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Effects of Biochar Types and Organic–Inorganic Fertilizer Ratios on Sorghum Growth, Physiology, and Yield in Tropical Soil

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ABSTRACT

This study aimed to investigate the interaction between biochar types and organic-inorganic fertilizer ratios, as well as their individual roles in enhancing sorghum's physiological activity, growth, and yield. A factorial completely randomized design (CRD) was employed, with two factors: (1) biochar type (coconut shell biochar and rice husk biochar) and (2) fertilizer ratio (100% goat manure, 50% goat manure +50% urea, and 100% urea). The experiment consisted of six treatment combinations, each replicated four times, resulting in 24 experimental units. Physiological parameters (e.g., total chlorophyll), growth traits (plant dry weight), and yield components (panicle length, number of seeds per panicle, and harvest index) were evaluated. The results showed that rice husk biochar combined with 50% goat manure +50% urea produced a harvest index comparable to coconut shell biochar with 100% goat manure. Both biochar types performed similarly in improving physiological activity, growth, and yield. However, the 50% goat manure +50% urea treatment significantly enhanced plant dry weight (108.64 g), total chlorophyll (53.86 mg·L^{-1}), panicle length (17.05 cm), and seed number per panicle (1,213.58 seeds), demonstrating its superiority over pure organic or inorganic fertilization.

1. INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is a highly adaptable crop with considerable potential for development in Indonesia. However, its current production remains relatively low. The Super 2 variety, which is predominantly cultivated, yields approximately 3 tons per hectare, despite its potential to produce up to 6.3 tons per hectare [1]. To enhance sorghum production, several cultivation techniques can be applied, including soil amendments like biochar and improved fertilization strategies. In recent years, the use of organic fertilizers has gained attention due to the negative environmental impacts of excessive inorganic fertilizer application. Key limiting factors include soil degradation (with an estimated 30-50% loss in arable soil quality in intensive farming regions) and low nitrogen use efficiency (NUE), which falls below 40% in conventional sorghum systems [2]. Organic fertilization approaches provide eco-friendly alternatives that contribute to pollution reduction while progressively enhancing soil characteristics. Yet, despite these benefits, organic cultivation techniques remain underadopted in sorghum farming primarily because they are often seen as less effective at promoting plant growth and grain yield compared to conventional systems. For instance, a recent short-term substitution trial demonstrated that replacing 50% of chemical nitrogen with organic fertilizer significantly improved soil nutrient availability, enhanced enzyme activities, altered microbial community structure, and increased sorghum grain yield to approximately 9,789 kg per hectare, surpassing yields under pure mineral fertilizer regimes ($P < 0.05$) [3].

Recent studies highlight biochar as a transformative soil amendment capable of mitigating these challenges. Lehmann et al. [4] demonstrated that biochar increases soil nitrogen retention by up to 20%, directly addressing NUE limitations in cereal crops.

In addition to fertilizers, soil amendments like biochar play an important role in sorghum cultivation. Biochar enhances soil properties, minimizes nutrient loss, and positively contributes to improving crop yields. It works by binding nutrients in the soil and releasing them gradually, based on plant needs. This helps prevent both nutrient deficiencies and toxic buildup [5]. Furthermore, biochar is effective in restoring degraded soils by reducing leaching and mitigating soil acidity [6]. This study aims to examine the interaction between different types of biochar and the ratio of organic to inorganic fertilizers, as well as to determine their combined effects on sorghum's physiological processes, growth, and yield.

2. MATERIALS AND METHODS

This study was conducted from March to October 2023 at the Experimental Garden of the Faculty of Agriculture, Universitas Sebelas Maret. Materials utilized included agricultural soil, Super 2 variety sorghum seeds, coconut shell biochar, rice husk biochar, goat manure, urea fertilizer, KCl fertilizer, SP-36 fertilizer, herbicides, fungicides, insecticides, 40×40cm polybags, irrigation equipment, and analytical instruments (lux meter, thermohygrometer, ombrometer, measuring tape, caliper, laboratory oven set at 80℃, digital scale with 0.01g precision, camera, mortar, pestle, filter paper, funnel, pipette, UV-Vis spectrophotometer, and cuvettes). The experiment was arranged in a factorial Completely Randomized Design (CRD) with two factors: biochar type (coconut shell and rice husk) applied at 15 $t.ha^{-1}$, and fertilizer composition (100% goat manure at 20 $t.ha^{-1}$, combined 50% goat manure-50% urea, and 100% urea at 200 kg ha^{-1}). This factorial arrangement yielded six treatment combinations, each replicated four times, resulting in 24 experimental units. Prior to initiating the experiment, comprehensive chemical analyses were performed on the soil, both biochar types, and fertilizers to determine their nutrient profiles and relevant properties, establishing baseline data for interpreting plant responses to treatments.

