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Productivity and Nutritional Quality of Four Elephant Grass (Pennisetum purpureum) Cultivars under Biochar and Organic Fertilizer Applications at the Third Harvest on Post-Nickel Mining Soil

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ABSTRACT

Nickel mining activities degrade soil quality, necessitating improvement. Post-mining reclamation requires strategic efforts with soil amendments and adaptive plants. Superior grass not only serves as a forage source but also improves soil quality and supports ecosystem stability on degraded land. This study aims to evaluate the effect of biochar and organic fertilizer (OF) (soil amendment agent, SAA) on the productivity and forage quality of the third harvest of four elephant grass cultivars on nickel post-mining land. The study used a factorial design consisting of: Control [–], Control [+], SAA1 = 5 tons/ha biochar + 20 tons/ha OF, and SAA2 = 10 tons/ha biochar + 20 tons/ha OF. Four elephant grass cultivars were utilized, namely: *P. purpureum*, *P. purpureum* cv. GU, *P. purpureum* cv. Mott, and *P. purpureum* cv. Thailand. The results showed that SAA2 treatment significantly increased dry matter (DM) production and forage digestibility compared to other treatments. *P. purpureum* cv. GU produced the highest DM yield (8.885.07 kg/ha) with good nutritional quality and the highest digestibility. The combination of SAA2 × *P. purpureum* cv. GU provided optimum DM productivity (12,094.80 kg/ha) and is recommended as a strategic alternative for providing forage while supporting post-nickel mining land reclamation.

KEYWORDS
Biochar; Forage production; Land reclamation; Organic fertilizer; Pennisetum purpureum

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1. Introduction

Intensive nickel mining activities have caused severe soil quality degradation, characterized by the loss of topsoil layers, low organic matter content, and reduced soil capacity to support vegetation growth (Nadalia and Pulunggono, 2020). These conditions result in post-mining land with low fertility, poor soil structure, and degraded soil biological activity. Therefore, post-mining land reclamation efforts are essential for restoring the land's ecological function and supporting environmental sustainability. One practical approach to reclaiming degraded land is to use soil amendments that improve the soil's physical, chemical, and biological properties. Soil amendments (such as biochar, organic waste, and calcite) and structured biological rehabilitation can improve soil pH, cation exchange capacity, organic matter content, and biological activity, as shown by several studies in Indonesia (Jayadi et al., 2022). Biochar is a soil-improving material produced by pyrolysis of organic matter under oxygen-limited conditions, resulting in a stable, carbon-rich solid. This process creates distinctive physicochemical properties, such as a porous structure, high cation exchange capacity, and nutrient storage ability (biochar with high pH, porous structure, and functional groups), depending on the raw material and pyrolysis temperature (Aziz et al., 2024; Shyam et al., 2025). Several studies have shown that the combination of biochar and organic fertilizers significantly increases soil organic matter content, microorganism activity, and nutrient availability, which are particularly important for marginal soil recovery. Organic biochar with local microorganisms enhances the growth and nutrient content of grasses grown in mixed substrates of iron tailings and mine topsoil (Li et al., 2024). In addition to soil improvement, adaptive and productive crop selection is also a key aspect in the success of land reclamation. Some research supports the use of several Perennial Cover Crops in Brazil to improve soil physical properties while achieving sufficient biomass (Pauletto et al., 2016).

Elephant grass (*Pennisetum purpureum*) is known as one of the superior feed plants, with rapid growth, high biomass production,

Table 1. Overburden soil quality

pH	CEC	Org. C	N Total	C/N	P	K	Sand	Silt	Clay
	(cmol(+)/kg)	————-%	————-		——-ppm	—–	——————	-%————	—-
7.8	8.89	0.50	0.09	5.00	94.29	16.97	37.00	57.00	6.00

CEC: cation exchange capacity; Org.C: organic carbon; N Total: nitrogen total; C/N: carbon to nitrogen ratio; P: phosphorus; K: kalium

and tolerance to unfavorable environmental conditions. Several elephant grass cultivars maintain proper nutritional quality despite longer regrowth, demonstrating their adaptability to agricultural management conditions (Leal et al., 2020). *P. purpureum* is a plant with a low-nutrient demand and good drought tolerance ability due to genetic mechanisms such as overexpression of lignin/flavonoid genes (PpCCoAOMT) that do not compromise growth rate (Song et al., 2022). Superior varieties of elephant grass, such as *P. purpureum* cv. GU, *P. purpureum* cv. Mott, and *P. purpureum* cv. Thailand has been developed to improve the productivity and quality of forage, potentially, and to be used in the rehabilitation of degraded land. In addition to serving as a source of ruminant feed, elephant grass also improves soil quality by accumulating organic matter and preventing surface erosion, thereby supporting ecosystem stability on reclaimed land.

