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Morphology, Biomass, and Forage Quality of *Sorghum bicolor* cv. Bioguma-2 Treated with Soil Ameliorants on Post-Coal Mining Land

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ABSTRACT

Reclamation of post-coal mining land is a valuable opportunity for transforming the land into agricultural cultivation of forage crops for livestock feed production. We conducted an experiment in the Asamasam coal mining spot, Tanah Laut Regency, South Kalimantan, to investigate the effect of some soil ameliorant materials, and *Sorghum bicolor* cv. Bioguma-2 (Bioguma-2 sorghum) on morphological characteristics and biomass production. Seven soil ameliorant treatments were tested: control (P0), single applications of humic acid (P1, 28 L ha^{-1}), dolomite (P2, 5.8 t ha^{-1}), and organic compost (P3, 15 t ha^{-1}), and treatment combinations of humic acid + compost (P4), dolomite + compost (P5), and humic acid + dolomite + compost (P6) with the same doses of P1, P2, and P3. The data were subjected to analysis of variance, and any significances between treatments were analyzed by Duncan's Multiple Range Test. The results indicated that the combined ameliorant materials improved morphological characteristics and biomass production. Treatment P6 showed the highest effectiveness on soil quality, plant survival rate, most morphological traits, and all yield parameters, followed by other treatments with comparatively lower performance. P6 produced the highest crude protein content across treatments. The combination of multi-ameliorants (humic acid, dolomite, and organic compost) is more effective than single ameliorants in improving soil quality, plant survival, morphological traits, and biomass yield of *Sorghum bicolor* cv. Bioguma-2 on post-coal mining land. These results indicate that using combined soil ameliorants is a promising strategy to enhance forage crop production on degraded mining soils. However, natural declines in plant performance during later harvest stages suggest the need for further nutrient management to sustain productivity over time.

***Keywords:** ameliorant; bioguma-2 sorghum; forage crops; performance; post-coal mining land*

INTRODUCTION

Extensive coal mining activities turn the soil into a compacted structure with low water-holding capacity and often high levels of toxic elements, like aluminum and heavy metals. As a result, soil quality is significantly degraded, leading to nutrient depletion, reduced organic matter, high acidity, poor physical structure, and low capacity to support plant growth. Empirical studies show that compared to undisturbed soils, mined lands have significantly lower total nitrogen, available phosphorus, and soil organic matter (Prathap *et al.*, 2016; Zhang *et al.*, 2022). In addition, subsidence areas show reduced soil water content and clay fractions, which impair microbial biomass and enzyme activities crucial for nutrient cycling (Ma *et al.*, 2019). Heavy metal contamination, including increased concentrations of chromium, copper, nickel, and lead, further exacerbates soil toxicity and hampers biological recovery (Prathap *et al.*, 2016). Nutrient depletion on mined lands primarily results from the removal of topsoil, accelerated erosion and leaching, soil acidification, and heavy-metal toxicity, which suppress microbial functions that are essential for nutrient cycling (Das *et al.*, 2024). Soil amelioration—one of the critical strategies to restore the productivity of these degraded landscapes—is essential to address this issue. The application of organic and inorganic ameliorants such as compost, humic acid, dolomite, and biochar is reportedly capable of improving soil fertility, reducing acidity, enhancing microbial activity, and supporting vegetation establishment on marginal lands (Ivanova *et al*., 2023; Zhang *et al*., 2022).

Previous studies have reported that coal mining significantly decreases key soil fertility indicators, including soil organic matter (SOM), total nitrogen (TN), phosphorus (P), and potassium (K). Wang *et al.* (2021) documented significant reductions in SOM, TN, and available P in subsided coalfields, influenced strongly by topographical factors. Similarly, artificial forests overlying subsided land in northern China show marked losses of soil nutrients and enzymatic activity (Zhang *et al*., 2025). It is mandatory for mining corporations to reclaim and repurpose post-coal mining land, such as for agriculture. As mentioned above, post-coal mining land (often known as marginal soil) suffers from low fertility, limited organic matter, poor structure, low water absorption capacity, and high aluminum (Herman *et al*., 2024). These result in plant degradation (Asnawi *et al*., 2023), loss of biodiversity (Sukarman & Abdul Gani, 2020), and slow plant growth (Lestari *et al*., 2019). Despite the poor characteristics, reclaimed post-coal mining land holds promising potential to cultivate sorghum as a biomass source, to support land rehabilitation, and to achieve renewable energy and agricultural diversification goals.

Sorghum (*Sorghum bicolor)*—known for its resilience and adaptability to suboptimal growing conditions—can stand marginal soils in reclaimed mining areas. As a versatile cereal crop with diverse applications in food, feed, and bioenergy production, sorghum can be classified into grain, energy, and silage sorghum based on its utilization traits. Furthermore, as the fifth most cultivated cereal globally, sorghum is valued for its excellent stress resistance, particularly to drought and saline-alkali conditions (Zheng *et al*., 2023), making it a feasible forage for the future (Malalantang *et al*., 2019). In a multiple cropping system, different sorghum varieties can be planted alongside up to 50% of the population of Indigofera (Telleng *et al*., 2016). Bioguma sorghum—a derivative variety of the Numbu sorghum plant (Nurhasanah *et al*., 2023)—grows to a height of 228.43 cm and produces 553.33 g of biomass per plant (Indriatama *et al*., 2023). Sorghum has been analyzed in relation to an integrated crop and land management of post-mining land (Munawwarah & Sulaeman, 2023), arbuscular mycorrhizal fungi (Wulandari *et al*., 2024), and hydroseeding (Anshari *et al*., 2023).

Rehabilitation of non-productive post-mining land into agricultural land is essential for land productivity. Land restoration strategies may include, but are not limited to, the addition of compost (Purnamayani *et al*., 2019; Rosa *et al*., 2023), the use of humic acid (Musfira *et al*., 2021; Ngapiyatun *et al*., 2024), and the application of dolomite lime (Firnia & Rohmawati, 2022; Calugaru *et al*., 2024). Despite the important contributions, research on the restoration of former coal mining land for planting sorghum is still limited. This study is carried out to examine the effects of ameliorant materials on bioguma sorghum's productivity in post-coal mining land.

