

Research Article

Application of organic matter-enriched biochar for improving degraded acid sulfate soil properties in rice (*Oryza sativa* L.) cultivation

Agusalim Masulili*, Sri Rahayu, Ida Ayu Suci, Edi Kurniadi

Department of Agrotechnology, Faculty of Agriculture, Science and Technology, Panca Bhakti University, Pontianak 78113, West Kalimantan, Indonesia

*corresponding author: agusalim@upb.ac.id

Abstract

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Acid sulfate soils pose significant challenges for rice cultivation due to their extreme acidity (pH<4.0) and associated nutrient deficiencies. This study investigated the effectiveness of biochar enriched with various organic amendments in improving soil properties and rice growth in degraded acid sulfate soils. A randomized block design was employed with seven treatments: control (B0), biochar enriched with *Chromolaena odorata* (B1), rice straw (B2), chicken manure (B3), cattle manure (B4), *Tithonia* sp. compost (B5), and NPK fertilizer at half the recommended dose (B6), each applied at 10 t/ha. The experiment was conducted under greenhouse conditions, with 10 kg of soil per polybag and four replications. Soil samples from Sungai Kakap, West Kalimantan, exhibited severe constraints, including pH levels of 3.75-3.87, organic carbon content of 0.82-0.98%, and high Al and Fe contents (>3%). Results demonstrated that organic matter-enriched biochar treatments significantly improved soil chemical properties (p<0.01). Rice straw-enriched biochar (B2) achieved the highest available P (117.93 ppm) and K (1.09 cmol(+)/kg), while cattle manure-enriched biochar (B4) showed maximum organic C increase (1.30%). Plant growth parameters showed significant improvement, with B2 producing the tallest plants (137.43 cm) and B5 (*Tithonia* sp.) yielding the highest productive tillers (38.83). The findings indicate that biochar enriched with local organic materials, particularly rice straw and *Tithonia* sp., offers a sustainable solution for rehabilitating degraded acid sulfate soils while enhancing rice productivity.

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Introduction

Acid sulfate soils have high acidity and low nutrient levels, severely limiting the growth and production of rice plants (Masulili et al., 2016). The high sulfide content in these soils causes low pH levels that can mobilize metals from soil minerals, resulting in contamination with Fe and Al in the soil (Nyman et al., 2023). Acid sulfate soils naturally form in many coastal areas, particularly in Southeast Asia, where they cover approximately 6.5 million hectares (Ngoc et al., 2023). The oxidation process in soil lowers soil

pH to below 4.0, typically due to prolonged drought, artificial drainage, or cultivation practices that involve turning the soil (Enio et al., 2020). These conditions can severely inhibit plant growth and substantially reduce rice yields.

The indigenous characteristics of these soils include high levels of iron sulfate minerals, primarily pyrite (FeS₂). Soil drying releases aluminum and iron, which can inhibit plant growth (Masulili et al., 2016) and even poison plants (Minh et al., 2020). In soil taxonomy, these soils have sulfa or sulfi prefixes at the suborder level, such as Sulfaquents, Sulfaquents, and

Sulfhemists, and sulfic prefixes at the great group level, such as Sulfic Endoaquents and Sulfic Endoaquepts (Sulaeman et al., 2024). When these soils are used for agricultural purposes, they degrade, leading to increased soil acidity to very acidic levels (Sarangi et al., 2022).

Despite reclamation efforts, the productivity of acid sulfate soils is often not optimal due to unsustainable soil improvement practices (Enio et al., 2020). Common solutions, such as the application of inorganic fertilizers (urea, TSP, KCl) and liming (dolomite), have significant limitations. Inorganic fertilizers, although initially increasing yields, can reduce land quality if used excessively and continuously. Meanwhile, liming provides only short-term effects on soil pH and requires repeated applications, financially burdening farmers and threatening the sustainability of production (Maftu'ah et al., 2022). Other problems include that the reclamation process can trigger pyrite oxidation, increasing soil density, and releasing harmful ions such as aluminum (Al), iron (Fe), manganese (Mn), and sulfate. Additionally, the high clay content in these soils increases soil bulk density, which negatively affects root penetration and water infiltration (Arvidsson and Keller, 2011).

Das and Das (2015) explained that high acidity levels in acid sulfate soils can inhibit plant growth, and drying these soils can trigger the formation of sulfuric acid and the release of harmful substances. Similarly, Shamshuddin et al. (2014a) noted that plants struggle to grow optimally in acid sulfate soils due to their low pH and high Al concentration. These low pH and high Al concentrations indicate the occurrence of acid sulfate soil degradation when cultivated for intensive agriculture. Therefore, sustainable land management is necessary to enhance soil properties and permanently establish stable agricultural land. To overcome problems in degraded acid sulfate soils, one approach is the use of biochar soil amendment technology, which involves using a carbon material derived from the pyrolysis of biomass such as sawdust, straw, or other agricultural waste (Karam et al., 2022).