Based on this, the combination of biochar and organic fertilizer for soil improvement, using superior elephant grass cultivars, is expected to increase forage productivity and improve soil conditions on post-nickel-mining land. Therefore, this study aims to evaluate the effect of combining biochar and organic fertilizer on the productivity and nutritional quality of four elephant grass cultivars in the third harvest on post-nickel-mining land. This research is expected to provide a scientific basis for developing a sustainable agricultural system based on post-mining land reclamation, which not only supports the availability of animal feed but also accelerates ecosystem recovery.

2. Materials and Methods

2.1. Cultivation

The research was conducted using overburden (OB) soil-based planting media sourced from the post-nickel mining site of PT Sentratama Karya Cemerlang in South Palangga District, South Konawe Regency, Southeast Sulawesi. The OB soil, left over from the excavation of nickel ore, was used as the next layer of reclaimed soil. Soil is taken at random for some OB dumping. Biochar is obtained from PT Sampangan, Bekasi, West Java, Indonesia, while the organic fertilizer Soil Conditioner Botanic Garden (SCBG) is a product of the National Research and Innovation Agency (BRIN).

The preparation of planting media involves drying the OB soil to facilitate homogenization. The homogenized OB soil was then weighed at 30 kg and placed into a polybag/planter bag with a capacity of 45 kg. The application of soil improvement agent treatment involves mixing the prepared planting media. The amount of organic fertilizer applied at 20 tons/ha is equivalent to 176 g/polybag. In contrast, 5 tons/ha of biochar is equivalent to 44 g/polybag, and 10 tons/ha is equivalent to 88 g/polybag. The dosages of biochar and organic fertilizers are based on soil analysis results for the planting medium (**Table 1**). Soil quality parameters were determined using standard laboratory methods. Soil pH was measured potentiometrically in a 1:2.5 (w/v) soil-to-water suspension. Cation exchange capacity (CEC) and exchangeable K were determined by extraction with 1 M ammonium acetate (NH_4OAc) at pH 7. Organic carbon was analyzed using the Walkley–Black wet oxidation method, while total nitrogen was determined by the Kjeldahl method. Available phosphorus was measured using the Bray I method. Soil texture fractions (sand, silt, and clay) were determined using the hydrometer method. Furthermore, the polybags are placed according to the random pattern determined in the greenhouse ecosystem.

Based on product information, the organic fertilizer used in this study had a pH of 7.92 and an electrical conductivity of 1.25 mS/cm. Its chemical composition comprised ash (40.01%), total C (22.59%), total N (1.25%), total P (0.51%), S (0.30%), K (0.62%), Ca (2.63%), Mg (0.28%), and Na (0.42%). The fertilizer also contained micronutrients, including Mn (598.59 ppm), Cu (29.55 ppm), Zn (151.87 ppm), and Fe (17.744,21 ppm). The contents of humic substances were 93.18 g/kg, consisting of humic acid (76.75 g/kg) and fulvic acid (16.43 g/kg). The biochar used in this study had a moisture content of 10.78% and an ash content of 4.16%. Its iodine adsorption capacity was 716.48 mg/g, with a fixed carbon content of 80.16%.

This study was designed using a Factorial Completely Randomized Design with two factors and four replicates, yielding a total of 64 research units. The first factor is in the form of soil amendment agent treatment, which includes: Control [−] (without the use of soil amendment agent), Control [+] (use of 20 tons/ha of organic fertilizer), application of biochar 5 tons/ha + organic fertilizer of 20 tons/ha (SAA1) and application of biochar of 10 tons/ha + organic fertilizer of 20 tons/ha (SAA2). The second factor in this study is four elephant grass cultivars (*P. purpureum*), including *P. purpureum* and *P. purpureum* cv. Gamma Umami (GU), *P. purpureum* cv. Mott, *P. purpureum* cv. Thailand (Thai.)

