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RESEARCH ARTICLE
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Response of Morphophysiological Characteristics of Several New Superior Rice Varieties with the Use of Bioactive Compost Charcoal as an Ameliorant on Acid Sulfate Soil

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ABSTRACT

This study aimed to evaluate the effect of using bioactive compost biochar (Arkoba) on the morphophysiological characteristics of several new superior rice varieties (NSRV) in acid sulfate soils. Conducted from June to November 2024 at the Laboratory of the Faculty of Agriculture, Science, and Technology at Panca Bhakti University, the research employed a completely randomized design with a factorial pattern. Two factors were tested: doses of Arkoba (0, 10, 15, and 20tons/ha) and rice varieties (Argo Ketapang, Inpari 32, Inpari 49, and Inpari Nutri Zinc). The results showed that the application of Arkoba significantly improved plant growth, with the highest dose (20tons/ha) significantly increased the total number of tillers, and the number of grains per panicle. The Inpari Nutri Zinc variety exhibited the highest grain weight per panicle and panicle length. The combination of the highest Arkoba dose with Inpari Nutri Zinc resulted in the highest grain yield, highlighting the interaction between Arkoba dosage and variety selection. These findings indicated that the use of Arkoba as a soil amendment, particularly at a dose of 20tons/ha, was an effective strategy for enhancing rice productivity in acid sulfate soils. Further research was recommended to optimize Arkoba application under various agroclimatic conditions.

Keywords: Acid Sulfate Soil; Bioactive Compost Charcoal; Rice Productivity; Rice Varieties; Soil Amendment

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INTRODUCTION

The reduction of agricultural land due to conversion to non-agricultural uses; each year, no less than 110,000 hectares were converted into non-agricultural land (Sudrajat et al., 2020). The population increase also impacted the rising demand for food, which threatened the national food security program (Pramono et al., 2021). According to 2022 data, Indonesia was the fourth largest rice-consuming country, with 35.37 million tons consumed, while rice production in Indonesia was 31.54 million tons, leaving Indonesia needing to fulfill a shortfall of 3.83 million tons (BPS, 2023). The government aimed to meet rice consumption by increasing production through new rice fields, including tidal land (Imanudin et al., 2023). West Kalimantan has 1,904,100 hectares of tidal land, much of which is acid sulfate soil (BPS, 2020). Research by Suyanto et al. (2023a, b) indicates that while acid sulfate soil can be used for paddy fields, challenges such as low macro-nutrient availability, high solubility of Fe, Al, and Mn, acidic pH, and pyrite presence must be addressed. In addition to expanding rice fields, production can also rise by using new superior rice varieties (NSRV) (Bobihoe et al., 2021). NSRV features morphophysiological traits that enhance rice productivity (Wang et al., 2021).

The growth and production differences among rice varieties depend on their adaptability and genetic traits (Khairullah et al., 2021). To boost production on acid sulfate soils, it is crucial to promote NSRV with high yields and adaptability, necessitating tests for their suitability in such conditions (Jalil et al., 2016). Sustainable soil ameliorants offer an efficient, low-cost solution for improving acid sulfate soil chemistry (Kakar et al., 2020). Utilizing agricultural waste as biochar through pyrolysis is an eco-friendly approach (Masulili et al., 2022). Biochar can be incorporated into organic fertilizers as bioactive compost charcoal via composting with bioactivators (Arkoba), enhancing soil fertility (Wang & Akdeniz, 2023).

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Agricultural waste can be processed into biochar through pyrolysis (Masulili et al., 2022). This biochar can absorb and release nutrients like soil colloids (Masulili et al., 2023). Recent studies highlight biochar's potential as a soil amendment to enhance soil health and crop productivity. Singh et al. (2023) found that biochar application significantly improves soil nutrient retention and microbial activity, leading to better plant growth. Fachini et al. (2023) noted that using biochar in rice cultivation increases yield and contributes to carbon sequestration, making it a viable option for sustainable agriculture in tropical regions. Huang et al. (2023) emphasized the challenges of acid sulfate soils in rice production, which often result in reduced yields due to low pH and high aluminum toxicity. Integrating biochar into agricultural practices is a promising strategy to mitigate soil degradation. Wang et al. (2022) suggested that biochar improves soil structure and enhances water retention, crucial for crop resilience in changing climates.

Biochar can be combined with organic fertilizer to create bioactive compost charcoal (Arkoba) (Wang & Akdeniz, 2023). Suyanto et al. (2019c) reported that Arkoba is made by mixing biochar and compost materials with lignocellulolytic microbes (bioactivators). Biochar in Arkoba enhances composting performance, microbial diversity, and activity, while reducing bulk density and nitrogen loss, and increasing pH, cation exchange capacity (CEC), organic matter, total carbon, and nutrients (Antonangelo et al., 2021; Mujtaba et al., 2021; Gao et al., 2023). Arkoba boosts soil C, N, and P, stabilizes aggregates, and stimulates microorganism activity (Forjan et al., 2018; Asadi et al., 2021). It acts as an ameliorant on acidic soil (Nain et al., 2024) and has improved the growth of canola on chromium-stressed soil (Naveed et al., 2021), cabbage on sandy loam (Izilan et al., 2022), and sorghum on coastal soil (Yin et al., 2022). Arkoba from coconut shells can enhance rice height, tiller number, and grain weight on acid sulfate soils (Suyanto et al., 2019c).

New superior varieties (NSRV) are breeding lines with advantages such as high yield potential, pest and disease tolerance, environmental stress tolerance, and quality traits, officially released by the government (Subekti & Sugiarti, 2022). Using locally adaptive varieties is essential for enhancing food crop productivity in West Kalimantan Province. To demonstrate their yield potential, varieties need specific environmental conditions (Marlina et al., 2019). Research by Suyanto et al. (2023d, e) indicates that not all varieties thrive in various agroecosystems, particularly on acid sulfate soil, meaning optimal results depend on suitable land conditions.