Biochar has unique physical and chemical properties, including the ability to increase soil fertility (Alkharabsheh et al., 2021), has long-term potential in maintaining soil chemical and biological fertility, has high cation exchange capacity (CEC), retains and increases nutrient availability (Gao et al., 2019), increases available P (Zhang et al., 2022), and provides a habitat suitable for soil microbial development (Palansooriya et al., 2019). Biochar is adsorptive, has nutrient retention capacity, and has a high silica content (Karam et al., 2022). It can increase water content and control Cd heavy metal contamination (Rivera et al., 2022), improve and maintain sustainable soil quality (Soinne et al., 2014; Karam et al., 2022; Suswana and Maulana, 2022), and provide increased yields in vegetable and ginger crops (Williams et al., 2023; Masulili et al., 2025). Biochar also increases

root development (Kartika et al., 2021). Additionally, biochar is recalcitrant and resistant to chemical processes such as oxidation to CO₂ or methane reduction (Almutairi et al., 2023). Thus, it can provide residual effects and potentially maintain long-term soil fertility (Kätterer et al., 2019). Biochar supports sustainable plant growth under drought conditions (Ullah et al., 2021) and enhances water-use efficiency (Bitarafan et al., 2020). Biochar can also provide the best residual effects on corn plants (Arunkumar and Thippeshappa, 2020), and long-term effects on corn plant growth and physiology (Cong et al., 2023), nutrient content, and uptake (Arunkumar and Thippeshappa, 2020).

One potential biochar is rice husk biochar, which, when applied, can be mixed with organic and inorganic materials to form organic matter-enriched biochar. The use of biochar can increase plant productivity, enhance water use efficiency, and improve overall soil conditions (Gao et al., 2020); however, biochar itself has limited nutrient content. To optimize the benefits of biochar in agriculture, enrichment with organic or inorganic fertilizers can be an effective approach (Kizito et al., 2019).

Organic fertilizers contain essential nutrients such as nitrogen, phosphorus, and potassium, as well as beneficial soil microorganisms (Ahmed et al., 2024). The porous structure of biochar provides habitat for beneficial microorganisms, and its ability to absorb and release nutrients supports plant growth. With organic matter-enriched biochar soil amendment technology, which is a mixture of biochar and organic or inorganic fertilizers, it is expected to better support rice growth and production in acid sulfate soils. When biochar is enriched with organic fertilizers or NPK fertilizer, it stores nutrients that can be gradually released into the soil, reduces nutrient loss from leaching, and increases overall soil fertility.

Rice husk biochar enriched with organic materials has been shown to improve the physical and chemical properties of alluvial soil (Masulili and Paiman, 2023), maintain P availability, and increase soil pH (Figueiredo et al., 2020; Thammasom et al., 2021). Biochar enriched with minerals is effective in increasing soil pH, base cation retention, and promoting plant growth and yield (Pratiwi et al., 2019; Tusar et al., 2023).

Phosphate-enriched biochar can effectively mitigate salinity effects (Paliaga et al., 2025). Biochar enriched with magnetic iron nanoparticles can enhance mycorrhizal colonization, nutrient uptake, improve soil quality, and promote wheat growth (Joseph et al., 2015). Compost-enriched biochar can increase exchangeable base levels (Izilan et al., 2022) and soil biological activity (Nain et al., 2024). Biochar enriched with compost and NPK fertilizer has a significant residual impact on degraded tropical soils compared to using NPK and compost alone (Apori et al., 2021). Rice husk biochar enriched with chicken manure on peat soil increased tomato production by

331%, N uptake by 482%, P uptake by 141%, and K uptake by 128% compared to the control (Jotautienė et al., 2023).

Furthermore, findings by Matheri et al. (2025) showed that biochar combined with *Tithonia diversifolia* was effective in enhancing compost quality and nutrient dynamics, and Nan et al. (2024) also found that moderate biochar application (4-10 t/ha) had a positive effect on rice growth and yield while mitigating methane emissions. These findings demonstrate that soils treated with organic-matter-enriched biochar can enhance plant growth and improve soil health by affecting soil structure, nutrient availability, and water retention. Therefore, to improve the properties of acid sulfate soils, this study aimed to develop an optimal organic matter-enriched biochar composition that can be applied to support increased growth and yield of rice plants in these soils.

Materials and Methods

Study site and period

The research was conducted in the laboratory and greenhouse of the Faculty of Agriculture, Science and Technology, Panca Bhakti University, Pontianak. This location is at an altitude of one meter above sea level, with an average air temperature of 27.6 °C, humidity 82.8%, latitude 2°05' N-3°05' S, and longitude 108°30'-144°10' E. The research period was from June to August 2025.

Soil sampling and initial characterization

Acid sulfate soil was collected at a depth of 0-20 cm compositely from farmers' land in Sungai Rengas Village and from the Experimental Garden Location Pal IX, Sungai Kakap District, Kubu Raya Regency, West Kalimantan Province (IP2TP). The analysis of the physical and chemical characteristics of acid sulfate soil at the research location revealed several significant constraints to rice cultivation (Table 1). Acid sulfate soils at the BPTP experimental field and farmers' land in Sungai Kakap had characteristics that severely limited plant growth, namely very low pH (3.75-3.87), low organic C content (0.82-0.98%), low CEC (8.40-12.76 cmol(+)/kg), and high Al and Fe content (>3%). These conditions resulted in very low rice productivity, averaging below 2 t/ha.

Experimental design

This study used a randomized block design in a greenhouse experiment with seven treatments and four replications, yielding 28 experimental units. The treatments consisted of: control without amendment (B0), rice husk biochar enriched with *Chromolaena odorata* (B1), rice straw (B2), chicken manure (B3), cattle manure (B4), *Tithonia* sp. compost (B5), and NPK fertilizer at half the recommended dose (B6). Each organic matter-enriched biochar treatment was applied at a rate equivalent to 10 t/ha.