Experimental preparation began with filling polybags with agricultural soil to a standardized volume. Following protocols established by Agegnehu et al. [7], biochar was thoroughly incorporated into the top 15 cm of soil within each polybag at the equivalent rate of 15 $t.ha^{-1}$, ensuring uniform distribution throughout the root zone rather than concentrated application in planting holes. This incorporation method maximizes root-biochar contact while maintaining soil physical structure integrity as recommended by Shaaban et al. [8]. Sorghum seeds were planted at a consistent 3 cm depth with two seeds per polybag, later thinned to one seedling per polybag at 14 days after emergence. Base fertilizer application coincided with planting and included the entire allocated goat manure, one-third of the total urea dosage, complete application of SP-36 (100 $kg.ha^{-1}$), and complete application of KCl (50 $kg.ha^{-1}$). A combination of organic and inorganic fertilizers, such as 100 $kg.ha^{-1}$ SP-18 and 100 $kg.ha^{-1}$ KCl, with 5,000 $kg.ha^{-1}$ cow manure was reported significantly increased soybean yield by 0.95–1.38 $t.ha^{-1}$ and improved soil physical properties on dry land in Gresik, East Java, Indonesia [9], these fertilizers were applied in a ring pattern 5 cm from the planting hole and incorporated to a depth of 5-7 cm to minimize volatilization and maximize nutrient availability. The remaining two-thirds of urea was applied as topdressing exactly 30 days after planting, distributed in a ring pattern 10 cm from the plant stem and lightly incorporated into the soil surface. Crop management included irrigation every 48 hours throughout the growing season, with adjustments during periods of natural rainfall to maintain optimal soil moisture. Weeds were controlled manually at 14-day intervals, while pest and disease management followed standard agricultural practices with twice-weekly monitoring and interventions when pest populations exceeded economic thresholds. Plants were harvested approximately 120 days after planting, when physiological maturity indicators were observed (yellowing and drying of leaves, firm and hard seeds).

Growth parameters measured included plant height (from soil surface to the tip of the uppermost fully expanded leaf), stem diameter (measured 10 cm above soil surface using a digital caliper, taking the average of two perpendicular measurements), and leaf count (including only fully expanded leaves with at least 75% green leaf area). Biomass parameters included plant dry weight, determined by separating plants into root, stem, and leaf components, then oven-drying at 80℃ for 48 hours until constant weight was achieved. The root-shoot ratio was calculated by dividing root dry weight by the combined stem and leaf dry weight. Physiological measurements included chlorophyll content analysis using the Arnon method, as described by Esteban et al. [10]. Leaf samples were collected from the middle portion of the youngest fully expanded leaf (typically the 3rd or 4th leaf from the top) between 9:00-11:00 AM to minimize diurnal variation. Three leaves per plant were sampled, with each measurement repeated three times per leaf to ensure accuracy. Net assimilation rate and relative growth rate were calculated using sequential destructive sampling data according to formulae described by Gardner et al. [11]. Yield components assessed included panicle length (measured from base to tip), number of seeds per panicle (determined by hand-counting all filled seeds), seed weight per panicle, seed weight per plant, seed weight per hectare (calculated by extrapolating individual plant yields), and harvest index (calculated as the ratio of economic yield to total aboveground biomass).

All observational data were subjected to analysis of variance (ANOVA) at a 5% significance level. Where significant differences were detected, treatment means were separated using Duncan's Multiple Range Test (DMRT) at the 5% level. Relationships between measured variables were evaluated using Pearson correlation analysis.

3. RESULTS AND DISCUSSION

3.1 Experimental site conditions

The experiment was conducted at coordinates 7°37'48"N and 110°56'52"E with an altitude of approximately 192 meters above sea level. Soil analysis revealed a Latosol soil type with low fertility characteristics: slightly acidic pH (6.0), 0.08% total nitrogen, 29.21 mg/100 g total phosphorus, 12.26 mg/100 g total potassium, 4.48C/N ratio, and 0.38% organic carbon content. The site exhibited an average light intensity of 18,324 lux at 9:00 AM, with midday temperatures (12:00-1:00 PM) ranging between 25.13-33.53℃, exceeding the optimal temperature range for sorghum growth (25-27℃) as established by Ishak et al. [12]. Meteorological conditions characterized by complete precipitation deficit during the experimental phase, synchronized with excessive atmospheric water vapor concentration (89.71%). The agronomic parameters generated in the study were found to be unsuitable for Sorghum bicolor cultivation, as they contradicted the established hydrometeorological requirements of 500–1500 mm of annual precipitation. This misalignment underscores the critical need for climate-adapted crop management strategies to ensure sustainable sorghum production [13].

3.2 Biochar and fertilizer characterization

Laboratory analysis demonstrated that rice husk biochar contained higher macronutrient concentrations than coconut shell biochar, particularly in terms of nitrogen, phosphorus, and potassium. Rice husk biochar contained 1.13% total N, 0.45% P_2O_5, 1.36% K_2O, and 61.18% organic carbon, while coconut shell biochar contained comparable organic carbon (54.51%). The higher carbon stability in rice husk biochar, as noted by Rahayu et al. [14], contributes to its effectiveness as a soil amendment. Carbon serves as an energy source for soil microorganisms that facilitate organic matter decomposition, improve soil structure, and enhance nutrient cycling processes

[15]. Hu et al. [16] demonstrated that underscores biochar's role in improving nitrogen availability and microbial activity in soil, contributing to more efficient nitrogen cycling and potentially reducing environmental risks associated with nitrogen loss, which helps explain the superior performance of rice husk biochar in our study.

Analysis of goat manure fertilizer revealed high macronutrient content: 2.50% total N, 46.17% organic carbon, and an ideal C/N ratio of 18.48, meeting quality standards established by Sulaeman et al. [17]. The elevated nitrogen content in goat manure stimulates plant growth and carbohydrate formation [18]. Elevated nitrogen levels in soil are associated with increased organic carbon content [19].

3.3 Vegetative growth response of sorghum

Neither coconut shell nor rice husk biochar treatments resulted in statistically significant differences in sorghum height, stem diameter, leaf number, dry weight, or root-shoot ratio. However, fertilizer treatments significantly affected stem diameter and plant dry weight. Sorghum plants receiving combined goat manure-urea fertilization developed significantly larger stem diameters (2.8±20.13 mm) compared to plants treated with urea alone (3.0±16.29 mm). Similarly, sorghum plants with goat manure-urea fertilization produced the greatest dry weight (30.1±108.64 g), significantly higher than plants fertilized with goat manure alone (17.0±68.19 g) (Table 1).