The prepared planting media is watered to maintain its moisture and left for 14 d to ensure the soil improvement agent stabilizes in the media. After 14 d, the elephant grass cuttings are planted according to the predetermined treatment. The cultivation process lasted nine months. Plants were watered once every 3 d without the use of advanced fertilizers. During cultivation, four harvests were carried out: the first trimming was done at 75 d after planting (DAP), followed by three additional harvests at 60 d intervals. This study focuses on the second crop yield (third harvest).

2.2. Grass production evaluation

The parameters evaluated in this study were forage productivity and quality. The stem Brix parameter was measured by squeezing water from the plant stem at the bottom, middle, and shoots, and then measuring the sugar content with a refractometer. The contents of crude protein, crude fiber, dry matter (DM), and organic matter (OM) were analyzed using AOAC (2005) methods. Dry matter production was calculated by converting fresh biomass yield into dry matter yield per clump (polybag) through the multiplication of fresh biomass weight by its dry matter content. Furthermore, an assumption of standard spacing

Table 2. Forage quality and production of four *P. purpureum* cultivars under SAA

		OM	DM	CP	CF	Biomass Prod. (kg)	DM Prod (kg/ha)
	°brix	————%————					
SAA							
Control [-]	5.24^{a}	84.93	11.22	9.91	26.50^{a}	3.07	5,502.93
Control [+]	6.15^{bc}	85.93	12.61	11.12	26.80^{a}	3.34	7.168.64
SAA1	6.32^{c}	86.71	13.30	11.19	26.93^{a}	2.88	7.129.48
SAA2	5.72^{ab}	85.88	10.46	10.82	28.31^{b}	4.16	7.671.12
CULTIVAR							
P. purpureum (C1)	6.02	86.90^{b}	13.51	9.97^{a}	28.52^{c}	3.00^{a}	$7.639.24^{b}$
P. purpureum cv. GU (C2)	5.86	86.48^{b}	11.17	10.12^{a}	28.15^{bc}	4.90^{b}	$8.885.07^{b}$
P. purpureum cv. Mott (C3)	5.61	82.91^{a}	9.81	12.97^{b}	24.75^{a}	2.06^{a}	$3.354.06^{a}$
P. purpureum cv. Thai (C4)	5.95	87.15^{b}	13.10	9.98^{a}	27.16^{b}	3.49^{ab}	$7.593.81^{b}$
SAA * CULTIVAR							
Control [-] * C1	5.20	85.07	11.42	9.19	27.71	3.13	6.805.70
Control [-] * C2	5.21	85.73	12.15	8.66	27.58	2.73	4.928.99
Control [-] * C3	5.01	81.57	9.10	11.60	24.63	2.30	2.937.48
Control [-] * C4	5.56	87.34	12.22	10.28	25.93	4.12	7.339.56
Control [+] * C1	6.49	87.47	16.36	10.80	27.63	2.97	9.009.46
Control [+] * C2	6.21	86.10	7.94	10.22	27.68	5.68	8.875.14
Control [+] * C3	6.11	83.93	11.46	13.14	24.75	1.66	3.424.60
Control [+] * C4	5.78	86.23	14.69	10.31	27.13	3.07	7.365.38
SAA1 * C1	6.37	87.99	15.69	10.30	28.29	2.48	7.761.38
SAA1 * C2	6.32	87.76	14.87	10.74	28.05	3.93	9.641.45
SAA1 * C3	5.85	83.06	9.61	14.46	25.01	2.13	3.863.32
SAA1 * C4	6.74	88.02	13.05	9.28	26.39	3.00	7.251.78
SAA2 * C1	6.03	87.09	10.59	9.57	30.44	3.44	6.980.41
SAA2 * C2	5.71	86.34	9.73	10.87	29.29	7.25	12.094.70
SAA2 * C3	5.45	83.06	9.07	12.71	24.61	2.16	3.190.80
SAA2 * C4	5.71	87.03	12.44	10.13	28.89	3.79	8.418.52
SEM	0.10	0.34	0.60	0.26	0.27	0.30	23.25
SAA	**	ns	ns	ns	**	ns	ns
CULTIVAR	ns	**	ns	**	**	**	**
INTERACTION	ns	ns	ns	ns	ns	ns	ns

Different superscripts within the same column indicate highly significant differences. OM: organic matter; DM: dry matter; CP: crude protein; CF: crude fiber.
Control [-]: without soil amendment agent; Control [+]: 20 tons/ha organic fertilizer.
SAA1: 5 tons/ha biochar + 20 tons/ha organic fertilizer; SAA2: 10 tons/ha biochar + 20 tons/ha organic fertilizer.
**: highly significant difference; ns: not significant; SEM: standard error of mean.
^{a,b,c} Means in the same column differ significantly.