The novelty of this research lies in using Arkoba, produced by mixing biochar and compost materials with live bioactivator microbes. The bioactivator, *Trichoderma* sp., was sourced from local tidal lands. Irianti & Suyanto (2016) found that *Trichoderma* sp. is the best lignocellulolytic microbe for decomposing rice straw. This study aims to evaluate the effects of bioactive compost charcoal (Arkoba) on the morphological and physiological characteristics of new superior rice varieties in acid sulfate soils, providing insights into sustainable agricultural practices to enhance rice productivity in challenging conditions.

MATERIALS & METHODS

This study will be conducted at the Laboratory and Green House of the Faculty of Agriculture, Science, and Technology at Panca Bhakti University in Pontianak, West Kalimantan Province, from June to November 2024. The research site was located at an elevation of one meter above sea level, with daily average temperature during the study ranged from 25.67 to 32.00°C, humidity during the study ranged from 65.75 to 92.75%, latitude between 2º05' N–3º05' S, and longitude between 108º30'–144º10' E. The materials used will include acid sulfate soil, four types of rice seed varieties, raw materials for making Arkoba (biochar from rice husks, straw, manure, sugar, lime, and *Trichoderma* sp.), fertilizers (Urea, SP36, KCl), organic pesticides, tarps, and polybags. The equipment includes a pyrolysis machine, straw chopper, seedling trays, hoes, measuring tape, pH meter, thermometer, scales, analytical balance, oven, sprayer, soil auger, and other supporting tools.

The study will use a completely randomized design (CRD) with a factorial pattern involving two factors: the first factor (I) is the Arkoba dosage, with four levels: D0=without Arkoba, D1=10tons/ha, D2=15tons/ha, and D3=20tons/ha. The second factor (II) is the type of new superior rice variety (NSRV): V1=Argo Ketapang, V2=Inpari 32, V3=Inpari 49, and V4=Inpari Nutri Zinc. Each treatment combination will be repeated three times. The F-test at 5% and Honest Significant Difference (HSD) test at 5% will be used to analyze treatment effects.

Prior to the study, composite soil samples will be taken from a depth of 0-20cm at various observation points, and the pyrite layer depth will be determined using an H_2O_2 solution. Soil samples will then be analyzed for their chemical and physical properties, which will be compared to soil fertility standards set by the Soil Research Institute in 2009 (Suyanto et al., 2023d).

Next, acid sulfate soil will be prepared as the planting medium by collecting soil with a hoe. The soil will then be air-dried for one week, sieved to a 1cm x 1cm size, and placed in polybags weighing 8 kg each. Before sowing, the seeds will be soaked in water for 15min; floating seeds will not be used, while those that sink will be sown. Seedling trays (4 trays) will be used, with one rice variety per tray (Suyanto et al., 2023d).

The Arkoba preparation involves the following steps: 1) producing biochar through pyrolysis of rice husks, 2) preparing compost materials from chopped rice straw (1-2cm pieces), and 3) making compost by mixing chopped straw, biochar, and manure in a 1:1:1 weight ratio. Agricultural lime (20 g) will be added to neutralize pH and provide Ca and Mg nutrients. The mixture will then receive a solution containing *Trichoderma* sp. bioactivator. For 100kg of compost material, a 500mL solution will be used. A sugar solution will be added as a nutrient source for microorganisms to accelerate composting. Moisture will be maintained by adding water if necessary, and the mixture will be covered with a plastic tarp to prevent external microorganisms from entering. The compost will be stored in a shaded area, protected from direct sunlight and rain. It will be turned once a week to lower the compost temperature and speed up the process, which will last 30 days. Arkoba will be applied two weeks before planting by incorporating it into the soil at the specified dosage (Suyanto et al., 2019c).

Planting will occur after seedlings are 21 days old, and they will be transplanted into polybags. Holes will be made in the soil 5cm deep, and three seedlings will be planted in each hole. Fertilizer will be applied three times: at 1, 3, and 6 weeks after planting (WAP). SP36 and KCl will each be applied in three equal doses, while Urea will be applied in two doses, each ½ dose at 1 and 3 WAP. Soil moisture will be maintained at saturation during the vegetative growth phase, and after the grains mature, soil moisture will be gradually reduced (Suyanto et al., 2023d).

Pest and disease control will be done by spraying organic pesticides at 2, 4, and 7 WAP. Weed control will be done by hand-weeding within the polybags at 3 and 6 WAP. Harvesting will occur when the plants reach 116-125 days after planting (DAP). The observed parameters in this study include: Plant Height, Number of Tillers, Number of Leaves, Number of Grains per Panicle, Grain Weight per Panicle, Grain Weight per Cluster, Weight of 100 Grains, Panicle Length, Root Volume, Dry Weight, Shoot-to-Root Ratio, Relative Growth Rate, and Nutrient Uptake (Suyanto et al., 2023d).

RESULTS & DISCUSSION

The analysis of alluvial soil showed several important characteristics that influenced soil fertility and productivity potential (Table 1). The soil displayed an acidic pH (4.65), which significantly affected nutrient availability within the soil. Recent studies indicated that soil pH below 5.5 increased aluminum solubility and reduced the availability of phosphorus, calcium, and magnesium (Gillespie et al., 2021). In acidic soils, phosphorus availability decreased significantly due to Al and Fe fixation (Rahman et al., 2018). Although the organic carbon content (2.14%) and total nitrogen (0.24%) were classified as moderate and sufficient to support plant growth, additional organic matter was essential to improve buffering capacity and nutrient availability (Voltr et al., 2021).

The high availability of phosphorus (P2O5) and potassium, measured at 15.27 ppm and 1.24cmol/kg, respectively, represented favorable conditions for plant growth. Recent research showed that P2O5 levels above 15 ppm were optimal for most cultivated crops (Sweeney & Ruiz Diaz, 2020). Additionally, the balance of high P and K concentrations was associated with yield increases of up to 40% in well-managed acidic soils (Glaser & Lehr, 2019).