Research findings indicate that the integrated application of goat manure and urea enhances nitrogen absorption in crops, leading to increased stem girth due to improved carbohydrate synthesis [20].

Urea provides rapidly available nitrogen, while goat manure effectively retains both nitrogen and water, optimizing plant absorption. Research by Rahayu et al. [21] confirms that goat manure not only improves soil fertility but also substantially increases water retention capacity. Nitrogen plays a vital role in maximizing photosynthesis rates, generating the carbohydrates essential for robust plant development. Furthermore, nitrogen is fundamentally important for all aspects of vegetative growth, particularly stem development [22].

Statistical analysis demonstrated a significant positive correlation between stem diameter and plant dry biomass (r=0.856), suggesting that increased stem girth facilitates higher biomass production through enhanced carbohydrate transport via expanded vascular structures. This relationship aligns with findings showing that phloem conductivity rises proportionally with stem cross-sectional dimensions, enabling more efficient resource distribution [23].

Table 1. The role of biochar type, goat manure, goat manure-urea, and urea on sorghum growth

Treatment	Plant Height (cm)	Stem Diameter (mm)	Number of Leaves	Plant Dry Weight (g)	Root-Shoot Ratio
Biochar					
Coconut shell	27.9±179.57	2.0±17.64	5.7±13.55	21.0±92.59	0.8±5.21
Rice husk	33.2±176.13	3.6±18.41	3.1±10.22	35.0±87.07	0.8±4.67
Fertilizer ratio					
Goat manure 100%	15.4±175.15	1.3±17.65ab	2.7±9.50	17.0±68.19b	1.2±5.09
Goat manure-Urea 50%-50%	31.3±196.94	2.8±20.13a	5.7±12.50	30.1±108.64a	0.3±5.02
Urea 100%	31.8±161.46	3.0±16.29b	5.1±13.66	22.3±92.65ab	0.9±4.71
Interaction	-	-	-	-	-
Sig biochar	0.77	0.45	0.08	0.58	0.12
Sig fertilizer ratio	0.06	0.01	0.17	0.01	0.62
CV (%)	18.80	16.04	20.43	31.84	19.60

Notes: 1. Numbers followed by the same letter in the same column indicate not significantly different by DMRT at 5% error level; 2. (-): No interaction; 3. Sig: Significance; 4. CV (%): Coefficient of Variance.

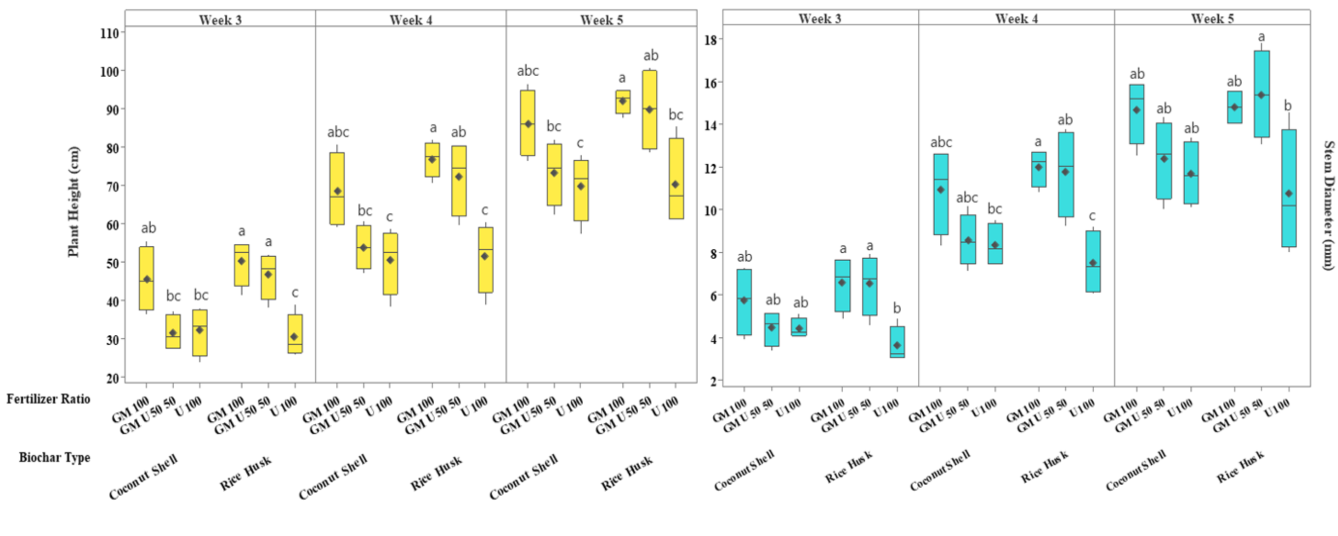


Figure 1. Vegetative growth of plant height and stem diameter of sorghum
Notes: Weeks 3-5 after planting, respectively. Means in the chart followed by common letters show no significant differences.