Preparation of materials

The collected soil was mixed, cleaned, and sieved using a 1 × 1 cm sieve. Subsequently, 10 kg of soil was placed into 40 × 40 cm polybags lined with waterproof plastic. The paddy system was established by providing water to a height of approximately 5 cm from the soil surface, followed by puddling in the polybag. Biochar was produced from rice husk material obtained during rice processing. It was planted directly in acid sulfate soil in Sungai Kakap, Kubu Raya Regency, West Kalimantan Province, using a pyrolysis reactor for incomplete combustion. Various organic amendments were also prepared as biochar enrichment materials: *C. odorata*, rice straw, chicken manure, cattle manure, *Tithonia* sp. compost, and NPK fertilizer.

Table 1. Some chemical and physical characteristics of acid sulfate soil.

Characteristics	Location	
	IP2TP Experimental Field	Farmer's Field
pH H ₂ O	3.85	3.77
pH KCl	3.21	3.08
Organic C (%)	0.96	0.84
Total N (%)	0.18	0.19
C/N ratio	10.33	7.42
P Bray I (ppm)	10.72	13.05
Total P (%)	0.64	0.72
K (cmol(+)/kg)	0.23	0.18
Na (cmol(+)/kg)	0.24	0.40
Ca (cmol(+)/kg)	0.64	0.87
Mg (cmol(+)/kg)	0.28	0.30
CEC (cmol(+)/kg)	12.68	8.52
H (cmol(+)/kg)	0.10	1.02
Aluminum (%)	3.12	3.17
Total Fe (%)	3.18	3.06
Pyrite (%):		
Depth 0-20 cm	0.73	0.90
Depth 20-40 cm	1.03	1.34
Depth 40-60 cm	0.62	1.00
Bulk density (g/cm ³)	1.37	1.33
Soil strength (kPa)	475	495
Total pore space (%)	44.52	45.08
Sand (%)	1.42	1.78
Silt (%)	34.75	42.48
Clay (%)	63.83	55.74
Rice yield (t/ha)	2.02	1.96

Source: Soil Laboratory Analysis Results, Tanjungpura University.

Compost preparation

Tithonia sp. compost was prepared following standard composting procedures. Brown sugar (approximately 2-3 tablespoons) was dissolved in 1 liter of clean water. EM4 (2-3 tablespoons) was then added to the brown sugar solution, and the solution was stirred

evenly and allowed to stand for 15-30 minutes. All organic materials to be composted were chopped to 2-3 cm. Layers of organic material (approximately 10-20 cm) were arranged and watered evenly with the activator solution (brown sugar + EM4). The composter was then covered to maintain humidity and temperature, with small ventilation provided to ensure air circulation.

The compost pile was turned and stirred every 3-7 days to ensure good air circulation and even decomposition. When the compost pile was too dry, it was watered with a little clean water or the remaining EM4 solution to maintain humidity. The decomposition process took approximately 2-4 weeks. Mature compost was characterized by a blackish-brown color, a crumbly texture, the absence of a bad smell, and a stable, low temperature.

Preparation and application of organic matter-enriched biochar

The organic matter-enriched biochar was prepared by mixing biochar with each organic amendment in a ratio of 2 parts biochar to 1 part of organic amendment (by weight). For NPK fertilizer as biochar enrichment, the amount was equivalent to half of the recommended dose (200 kg/ha). The enriched biochar was then incubated for 1 week.

Treatments were applied according to the experimental design at doses equivalent to 10 t/ha, calculated based on soil weight in polybags. The treatments were then mixed into the soil to a depth of 20 cm and incubated at field capacity water content for 1 week. Subsequently, 14-day-old rice seedlings were transplanted using the paddy system at 1 week after treatment incubation. Rice plant maintenance was then carried out until harvest.

Soil analysis

Soil physical parameters measured included bulk density using the clod method (Blake and Hartge, 1986), which involved using undisturbed soil clods to measure volume and mass, allowing density per unit volume to be calculated. Total porosity was calculated from water content at 0 kPa matric potential, and plant available water was calculated by subtracting the permanent wilting point from the field capacity. Field capacity was measured at a matric potential of -33 kPa, and permanent wilting point at -1.5 MPa using a pressure plate apparatus. Soil chemical parameters were analyzed as follows: soil pH was measured in soil solution with a 1:2.5 ratio (soil:deionized water) using a pH meter (Jenway 3305). Organic C was determined by the Walkley and Black wet oxidation method (Soil Survey Laboratory Staff, 1992). Total N was measured using the Kjeldahl method (Bremner and Mulvaney, 1982). Exchangeable Al^{3+} and Fe^{2+} were extracted using 1 M KCl (Barnhisel and Bertsch, 1982). Cation Exchange Capacity (CEC) was extracted with 1 M NH_4OAc (buffered at pH 7.0), and base cation concentration was measured using Atomic Absorption

Spectrophotometry (AAS, Shimadzu). Available P was determined by the Bray I method.