MATERIALS AND METHODS

Research Area

The research was conducted on a post-coal mining land at PT. Arutmin Indonesia Asamasam Mine, Tanah Laut Regency, South Kalimantan, Indonesia (Figure 1), from October 2023 to September 2024. The research area was located at approximately -3.865000 latitude and 115.104324 longitude, with extensive flatland topographic characteristics. The site used to be a coal mining operation without a land rehabilitation history. This research included land preparation, soil ameliorants application (P1 to P6) in the research plot, sorghum planting, pest control, harvesting, and soil analysis. The soil properties are presented in Table 1.

Experimental Design

A completely randomized design (CRD) was applied to analyze seven treatments (P0–P6) and four replicates, totaling 28 plots. Treatments were randomized across the experimental area; a serpentine layout was set to minimize directional gradients, but rows were not considered analytical blocks. Each plot comprised seven ridges with 33 planting holes per ridge (231 plants per plot). For data analysis, plot means (based on seven

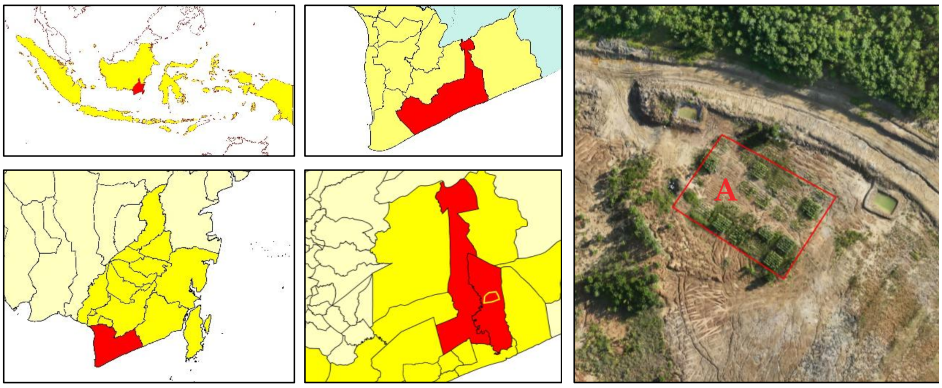

Figure 1. Research location (point A) in post-coal mining land of PT. Arutmin Indonesia Asamasam Mine, Tanah Laut Regency, South Kalimantan, Indonesia

Table 1. Chemical characteristics of the research plots' soil

Variables	Treatments							SEM	p
	P0	P1	P2	P3	P4	P5	P6		
pH									
H_2O	4.35^{E}	4.36^{E}	5.36^{C}	4.47^{D}	5.99^{B}	6.41^{A}	6.45^{A}	0.171	<0.001
KCl	3.36^{G}	3.61^{F}	3.98^{D}	3.93^{E}	4.27^{C}	5.35^{B}	6.41^{A}	0.193	<0.001
C-Organic (%)	0.38^{E}	0.41^{D}	0.41^{C}	1.43^{C}	1.45^{B}	1.46^{B}	1.52^{A}	0.092	<0.001
N-Total (%)	0.23^{D}	0.26^{C}	0.26^{C}	0.27^{BC}	0.29^{B}	0.29^{B}	0.31^{A}	0.005	<0.001
P2O5 Potential (mg 100/g)	11.20^{E}	13.70^{D}	13.80^{D}	18.00^{C}	19.60^{B}	19.80^{B}	24.48^{A}	0.818	<0.001
K2O Potential (mg 100/g)	19.55^{D}	19.80^{CD}	19.38^{D}	20.20^{C}	49.10^{B}	49.25^{B}	50.50^{A}	2.847	<0.001
CEC (me/100 g)	17.65^{G}	21.34^{E}	20.52^{F}	21.96^{D}	22.26^{C}	23.88^{B}	33.64^{A}	0.900	<0.001

Note: Means in the same row with different superscript differ significantly ($p<0.01$); CEC= Cation exchange capacity; P0= control; P1= humic acid; P2= dolomite; P3= organic compost; P4= humic acid and organic compost; P5= dolomite and organic compost; P6= humic acid, dolomite, and organic compost.

randomly selected plants—one per ridge) were used as the experimental units to avoid pseudo-replication.

Soil Chemical Analysis

Soil samples were collected from the reclamation land at post-mining sites in five representative locations to a depth of 20 cm (Widawati & Suliasih, 2019). The samples were analyzed for chemical properties, including pH, organic carbon, nitrogen, phosphorus, potassium, and cation exchange capacity (CEC).

Soil Ameliorant Materials

Soil ameliorants used in this research included humic acid, dolomite ($CaMg(CO_3)_2$), and organic compost. The organic compost—made of 65% cattle manure and 35% chicken manure—was fermented for 3 weeks prior to application. The compost had a pH of 7.27, measured in a 1:5 ratio of compost to distilled water and suspended in a calibrated pH meter. The soil ameliorants were made into seven treatments and four replications, resulting in 28 soil plots (5 x 5 m). The treatments were control (P0) without ameliorants, P1 (28 l ha^{-1} humic acid), P2 (5.8 t ha^{-1} dolomite), and P3 (15 t ha^{-1} organic compost). The combined treatments were P4 (28 L ha^{-1} humic acid + 15 t ha^{-1} organic compost), P5 (5.8 t ha^{-1} dolomite + 15 t ha^{-1} organic compost), and P6 (28 L ha^{-1} humic acid + 5.8 t ha^{-1} dolomite + 15 t ha^{-1} organic compost). We excluded the combination of dolomite and humic acid treatment without compost to preserve the statistical power because the agronomic benefits of humic substances and liming are attenuated in low-SOC (soil organic carbon) matrices on carbon-poor post-mining soils with depauperate microbial activity. Therefore, compost was adopted as the baseline organic substrate to rebuild soil organic matter (SOM) and to support microbially mediated nutrient cycling (Heisey *et al*., 2022; Miralles *et al*., 2021; Miu *et al*., 2022).