Different fertilizer ratios showed no significant impact on sorghum's root-shoot ratio, plant height, or leaf count. Sorghum plants treated with goat manure, goat manure-urea combination, and urea alone displayed comparable root-shoot ratios (1.2±5.09, 0.3±5.02, and 0.9±4.71, respectively) as shown in Table 1. The root-shoot ratio indicates how plants distribute photosynthates during growth higher values mean more resources are allocated to shoot development rather than root growth. This physiological ratio serves as a critical biomass investment indicator, where elevated values correlate with preferential shoot development, while reduced ratios signal enhanced root system investment [24]. The elevated root-shoot ratios observed in sorghum treated with goat manure and goat manure-urea combinations stem from goat manure's exceptional ability to enhance soil water retention, maintaining consistent moisture levels [25]. This became particularly important during the experiment when rainfall was insufficient, creating water-limited conditions. Plants with adequate water access prioritize shoot development, resulting in higher root-shoot ratios, while water-stressed plants typically suppress shoot growth and accelerate root development as a survival strategy to maximize water uptake, producing lower root-shoot ratios [26]. However, water availability isn't the only factor affecting root-shoot ratios, nitrogen uptake plays a crucial role as well [27]. The similar root-shoot ratio observed in urea-fertilized sorghum can be attributed to nitrogen's rapid availability, which specifically promotes shoot bud formation.

The experimental data in Figure 1 demonstrate the dynamic effects of different fertilizer combinations and biochar substrates on plant morphological development over a critical three-week growth period. The temporal analysis reveals significant variations in plant performance, with distinct patterns emerging across treatment combinations and measurement periods.

The plant height measurements demonstrate substantial variation across treatment combinations, with notable improvements observed in most applications compared to baseline conditions. Research indicates that biochar integration with organic fertilizers creates synergistic effects that enhance plant vertical growth through improved nutrient availability and soil physical properties [28].

The temporal progression from week 3 to week 5 reveals accelerated growth rates in treatments combining organic and inorganic fertilizers. Investigations into fertilizer integration strategies demonstrate that goat manure combined with urea applications consistently produces superior height development compared to single-source fertilizer treatments [29]. The enhanced performance results from complementary nutrient release patterns, where urea provides immediate nitrogen availability while goat manure ensures sustained nutrient supply throughout the growing period. Research confirms that integrated fertilizer management approaches can increase plant height by 15-18% compared to individual fertilizer applications, particularly when biochar amendments are incorporated into the growing medium [30].

Stem diameter measurements provide critical insights into plant structural development and overall vigor under different treatment regimens. The data indicate progressive diameter increases across most treatment combinations, with specific biochar types demonstrating superior performance in promoting radial growth. Scientific investigations reveal that biochar applications enhance stem diameter development through multiple mechanisms, including improved water retention, enhanced nutrient exchange capacity, and optimized root zone conditions. The differential performance between coconut shell and rice husk biochar reflects their distinct physicochemical properties and nutrient release characteristics. Research demonstrates that rice husk biochar typically exhibits superior performance in promoting stem diameter growth due to its higher surface area and enhanced nutrient retention capacity [31].

The temporal analysis demonstrates that biochar type selection and fertilizer formulation significantly influence plant morphological development patterns. Rice husk biochar applications combined with goat manure-urea combinations (50%:50%) provided optimal conditions for sustained plant height and stem diameter development throughout the five-week evaluation period. These findings support the adoption of integrated biochar-fertilizer systems for enhanced agricultural productivity while promoting sustainable farming practices.

3.4 Physiological responses of sorghum

Neither biochar type significantly affected net assimilation rate, relative growth rate, or leaf chlorophyll content. However, fertilizer treatments significantly influenced relative growth rate and chlorophyll content. Urea fertilization produced the highest relative growth rate (271.4±677.25 mg.week^{-1}), significantly greater than goat manure fertilization (158.9±385.25 mg.week^{-1}) (Figure 2).

Table 2. Correlations between variables

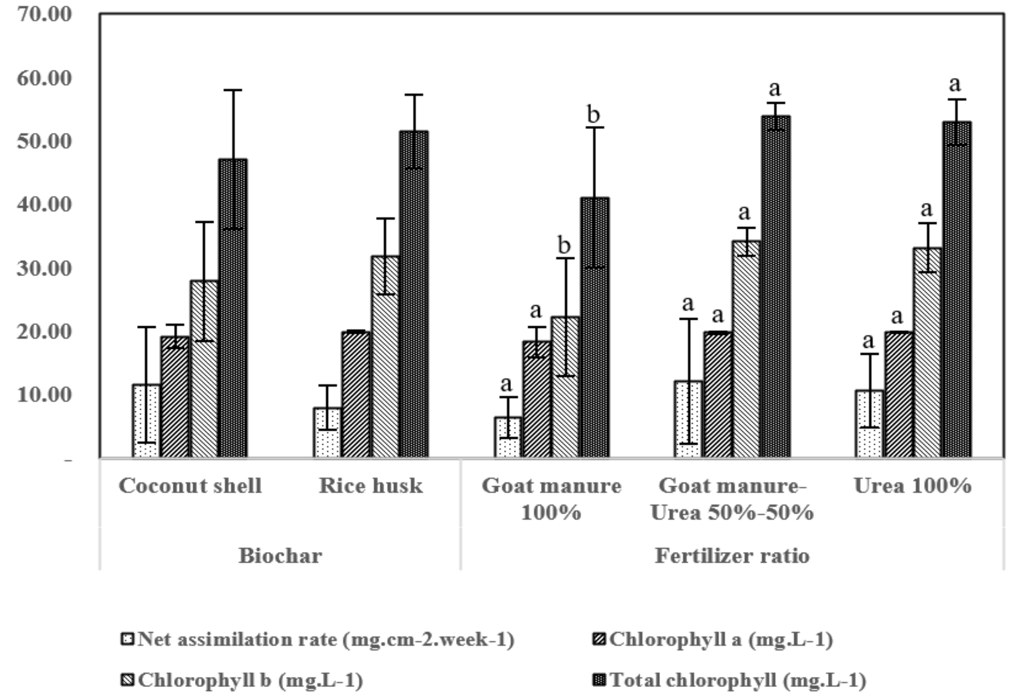
	PH	SD	NL	DW	RSR	NAR	RGR	CC	PL	NSPP	SWPP	SWPl	SWPh	HI
PH	1													
SD	.471*	1												
NL	.309	.294	1											
DW	.785**	.856**	.450*	1										
RSR	.197	-.164	-.024	-.012	1									
NAR	.277	.413*	.180	.500*	.002	1								
RGR	.099	.507*	.229	.454*	.164	.747**	1							
CC	.005	.462*	.167	.340	-.263	.238	.340	1						
PL	.528**	.674**	.549**	.717**	.014	.191	.142	.260	1					
NSPP	.766**	.768**	.187	.866**	-.043	.357	.234	.177	.712**	1				
SWPP	.781**	.750**	.184	.861**	-.048	.359	.206	.160	.717**	.997**	1			
SWPl	.860**	.748**	.337	.928**	.028	.346	.287	.167	.688**	.932**	.930**	1		
SWPh	.861**	.744**	.336	.928**	.025	.346	.282	.168	.689**	.933**	.931**	1.000**	1	
HI	.817**	.450*	.344	.674**	.111	.113	.072	-.116	.571**	.736**	.740**	.871**	.871**	1