The main constraints identified were the very low calcium content (8.74cmol/kg) and the low cation exchange capacity (CEC) (15.81cmol/kg). Calcium deficiency in low-pH conditions has been shown to reduce root growth by up to 45% and inhibit nutrient uptake (Duan et al., 2022). Although low CEC is a characteristic of acidic alluvial soils, it could be improved through organic matter management (Zielewicz et al., 2022). The high base saturation level (85.14%) indicated good fertility potential, with previous research suggesting that base saturation above 80% generally supported plant growth even in low-pH conditions (Chaganti et al., 2021). The silty clay texture provided favorable physical characteristics, with optimal water retention capacity and root aeration properties (Bell et al., 2024).

The high levels of sodium (0.86cmol/kg) and magnesium (2.62cmol/kg) required careful monitoring, as an unbalanced Ca ratio could disrupt K and micronutrient absorption (Escobedo-Monge et al., 2022). The presence of H+ (0.99cmol/kg) and Al3+ (1.09cmol/kg) indicated potential toxicity, as Al3+ levels above 1cmol/kg are known to inhibit root growth and reduce yield by up to 35% (Wei et al., 2021). These findings suggested that while the soil had several characteristics favorable to agriculture, specific management strategies were needed to address the identified limitations and optimize the soil's production potential.

Before being used as an organic matter source, Arkoba rice husk underwent nutrient content analysis. The analysis results, shown in Table 2, indicated interesting chemical characteristics. Arkoba had a pH of 6.42, which suggested a near-neutral condition. The C-organic content was very high at 34.98%, while nitrogen (N) content reached 0.68%. The C/N ratio of Arkoba rice husk was relatively high, at 51.44. For other macronutrients, Arkoba contained phosphorus (P) at 1.29% and potassium (K) at 0.97%. Additionally, Arkoba also contained secondary nutrients such as calcium (Ca) at 0.48% and magnesium (Mg) at 0.15%.

Table 1: Alluvial soil analysis

Parameters		Value	Criteria
pH H2O pH KCl		4.65 3.76	Acidic
C-Organic	%	2.14	Moderate
Total Nitrogen	%	0.24	Moderate
P2O5	Ppm	15.27	High
Kalium	cmol (+) kg^{-1}	1.24	Very High
Natrium	cmol (+) kg^{-1}	0.86	High
Kalsium	cmol (+) kg^{-1}	8.74	Very Low
Magnesium	cmol (+) kg^{-1}	2.62	High
CTC	cmol (+) kg^{-1}	15.81	Low
Base Saturation	%	85.14	Very High
Hidrogren	cmol (+) kg^{-1}	0.99	
Aluminium	cmol (+) kg^{-1}	1.09	
Texture Sand Silz Clay	% % %	2.9566.82 30.23	Silty Clay

Table 2: Results of Rice Husk Arkoba Analysis Top of Form

Parameters	Value
pH	6.42
C-organic (%)	34.98
N (%)	0.68
C/N Rasio	51.44
P (%)	1.29
K (%)	0.97
Ca (%)	0.48
Mg (%)	0.15

Based on this composition, Arkoba rice husk had strong potential as an organic matter source to improve soil quality and provide essential nutrients for plants. The high C-organic content could contribute to enhancing soil structure and increasing soil microbial activity. Although the C/N ratio was high, the presence of significant levels of macronutrients such as N, P, and K indicated that Arkoba could serve as a nutrient source for plant growth. The Ca and Mg content could also aid in balancing nutrient availability within the soil.

The results of rice plant growth analysis showed a dynamic development pattern throughout the observation period. At 3 WAP (Weeks After Planting), variance analysis revealed a highly significant effect (P<0.01) of Arkoba treatment (D) on all growth parameters (Table 3). This was in line with findings by Chen et al. (2021), who reported that biochar application significantly improved rice growth and yield by enhancing nutrient availability and improving soil physical properties. Additionally, Olszyk et al. (2020) confirmed that biochar can increase crop growth, including rice, by affecting nitrogen uptake and overall plant health. Treatment D2 consistently showed the best results for all growth parameters at 3 WAP, with plant height reaching 73.4cm, 15.3 tillers, and 38.1 leaves (Table 4). In their study, Yu et al. (2019) found that an optimal biochar dose could increase vegetative plant growth by up to 35% compared to the control by enhancing cation exchange capacity and nutrient retention in the soil.

Observations at 5 WAP (Weeks After Planting) showed a similar trend, with Arkoba treatment still having a highly significant effect (P<0.01) on all parameters (Table 3). Treatment D2 produced a plant height of 110.3cm, 37.3 tillers, and 68.1 leaves, which were significantly higher than the other treatments (Table 6). Chen et al. (2021) demonstrated that biochar application could increase crop yields by improving nutrient use efficiency and enhancing soil physical properties.

At 7 WAP, the effect of Arkoba treatment became even more apparent, with a significant increase in growth parameters. Treatment D2 resulted in a plant height of 130.4cm and 42.8 tillers, showing an increase of 8.9% and 18.8%, respectively, compared to the control (Table 8). Khan et al. (2024) reported that biochar use could enhance plant growth by improving soil microbial activity and nutrient availability. Observations at 9 WAP showed the culmination of the treatment effect, with D2 producing the tallest plant height (142.9cm) and the highest number of tillers (44.8) (Table 10). Butnan & Vityakon (2023) found that sustained biochar application could improve crop yields by enhancing soil characteristics and optimizing nutrient uptake.

Regarding variety, V1 (Argo) consistently showed the best performance in vegetative growth parameters (Table 5, 7, 9, and 11). Atkinson et al. (2010) identified that varietal responses to soil amendments were strongly influenced by genetic characteristics and specific adaptability of the variety. Dry weight analysis showed a significant increase under treatment D2, reaching 172.6 g at 9 WAP, indicating higher biomass accumulation (Table 10). Alkharabsheh et al. (2021) reported that increased plant biomass positively correlated with improvements in soil physicochemical properties due to biochar application.