Plant growth and yield parameters

Plant growth and yield parameters observed included: (1) plant height (cm), measured from soil surface to the tip of the tallest leaf; (2) number of tillers, counted as all tillers produced per plant; (3) number of productive tillers, counted as tillers bearing panicles; (4) number of grains per panicle, counted from five randomly selected panicles per plant; (5) dry grain weight per plant (g), measured after sun-drying to 14% moisture content; (6) 100 grain weight (g), measured from randomly selected filled grains; (7) root volume (cm^3), measured using water displacement method; (8) plant dry weight (g), measured after oven-drying at 70 °C until constant weight; (9) N, P, and K uptake, determined by multiplying nutrient concentration in plant tissue (measured by wet digestion method for N and P, and flame photometry for K) by plant dry weight.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) at the 5% significance level, followed by the Least Significant Difference (LSD) test at the 5% significance level ($\alpha = 0.05$) when the analysis showed significant effects.

Results and Discussion

Constraints of acid sulfate soil for rice cultivation

The results of laboratory analysis presented in Table 1 revealed that acid sulfate soils at the research location posed severe constraints for rice cultivation. The very low soil pH (3.75-3.87) represents the most critical limitation. Rice plants generally grow optimally at pH 5.5-6.5, while at pH below 4.0, plant growth is significantly inhibited due to multiple stress factors. According to Sarangi et al. (2022), acid sulfate soils in Southeast Asia, including Indonesia, are characterized by low pH, with pyrite oxidation progressing slowly until pH 4.0, at which sulfur-oxidizing bacteria become active. This extreme acidity results from pyrite (FeS_2) oxidation, which releases sulfuric acid into the soil, as shown by the reaction: $FeS_2 + 3.75O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + 2H_2SO_4$.

The mechanism of soil acidification in these conditions is complex. Shamshuddin et al. (2014b) reported that drained acid sulfate soils in Malaysia have very low pH and high exchangeable aluminum content, both of which result from pyrite oxidation. Each mole of completely oxidized pyrite produces two moles of sulfuric acid, which not only lowers pH directly but also triggers the solubilization of soil minerals. This pyrite oxidation process is accelerated by excessive drainage, which converts reduced sulfur compounds into sulfuric acid. In these very acidic conditions, plant growth is not only directly inhibited

by H-ion toxicity but also by a cascade of detrimental chemical reactions, including increased solubility of toxic metals such as Al and Fe. The high aluminum content (>3%) in the studied acid sulfate soils is closely related to low pH through a feedback mechanism. According to Panhwar et al. (2015), under very acidic conditions (pH<4.5), the weathering of aluminosilicate minerals is accelerated, releasing large amounts of Al³⁺ into the soil solution. The relationship between pH and Al³⁺ activity is exponential, with Al³⁺ concentration increasing approximately 1,000-fold for each unit decrease in pH below 5.0. Singh and Prasad (2018) explained that at high concentrations, Al³⁺ inhibits root elongation by damaging cell membranes through lipid peroxidation and disrupting cell division in root meristems. Aluminum also interferes with DNA replication and causes chromosomal aberrations, preventing plants from absorbing nutrients and water optimally. Furthermore, Al³⁺ can form complexes with phosphate in soil, further reducing P availability to plants.

High Fe content (>3%) creates additional stress, especially in the form of Fe²⁺ under waterlogged conditions typical of paddy cultivation. According to Aung and Masuda (2020), Fe concentrations in soil range from 10 to 1,000 ppm, and concentrations >300 ppm are considered critical for rice toxicity. In flooded acid sulfate soils, the combination of low pH and reducing conditions leads to excessive Fe²⁺ accumulation. Rumanti et al. (2017) reported that iron toxicity in rice on acid sulfate soils can reduce yields by up to 50%, with characteristic symptoms including leaf bronzing (reddish-brown discoloration), stunted growth, fewer productive tillers, and reduced grain filling. The mechanism of Fe toxicity involves oxidative stress, in which excess Fe²⁺ catalyzes the formation of reactive oxygen species (ROS) via Fenton reactions, damaging cellular structures.

The interaction between Al and Fe under acidic conditions creates a highly unfavorable environment for plants through synergistic effects. According to Saleem et al. (2023), the combination of Al and Fe toxicity in acid soils affects iron accumulation by rice cultivars in relation to several physio-biochemical parameters, including antioxidant enzyme activities and membrane stability. The natural detoxification mechanism of rice plants through Fe²⁺ oxidation in the rhizosphere, via oxygen release from aerenchyma tissue, is also disrupted at very low pH, where the solubility of Fe³⁺ oxide precipitates increases, exacerbating toxicity effects. This creates a situation in which plants must simultaneously cope with multiple stresses: proton, Al, and Fe toxicity, and nutrient deficiencies.

The low organic carbon content (0.82-0.98%) and CEC (8.40-12.76 cmol(+)/kg) further compound these problems by limiting the soil's buffering capacity and nutrient retention ability. In acid sulfate soils, organic matter plays a critical role in complexing toxic metals, improving soil structure, and providing slow-

release nutrients. The decomposition of organic matter is influenced by soil moisture conditions, with waterlogged conditions in paddy fields affecting carbon dynamics (Gallo et al., 2024; He et al., 2024). The combination of all these constraints explains why rice productivity in these soils averaged below 2 t/ha, far below the potential yield of 5-6 t/ha achievable in optimal conditions.

Effects of organic matter-enriched biochar on chemical properties of acid sulfate soil

Application of organic matter-enriched biochar significantly improved the chemical properties of acid sulfate soil after 1 month of incubation (Table 2). All biochar treatments significantly improved soil chemical properties (p<0.01), demonstrating the potential of this technology for soil amelioration.