Notes: 1. PH (Plant Height), SD (Stem Diameter), NL (Number of Leaves), DW (Plant Dry Weight), RSR (Root-Shoot Ratio), NAR (Net Assimilation Rate), RGR (Relative Growth Rate), CC (Chlorophyll Content), PL (Panicle Length), NSPP (Number of Seeds Per Panicle), SWPP (Seed Weight Per Panicle), SWPl (Seed Weight Per Plant), SWPh (Seed Weight Per Hectare), HI (Harvest Index); 2. *= significance 95%, **= significance 99%.

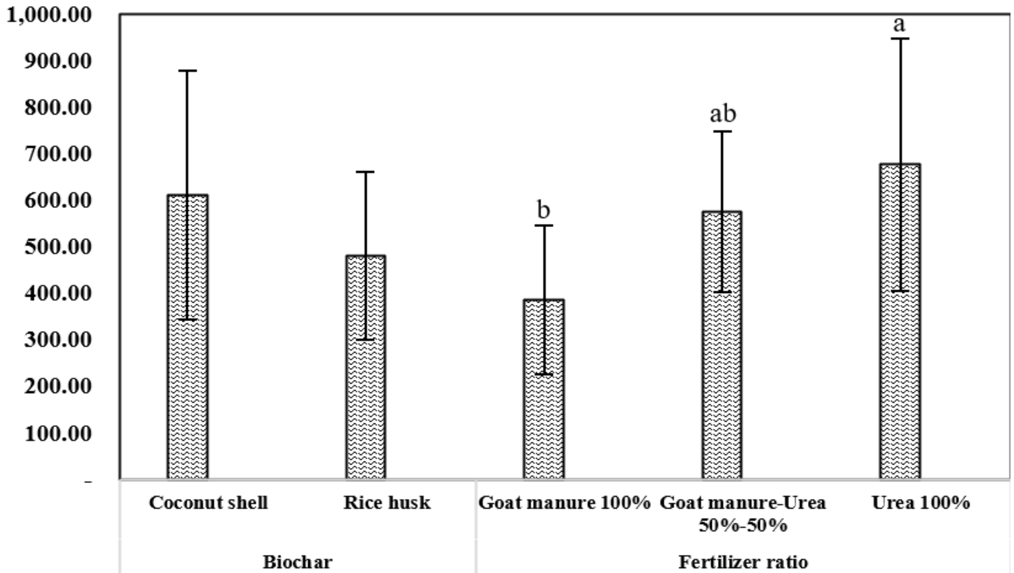
Combined goat manure-urea fertilization resulted in the highest chlorophyll b (2.2±34.12 mg.L^{-1}) and total chlorophyll (2.2±53.86 mg.L^{-1}) concentrations, significantly exceeding values from goat manure treatment (9.3±22.14 mg.L^{-1} and 11±41.04 mg.L^{-1}, respectively) (Figure 2(a)). The synergistic effect of goat-derived organic matter combined with urea-based nitrogen sources promotes enhanced nutrient accessibility, resulting in elevated chlorophyll concentrations and improved plant physiological performance [32]. Nitrogen is not only critical for plant growth but also plays a vital physiological role in chlorophyll synthesis, as it is a key component in its formation [33]. This effect of goat manure-urea on chlorophyll levels directly supports sorghum growth, as seen in the improved stem diameter and dry weight of the plants (Table 1). A correlation analysis further confirmed that leaf chlorophyll content has a moderately strong positive relationship with stem diameter (r=0.462) (Table 2).

Interestingly, our results revealed lower chlorophyll a level compared to chlorophyll b (Figure 2), suggesting that the sorghum plants experienced stress due to a lack of rainfall during the study, which restricted water availability (drought conditions). Under such environmental stress, plants activate the chlorophyllase enzyme, which breaks down chlorophyll and reduces its overall concentration [34].

Figure 3 illustrates the effects of different fertilizer ratios and biochar types on chlorophyll b and total chlorophyll content in plants. Treatments included 100% goat manure (GM 100), a combination of goat manure and urea (GM+U 50+50), and 100% urea (U 100), each combined with either coconut shell or rice husk biochar.