Land Preparation and Application of Soil Ameliorants

The land was tilled using a hand tractor before staking and forming a ridge to incorporate ameliorants uniformly. Stakes were then installed to mark the borders of the 28 research plots (at 5 x 5 m, with a 2-m interval). Each plot was divided into seven ridges with a 75-cm spacing between ridges and 15-cm spacing between seeds within each ridge, resulting in 231 planting holes per plot. Ameliorants were applied only once, four weeks before planting, manually by spreading the material over the treatment plots. A base fertilizer (organic compost) was applied at 5 t ha^{-1} two weeks before planting.

Sorghum Planting and Plant Maintenance

This study used *S. bicolor* cv. Bioguma-2 (Bioguma-2 sorghum) developed by the Agricultural Research and Development Agency (Balitbangtan) of the Ministry of Agriculture of the Republic of Indonesia. The sorghum seeds were planted in 231 holes dug into the soil. Prior to planting, the seeds were treated with the insecticide *Confidor*® to deter ant infestations. Each hole was filled with 3 to 4 seeds at approximately a 5-cm depth and then covered with composted manure. Thinning was performed on days 5 and 14 after sowing (DAS), leaving two plants in each hole.

The first fertilization—with a combination of 300 kg ha^{-1} urea, 100 kg ha^{-1} SP36, and 60 kg ha^{-1} KCl—was carried out at 14 DAS. Urea was applied in ratoon 2: 100 kg ha^{-1} on 14 DAS and 200 kg ha^{-1} at 30 DAS. The fertilizers SP36 and KCl were applied as a single dose on 14 DAS. Fertilization was conducted at the same growth stage and in the exact dosage for each planting cycle. Pest control was initiated once the sorghum plants emerged, with biweekly applications of *Regent*® insecticide to control grasshoppers (*Oxya serville*) and brown planthoppers (*Nilaparvata lugens*), and *Prevaton*® to combat armyworms (*Spodoptera litura*). The trial was conducted under rainfed conditions, without supplemental irrigation. Soil moisture was maintained by rainfall, typical of the site during the study period. Harvesting was performed when the sorghum reached the soft dough stage at 100 DAS; subsequent harvests (stages 2 and 3) were carried out 100 days after the previous harvest. The soft dough stage marks the period after the milk stage and before the stiff dough stage, characterized by fully developed grains that have started to harden but can still be compressed by hand.

Variables and Data Analysis

The Bioguma-2 sorghum was harvested thrice—at the initial harvest, ratoon 1, and ratoon 2—100 days after sowing (DAS), corresponding to the soft dough stage of the sorghum. We observed the agronomic parameters (plant survival rate, plant height, stem diameter, leaf length and width, leaf number, and tiller count), the fresh biomass, dry weight of the sorghum, and Brix. The nutritional composition analyzed in this study includes dry matter content, ash content, crude protein, crude fat, and crude fiber. Soil conditions before and after the research were examined for the soil pH, content of carbon (C), nitrogen (N), phosphorus (P), potassium (K), and cation exchange capacity (CEC). The obtained data were subjected to analysis of variance (ANOVA), followed by Duncan's multiple range test (DMRT) for significant differences between treatments. The analysis was performed using IBM SPSS Statistics software, version 27.0.

RESULTS

This study aimed to evaluate the effect of various soil ameliorants on the chemical properties of post-coal mining soil and their subsequent impacts on the growth and biomass production of Bioguma-2 sorghum. The results are presented in two parts: chemical characteristics of the soil across treatments and the morphological traits and biomass yield of sorghum.

Chemical Characteristics of Research Plots Soil

This study investigated the chemical characteristics of soil in experimental plots subjected to different treatments (P0–P6) and their influence on key soil fertility parameters—soil pH, organic carbon, nitrogen, phosphorus, potassium, and cation exchange capacity (CEC). Table 1 shows that the soil pH measured in distilled water (pH H_2O) varied significantly across treatments ($p<0.001$), ranging from 4.35 in P0 to 6.45 in P6. Similarly, soil pH measured in 1 N KCl showed significant variation ($p<0.001$) in an increasing trend, from 3.36 in P0 to 6.41 in P6. A steady increase across treatments was observed in organic carbon content, from 0.38% in P0 to 1.52% in P6 ($p<0.001$), and in total nitrogen (N-total), from 0.23% to 0.31%, with significant differences between treatments ($p<0.001$). Similarly, potential phosphorus (P_2O_5) content increased from 11.20 mg/100 g in P0 to 24.48 mg/100 g in P6, and potential potassium (K_2O) content rose from 19.38 mg/100 g to 50.50 mg/100 g ($p<0.001$ for both). Cation exchange capacity (CEC) also showed significant increases with treatment level ($p<0.001$), from 17.65 me/100 g in P0 to 33.64 me/100 g in P6.

Plant Survival Rate

The application of soil ameliorants significantly affected ($p<0.01$) the survival rate of Bioguma-2 sorghum grown on post-coal mining land (Figure 2). The highest survival rate was observed in treatment P6 (80.52%), followed by P5 (60.50%), P4 (56.82%), P3 (53.79%), P2 (45.24%), and P1 (44.48%). The lowest survival rate was recorded in the control group, P0 (21.43%). Statistical grouping based on superscripts (A–E) indicates significant differences between treatments at $p<0.01$ (see Figure 2).

Morphological Characteristics of Bioguma-2 Sorghum

The application of ameliorant treatments significantly affected the morphological performance of Bioguma-2 sorghum on post-coal mining land across the initial, ratoon 1, and ratoon 2 stages. We found that the plant height was consistently treatment-dependent ($p<0.001$). At the initial stage, P6 and P5 produced the tallest plants (215.60 and 213.10 cm), while the control (P0) resulted in the shortest (109.80 cm). Similarly, at both ratoon stages, P6 plants remained the highest and P0 plants were the lowest (112.50 cm vs. 40.60 cm). Stem diameter also differed significantly ($p<0.001$) at the initial stage, where P5, P6, and P4 had the thickest stems (2.23, 2.15, and 2.13 cm), while P0 had the thinnest (1.30 cm). These differences were consistent between ratoon 1 and 2.