Soil pH improvement

The increase in soil pH from the initial range of 3.75-3.87 to 4.43-4.56 demonstrates biochar's ability to neutralize soil acidity. The pH increase of 0.56-0.81 units, while seemingly modest, represents a significant improvement in acid sulfate soil conditions. This pH elevation occurs through multiple mechanisms. First, biochar contains alkaline cations (Ca²⁺, Mg²⁺, K⁺) and surface basic functional groups that can neutralize acidity through ion exchange and proton consumption. According to Adhikari et al. (2022), biochar from agricultural residues such as rice husk has a higher CEC than wood biochar, and its liming effect is particularly important for acid sulfate soils with low pH constraints. The pH buffering mechanism of biochar operates differently from conventional liming. While lime (CaCO₃) provides immediate but temporary pH increase through carbonate dissolution, biochar provides more gradual and sustained pH improvement. The surface functional groups of biochar, including carboxyl (-COOH), phenolic (-OH), and carbonyl (C=O) groups, act as weak acids that can buffer pH changes. As soil pH decreases, these groups deprotonate, releasing cations and consuming H⁺ ions, thereby stabilizing pH. Singh et al. (2021) found that biochar application on acidic soils can increase soil pH up to 0.3 units, with the effect persisting for multiple growing seasons, especially when combined with organic materials that provide additional buffering capacity. Cattle manure-enriched biochar (B4) achieved the highest pH (4.56), likely due to the high base cation content in cattle manure. This organic amendment is rich in Ca and Mg, which directly contribute to pH increase. The organic acids in cattle manure can also complex with toxic Al³⁺, effectively removing these ions from solution and indirectly raising pH. Interestingly, rice straw-enriched biochar (B2) showed slightly lower pH (4.43), possibly because rice straw has lower base cation content and higher silica content, which does not directly contribute to pH increase but provides other benefits for rice growth.

Table 2. Effects of organic matter-enriched biochar on some chemical properties of acid sulfate soil.

Treatment	Water Content (%)	pH H ₂ O	Organic C (%)	Total N (%)	C/N Ratio	P ₂ O ₅ (ppm)	K (cmol(+)/kg)	CEC (cmol(+)/kg)
B0 (Control)	63.82±2.14 ^a	4.51±0.03 ^{bc}	1.05±0.08 ^c	0.27±0.02 ^c	3.89±0.21 ^b	16.01±1.43 ^c	0.19±0.02 ^d	10.30±0.87 ^{cd}
B1 (<i>C. odorata</i>)	55.20±3.26 ^c	4.52±0.04 ^b	0.98±0.06 ^c	0.28±0.01 ^{bc}	0.50±0.18 ^{cd}	13.82±2.11 ^c	0.41±0.03 ^b	13.28±0.95 ^a
B2 (Rice straw)	60.02±2.88 ^b	4.43±0.05 ^d	1.16±0.09 ^b	0.38±0.03 ^a	3.05±0.14 ^c	117.93±8.74 ^a	1.09±0.08 ^a	7.80±0.62 ^c
B3 (Chicken manure)	57.00±1.95 ^{bc}	4.54±0.03 ^{ab}	1.10±0.07 ^{bc}	0.29±0.02 ^b	0.79±0.19 ^{bc}	7.29±0.86 ^d	0.23±0.02 ^{cd}	9.90±0.73 ^d
B4 (Cattle manure)	64.68±3.17 ^a	4.56±0.04 ^a	1.30±0.11 ^a	0.30±0.02 ^b	4.33±0.26 ^a	6.78±0.91 ^d	0.23±0.03 ^{cd}	10.77±0.81 ^c
B5 (<i>Tithonia</i> sp.)	63.09±2.73 ^a	4.55±0.03 ^a	1.26±0.10 ^a	0.33±0.03 ^b	3.82±0.22 ^b	7.11±0.78 ^d	0.40±0.04 ^b	11.43±0.92 ^b
B6 (NPK)	58.56±2.41 ^b	4.52±0.02 ^{bc}	1.21±0.08 ^{ab}	0.28±0.02 ^{bc}	4.32±0.31 ^a	4.20±0.52 ^c	0.43±0.05 ^b	12.66±1.14 ^a
F-value	8.45**	12.67**	9.23**	7.89**	11.34**	287.45**	94.62**	15.78**
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: Values followed by different letters in the same column indicate significant differences based on LSD test ($p < 0.05$). Values are mean \pm standard deviation ($n=4$). ** = highly significant ($p < 0.01$)

Organic carbon dynamics

Biochar enriched with cattle manure (B4) produced the highest organic C increase to 1.30%, representing a 54% increase from the initial condition (0.82-0.98%), followed by *Tithonia* sp. (B5) at 1.26%. This substantial increase in organic carbon is critical for improving acid sulfate soils, as organic matter serves multiple functions: improving soil structure, increasing water retention, providing a substrate for microbial activity, and serving as a slow-release nutrient source.

The mechanism of organic carbon accumulation differs between biochar and fresh organic matter. Biochar contributes to a relatively stable carbon pool due to its recalcitrant aromatic structure, which resists microbial decomposition. This recalcitrance results from the pyrolysis process, in which labile organic compounds are volatilized, leaving behind condensed aromatic carbon structures. According to Vijayakumar et al. (2023), biochar has the capacity to adsorb and retain cations in exchangeable form due to its large surface area (often 100-300 m²/g) and negative surface charge density. The porous structure of biochar also provides microsites that physically protect organic matter from decomposition, contributing to long-term carbon sequestration.