(a)



(b)

Figure 2. The role of biochar type, goat manure, goat manure-urea, and urea on physiological activities: (a) net assimilation rate, chlorophyll a, chlorophyll b, total chlorophyll, and (b) relative growth rate

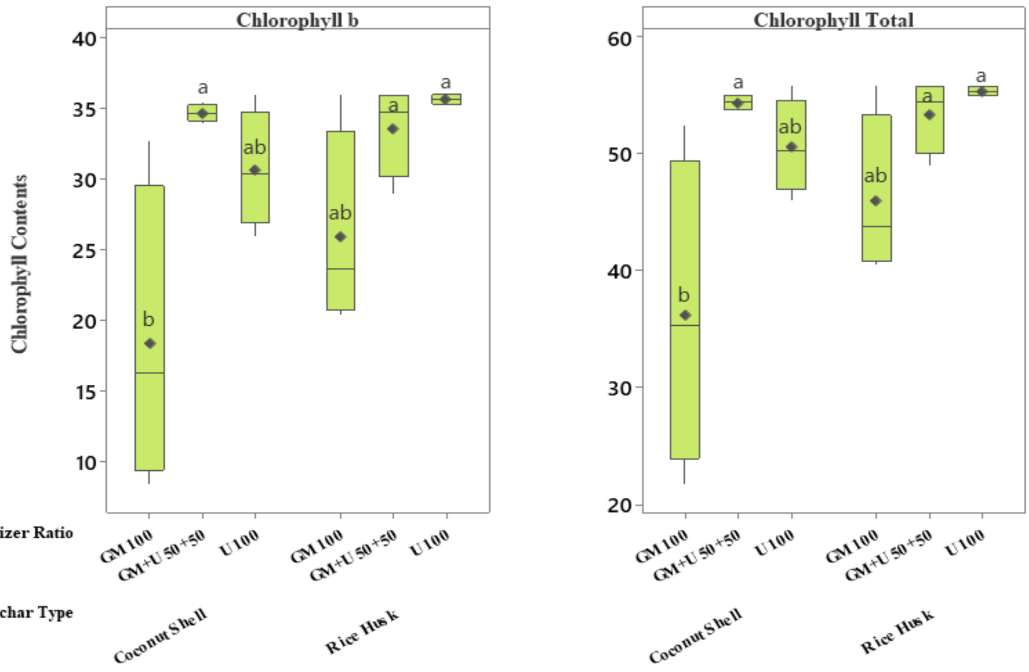


Figure 3. Changes in chlorophyll content for each treatment

Chlorophyll b and total chlorophyll content were generally higher in treatments involving urea or a combination of goat manure and urea compared to goat manure alone, particularly when paired with rice husk biochar. The statistical grouping shows that urea 100% and combined goat manure+urea 50%+50% treatments often resulted in significantly higher chlorophyll content than goat manure 100%, especially for rice husk biochar. This finding is consistent with research demonstrating that the application of mineral fertilizers such as urea can enhance chlorophyll synthesis, as nitrogen is a key component of chlorophyll molecules and supports leaf development and photosynthetic efficiency [35]. Silva Júnior et al. [36] reported that increasing urea concentrations led to substantial increases in both chlorophyll b and total chlorophyll content in orchids, highlighting the direct role of nitrogen in promoting chlorophyll biosynthesis.

The type of biochar also influenced chlorophyll content. Treatments with rice husk biochar tended to yield higher and more consistent chlorophyll levels than those with coconut shell biochar. This aligns with studies showing that biochar can improve soil nutrient availability, thereby enhancing plant physiological traits such as chlorophyll content [37]. For instance, Zhao and Zhang [38] found that moderate biochar application rates significantly improved chlorophyll content in corn leaves, while excessive rates could have adverse effects due to increased soil pH 7. Similarly, biochar produced from different feedstocks can vary in its impact on nutrient retention and plant growth, with some types (like rice husk biochar) being particularly effective at supporting photosynthetic pigment accumulation [39].

3.5 Yield component and yield of sorghum

Biochar type did not significantly influence panicle length or seed number per panicle, but fertilizer treatments produced significant differences. Combined goat manure-urea fertilization resulted in the longest panicles (1.3±17.05 cm) and highest seed count per panicle (670.6±1213.58 seeds), significantly exceeding values from goat manure treatment (only 2.5±13.47 cm length and 223.20±554.67 seeds, respectively) (Table 3).

Table 3. The role of biochar type, goat manure, goat manure-urea, and urea on sorghum yield

Treatment	Panicle Length (cm)	Number of Seeds per Panicle	Seed Weight per Panicle (g)	Seed Weight per Plant (g)	Seed Weight per Hectare (t. ha^{-1})
Biochar					
Coconut shell	1.7±15.53	378.9±821.29	11.0±23.39	10.4±28.38	0,7±2.03
Rice husk	2.7±14.53	622.0±776.73	17.8±22.42	17.9±25.82	1.3±1.84
Fertilizer ratio					
Goat manure 100%	2.5±13.47b	223.2±554.67b	6.5±16.43b	10.9±20.38b	0.8±1.46b
Goat manure-Urea 50%-50%	1.3±17.05a	670.6±1213.58a	19.0±34.97a	17.1±36.99a	1.2±2.64a
Urea 100%	1.3±14.57b	195.0±628.79b	6.0±17.32b	9.8±23.93ab	0.7±1.71ab
Interaction	-	-	-	-	-
Sig biochar	0.15	0.52	0.58	0.38	0.42
Sig fertilizer ratio	<0.05	0.01	0.01	0.03	0.03
CV (%)	13.10	28.50	28.13	25.90	20.75

Notes: 1. Numbers followed by the same letter in the same column indicate not significantly different by DMRT at 5% error level; 2. (-): No interaction; 3. Sig: Significance; 4. CV (%): Coefficient of Variance.

