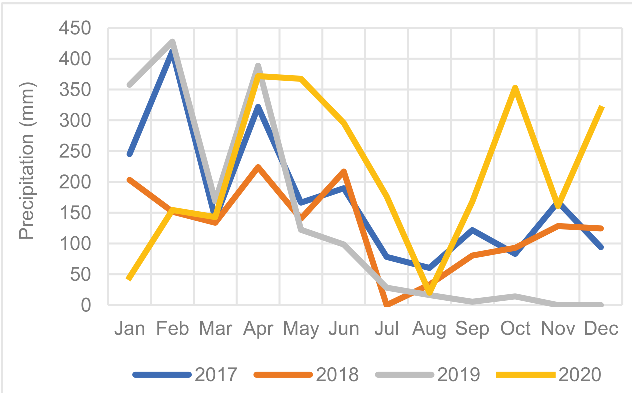

Fig. 1. Precipitation data in the time period 2017–2020; source: own study

CONCLUSIONS

It can be concluded that recently mined land can be replanted with forage crops for phytoremediation purposes. *M. maximus* 'Purple guinea' and 'Riversdale' grasses are potential livestock feed sources on ex-mining land due to their four-year productive stability and low lead (Pb) concentration in their shoots, which is below the safe threshold for cattle. Additionally, these grasses have stable forage production year after year. To improve the productivity of these tolerant forages, additional research is needed on forage plant breeding, especially to enhance their quality. Furthermore, future research should also investigate the accumulation of Pb in cattle tissue over a specific period of time to ensure that its consumption does not pose a health risk to humans.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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