Table 3: F Calculated Number of Tillers 7 WAP (5.80**), 9 WAP (5.80**) F Calculated Number of Leaves 3 WAP (5.14**), 5 WAP (5.14**)

Treatment (D)	F Calculated for					
	Plant Height	Number of Tillers	Number of Leaves	Dry Weight	F Table 5%	F Table 1%
3 WAP						
Arkoba (D)	5.73**	60.04**	22.54**	51.87**	3.40	5.61
Variety (V)	4.93**	4.38*	5.14*	28.13**	3.00	4.71
Interaction (D x V)	0.49ns	2.44ns	0.47ns	1.67ns	2.50	3.67
5 WAP						
Arkoba (D)	5.73**	60.04**	22.54**	51.87**	3.40	5.61
Variety (V)	4.93**	4.38*	5.14*	28.13**	3.00	4.71
Interaction (D x V)	0.49ns	2.44ns	0.47ns	1.67ns	2.50	3.67
7 WAP						
Arkoba (D)	7.72**	53.50**	16.87**	16.31**	3.40	5.61
Variety (V)	9.86**	5.80*	8.52**	72.77**	3.00	4.71
Interaction (D x V)	0.89ns	1.37ns	0.60ns	1.53ns	2.50	3.67
9 WAP						
Arkoba (D)	7.67**	53.50**	18.39**	17.78**	3.40	5.61
Variety (V)	11.59**	5.80*	7.45**	20.57**	3.00	4.71
Interaction (D x V)	0.88ns	1.37ns	0.45ns	1.59ns	2.50	3.67

Note: **: Significantly different at the 1% level; *: Significantly different at the 5% level; ns: Not significantly different.

Table 4: Tukey's HSD Test Results on the Independent Effect of Arkoba Dosage 3 Weeks After Planting (WAP)

Arkoba Dosage	Average Plant Height (cm)	Average Number of Tillers	Average Number of Leaves	Average Dry Weight (g)
D0	66.2±3.6a	8.0±0.9a	24.8±2.4a	2.2±0.5a
D1	66.0±5.1a	10.3±1.6b	32.5±4.2b	2.6±0.6a
D2	73.4±4.3b	15.3±1.4c	38.1±3.6c	3.9±0.4b

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 5: Tukey's HSD Test Results on the Independent Effect of Varieties 3 Weeks After Planting (WAP)

Variety	Average Plant Height (cm)	Average Number of Tillers	Average Number of Leaves	Average Dry Weight (g)
V1	74.8±3.8b	12.2±2.5b	36.7±5.7b	3.9±0.5c
V2	64.7±5.3a	11.3±3.1ab	32.1±6.0ab	2.3±0.7a
V3	65.8±6.6a	11.8±3.2b	30.4±6.4 ab	3.0±0.8b
V4	68.9±4.5ab	9.6±2.6a	27.9±4.1a	2.4±0.8a

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 6: Tukey's HSD Test Results on the Independent Effect of Arkoba Dosage 5 Weeks After Planting (WAP)

Arkoba Dosage	Average Plant Height (cm)	Average Number of Tillers	Average Number of Leaves	Average Dry Weight (g)
D0	102.0±7.3a	30.0±0.9a	55.5±3.0a	36.7±3.8a
D1	102.6±3.5a	31.8±1.2b	62.5±4.2b	37.3±3.4a
D2	110.3±5.5b	37.3±1.4c	68.1±3.6c	42.2±3.8b

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 7: Tukey's HSD Test Results on the Independent Effect of Varieties 5 Weeks After Planting (WAP)

Variety	Average Plant Height (cm)	Average Number of Tillers	Average Number of Leaves	Average Dry Weight (g)
V1	113.4±4.6b	33.6±2.4ab	67.7±4.8b	46.3±3.5b
V2	99.4±7.3a	33.3±3.1ab	62.1±6.0ab	36.9±3.9a
V3	101.7±6.7a	33.8±3.2b	60.4±6.4a	36.2±3.2a
V4	105.2±6.1ab	31.6±2.6a	57.9±4.1a	35.6±3.0a

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 8: Tukey's HSD Test Results on the Independent Effect of Arkoba Dosage 7 Weeks After Planting (WAP)

Arkoba Dosage	Average Plant Height (cm)	Average Number of Tillers	Average Number of Leaves	Average Dry Weight (g)
D0	119.8±4.5a	36.0±0.9a	79.5±3.9a	89.6±4.9a
D1	122.0±5.3a	37.8±1.2b	85.5±4.2b	88.6±6.3a
D2	130.4±7.5b	42.8±1.7c	91.1±3.6c	95.6±5.8b

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 9: Tukey's HSD Test Results on the Independent Effect of Varieties 7 Weeks After Planting (WAP)

Variety	Average Plant Height (cm)	Average Number of Tillers	Average Number of Leaves	Average Dry Weight (g)
V1	133.6±6.2b	39.6±2.4b	92.0±3.7b	104.8±3.6c
V2	119.7±9.2a	39.3±3.1b	85.1±6.0a	88.0±2.7ab
V3	117.2±3.6a	39.8±3.2b	83.4±6.4a	88.3±4.9b
V4	125.9±5.0ab	36.9±1.9a	80.9±4.1a	83.9±2.6a

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 10: Tukey's HSD Test Results on the Independent Effect of Arkoba Dosage 9 Weeks After Planting (WAP)

Arkoba Dosage	Average Plant Height (cm)	Average Number of Tillers	Average Number of Leaves	Average Dry Weight (g)
D0	136.3±5.9a	38.0±0.9a	106.0±3.5a	129.2±22.5a
D1	135.7±4.4a	39.8±1.2b	112.5±4.2b	134.7±16.0a
D2	142.9±5.0b	44.8±1.7c	118.1±3.6c	172.6±23.5b

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 11: Tukey's HSD Test Results on the Independent Effect of Varieties 9 Weeks After Planting (WAP)