1 × 0.5 m for *P. purpureum* on field cultivation was applied, resulting in an estimated planting density of 20.000 clumps per hectare. Accordingly, dry matter production per hectare was determined by multiplying the dry matter yield per clump by 20.000 clumps, as expressed in the following formula:

$$\text{DM Production (kg/ha)} = (\text{Biomass production per clump} \times \%\text{DM}) \times 20.000$$

2.3. In vitro digestibility

In vitro dry matter digestibility (IVDMD) and organic matter digestibility (IVOMD) were determined using the two-stage technique of Tilley and Terry (1963). A total of 64 samples were analyzed in duplicate. Approximately 0.5 g of air-dried and ground sample (passed through a 1 mm sieve) was incubated with buffered rumen fluid (1:4, v/v) under anaerobic conditions at 39°C for 48 h. Rumen fluid was collected from fistulated cattle fed a forage-based diet. After the first incubation, the residues were subjected to pepsin–HCl digestion (0.2% pepsin in 0.1 N HCl) for an additional 48 h. The undigested residues were filtered and oven-dried at 105°C to constant weight for dry matter determination, then burned at 550°C to determine organic matter. Digestibility coefficients were calculated based on the difference between the initial substrate and the residue after incubation.

2.4. Data analyzed

The experiment was arranged in a completely randomized design with a factorial arrangement of treatments, consisting of biochar application and elephant grass cultivars. All data were analyzed using analysis of variance (ANOVA) at the 95% confidence level ($\alpha = 0.05$) in SPSS. Prior to analysis, the assumptions of normality and homogeneity of variances were tested. When significant main effects or interactions were detected ($p<0.05$), mean comparisons among treatment combinations were performed using Duncan's New Multiple Range Test (DMRT).

Table 3. In vitro digestibility of four *P. purpureum* cultivars under SAA

	IVDMD	IVOMD
	(%)	
SAA		
Ctrl [-]	54.35^{b}	51.17^{b}
Ctrl [+]	53.16^{b}	49.83^{b}
SAA1	44.68^{a}	42.88^{a}
SAA2	46.23^{a}	45.00^{a}
CULTIVAR		
P. purpureum (C1)	46.91^{a}	43.77^{a}
P. purpureum cv. GU (C2)	48.03^{a}	46.66^{a}
P. purpureum cv. Mott (C3)	54.87^{b}	52.50^{b}
P. purpureum cv. Thai (C4)	48.16^{a}	45.49^{a}
SAA ∗ CULTIVAR		
Ctrl[-]*C1	51.69^{de}	48.93
Ctrl[-]*C2	53.20^{ef}	49.30
Ctrl[-]*C3	59.73^{fg}	55.13
Ctrl[-]*C4	52.41^{ef}	48.17
Ctrl[+]*C1	52.81^{ef}	47.06
Ctrl[+]*C2	50.77^{ef}	47.24
Ctrl[+]*C3	60.63^{g}	58.96
Ctrl[+]*C4	47.02^{abcd}	44.36
SAA1*C1	40.72^{ab}	39.52
SAA1*C2	45.20^{abc}	42.94
SAA1*C3	45.03^{bcde}	42.86
SAA1*C4	42.37^{ab}	40.45
SAA2*C1	40.59^{a}	39.01
SAA2*C2	43.46^{ab}	46.41
SAA2*C3	49.10^{cde}	48.05
SAA2*C4	50.23^{cde}	47.27
SEM	0.89	0.85
SAA	**	**
Cultivar	**	**
Interaction	**	ns

Different superscripts within the same column indicate highly significant differences. OM: organic matter; DM: dry matter; CP: crude protein; CF: crude fiber. Control [-]: without soil amendment agent; Control [+]: 20 tons/ha organic fertilizer. SAA1: 5 tons/ha biochar + 20 tons/ha organic fertilizer; SAA2: 10 tons/ha biochar + 20 tons/ha organic fertilizer. **: highly significant difference; ns: not significant; SEM: standard error of the mean. ^{a,b,c} Means in the same column differ significantly.