Treatments significantly influenced leaf production at each stage. During the initial phase, P3 (11.75) had the most leaves, followed by P1 (8.50; $p=0.002$). In ratoon 1 and 2, P6 produced the most leaves (10.50 and 9.50, respectively), while P0 had the least (8.50 and 7.50; $p<0.001$). Leaf length also varied ($p<0.001$), with the longest leaves at the initial stage observed in P2 (77.00 cm), P3 (76.60 cm), and P4 (76.13 cm). P3 consistently maintained this superiority across all ratoons. A similar trend was identified in leaf width ($p<0.001$), in which the widest leaves were P4 (8.73 cm), P6 (8.68 cm), and P5 (8.54 cm) in the initial stage, and the narrowest was P0 (7.00 cm). In the ratoons, P6 consistently produced the widest leaves (8.15 cm and 8.00 cm).

We observed significant differences in tillering across treatments in ratoon 1 ($p=0.015$), where P6

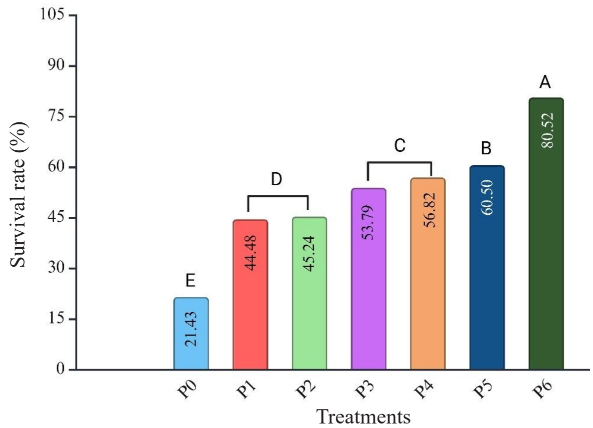

Figure 2. The graphic survival rate of Bioguma-2 sorghum in post-coal mining land. Different superscripts (A, B, C, D, E) differ significantly ($p<0.01$). P0= control; P1= humic acid; P2= dolomite; P3= organic compost; P4= humic acid and organic compost; P5= dolomite and organic compost; P6= humic acid, dolomite, and organic compost.

produced the most tillers (2.50) and P0 the fewest (1.25). In ratoon 2, the variation was not statistically significant (p=0.188), although P6 still had the most tillers (2.00). Collectively, these results showed that the ameliorant treatments—particularly P6 and P5—produced sustained improvements in plant stature, leaf growth, and tillering, indicating robust morphological advantages for revegetation or bioenergy production on degraded mining soils.

Yield Production and Brix Content of Bioguma-2 Sorghum

Table 3 shows that across all harvest stages (ratoon 1, ratoon 2), ameliorant treatments strongly affected fresh and dry yields (all p<0.001). In the initial harvest, fresh yield ranged from 6.25 t ha^{-1} (P0) to 40.84 t ha^{-1} (P6) and 34.64 t ha^{-1} (P5). Fresh yield in ratoon 1 varied from 0.56 t ha^{-1} (P0) to 18.76 t ha^{-1} (P6), and in ratoon 2 from 0.20 t ha^{-1} (P0) to 10.25 t ha^{-1} (P6). Dry yield followed the same ranking: initial at 1.96–13.26 t ha^{-1} (P0–P6), ratoon 1 at 0.17–6.10 t ha^{-1}, and ratoon 2 at 0.06–3.23 t ha^{-1}, consistently identifying P6 (and generally P5) as the top-performing treatments.

Brix also improved with ameliorants (p<0.001). At the initial stage, it increased from 10.50% (P0) to 15.00% (P6), while ratoon 1 and 2 were 9.50%–14.50% and 8.50%–13.00%, respectively. P6 consistently showed the highest effect across treatments and stages. These results indicated that the combined ameliorants strategy markedly enhanced both quantity (fresh/dry yield) and quality (Brix) of Bioguma-2 sorghum on post-coal mining land across successive harvests.

Nutritional Composition of Bioguma-2 Sorghum

The nutritional composition of Bioguma-2 sorghum varied across treatments (P0–P6) and harvest stages (initial, ratoon 1, and ratoon 2), as shown in Table 4. The dry matter (DM) content generally increased across treatments, with the highest values consistently found in P6 at all stages (32.47%, 32.49%, and 31.63%, respectively). The ash content exhibited significant variation among the treatments across all harvest stages