Table 4. The role of biochar type with various fertilizer ratios on the harvest index

Biochar	Fertilizer Ratio			Mean
	Goat Manure 100%	Goat Manure-Urea 50%-50%		Urea 100%
Coconut shell	2.7±25.75a	2.8±23.03ab	2.9±20.21b	3.7±23.00
Rice husk	3.1±17.82b	2.6±25.92a	3.1±19.36b	4.0±21.03
Mean	4.2±21.79	2.0±24.47	3.7±19.78	+
Sig	0.02			
CV (%)	18.9			

Notes: 1. Numbers followed by the same letter in the same row and column indicate not significantly different by DMRT at 5% error level; 2. (+): There is interaction; 3. Sig: Significance; 4. CV (%): Coefficient of Variance.

This outcome can be attributed to the combined effect of goat manure and urea in sustaining nitrogen (N) uptake, which plays a crucial role in supporting the formation of panicles and seeds. The formation of panicles requires a substantial supply of nitrogen, especially during the crucial period of panicle primordium differentiation. Sufficient nitrogen during this phase greatly enhances panicle development in sorghum [40]. Adequate nitrogen availability is crucial for supporting the reproductive processes in plants, as it significantly promotes both the initiation and successful maturation of seeds [41].

The harvest index was significantly influenced by the interaction between biochar type and fertilizer ratio (Table 4). Notably, sorghum treated with rice husk biochar and goat manure-urea fertilizer achieved the highest harvest index (2.6±25.92), showing a statistically significant difference compared to rice husk biochar with goat manure alone (3.1±17.82).

The combination of biochar source and fertilizer application rate had a marked effect on the harvest index of sorghum. Specifically, plants receiving rice husk biochar together with a mixture of goat manure and urea exhibited the greatest harvest index values, which were significantly higher than those observed in treatments with rice husk biochar and goat manure alone. This increase in harvest index suggests a more effective partitioning of assimilates toward grain production as opposed to vegetative biomass [42].

The superior performance of rice husk biochar with goat manure-urea stems from its enhanced phosphorus (P) and potassium (K) availability, which promotes greater assimilate partitioning to harvestable organs. Rice husk biochar not only provides these essential nutrients but also helps retain them in the soil [43]. Phosphorus (P) and potassium (K) are essential for directing assimilate allocation to reproductive organs; their optimal concentrations enhance the translocation of photosynthates to these tissues [44]. Additionally, the application of urea at 100 kg.ha^{-1} provides supplementary nitrogen (N), which is vital for the development of sorghum seeds.

Interestingly, the harvest index of sorghum treated with rice husk biochar and goat manure-urea (2.6±25.92) was not significantly different from that of plants treated with coconut shell biochar and goat manure (2.8 ± 23.03) (Table 4). This comparable performance is likely due to the efficiency of nutrient absorption enabled by coconut shell biochar in combination with goat manure. Even with a limited nutrient supply, this treatment supported sufficient seed development, resulting in a similarly high harvest index. Efficient nutrient uptake, particularly nitrogen, enhances photosynthesis, which is critical for reproductive development during the generative phase [45]. While sufficient nitrogen enhances the harvest index by promoting grain yield, excessive nitrogen application can redirect assimilate allocation toward vegetative growth, thereby diminishing the harvest index [46].

Figure 4 illustrates a comparative evaluation of different fertilizer applications and biochar type on grain yield and plant dry weight, demonstrating the complex interactions between organic manure, inorganic fertilizers, and biochar substrates in agricultural production systems. This analysis reveals significant variations in plant performance across treatment combinations, highlighting the importance of integrated nutrient management approaches in modern sustainable agriculture.

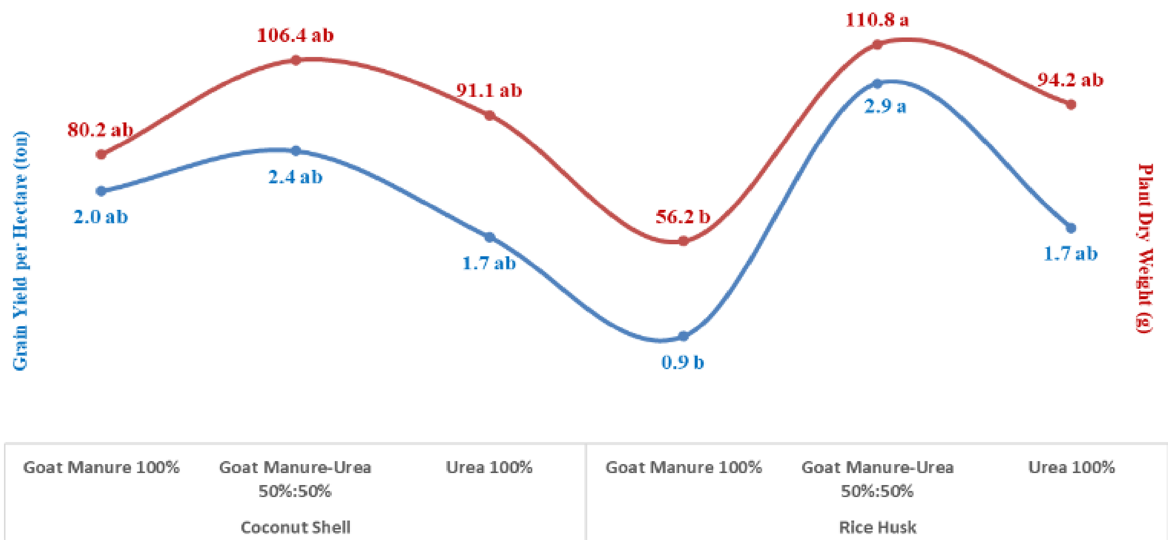


Figure 4. The role of biochar type with various fertilizer ratios on grain yield and plant dry weight