Variety	Average Plant Height (cm)	Average Number of Tillers	Average Number of Leaves	Average Dry Weight (g)
V1	147.2±5.2b	41.6±2.4b	118.3±4.2b	180.2±16.5b
V2	136.2±6.3a	41.3±3.1b	112.1±6.0ab	120.1±20.7a
V3	132.7±5.3a	41.8±3.2b	110.4±6.4a	122.2±18.2a
V4	137.1±3.8a	38.9±1.9a	107.9±4.1a	159.4±29.8b

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 12: ANOVA Results for the Ratio of Shoots to Roots

Treatment (D)	F Calculated Plant Height	F Table 5%	F Table 1%
Arkoba (D)	3.90*	3.40	5.61
Variety (V)	6.67**	3.00	4.71
Interaction (D x V)	1.41ns	2.50	3.67

Note: **: Significantly different at the 1% level; *: Significantly different at the 5% level; ns: Not significantly different.

The interaction between Arkoba treatment and variety (D x V) did not show a significant effect on all growth parameters during the observation period (Table 3). Lu et al. (2023) explained that the lack of significant interaction could be due to the dominance of the main effects of each treatment factor. This consistent growth trend indicated the effectiveness of Arkoba in promoting rice plant growth, particularly at the highest dose (D2). Afshar & Mofatteh (2024) emphasized that biochar use could be an effective strategy to increase crop productivity by improving soil quality and optimizing nutrient uptake, while also providing the added benefit of climate change mitigation.

Variance analysis revealed that the Arkoba treatment (D) had a significant effect at the 5% level, while variety (V) showed a highly significant effect at the 1% level on the shoot-to-root ratio, with no significant interaction between the two (Table 12). Li et al. (2024) confirmed that biochar consistently affected plant productivity and nutrient cycling, with effects varying depending on plant characteristics and environmental conditions. The results of Tukey's HSD test on the independent effect of Arkoba (Table 13) showed that treatment D1 produced the highest shoot-to-root ratio (4.9±0.6), significantly different from the control (D0: 3.9±0.4). Khan et al. (2024) reported that biochar application increased plant productivity by an average of 14.5%, with greater improvements observed in acidic, sandy soils. Liu et al. (2020) also confirmed that the effectiveness of biochar depended heavily on experimental conditions, including application dose and soil properties.

Table 13: Tukey's HSD Test Results on the Independent Effect of Arkoba Dosage on Shoot-to-Root Ratio

Arkoba Dosage	Average Shoot-to-Root Ratio
D0	3.9±0.4a
D1	4.9±0.6b
D2	4.5±1.0ab

Note: Average values followed by the same letter were in column not significantly different based on Tukey's HSD Test at a 0.05 significance level.

The effect of variety on the shoot-to-root ratio (Table 14) displayed a clear differentiation, with variety V1 reaching the highest value (5.2±0.8). Huang et al. (2019) found that continuous biochar application on rice plants significantly affected yield and yield components, including biomass allocation between shoots and roots. Wang et al. (2018) added that biochar could increase drought tolerance in rice by regulating root morphology and antioxidant metabolism. Haefele et al. (2011) also confirmed the positive effects and fate of biochar derived from rice residues in rice-based systems. Biochar improved rice seedling growth and nutrient recovery, which contributed to increased plant biomass.

The increase in the shoot-to-root ratio could be attributed to improved soil properties resulting from biochar application. Dong et al. (2024) explained that

Table 14: Tukey's HSD Test Results on the Independent Effect of Varieties on Shoot-to-Root Ratio

Variety	Average Shoot-to-Root Ratio
V1	5.2±0.8c
V2	3.6±0.3a
V3	4.0±0.7ab
V4	4.9±1.0bc

Note: Average values followed by the same letter in column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

biochar could improve the physical and chemical properties of highly weathered soils in tropical regions. The growth enhancement mechanism could be explained through several pathways. Krounbi et al. (2021) identified that biochar influenced soil biota, which in turn increased nutrient availability for plants. Kammann et al. (2015) and Sun et al. (2017) found that biochar could improve nitrogen uptake by plants through increased nitrate retention and enhanced plant growth. Improved nutrient and water retention also contributed to the increased shoot-to-root ratio. Major et al. (2012) reported that biochar could reduce nutrient leaching in soils, while Uzoma et al. (2011) confirmed the positive impact of biochar on the hydraulic properties of sandy soils and nutrient retention. Zhang et al. (2016) added that biochar helped improve plant productivity and reduce greenhouse gas emissions under balanced fertilization conditions.

Based on the variance analysis results, the Arkoba treatment (D) did not show a significant effect on the relative growth rate (RGR) during all observation periods (Table 15). However, the variety factor (V) had a highly significant effect ($P<0.01$) on RGR 1 and RGR 3, while no significant effect was observed on RGR 2. This finding is consistent with recent research by Song et al. (2024), who demonstrated that genetic variation among rice varieties significantly influences growth patterns, often overshadowing the effects of agronomic treatments. The results indicate that the genetic characteristics of rice varieties play a crucial role in determining their growth rates, which aligns with the findings of Zhou et al. (2024), who explored the genomic patterns of variations in rice and highlighted the importance of genetic diversity in improving agronomic traits. This suggests that while treatments like Arkoba may not significantly alter RGR, the inherent genetic makeup of the rice varieties is a more critical factor in their growth performance. In the analysis of the independent effect of variety (Table 16), V2 displayed the highest RGR 1 value (0.25g/g/week), significantly different from the other varieties. Huang et al. (2017) reported that growth rate differences during the early vegetative phase were strongly influenced by the genetic characteristics of the varieties and the varying nutrient use efficiency among them. For RGR 3, V1 and V4 had higher values (0.04g/g/week) compared to V2 and V3 (0.01g/g/week).