Table 2. Morphological characteristics of Bioguma-2 Sorghum at harvest age

Variables	Harvest stages	Treatments							SEM	p
		P0	P1	P2	P3	P4	P5	P6		
Plant height (cm)	Initial	109.80^{C}	142.40^{BC}	150.70^{BC}	183.50^{AB}	187.10^{AB}	213.10^{A}	215.60^{A}	7.789	<0.001**
	Ratoon 1	112.50^{F}	120.40^{E}	130.50^{D}	140.70^{C}	146.00^{B}	195.00^{A}	198.70^{A}	6.170	<0.001**
	Ratoon 2	40.60^{G}	60.30^{F}	75.50^{E}	80.20^{D}	95.60^{C}	185.00^{B}	192.80^{A}	10.746	<0.001**
Stem diameter (cm)	Initial	1.30^{C}	1.45^{C}	1.70^{B}	1.78^{B}	2.13^{A}	2.23^{A}	2.15^{A}	0.068	<0.001**
	Ratoon 1	1.10^{C}	1.30^{BC}	1.18^{BC}	1.38^{B}	2.03^{A}	2.13^{A}	2.08^{A}	0.836	<0.001**
	Ratoon 2	1.00^{B}	1.15^{B}	1.05^{B}	1.30^{B}	1.95^{A}	2.00^{A}	2.08^{A}	0.089	<0.001**
Number of leaves	Initial	9.75^{BC}	8.50^{C}	10.50^{AB}	11.75^{A}	10.50^{AB}	10.50^{AB}	10.75^{AB}	0.230	0.002**
	Ratoon 1	8.50^{B}	8.50^{B}	9.50^{AB}	9.75^{A}	9.50^{AB}	9.75^{A}	10.50^{A}	0.158	<0.001**
	Ratoon 2	7.50^{B}	7.50^{B}	8.50^{AB}	8.75^{A}	8.50^{AB}	8.75^{A}	9.50^{A}	0.158	<0.001**
Leaf length (cm)	Initial	60.78^{C}	65.50^{BC}	77.00^{A}	76.60^{A}	76.13^{A}	74.00^{A}	72.90^{AB}	1.298	<0.001**
	Ratoon 1	60.00^{E}	65.25^{D}	70.00^{BC}	75.00^{A}	70.18^{BC}	72.00^{B}	68.00^{C}	0.898	<0.001**
	Ratoon 2	58.00^{E}	63.25^{D}	68.00^{BC}	73.00^{A}	68.18^{BC}	70.00^{B}	66.00^{C}	0.898	<0.001**
Leaf width (cm)	Initial	7.00^{D}	7.10^{D}	7.53^{CD}	7.90^{BC}	8.73^{A}	8.54^{AB}	8.68^{A}	0.143	<0.001**
	Ratoon 1	6.48^{d}	6.70^{D}	7.18^{C}	7.18^{C}	7.75^{B}	7.45^{BC}	8.15^{A}	0.106	<0.001**
	Ratoon 2	6.25^{b}	6.38^{b}	7.00^{ab}	7.00^{ab}	7.18^{ab}	7.13^{ab}	8.00^{a}	0.155	0.041*
Number of tillers	Ratoon 1	1.25^{c}	1.75^{bc}	2.00^{ab}	2.25^{ab}	2.00^{ab}	2.25^{ab}	2.50^{a}	0.103	0.015*
	Ratoon 2	1.00	1.50	1.50	1.50	1.50	1.75	2.00	0.095	0.188

Note: Means in the same row with different superscripts differ significantly at p<0.05 (*) or p<0.01 (**). Single asterisk (*) indicates significance at p<0.05, and double asterisks (**) indicate significance at p<0.01. P0= control; P1= humic acid; P2= dolomite; P3= organic compost; P4= humic acid and organic compost; P5= dolomite and organic compost; P6= humic acid, dolomite, and organic compost.

Table 3. Yield production and Brix content of Bioguma-2 Sorghum in post-coal mining land

Variables	Harvest stages	Treatments							SEM	p
		P0	P1	P2	P3	P4	P5	P6		
Fresh yield (t/ha)	Initial	6.25^{G}	9.82^{F}	11.22^{E}	18.22^{D}	21.03^{C}	34.64^{B}	40.84^{A}	2.326	<0.001
	Ratoon 1	0.56^{G}	3.16^{F}	4.03^{E}	8.76^{D}	10.04^{C}	14.56^{B}	18.76^{A}	1.164	<0.001
	Ratoon 2	0.20^{E}	0.90^{DE}	1.30^{DE}	1.50^{D}	4.00^{C}	6.00^{B}	10.25^{A}	0.651	<0.001
Dry yield (t/ha)	Initial	1.96^{G}	3.15^{F}	3.51^{E}	5.86^{D}	6.69^{C}	11.10^{B}	13.26^{A}	0.757	<0.001
	Ratoon 1	0.17^{G}	1.01^{F}	1.28^{E}	2.77^{D}	3.20^{C}	4.66^{B}	6.10^{A}	0.377	<0.001
	Ratoon 2	0.06^{E}	0.25^{DE}	0.37^{D}	0.42^{D}	1.22^{C}	1.88^{B}	3.23^{A}	0.206	<0.001
Brix (%)	Initial	10.50^{E}	12.00^{D}	12.50^{CD}	12.50^{CD}	13.50^{BC}	14.00^{AB}	15.00^{A}	0.285	<0.001
	Ratoon 1	9.50^{E}	11.00^{D}	11.50^{CD}	11.50^{CD}	12.50^{BC}	13.50^{AB}	14.50^{A}	0.313	<0.001
	Ratoon 2	8.50^{C}	10.50^{B}	10.50^{B}	10.50^{B}	12.00^{AB}	12.75^{A}	13.00^{A}	0.306	<0.001

Note: Means in the same row with different superscripts differ significantly (p<0.01). P0= control; P1= humic acid; P2= dolomite; P3= organic compost; P4= humic acid and organic compost; P5= dolomite and organic compost; P6= humic acid, dolomite, and organic compost.

Table 4. Nutritional composition of Bioguma-2 sorghum based on harvest stage

Variables	Harvest stages	Treatments							SEM	p
		P0	P1	P2	P3	P4	P5	P6		
Dry matter (%)	Initial	31.41	31.29	32.04	32.18	31.83	32.05	32.47	0.121	0.084
	Ratoon 1	30.26	31.92	31.66	32.00	31.87	32.01	32.49	0.227	0.219
	Ratoon 2	26.80	27.91	29.23	29.05	30.63	31.33	31.63	0.879	0.777
Ash (%DM)	Initial	13.68^{C}	12.42^{E}	13.03^{D}	13.96^{BC}	14.67^{A}	14.33^{AB}	13.96^{BC}	0.144	<0.001
	Ratoon 1	14.27^{A}	12.56^{B}	13.96^{A}	12.90^{B}	13.79^{A}	14.22^{A}	13.77^{A}	0.128	<0.001
	Ratoon 2	14.22^{A}	14.20^{AB}	13.50^{C}	12.35^{D}	12.24^{D}	13.75^{BC}	13.94^{ABC}	0.153	<0.001
Crude protein (%DM)	Initial	11.64^{C}	11.81^{C}	12.06^{BC}	12.46^{ABC}	13.01^{AB}	13.07^{AB}	13.47^{A}	0.153	<0.001
	Ratoon 1	12.00^{C}	12.38^{BC}	12.46^{BC}	13.22^{ABC}	13.39^{AB}	13.91^{A}	14.04^{A}	0.174	<0.001
	Ratoon 2	11.61^{D}	12.28^{CD}	12.44^{CD}	12.98^{BC}	13.45^{AB}	13.60^{AB}	14.04^{A}	0.167	<0.001
Crude fat (%DM)	Initial	6.35^{BC}	6.35^{BC}	6.59^{AB}	6.92^{A}	6.84^{A}	6.85^{A}	6.06^{C}	0.066	<0.001
	Ratoon 1	6.86^{A}	6.50^{A}	6.69^{A}	5.90^{B}	6.28^{AB}	6.85^{A}	5.87^{B}	0.088	<0.001
	Ratoon 2	6.65^{A}	6.39^{A}	6.42^{A}	6.24^{A}	6.59^{A}	5.71^{B}	6.72^{A}	0.075	<0.001
Crude fiber (%DM)	Initial	35.67^{B}	34.19^{C}	34.53^{C}	37.49^{A}	34.57^{C}	35.67^{B}	33.81^{C}	0.231	<0.001
	Ratoon 1	35.62^{B}	33.27^{E}	36.22^{A}	34.74^{D}	35.01^{CD}	35.42^{BC}	33.56^{E}	0.198	<0.001
	Ratoon 2	36.76^{A}	35.04^{B}	35.05^{B}	34.55^{C}	33.70^{D}	33.86^{D}	35.16^{B}	0.185	<0.001