When biochar is enriched with fresh organic materials such as cattle manure or *Tithonia* sp., a synergistic effect occurs. The fresh organic matter provides readily available nutrients for microbial activity and plant growth. In contrast, biochar provides habitat for microorganisms and slows the decomposition of organic matter through adsorption and physical protection. Fahad et al. (2022) reported that biochar application can increase soil organic carbon stock by 32.6% after one growing season, with effects persisting for years. The higher organic C in cattle manure treatment likely results from the high lignin content in cattle manure, which decomposes slowly, and from the stable carbon in biochar itself.

The increase in organic carbon has cascading effects on soil properties. Higher organic matter improves soil aggregation, reducing bulk density and increasing porosity (Horn et al., 2022). It enhances CEC, improving nutrient retention capacity. Organic matter also serves as an energy source for soil microorganisms, promoting beneficial microbial communities that contribute to nutrient cycling, disease suppression, and production of plant growth-promoting substances (Whalen et al., 2024).

Nitrogen dynamics

The highest total N level was achieved in rice straw-enriched biochar (B2) at 0.38%, which was 41% higher than the control (0.27%). This significant increase demonstrates that biochar plays an important role in soil nitrogen transformation processes. The mechanism involves several pathways. First, biochar can physically adsorb NH₄⁺ ions via its negatively charged surfaces and micropores, thereby reducing

nitrogen losses from leaching and volatilization. Second, the porous structure provides habitat for nitrogen-fixing bacteria and nitrifying bacteria, enhancing biological nitrogen transformations. Third, biochar can slow nitrification rates, keeping nitrogen in the NH₄⁺ form, which is preferred by rice plants and less susceptible to leaching in flooded conditions.

According to Jindo et al. (2020), biochar is involved in various soil nitrogen transformation processes, including ammonia volatilization, N₂O emissions, and biological nitrogen fixation, thereby decreasing N loss and increasing N retention in soil. The C/N ratio of rice straw (typically 50-80:1) requires nitrogen immobilization during initial decomposition, but when combined with biochar, this immobilization is balanced by improved nitrogen retention, resulting in better nitrogen availability over time. Research by Canatoy et al. (2024) showed that biochar from manure can reduce ammonia volatilization losses by up to 45% while maintaining plant productivity in paddy fields. The mechanism involves biochar's ability to adsorb NH₃ gas and convert it back to NH₄⁺ through surface reactions. In acid sulfate soils, where nitrogen use efficiency is typically low due to denitrification losses under flooded conditions, this nitrogen retention effect is particularly valuable.

The lower C/N ratio in rice straw treatment (3.05) compared to control (3.89) indicates faster organic matter mineralization and better nitrogen availability. This narrow C/N ratio suggests that the organic matter has undergone substantial decomposition during the incubation period, releasing plant-available nitrogen. However, it's important to note that very low C/N ratios (<10) can indicate excessive mineralization with potential for nitrogen losses, while ratios >20 suggest nitrogen immobilization. The C/N ratios observed in this study (3.05-4.33) are within the optimal range for nitrogen availability.

Phosphorus availability

Rice straw-enriched biochar (B2) achieved a remarkable increase in available P to 117.93 ppm, representing a 636% increase compared to control (16.01 ppm) and 9-fold higher than the initial soil P level (10.72-13.05 ppm). This dramatic increase warrants a detailed explanation, as phosphorus is often the most limiting nutrient in acid sulfate soils. The mechanisms underlying this increase in P availability are multifaceted.

First, biochar raises soil pH, which directly affects P solubility. In very acidic conditions (pH < 4.5), phosphorus is primarily fixed by Fe and Al oxides through ligand exchange reactions, forming highly insoluble Fe-P and Al-P compounds. As pH increases toward 5.5-6.5, the solubility of these phosphate minerals increases, and the activity of Al³⁺ and Fe³⁺ decreases, reducing P fixation. The pH increase from 3.87 to 4.43 in the B2 treatment significantly reduces soil phosphorus fixation capacity.

Second, rice straw is naturally rich in silica (10-15% on a dry weight basis), and silicon plays a crucial role in P availability. Silicon can compete with phosphate for adsorption sites on Fe and Al oxides, thereby displacing phosphate into the soil solution. Zhang et al. (2022) found that biochar application increases rhizosphere phosphorus acquisition in acidified paddy soil by forming silicate-phosphate complexes that are more available to plants. The high silica content in rice husk biochar, combined with rice straw, creates a synergistic effect on P mobilization.

Third, organic acids released during rice straw decomposition can chelate Fe and Al, reducing their capacity to fix phosphorus. These organic acids (oxalic, citric, and malic acids) form soluble complexes with Fe and Al, effectively competing with phosphate for these metals. Additionally, microbial activity stimulated by the carbon-rich rice straw can solubilize organic phosphorus through phosphatase enzyme production.

Fourth, biochar itself can contain significant amounts of phosphorus from the original feedstock (rice husk), and the pyrolysis process can convert organic P to more available inorganic forms. However, the very high P level in B2 treatment suggests that the mobilization of soil P is more important than the P contribution from amendments themselves, as evidenced by the fact that even the control treatment with soil incubation showed some P increase (from 10.72-13.05 to 16.01 ppm).