All varieties showed a pattern of declining relative growth rate (RGR) with increasing plant age (Table 16), where RGR 1 values (0.20-0.26g/g/week) were higher than RGR 2 (0.06-0.08g/g/week) and RGR 3 (0.00-0.05g/g/week). Recent research by Shin et al. (2020) explained that the decline in RGR is a normal physiological process associated with changes in photosynthate allocation and the role of hormones like cytokinins in rice plant development. This decline is often linked to the plant's transition from vegetative growth to reproductive stages, where resource allocation shifts to support grain filling rather than leaf and stem growth.

The absence of a significant interaction between Arkoba treatment and variety indicated that each variety's RGR response was independent of Arkoba treatment. Gu et al. (2022) supported this finding, showing that the effects of fertilization and soil amendments on rice growth were more related to changes in soil characteristics than interactions with plant genotype. Pan et al. (2017) added that the effectiveness of agronomic inputs in enhancing plant growth depended heavily on the timing of application and growing environment conditions.

A comprehensive analysis of yield components and rice plant growth showed a significant response to Arkoba application and variety differences (Table 17). The Arkoba treatment had a highly significant effect ($P<0.01$) on tiller formation and productive tillers, with the D2 dose producing the highest number of tillers (34.6±3.0) and the most productive tillers (19.5±1.2), increasing by 12.7% and 11.4%, respectively, compared to the control (Table 18). Recent findings by Chen et al. (2021) reported that biochar application improved plant productivity by enhancing soil physical properties and nutrient availability, with an average yield increase of 15.53% to 24.43% in rice under water-saving irrigation conditions. Anisuzzaman et al. (2021) stated that the increase in tillers was associated with improved soil aeration and increased cation exchange capacity, facilitating more efficient nutrient uptake.

Genetic differentiation among varieties was evident in tiller formation, where V1 showed the highest number of tillers (39.2±1.3) but had fewer productive tillers (16.8±0.7) (Table 19). Zhao et al. (2020) identified key genes controlling tiller formation in rice and their regulation of plant productivity. They found that the photoperiodic heading

Table 15: ANOVA Results for Relative Growth Rate (RGR)

Treatment (D)	F Calculated RGR 1	F Calculated RGR 2	F Calculated RGR 3	F Table 5%	F Table 1%
Arkoba (D)	1.59ns	0.78ns	0.78ns	3.40	5.61
Variety (V)	8.80**	0.90ns	14.44**	3.00	4.71
Interaction (D x V)	1.90ns	1.57ns	1.98ns	2.50	3.67

Note: **: Significantly different at the 1% level; *: Significantly different at the 5% level; ns: Not significantly different.

Table 16: Tukey's HSD Test Results on the Independent Effect of Varieties on Relative Growth Rate (RGR) Values

Variety	Average RGR 1 (3 WAP)	Average RGR 2 (5 WAP)	Average RGR 3 (7 WAP)
V1	0.214±0.007a	0.068±0.005	0.040±0.006b
V2	0.250±0.016c	0.073±0.008	0.016±0.012a
V3	0.221±0.018ab	0.075±0.006	0.018±0.010a
V4	0.242±0.014bc	0.072±0.006	0.047±0.009b

Note: **: Significantly different at the 1% level; *: Significantly different at the 5% level; ns: Not significantly different.

gene HD1 directly influences the productive tiller ratio, highlighting the complex genetic interactions that affect tiller dynamics. Additionally, Long et al. (2024) emphasized that the expression of genes related to tiller formation is influenced by a complex interaction between genotype and environmental conditions, including nutrient availability and soil moisture status.

In terms of yield components, the Arkoba treatment had a highly significant effect on grain formation and filling. The D2 dose produced 97.6±5.9 grains per panicle with a weight of 11.7±0.5 g, about 12% higher than the control (Table 18). Schmidt et al. (2019) reported that biochar increased the availability of phosphorus and potassium, which play essential roles in grain filling. Liu et al. (2020) confirmed that an increase in the number of grains per panicle positively correlated with improved soil nutrient status, especially phosphorus, which is vital for seed formation and filling. Although Arkoba did not show a significant effect on grain weight per hill and 100-grain weight, the variety factor had a highly significant effect ($P<0.01$) (Table 17). V4 reached the highest grain weight per hill (182.1±31.5 g) (Table 19). Li et al. (2018) confirmed that yield variation among varieties was closely related to the efficiency of photosynthate translocation and sink capacity. Long et al. (2024) explained that differences in grain weight among varieties were also influenced by genetic variation in the expression of genes regulating carbohydrate and protein metabolism during seed filling.

Varieties had a highly significant effect on panicle length, with V4 reaching the highest value (29.0±1.5cm) (Table 19). Chen et al. (2024) explained that panicle length is a genetically controlled trait but is responsive to nutrient management. For root volume, although neither treatment factor showed a significant effect, the D2V4 combination reached the highest value (170.0±33.1cm³) (Table 20). Xu et al. (2022) added that improved root architecture contributed to increased nutrient uptake efficiency and adaptation to environmental stress.

This yield increase mechanism was explained by Glaser and Lehr (2019) through improvements in soil physical properties (porosity, aggregation, water-holding capacity), chemical properties (availability of P and K, cation exchange capacity), and biological activity stimulation. Dai et al. (2020) confirmed that biochar increased beneficial microbial populations and soil enzyme activity. Biederman and Harpole (2012) added that biochar's positive effect on crop yields was associated with increased mycorrhizal colonization and nutrient availability.

Table 17: ANOVA Results for Number of Tillers, Number of Productive Tillers, Number of Grains per Panicle, Grain Weight per Panicle, Grain Weight per Hill, Weight of 100 Grains, Panicle Length, and Root Volume

Treatment (D)	F Calculated Number of Tillers	F Calculated Number of Productive Tillers	F Calculated Number of Grains per Panicle	F Calculated Grain Weight per Panicle	F Calculated Grain Weight per Hill	F Calculated Weight of 100 Grains	F Calculated Panicle Length	F Calculated Root Volume	F Table 5%	F Table 1%
Arkoba (D)	19.59**	15.00**	15.11**	37.54**	2.09ns	1.54ns	0.45ns	2.08ns	3.40	5.61
Variety (V)	57.90**	5.36**	5.87**	4.98**	5.33**	5.27**	19.56**	1.18ns	3.00	4.71
Interaction (D x V)	1.46ns	1.43ns	1.37ns	0.71ns	1.54ns	0.65ns	0.23ns	1.46ns	2.50	3.67

Note: *: Significantly different at the 1% level; : Significantly different at the 5% level; ns: Not significantly different.