3. Results and Discussion

3.1. Soil condition

The overburden soil described in **Table 1** exhibits properties indicative of low soil fertility and limited potential to support plant growth without amendment. The soil's organic carbon concentration (0.50%) and total nitrogen (0.09%) are far below typical thresholds for fertile mineral soils, which generally require higher organic matter to sustain nutrient cycling, water retention, and biological activity; soils with SOC significantly below 1%–2% are widely regarded as degraded or poor in quality, often responding positively only to organic amendments or reclamation practices (e.g., SOC thresholds suggested at ∼2% to sustain soil quality in tropical systems). Low levels of organic carbon and nitrogen also constrain soil microbial activity and nutrient mineralization, which in turn can reduce crop productivity and impede revegetation on disturbed land (Patrick et al., 2013). Furthermore, the measured cation exchange capacity (CEC = 8.89 cmol(+)/kg) and limited concentrations of available nutrients (P and K) underscore the poor chemical fertility status of this overburden soil, consistent with findings that mining disturbance often leads to a decline in organic matter, structural deterioration, and reduced nutrient retention capacity in mine-affected soils (Semy et al., 2021). Together, these characteristics align with global observations of post-mining, highly weathered soils, in which low SOC, low CEC, and poor nutrient availability pose significant challenges for achieving sustainable plant growth without targeted soil amelioration strategies.

3.2. °Brix content and forage chemical composition

The °brix value indicates the total concentration of dissolved solids in plant tissues, which is related to the accumulation of photosynthetic carbohydrates. The results showed no interaction between SAA use and cultivars on °brix values (**Table 2**). Separately, soil amendment treatment with a combination of biochar and organic fertilizer (SAA) had a significant effect on °brix ($p<0.01$). Meanwhile, differences among cultivars do not affect °brix. SAA1 and SAA2 treatments resulted in higher °brix values than the controls (6.32 and 5.72, respectively), whereas the control [−] was only 5.24. This increase in °brix value reflects enhanced photosynthetic activity and carbohydrate accumulation efficiency, which are thought to be influenced by increased nutrient availability and soil water storage capacity resulting from biochar addition. The combination of biochar and organic fertilizer increases soil nutrient availability and physical properties, thereby enhancing crop yields and quality, supporting the idea that the increase in total dissolved sugar, closely related to °brix, could result from a similar mechanism (Chen et al., 2022). The use of biochar-based fertilizers improves soil conditions by increasing soil moisture and density, thereby enhancing water availability, which directly supports photosynthesis and sugar accumulation (Zhu et al., 2025). Improving soil quality with amending agents can also enhance photosynthesis, leading to increased carbohydrate accumulation and the distribution of dry matter, which can raise the °brix value (Chen et al., 2023). In addition, plant chlorophyll levels increase with biochar use, affecting the quality and efficiency of photosynthesis (Khan et al., 2021).

The organic matter (OM) content was unaffected ($p>0.05$) by SAA use and remained relatively stable across cultivars. Still, three cultivars (*P. purpureum*, *P. purpureum* cv. Thai., and *P. purpureum* cv. GU) had highly significant ($p<0.01$) higher OM content than *P. purpureum* cv. Mott, which reached 86.90%, 87.15%, and 86.48%, respectively (**Table 2**). The non-significant influence of soil improvement agents on the OM content of elephant grass is because the content of OM is determined more by the genetic and physiological properties of the plant than by soil conditions. Although biochar and organic fertilizers improve the properties of marginal soils, their effects are more pronounced on biomass growth and yield, rather than on the proportion of organic compounds in plant tissues. In general, cv Mott has a lower OM content than other cultivars such as *P. purpureum* cv GU (Umami et al., 2023). Some cultivars of *P. purpureum* (e.g. cv. Mott, cv. Thailand, cv. Purple, cv. Zanzibar) are known to have different cell wall deposition patterns, so the levels of OM are intrinsically different even though they grow in the same environmental conditions (Maleko et al., 2019).

The combination of SAA use and different elephant grass cultivars showed no interaction with crude protein (CP) content (**Table 2**). The highest CP was observed in the cv. Mott (12.97%), which is significantly different from that of other cultivars ($p<0.01$). This suggests that *P. purpureum* cv. Mott has a higher potential tissue nitrogen content, despite their relatively lower dry matter production. Differences in morphology, production, and nutrient composition support the claim that *P. purpureum* cv. Mott (dwarf cultivar) can have higher nitrogen/protein content despite lower DM. The dwarf genotype has superior nutritional value due to its higher leaf-to-stem ratio (Silva et al., 2023).