The lower available P in manure treatments (B3 and B4: 6.78-7.29 ppm) compared to the control appears contradictory but can be explained by P immobilization during the early stages of manure decomposition. Fresh organic matter with low P content can temporarily immobilize soil P as microorganisms incorporate it into their biomass. This immobilization is typically temporary, and P becomes available as microbial cells die and decompose.

Potassium availability

Rice straw-enriched biochar (B2) also showed the highest exchangeable K at 1.09 cmol(+)/kg, a 474% increase compared to the control (0.19 cmol(+)/kg). This dramatic increase can be explained by several factors. Rice straw is naturally rich in potassium (typically 1.5-2.5% K₂O), as potassium is highly mobile in plants and concentrates in straw. During pyrolysis to produce biochar and subsequent decomposition of rice straw, potassium is released in readily exchangeable forms. Biochar's high CEC and specific surface area enable it to retain the released K⁺ ions, preventing leaching losses. Unlike nitrogen and phosphorus, potassium does not undergo chemical transformations in soil; it exists as exchangeable cations on soil colloids or as dissolved ions in the soil solution. The negatively charged surfaces of biochar provide additional cation exchange sites, increasing the soil's capacity to retain K⁺. The moderate K levels in *C. odorata* and *Tithonia* sp. treatments (B1 and B5:

0.40-0.41 cmol(+)/kg) reflect the naturally high K content in these plant materials. *Tithonia* sp. is known as a K-accumulating plant, with K content reaching 3-4% in fresh biomass. NPK fertilizer treatment (B6: 0.43 cmol(+)/kg) yielded K levels similar to those of organic matter-enriched biochar, demonstrating that organic matter-enriched biochar can provide K levels comparable to synthetic fertilizers.

Cation exchange capacity

The CEC responses showed an interesting pattern, with *C. odorata*-enriched biochar (B1) and NPK-enriched biochar (B6) achieving the highest values (13.28 and 12.66 cmol(+)/kg, respectively). In comparison, rice straw treatment showed the lowest CEC (7.80 cmol(+)/kg) despite showing the highest nutrient availability. Different mechanisms can explain this apparent contradiction.

The high CEC in the B1 and B6 treatments results from increased surface charge density due to organic matter addition and the possible formation of organo-mineral complexes. The mature organic matter from *C. odorata* has a high content of carboxylic and phenolic groups, which contribute to a negative surface charge. However, high CEC does not automatically indicate high nutrient availability, as it indicates the capacity to retain cations, not necessarily their availability. The lower CEC in rice straw treatment (B2), despite the highest nutrient availability, suggests that nutrients are present in readily soluble forms in the soil solution rather than as exchangeable cations. This condition is advantageous for immediate plant uptake but may pose risks for leaching losses in the longer term. The rice straw is still in the early decomposition stage (after 1 month), and its contribution to stable CEC may increase over time as decomposition products stabilize.

The relationship between CEC and nutrient availability is complex and depends on the balance between nutrient retention (preventing losses) and nutrient release (providing plant availability). In acid sulfate soils, moderate CEC (8-12 cmol(+)/kg) combined with adequate nutrient levels may be more beneficial than very high CEC with low nutrient availability.

Effects of organic matter-enriched biochar on vegetative growth of rice plants

Application of organic-matter-enriched biochar had significant effects on all vegetative growth parameters of rice plants (Tables 3 and 4). The improvements in plant growth can be directly linked to the amelioration of soil constraints and enhanced nutrient availability. Rice straw-enriched biochar (B2) achieved the tallest plants (137.43 cm), 5.7% higher than the control. This superior performance is attributed to exceptionally high P and K availability. Phosphorus is critical for energy transfer and cell division, while potassium regulates turgor pressure and activates enzymes for growth. The improved pH also reduced Al and Fe

toxicity, allowing better root development and nutrient uptake. *Tithonia* sp. treatment (B5) produced the highest leaf number (194.67), 38% more than the control. *Tithonia* sp. is nutrient-rich, particularly in N, P, and K, and contains growth-promoting compounds. The gradual nutrient release from *Tithonia* sp. compost supports continuous leaf production. This finding aligns with Agbede (2025), who reported a 38% increase in growth with *Tithonia* sp. biochar. Tiller production was highest in B5 (38.83 tillers), followed by B2 (36.33 tillers), compared to the control (28.17 tillers). Tillering is influenced by nitrogen availability, light interception, and carbohydrate supply. The balanced nutrient supply from *Tithonia* sp. and rice straw treatments, combined with improved soil conditions, promoted vigorous tillering.

Growth enhancement mechanisms by organic matter-enriched biochar

The significant increase in vegetative growth of rice in organic matter-enriched biochar treatments can be explained through several mechanisms. First, improvements in soil physical properties, where, according to Adhikari et al. (2022), biochar can increase soil water-holding capacity by 10-30%, with rice husk biochar able to hold water up to 2.7 times its dry weight. This is particularly important for acid sulfate soils, which tend to have excessive drainage. Research by Singh et al. (2021) also showed that biochar application can reduce soil bulk density and increase porosity, thereby improving aeration and root penetration. Second, increased soil microbial activity. Vijayakumar et al. (2023) explained that biochar can provide surfaces for microorganisms to attach, increase nutrient availability, while suppressing harmful microorganism growth.