Note: Means in the same row with different superscripts differ significantly ($p<0.01$). P0= control; P1= humic acid; P2= dolomite; P3= organic compost; P4= humic acid and organic compost; P5= dolomite and organic compost; P6= humic acid, dolomite, and organic compost.

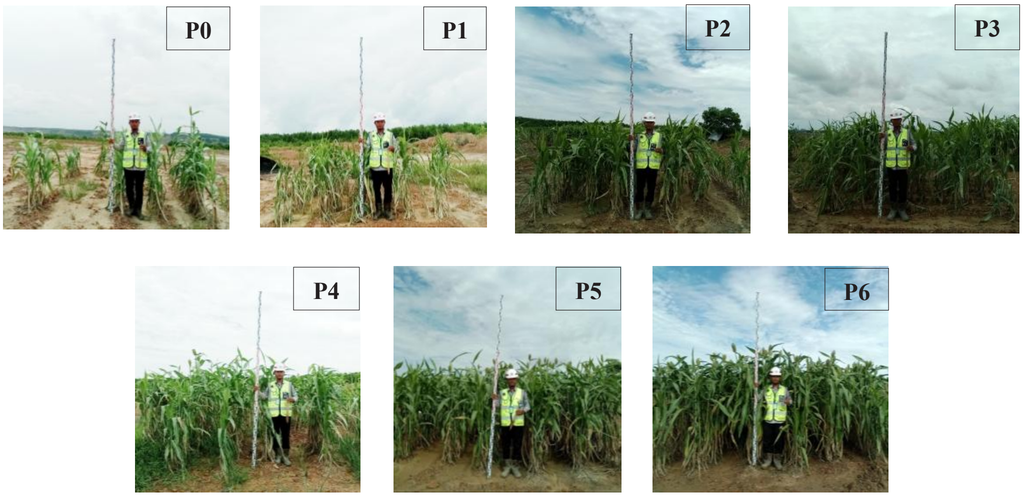

Figure 3. Comparison of morphological characteristics of Bioguma-2 sorghum. P0= control; P1= humic acid; P2= dolomite; P3= organic compost; P4= humic acid and organic compost; P5= dolomite and organic compost; P6= humic acid, dolomite, and organic compost.

($p<0.001$). At the initial stage, P4 had the highest ash percentage at 14.67%, while P1 had the lowest at 12.42%. A similar pattern was found in the ratoon stages, where P0 and P1 had higher ash values compared to P3 and P4 in the second ratoon. Crude protein content significantly increased with the application of ameliorant across all stages ($p<0.001$). The highest crude protein was consistently recorded in P6 (13.47%, 14.04%, and 14.04%), while P0 had the lowest (11.64%, 12.00%, and 11.61%). Crude fat content was also significantly affected by treatments ($p<0.001$). During the initial stage, P3, P4, and P5 recorded the highest crude fat values, while P6 was the lowest. In the first ratoon, fat content peaked in P0 and P5, while the lowest was in P3 and P6. In ratoon 2, fat values remained consistent across treatments, ranging from 5.71% to 6.72%. Crude fiber content varied significantly across treatments and growth stages ($p<0.001$). Generally, the highest fiber values were recorded in treatments P0 and P3, while the lowest values were observed in treatment P6 during both the initial and first ratoon stages. In ratoon 2, P0 had the highest fiber content (36.76%), whereas P4 and P5 had the lowest.

DISCUSSION

Enhancement of Soil Chemical Properties by Ameliorant Treatments

Soil chemical quality improvements depend on the quantity of ameliorants applied to it and the functional complementarity of these substances. In acidic soils with low organic matter (SOM), a three-way combination of ameliorants offers synergistic benefits. First, dolomite neutralizes soil acidity and supplies Ca–Mg, thus raising pH and base saturation. Then, compost adds soil organic matter (SOM) that increases CEC, buffers pH, and delivers slow-release nutrients while supporting microbial activity. Lastly, humic acid complexes nutrients, enhances root physiological responses, and promotes aggregation, which increases nutrient availability and retention (Alsudays *et al.*, 2024; Rose *et al.*, 2024; Stewart-Wade, 2020). Compost efficacy is highly contingent upon the type of feedstock and maturity. The combination of well-matured plant manure with moderate carbon to nitrogen (C:N) typically yields the most consistent gains; therefore, quality testing prior to field use is recommended. For field conditions, base-dressing rates of ~10–15 t ha^{-1} are generally effective on acidic, low-SOM soils. In addition, dolomite has reportedly improved soil conditions by supplying essential cations and elevating soil pH (Krismawati *et al.*, 2022; Wahyudi *et al.*, 2019).