The crude fiber (CF) value of elephant grass in this study ranged from 26.50% to 28.31%. The application of soil amendment agent has a highly significant effect ($p<0.01$) on the content of forage crude fiber. SAA2 showed the highest CF content (28.31%), followed by SAA1 (26.93%), the Control [+] (26.80%), and the Control [−] (26.50%). An increase in crude fiber in treatment with high doses of biochar indicates a change in the structure and availability of nutrients in the soil that affects the development of plant tissues. Biochar applications significantly improve soil pH, cation exchange capacity (CEC), and other soil chemical statuses (Singh et al., 2022) . This can increase soil pH, CEC, and nutrient availability, thereby stimulating the formation of plant structural biomass, including lignin and cellulose.

The analysis showed that elephant grass cultivars had a highly significant effect on CF content ($p<0.01$). *P. purpureum* (C1) cultivars have the highest CF (28.52%), followed by *P. purpureum* cv. GU (28.15%), *P. purpureum* cv. Thai. (27.16%), while *P. purpureum* cv. Mott (24.75%) had the lowest content. These differences indicate genetic variation between cultivars in the formation of plant structural tissues. Previous studies have shown that tall cultivars of *P. purpureum*, such as *P. purpureum* cv. GU and *P. purpureum* cv. Thai. tended to have thicker stems, higher plant height, and a higher proportion of lignocellulose than dwarf cultivars like *P. purpureum* cv. Mott. Cultivars belonging to the tall genotype have a high biomass accumulation, while dwarfs have a larger leaf-to-stem ratio and higher nutritional value due to their higher leaf proportions (Silva et al., 2023). Taiwan and King cultivars have a higher CF content and larger stem morphology compared to *P. purpureum* cv. Mott, which has smoother leaves and higher digestibility (Budiman et al., 2012).

The study found that biochar application did not significantly increase plant biomass production ($p>0.05$). Biochar promotes the co-deposition of hemicellulose and lignin on the cell walls of rice stalks, thereby strengthening the plant structure and increasing resistance to mechanical collapse (lodging) (Miao et al., 2022). Furthermore, biochar is known to increase soil pH significantly and CEC, thereby increasing the availability of nutrients such as N, P, K, Ca, and Mg that are essential for the synthesis of plant structural biomass (Alkharabsheh et al., 2021). Long-term research also shows that biochar applications increase plant lignin accumulation (Chen et al., 2024). Therefore, the mechanisms of lignin and hemicellulose formation after biochar application are highly consistent with the chemical alteration of the soil by biochar, which becomes more conducive to the formation of structural biomass. Biochar application significantly improved the associated characteristics of the stem cell wall, leading to a significant increase in hemicellulose and lignin in biochar-treated samples (Miao et al., 2022).

The high CF content indicates an increase in structural components such as cellulose, hemicellulose, and lignin, which are essential for the plant's physical strength but can decrease the digestibility and energy value of the forage. Therefore, an increase in CF content under high-dose biochar (SAA2) treatment should be considered alongside the rise in dry biomass, as high production may mask a relative decline in quality. However, an increase in CF levels is not always accompanied by improved forage nutrient quality, as high CF fractions tend to decrease dry matter digestibility (DMD) and organic matter digestibility (OMD). In this study, the treatment with the highest CF content (SAA2) showed relatively lower DMD and OMD values than the control, indicating a balance between productivity and forage nutrient quality. Overall, the use of medium-dose biochar (SAA1) can be considered an optimal strategy because it balances productivity, CF content, and forage digestibility in low-fertility nickel post-mining soils.

3.3. Dry matter production

Dry matter production is the main parameter used to describe forage productivity. The results showed no significant difference between SAA treatments ($p>0.05$) (**Table 2**). The absence of a substantial effect of SAA administration on dry matter production across four *P. purpureum* cultivars suggests that improvements in soil chemical and physical properties by biochar and organic fertilizers are gradual ((Lehmann and Joseph, 2024). In addition, genetic differences between cultivars are more dominant in determining production than the effects of short-term soil amendment (Budiman et al., 2012). The impact of SAA was likely to be more pronounced on improved forage quality, such as nitrogen content and digestibility, than on increased total DM.