Table 18: Tukey's HSD Test Results on the Independent Effect of Arkoba Dosage on Number of Tillers, Productive Tillers, Grains per Panicl e, and Grain Weight per Panicle

Arkoba Dosage	Average Number of Tillers	Average Productive Tillers	Average Grains per Panicle	Average Grain Weight per Panicle
D0	30.7±3.1a	17.5±0.6a	87.1±3.3a	9.9±0.3a
D1	30.0±3.2a	17.1±0.8a	85.5±4.1a	9.7±0.5a
D2	34.6±3.0b	19.5±1.2b	97.6±5.9b	11.7±0.5b

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 19: Tukey's HSD Test Results on the Independent Effect of Varieties on Number of Tillers, Productive Tillers, Grains per Panicle, Grain Weight per Panicle, Grain Weight per Hill, Weight of 100 Grains, and Panicle Length

Variety	Average Number of Tillers	Average Productive Tillers	Average Grains per Panicle	Average Grain Weight per Panicle	Average Grain Weight per Hill	Average Weight of 100 Grains	Average Panicle Length
V1	39.2±1.3b	16.8±0.7a	83.5±3.8a	9.8±0.7a	141.0±4.9a	12.2±0.2a	26.1±1.7b
V2	28.5±1.8a	18.0±1.0ab	89.9±4.9ab	10.5±0.8ab	163.7±16.3ab	13.1±0.7ab	21.4±1.7a
V3	29.4±1.9a	18.5±1.0b	92.7±5.0b	10.8±0.8b	174.5±14.6b	13.5±0.6b	22.5±1.6a
V4	30.0±3.5a	18.8±2.0b	94.2±9.8b	10.8±1.2b	182.1±31.5b	13.4±0.8b	29.0±1.5b

Note: Average values followed by the same letter in a column were not significantly different based on Tukey's HSD Test at a 0.05 significance level.

Table 20: Average Observation Values on Number of Tillers, Productive Tillers, Grains per Panicle, Grain Weight per Panicle, Grain Weight per Hill, Weight of 100 Grains, Panicle Length, and Root Volume

Treatment	Average Number of Tillers	Average Productive Tillers	Average Grains per Panicle	Average Grain Weight per Panicle	Average Grain Weight per Hill	Average Weight of 100 Grains	Average Panicle Length	Average Root Volume
D0V1	38.7±2.5	16.5±1.0	80.7±8.7	9.3±0.6	143.6±18.4	12.3±0.8	25.9±9.5	126.7±86.5
D0V2	28.6±4.1	18.1±2.5	90.7±12.3	10.3±1.5	176.5±49.6	13.6±1.9	21.8±9.6	137.8±25.3
D0V3	28.0±2.9	17.8±1.7	89.0±8.6	10.1±1.0	169.5±34.3	13.3±1.3	22.2±7.5	162.2±93.1
D0V4	27.7±2.5	17.6±1.5	88.0±7.5	10.0±0.9	165.5±29.7	13.1±1.2	28.3±4.2	104.4±53.2
D1V1	37.7±1.7	16.1±0.7	80.3±3.3	9.0±0.4	136.2±12.0	11.9±0.5	25.9±3.7	130.0±105.7
D1V2	26.6±5.5	16.9±3.3	84.7±16.5	9.6±2.0	153.0±64.2	12.6±2.6	20.8±4.3	117.8±25.3
D1V3	28.4±1.7	18.1±1.0	90.3±5.2	10.2±0.6	174.8±21.1	13.5±0.8	21.6±4.7	121.1±66.9
D1V4	27.2±8.5	17.3±5.1	86.7±25.4	9.8±3.0	161.7±96.2	12.9±4.0	29.6±8.0	121.1±45.6
D2V1	41.2±2.1	17.9±0.8	89.4±4.2	10.9±0.5	143.1±14.9	12.3±0.6	26.6±4.2	137.8±41.7
D2V2	30.4±3.9	18.9±2.3	94.3±11.7	11.5±1.4	161.4±44.1	13.1±1.8	21.6±2.7	113.3±24.8
D2V3	31.9±7.0	19.7±4.2	98.7±21.1	12.0±2.5	179.2±82.7	13.7±3.3	23.7±2.6	148.9±33.5
D2V4	35.0±8.4	21.6±5.0	108.0±25.2	12.5±2.0	219.2±110.8	14.2±1.5	29.1±2.8	170.0±33.1

Joseph et al. (2021) emphasized the importance of selecting optimal dosages and responsive varieties to maximize the benefits of biochar application. Ye et al. (2019) highlighted the economic and sustainability considerations of applying this technology in sustainable farming systems. Singh et al. (2023) recommended an integrated approach in biochar use, considering soil characteristics, crop needs, and specific agroclimatic conditions of the location.

The nutrient absorption analysis (Fig. 1-3) showed significant variation in the absorption of N, P, and K across various treatment combinations of Arkoba dosage and rice varieties. The D0V1 treatment achieved the highest N absorption at 6.20 g, followed by D2V1 (5.90 g) and D1V1 (5.70 g) (Fig. 1), indicating the superiority of variety V1 in nitrogen absorption efficiency. These findings align with the results of Huang et al. (2019), who reported that continuous application of biochar can enhance nitrogen absorption and use efficiency in rice through increased soil N availability and optimization of N metabolic processes in plants.