Consistent with this synergy, treatment P6 (humic acid + compost + dolomite) in our study produced the largest, statistically robust improvements in soil chemical properties (p<0.001), including pH (from 4.35 in P0 to 6.45), organic carbon (from 0.38% to 1.52%), total nitrogen (from 0.23% to 0.31%), available phosphorus and potassium, and CEC (from 17.65 to 33.64 me/100 g). Mechanistically, the liming effect of dolomite shifted pH into a range that reduces Al^{3+} toxicity and enhances phosphate availability; compost increased exchange sites and buffering through added soil organic matter (SOM); and humic substances improved nutrient complexation and root uptake—yielding greater nutrient availability than any single or two-way ameliorants.

Relationship Between Soil Quality and Plant Survival

Plant survival is closely related to soil chemical quality. In this study, survival rate increases with the soil pH, indicating that ameliorant treatments have resulted in a more optimal pH. It is aligned with previous studies that the optimal range of soil pH allows more plants to survive (Crespo-Mendes *et al.*, 2019) and that the survival rate of sorghum ranges from 60% to 80%, depending on the variety (Yartsev *et al.*, 2024). In this study, the highest survival rate is 80.52%, observed in treatment P6, with the highest pH and nutrient content, whereas P0 (control) was only 21.43% (p<0.01). These results indicated a strong positive correlation between the use of ameliorant and plant viability.

Treatments incorporating different ameliorant materials showed increased survival rates. In this study, humic acid acted as a plant regulator and contributed to significant quantities of plant growth hormones. It was in line with previous studies that growth hormones can stimulate root and crown growth, thus maintaining plants in stressful conditions (Khan *et al.*, 2023). In addition, organic compost can enhance stress resilience in plants by gradually providing nutrients (Ahmed *et al.*, 2023) and promote robust plant growth and development by serving as a slow-release source of essential nutrients, including nitrogen, phosphorus, and potassium (Suvendran *et al.*, 2025).

Morphological Performance of Sorghum in Response to Ameliorants

The improvement in soil quality has been reported to positively correlate with the morphological characteristics of the plants (Cuiyun *et al.*, 2023; Drăghici *et al.*, 2024), including plant height (Maftuchah *et al.*, 2021). In general, we observed that the combination of ameliorant materials (humic acid, organic compost, and dolomite) resulted in the best morphological characteristics of Bioguma-2 sorghum (see Table 2). First, plant height in P6 reached 215.60 cm at the initial stage, remained superior during ratoon stages, and was significantly higher than P0 (109.80 cm) (p<0.001). It has been reported that the determining factors for plant morphological characteristics include the availability of macronutrients such as nitrogen, phosphorus, and potassium. Khalofah *et al.* (2022) reported that increasing nitrogen, phosphorus, and potassium levels significantly improved plant height, leaf length, and leaf width. The cation exchange capacity (CEC) enhances nutrient availability in the soil, reduces the competition effects between cations such as Ca, Mg, and K (Yang *et al.*, 2024), and affects plant height. Secondly, we observed a statistically significant relationship between plant height and stem diameter, where taller plants in P5 and P6 also had thicker stems (2.23 cm and 2.15 cm, respectively). This finding confirms Abdullah *et al.* (2024), who found a positive correlation between height and stem diameter.

The third morphological characteristic is the number of leaves. Calcium (Ca) and magnesium (Mg) in dolomite stimulate cell turgor and chlorophyll formation, which enhances the products of photosynthesis(Sambi *et al.*, 2023). At the same time, dolomite supplies phosphorus nutrients that promote plant growth, which is evident in the increased number of leaves and taller plants. Composting, through the decomposition of organic materials, positively influences leaf parameters. These findings confirm a previous study that compost improves leaf characteristics (Kortei, 2016) and that organic fertilizers improve soil health by increasing soil organic matter (SOM), boosting nutrient uptake, enhancing water-holding capacity, and improving cation exchange capacity (CEC) (Liu *et al.*, 2024). Therefore, enhancing soil health can naturally support better plant growth.

We found that water availability influenced the next morphological characteristic, the number of tillers in sorghum plants. A significant difference was observed in ratoon 1 (p=0.015), where P6 had 2.50 tillers while P0 only had 1.25 in P0, highlighting the role of improved soil structure and moisture retention. Despite all plants receiving the same irrigation, we discovered that different ameliorant treatments influenced soil conditions, resulting in varying water absorption capacities among the plants. It confirms Dariah *et al.* (2021), who reported that soil ameliorant treatment positively affected water aggregate stability. Under water stress, ameliorants positively affect yields, suggesting improved water retention and nutrient availability (Ismail *et al.*, 2025).

Biomass Yield and Juice Quality (Brix)

Healthy soils improve nutrient availability, water retention, and root development, all of which are essential for strong crop yields (Srivastava *et al.*, 2024). In our study, yields declined across harvest stages in every treatment (see Table 3). Even in the top treatment

(P6), the fresh yield decreased from 40.84 t ha^{-1} (initial) to only 46% or 18.76 t ha^{-1} in ratoon 1 and to 25% or 10.25 t ha^{-1} in ratoon 2. A similar pattern was observed in dry matter yields, where they decreased from 13.26 t ha^{-1} (initial stage) to 6.10 t ha^{-1} (ratoon 1) to 3.23 t ha^{-1} (ratoon 2), marking 46% and 24% of the initial stage in the respective ratoons. Brix values—an indicator of juice quality—were the highest in P6 across all stages (15.00%, 14.50%, and 13.00% for the initial stage, ratoon 1, and ratoon 2, respectively). It indicated a greater biomass and improved juice quality, relevant for both silage and bioethanol (Costa *et al.*, 2021).