In terms of differences between cultivars, the results show that *P. purpureum* cv. GU (8.885.07 kg/ha), *P. purpureum* cv. Thailand (7.593.81 kg/ha) and *P. purpureum* (7.639.24 kg/ha) have higher DM production compared to *P. purpureum* cv. Mott (3.354.06 kg/ha). These results show that *P. purpureum* cv. The GU was one of the cultivars with a great capacity for adaptation to post-nickel-mining soil conditions and high efficiency in utilizing available nutrients. This variety is classified as superior, with better production performance and quality than several other varieties (Nasution et al., 2025). This production was lower than the potential *P. purpureum* cv. GU, which reached 137.200 kg ha^{-1} of fresh yield (equivalent to 15.325 kg ha^{-1} of DM) (Muafi et al., 2024) is closely associated with the degraded characteristics of post-nickel mining land. Post-mining soils are typically characterized by severe topsoil loss, low OM content, limited cation exchange capacity, and imbalanced macronutrient and micronutrient availability, collectively restricting plant growth and biomass accumulation. In addition, poor soil structure, dominance of coarse soil texture, and low water-holding capacity reduce nutrient and water-use efficiency, thereby constraining the expression of Napier grass's genetic yield potential. Previous studies have demonstrated that although *P. purpureum* exhibits a relatively high tolerance to marginal environments, its productivity declines markedly under post-mining soil conditions due to deteriorated physical and chemical soil properties (Bradshaw, 2000; Sheoran et al., 2010).

Although no significant interaction between SAA and cultivar was detected for DM production ($p>0.05$), the markedly high DM yield observed under the SAA2 × C2 combination can be explained by the additive effects of soil amendment and cultivar genetic potential rather than an actual synergistic interaction. Numerous studies have demonstrated that biochar and organic amendments improve plant biomass and DM yields primarily through enhanced soil structure, nutrient availability, and water retention, thereby promoting greater fresh biomass accumulation, which subsequently translates into higher dry matter production (Lehmann et al., 2011; Jeffery et al., 2017). In addition, substantial genetic variation among cultivars in biomass productivity has been widely reported, indicating that specific genotypes inherently possess higher dry matter yield potential regardless of treatment interactions (Nayak et al., 2020). Consequently, *P. purpureum* cv. GU likely demonstrated its superior biomass production when grown under the most favorable soil conditions provided by SAA2, resulting in the highest absolute DM yield. Similar patterns have been reported in genotype × amendment studies, in which main effects predominantly drove yield differences, whereas interaction terms were not statistically significant due to parallel response trends among genotypes (Junaidi et al., 2018). Moreover, DM production is often more strongly influenced by total fresh biomass accumulation than by variation in DM concentration, reinforcing the idea that improved soil conditions can substantially increase DM yield without necessarily generating significant interaction effects (Jeffery et al., 2017). Biochar enhances water retention and soil microbial activity, while organic fertilizers sustainably provide macro- and micro-nutrients (Lehmann et al., 2011). The combination of the two enhances nutrient absorption and photosynthesis, thereby increasing plant DM accumulation.

3.4. In vitro dry and organic matter digestibility

The digestibility value of IVDMD and IVOMD describes the extent to which forage nutrients can be utilized by livestock. Results showed that SAA treatment had a significant effect on IVDMD and IVOMD ($p<0.01$). The control [+] treatment had the highest IVDMD and IVOMD values (53.16% and 49.83%), followed by control [−] (54.35% and 51.17%). Meanwhile, SAA1 and SAA2 treatments showed slightly lower values, ranging from 44.68% to 46.23% for IVDMD and 42.88% to 45.00% for IVOMD, respectively. This decrease may be due to the increased physiological lifespan of plants, resulting from faster growth in more fertile soils and higher cell wall lignification (Van Soest, 1994).

The differences between cultivars are also noticeable, where *P. purpureum* cv. Mott showed the highest digestibility (IVDMD 54.87%; IVOMD 52.50%), which was significantly different ($p<0.01$) from that of the other three cultivars. This indicates that the network structure cv. Mott is smoother, and higher leaf proportions favor improved digestibility (Budiman et al., 2012; Dumadi et al., 2021). On the contrary, *P. purpureum* cv. GU and *P. purpureum* cv. Thai have a thicker stem structure, so the CF content is higher. Thus, although *P. purpureum* cv. GU excels in biomass production, *P. purpureum* cv. Mott is superior in feed quality and digestibility. *P. purpureum* cv. Mott is known for its greater number of tillers, higher leaf-to-stem ratio, and higher dry matter content (Kurniawan et al., 2025).