The coconut shell biochar treatments revealed distinct patterns in plant growth responses. Pure goat manure application (100%) resulted in a moderate grain yield of 2.0 tons per hectare and a relatively low plant dry weight of 80.2 g. The combination treatment of goat manure-urea (50%:50%) demonstrated enhanced performance, achieving 2.4 tons per hectare for grain yield and significantly increased plant dry weight of 106.4 g. Conversely, the pure urea treatment (100%) showed reduced effectiveness with grain yield declining to 1.7 tons per hectare, though plant dry weight remained substantial at 91.1 g.

Contemporary research supports these findings, as organic fertilizers derived from animal manures exhibit a more sustained nutrient release compared to synthetic fertilizers, enhancing long-term soil fertility and minimizing environmental risks [47]. The enhanced performance of combination treatments aligns with established principles that balanced nutrient delivery systems optimize plant metabolic processes more effectively than single-source applications [48].

Rice husk biochar treatments exhibited markedly different response patterns compared to coconut shell biochar applications. Pure goat manure treatment achieved minimal grain yield of 0.9 tons per hectare but demonstrated the lowest plant dry weight at 56.2 g. The combination treatment (goat manure-urea 50%:50%) produced exceptional results, yielding 2.9 tons per hectare for grain and the highest recorded plant dry weight of 110.8 g across all treatments. Pure urea application resulted in intermediate performance with 1.7 tons per hectare of grain and 94.2 g of plant dry weight.

The superior performance of rice husk-based combination treatments can be attributed to the unique physicochemical properties of rice husk biochar. Research indicates that rice husk materials enhance soil porosity and water retention capacity while providing essential silica compounds that strengthen plant cellular structures [49]. Additionally, the gradual decomposition of rice husk components creates favorable conditions for microbial activity, which facilitates improved nutrient cycling and availability [50].

Statistical analysis revealed significant differences between treatment combinations. The rice husk biochar consistently outperformed coconut shell biochar applications, particularly evident in the combination treatments where rice husk-based formulations achieved 20.8% higher seed weight and 4.1% greater plant dry weight compared to coconut shell equivalents.

The differential performance between substrates can be explained by their distinct compositional characteristics. Coconut shell biochar exhibits pronounced drainage capabilities and long-term structural integrity, making it well-suited for sustained cultivation systems [51]. However, rice husk biochar offers superior nutrient retention capabilities and enhanced microbial habitat formation, resulting in more efficient nutrient utilization by plant root systems [52].

The synergistic effects observed in combination treatments (goat manure-urea 50%:50%) across both biochar types demonstrate the importance of balanced fertilization approaches. Pure organic applications, while environmentally sustainable, may result in nutrient deficiencies during critical growth periods due to slower mineralization rates [53]. Conversely, long-term use of purely synthetic fertilizers can induce nutrient imbalances, especially when only N, P, and K are supplied while neglecting secondary and micronutrients, which destabilizes soil nutrient cycling and suppresses critical microbial processes [54].

The optimal performance of combination treatments reflects the complementary nature of organic and synthetic nutrient sources. Goat manure provides slow-release organic matter that improves soil structure and supports beneficial microbial populations, while urea supplies readily available nitrogen for immediate plant uptake during periods of high metabolic demand [55].

The experimental results clearly demonstrate that biochar selection and fertilizer combination strategies significantly influence plant growth parameters. Rice husk biochar combined with balanced goat manure-urea formulations (50%:50%) provided optimal conditions for both grain yield and plant biomass accumulation. These findings support the implementation of integrated organic-synthetic fertilization approaches for enhanced agricultural productivity while maintaining environmental sustainability objectives.

4. CONCLUSIONS

This study demonstrated significant interactions between biochar type and fertilizer composition on sorghum productivity, with key findings as follows: Rice husk biochar combined with a balanced 50%-50% goat manure-urea mixture achieved comparable harvest index values to coconut shell biochar with 100% goat manure application. Both coconut shell and rice husk biochar demonstrated equivalent effectiveness in enhancing critical growth parameters including plant height, stem diameter, leaf production, plant dry weight, root-shoot ratio, net assimilation rate, relative growth rate, leaf chlorophyll content, panicle length, seed quantity per panicle, and comprehensive seed weight metrics (per panicle, per plant, and per hectare).

The 50%-50% goat manure-urea combination delivered superior results across multiple performance indicators: substantially increased stem diameter (20.1 mm), enhanced plant dry weight (108.6 g), elevated chlorophyll b (34.1 $mg.L^{-1}$) and total chlorophyll (53.9 $mg.L^{-1}$) levels, extended panicle length (17 cm), maximized seed count per panicle (1214 seeds), and optimized seed weight at all measurement scales per panicle (35 g), per plant (37 g), and per hectare (2.6 $t.ha^{-1}$).

For sustainable agricultural practices, coconut shell biochar with 100% goat manure represents an environmentally responsible option for sorghum cultivation while maintaining excellent harvest index values. While inorganic fertilizers remain viable for sorghum production, their integration with organic fertilizers consistently delivers superior agronomic outcomes.

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