From a physiological standpoint, ratoon regrowth depends on non-structural carbohydrate (NSC) reserves stored in stubble and roots; repeated cutting and an aging root system reduce regrowth vigor. Biomass recovery of the rainfed, acidic, low-SOM post-mining land in this study was further limited by the nutrient drawdown—especially N and K—together with water stress and untilled rhizosphere (Wang *et al.*, 2024; Zhou *et al.*, 2022). These constraints explain the consistent decline from the initial harvest to ratoon 1 and ratoon 2 across treatments. Conversely, Leavitt *et al.* (2023) and Qi *et al.* (2024) reported that the second cuts, which equaled or exceeded the first, usually occurred in well-managed stands with adequate N split/top-dressing and an appropriate cutting height that preserves basal buds, often under favorable moisture. Such conditions were nonexistent on our site, which explained the low ratoon yields. Consistent with these agronomic limitations, soil acidification has been shown to depress growth and yield in related ratooning systems (Pang *et al.*, 2025). Here, poorer crop performance is frequently accompanied by modest declines in Brix, thus reinforcing Brix as a practical product-quality indicator (Costa *et al.*, 2021).

To mitigate ratoon decline on acidic post-mining soils, future management should consider light post-harvest tillage to refresh the rhizosphere, supplemental organic fertilization to sustain nutrient supply, and optimized N management (rate and split/top-dressing). Where feasible, maintaining an appropriate cutting height (to protect basal buds) and improving soil moisture availability are also recommended (Wang *et al.*, 2024; Zhou *et al.*, 2022).

Nutritional Composition of Bioguma-2 Sorghum

The nutritional composition of Bioguma-2 sorghum was influenced by ameliorant treatments (P0–P6) across all harvest stages. The most consistent gain occurred in crude protein (CP), where P6 (humic acid + dolomite + organic compost) had the highest CP at each harvest (13.47–14.04% DM). This percentage is slightly above the figure reported for brown-midrib (BMR) forage sorghum, which averaged at 10.4%, 9.4%, 8.2%, and 8.1% DM at boot, flower, and milk and soft-dough stages, respectively (stage-specific means), and where the BMR trait primarily improves fiber digestibility rather than CP per se (Lyons *et al.*, 2019; McCary *et al.*, 2020; Pupo *et al.*, 2022). In sorghum–sudangrass hybrids (SSG) in pasture settings, CP frequently remained less than 13% of DM across seasons and systems (Guretzky *et al.*, 2021). In this study, CP in P6 exceeded 10% of DM, which was similar to the whole-plant sweet-sorghum silage/fresh material (Zhang *et al.*, 2015) but markedly higher than the physiologically mature grain sorghum stover CP at 3.2–5.4% of DM (Tulu *et al.*, 2025). It is evident that combined organic-inorganic ameliorants have raised CP concentration optimally, confirming previous findings that mixed ameliorants enhance N status and overall forage quality with possible fiber/lignin trade-offs affecting digestibility (Colombini *et al.*, 2012).

Dry matter (DM) content also increased with ameliorant application, with P6 consistently having the highest values across stages, although not significantly different from other treatments ($p>0.05$). This increase may be attributed to improved nutrient availability and soil structure, which enhances biomass production and physiological maturity. These results are consistent with de Silva *et al.* (2020), who found that modern sorghum hybrids respond positively to nitrogen fertilization with increased dry matter production and nutrient accumulation. This indicates that the water content of sorghum across treatments was relatively similar. In other words, the application of soil ameliorants enhanced total biomass production, thereby increasing the absolute dry matter yield, but did not alter the proportion of water retained in the plant tissues. Similar DM percentages across treatments suggest that the physiological water status of the plants remained stable despite differences in growth and biomass accumulation.

Ash content, reflecting total mineral accumulation, was significantly affected by treatment and harvest stages. Higher ash concentrations in P4 and P5 during the initial harvest and in P0 and P1 during the second ratoon suggested variations in nutrient uptake dynamics, likely influenced by organic matter interactions and nutrient release rates. These observations align with reports by Koláčková *et al.* (2020) that sorghum thrives under variable fertility conditions and that nutrient uptake can be modulated by soil properties and ameliorant types.

Crude fat content showed inconsistent trends across treatments and stages. In the initial harvest, treatments P3–P5 exhibited higher fat content, whereas P6 had comparatively lower values. This suggests that fat synthesis may respond differently to ameliorant combinations, potentially linked to variations in metabolic allocation or plant stress response. By ratoon 2, differences in fat content diminished, indicating stabilization across treatments. Crude fiber (CF) content was the highest in P0 and P3 during the early stages but generally lower in the combined treatments of P4–P6, indicating improved forage quality and potential digestibility benefits. However, Sher *et al.* (2022) insist that increased organic input can sometimes raise lignin levels, which may offset digestibility gains despite lower fiber concentrations.

In addition to nutrient composition, the broader adaptability of sorghum should be acknowledged. Sorghum is known for its resilience in suboptimal environments, including dry and nutrient-poor soils (Koláčková *et al.*, 2020). The use of brown midrib (BMR) mutant lines, such as GH2.3, has shown the potential to improve forage digestibility (Wahyono *et al.*, 2023).

These genetic improvements, combined with effective soil management strategies like P6 in this study, could further enhance forage value. Furthermore, while potassium is the most absorbed nutrient by sorghum, it may be unnecessary in soils with adequate K levels (Silva *et al*., 2020), suggesting the importance of site-specific fertilization strategies.

CONCLUSION

The combined application of humic acid, dolomite, and organic compost significantly improved soil chemical properties, plant survival, growth, biomass yield, and nutritional composition of Bioguma-2 sorghum, which was planted on the post-coal mining land in South Kalimantan. Enhanced soil pH, nutrient availability, and cation exchange capacity (CEC) were closely linked to better morphological traits and higher crude protein content. These findings underscore the significance of integrated soil ameliorants in restoring degraded lands and enhancing the forage quality. Further research should explore long-term impacts and genotype-specific responses to optimize sorghum productivity under various environmental conditions.

CONFLICT OF INTEREST

L. Abdullah serves as editor of the Tropical Animal Science Journal but has no role in the decision to publish this article. The authors also declare that they have no conflicts of interest—financial, personal, or otherwise—that could have influenced or be perceived to influence the content of this manuscript.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the authors used Scopus AI strictly to support literature discovery (e.g., surfacing relevant papers and refining search queries), and Grammarly to check grammar, clarity, and concision. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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