3.5. Interaction of soil and cultivar amendment treatment

Analysis of the interaction between SAA and cultivar showed a significant influence on the IVDMD ($p<0.01$), whereas IVOMD showed no significant interaction. Combination of SAA2 × *P. purpureum* cv. GU produces the highest yield while maintaining relatively good digestibility (DMD 43.46%; OMD 46.41%). This shows that *P. purpureum* cv. GU can benefit from improved soil conditions created by biochar and organic fertilizers without experiencing a significant decrease in feed quality. The combination of biochar and organic fertilizer increases nutrient availability and soil microbial activity (Hu et al., 2024; Li et al., 2024).

The results showed a trade-off between forage productivity and nutrient quality. However, biomass increased with soil amendment, and the CF fraction tended to increase due to cell wall lignification. Although biomass production increases with biochar + mineral fertilizers, the lignin/NDF/ADF content does not always increase proportionally, suggesting that biochar may help prevent over-lignification of the cell wall (Stopa et al., 2023). Field research on Sudan grass shows that biochar increases forage productivity and improves soil properties without significantly compromising quality (Ginebra et al., 2022). Studies on rice varieties show that biochar promotes the co-deposition of hemicellulose and lignin in the stem cell wall, which increases the plant's lodging resistance. However, plant and harvesting conditions can be arranged to prevent excessive lignification, thereby maintaining digestibility (Miao et al., 2022). Agronomically, the combination of SAA2 with P. purpureum cv. GU yields optimal results, producing high biomass with quality that remains suitable for forage.

3.6. Implications for post-mining soil rehabilitation

Post-nickel mining soil exhibits poor organic matter, low CEC, dense soil structure, and extreme pH. The results of this study show that applying biochar and organic fertilizers improved these conditions by increasing organic matter content. Combination of SAA2 × cv. GU shows the greatest potential for supporting post-mining land reclamation because it can produce high biomass while improving soil properties.

Apart from serving as a feed source for livestock, planting superior elephant grass also provides critical ecological benefits. Elephant grass cover reduces surface runoff and soil erosion by almost 99% (Satriagasa and Suryatmojo, 2020). Elephant grass can also serve as a biomass bank, significantly increasing soil carbon storage, especially in the 0-30 cm depth range (Lok et al., 2013). Elephant grass is well-suited for growing on marginal land, is often used for erosion control, and can absorb carbon from the atmosphere and soil into its biomass (Johannes et al., 2024).

Elephant grass cultivation is not only agronomically beneficial for feed but also makes a significant ecological contribution to soil stability, land cover, and climate mitigation through carbon storage. The implementation of a soil amendment strategy based on biochar and organic fertilizers can be an effective and sustainable approach to post-nickel-mining land rehabilitation and environmentally sound livestock systems. Overall, the results showed that the combination of 10 tons/ha biochar and 20 tons/ha organic fertilizer (SAA2) was effective across four *P. purpureum cultivars*. *P. purpureum* cv. GU provides the best results for DM production and nutrient utilization efficiency. This treatment is recommended as a synergistic strategy to provide forage and improve the quality of post-nickel mining soil.

4. Conclusion

The application of biochar and organic fertilizers had no significant effect on the dry matter production of four *P. purpureum* cultivars, but improved forage quality by enhancing soil properties and plant physiological activity. *P. purpureum* cv. GU shows the highest biomass production with good digestibility, while *P. purpureum* cv. Mott has the highest nutritional quality but lower production, indicating a trade-off between productivity and quality. A combination of 10 tons/ha biochar + 20 tons/ha organic fertilizer and *P. purpureum* cv. GU provides the most balanced results, so it is recommended for sustainable forage management and land reclamation after nickel mining.

5. Conflict of interest

The authors confirm the absence of any competing interests in this article.

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8. Author's contribution

WK, CH, and NU designed the study. WK performed the fieldwork experiments and data analysis, conducted the literature search, and wrote the original manuscript. WK, CH, and NU performed data interpretation, edited, and reviewed the manuscript. CH and NU supervised the study.

9. Ethics approval

All experimental procedures involving rumen fluid collection for in vitro analysis were approved by the Institutional Ethics Committee of Universitas Gadjah Mada under ethical clearance No.: 00007/III/UN1/LPPT/EC/2024.

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