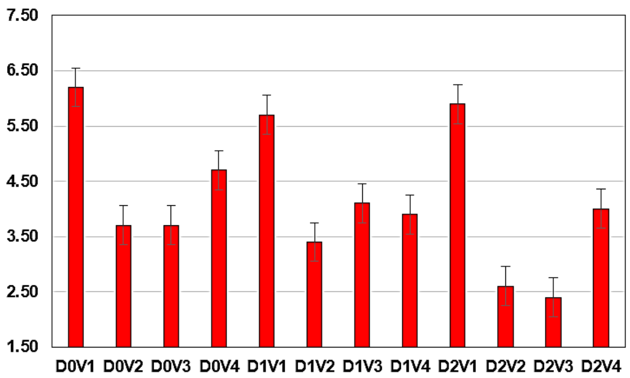

Fig. 1: N Nutrient Uptake/Absorption (g/plant) in Each Treatment.

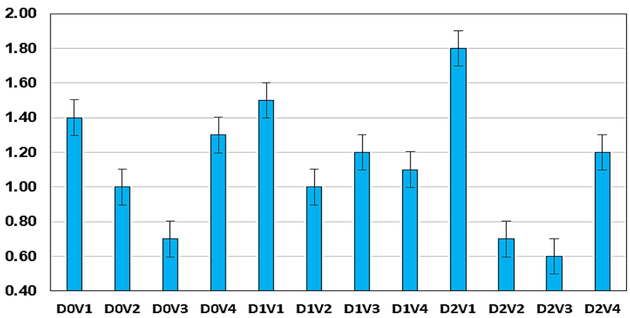

Fig. 2: P Nutrient Uptake/Absorption (g/plant) in Each Treatment.

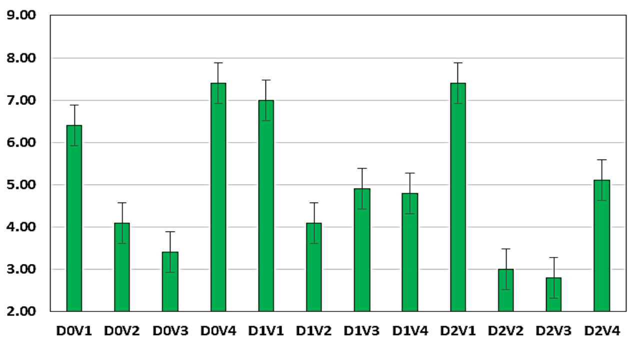

Fig. 3: K Nutrient Uptake/Absorption (g/plant) in Each Treatment.

In terms of P absorption, variation ranged from 0.60 to 1.80 g per plant, with the D2V1 treatment showing the highest value (Fig. 2). Sun et al. (2017) confirmed that the addition of biochar can improve root growth and nutrient absorption in rice, particularly phosphorus, by improving soil physical characteristics and increasing the activity of phosphate-solubilizing microbes. The increased P absorption is closely related to biochar's ability to modify soil pH and create a more conducive environment for phosphorus availability.

K absorption varied from 2.80 to 7.40g/plant, with the D2V1 and D0V4 treatments achieving the highest values (Fig. 3). Xu et al. (2023) explained that nutrient availability influenced by biochar plays a more critical role in plant growth than water-holding capacity. Liu et al. (2018), through their meta-analysis, revealed that the effectiveness of biochar in increasing plant productivity greatly depends on experimental conditions, including initial soil characteristics and application dosage. The observed nutrient absorption pattern can also be explained by improvements in soil physical properties induced by biochar. Buss et al. (2022) demonstrated that biochar application can enhance soil aggregate stability and water availability, which in turn facilitates nutrient movement and absorption by plant roots. This increased aggregate stability contributes to creating a better rooting environment for nutrient absorption.

The variation in nutrient absorption among treatments highlights the complexity of interactions between biochar, plant varieties, and soil nutrient dynamics. The combination of optimal biochar dosage (D2) with varieties that have high nutrient absorption efficiency (V1) resulted in the best performance in terms of nutrient absorption. This indicates the importance of variety selection and optimization of biochar dosage in rice nutrient management. These findings provide practical implications for the development of more efficient and sustainable fertilization strategies in rice production systems. Overall, the study concluded that the application of Arkoba at a D2 dosage had the most favorable effect on rice plant growth and yield, as evidenced by significant increases in both vegetative parameters and yield components. The D2 treatment resulted in a higher number of tillers (34.6±3.0), productive tillers (19.5±1.2), and grains per panicle (97.6±5.9) compared to other treatments. From the variety perspective, V4 showed superiority in terms of grain weight per clump (182.1±31.5g) and panicle length (29.0±1.5cm), while the D2V4 treatment combination achieved the highest grain weight per clump (219.2±110.8g). Although there was no significant interaction between Arkoba dosage and variety, both factors independently contributed positively to improved rice growth and productivity. These results indicate that the use of Arkoba as a soil amendment, particularly at the D2 dosage, can be an effective strategy for increasing rice production, especially when combined with the appropriate variety selection. Further research is needed to optimize Arkoba application under various agroclimatic conditions and different cultivation systems.

Conclusion

The research results showed that the application of

Arkoba had a highly significant effect on rice plant growth and yield, with the D2 dosage showing the best performance, marked by an increase in total tillers (34.6±3.0), productive tillers (19.5±1.2), and grains per panicle (97.6±5.9). Variety response showed clear differentiation, with V4 excelling in grain weight per clump (182.1±31.5g) and panicle length (29.0±1.5cm), while the D2V4 combination produced the highest grain weight per clump (219.2±110.8g). This improvement was achieved through enhancements in soil physical, chemical, and biological properties. These findings imply that the application of Arkoba at the D2 dosage, combined with the appropriate variety selection, can be an effective strategy to increase rice productivity while supporting sustainable agriculture. Optimizing this technology requires further research to assess its effectiveness under various agroclimatic conditions, as well as policy support for large-scale implementation.

Conflict of Interest: All authors declare that they have no conflicts of interest.

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