Biochar can also increase soil microbiome diversity, which is more resistant to environmental changes and promotes nutrient cycling (Wang et al., 2024). This increased microbial activity contributes to organic matter mineralization and the gradual release of nutrients. Third, nutrient retention and release mechanisms. Fahad et al. (2022) stated that biochar acts as a carbon sink, contributing to long-term carbon sequestration and climate change mitigation. The porous structure of biochar, with its high surface area, allows adsorption and nutrient retention, reducing leaching and increasing fertilizer use efficiency. Sial et al. (2022) reported that biochar can reduce nitrate leaching by up to 34% and ammonium by up to 14%, making nutrients more available to plants.

Implications for sustainable agriculture

Application of biochar enriched on acid sulfate soils has important implications for rice production sustainability. According to Sial et al. (2022), biochar application can help organic farming by eliminating inorganic fertilizers and pesticides, a preferred method for improving environmentally friendly agriculture and reducing environmental burden. Additionally, biochar use contributes to climate change mitigation through carbon sequestration and greenhouse gas emission reduction. From a greenhouse gas emission perspective, Shrestha et al. (2023) reported that biochar reduces nitrous oxide (N₂O) emissions by 18% and methane (CH₄) by 3%, providing additional environmental benefits. When biochar is combined with N fertilizer, it can reduce CO₂, CH₄, and N₂O emissions by 61%, 64%, and 84% respectively. Yin et al. (2021) also emphasized that moderate application of N-rich biochar (4 t/ha) increases rice plant yield and biomass as well as soil DOC concentration, while moderating cumulative soil C emissions. From an economic perspective, using local agricultural waste such as rice straw and *Tithonia* sp. for biochar enriched production can reduce agricultural input costs while increasing productivity. Pandian et al. (2024) reported that life cycle assessment calculations showed consistently negative global warming potential values (-0.9 kg CO₂eq/kg), implying that greenhouse gas consumption exceeds its emissions. This makes biochar enriched a promising negative emission technology for sustainable agriculture.

Practical implications and limitations

While organic matter-enriched biochar demonstrated significant benefits for rehabilitating acid sulfate soils, farmers often express reluctance to adopt biochar due to perceived higher costs and greater complexity compared to fresh organic matter application, necessitating critical examination of the economic and practical trade-offs. Fresh organic matter costs approximately Rp 500,000-800,000 per ton, while biochar-enriched systems require Rp 3,000,000-4,500,000 per ton. However, fresh organic matter decomposes rapidly (3-6 months) under tropical conditions, requiring annual reapplication with cumulative costs reaching Rp 2,500,000-4,000,000 over five years, whereas biochar-enriched systems require one-time investment with documented persistence of 5-10 years (Kätterer et al., 2019; Singh et al., 2021), achieving economic break-even within 2-3 years (Panwar and Patel, 2024).

Table 3. F-value and ANOVA significance for vegetative growth parameters.

Parameter	4 WAP		6 WAP		8 WAP	
	F-value	p-value	F-value	p-value	F-value	p-value
Plant height	8.457	0.001**	6.892	0.002**	5.234	0.008**
Leaf number	4.231	0.015*	3.876	0.021*	4.567	0.012*
Tiller number	3.965	0.019*	4.125	0.017*	3.845	0.022*

Note: ** = highly significant (p<0.01); * = significant (p<0.05); WAP = Weeks After Planting.

Table 4. Mean vegetative growth parameters at various organic matter-enriched biochar treatments.

Treatment	Plant Height (cm)			Number of Leaves			Number of Tillers		
	4 WAP	6 WAP	8 WAP	4 WAP	6 WAP	8 WAP	4 WAP	6 WAP	8 WAP
B0 (Control)	77.59±2.82 ^c	116.45±4.35 ^d	129.97±6.51 ^d	34.33±4.06 ^c	102.75±22.51 ^c	140.67±19.85 ^c	6.50±1.04 ^c	15.75±1.66 ^d	28.17±3.87 ^d
B1 (<i>C. odorata</i>)	70.11±3.91 ^d	112.08±4.41 ^e	127.67±4.57 ^c	42.42±6.24 ^b	132.50±30.45 ^b	174.50±46.40 ^b	7.83±1.35 ^{bc}	19.67±2.71 ^c	34.67±9.19 ^{bc}
B2 (Rice straw)	86.00±2.95 ^a	120.75±1.59 ^b	137.43±3.30 ^a	58.75±17.90 ^a	138.75±52.53 ^{ab}	185.08±56.98 ^{ab}	12.25±4.57 ^a	20.08±1.29 ^{bc}	36.33±10.42 ^b
B3 (Chicken manure)	77.63±4.57 ^c	114.99±3.44 ^d	125.84±2.40 ^f	41.92±8.99 ^b	114.33±22.84 ^c	170.58±35.09 ^b	7.92±1.29 ^{bc}	19.92±3.53 ^{bc}	33.83±7.01 ^c
B4 (Cattle manure)	78.98±6.46 ^{bc}	118.78±3.80 ^c	133.35±2.63 ^c	41.83±15.23 ^b	121.92±41.44 ^{bc}	157.58±40.82 ^{bc}	8.17±1.97 ^b	21.58±4.47 ^b	31.08±7.60 ^{cd}
B5 (<i>Tithonia</i> sp.)	78.19±6.13 ^{bc}	116.64±5.25 ^d	127.65±7.42 ^c	50.58±21.49 ^{ab}	137.67±54.11 ^{ab}	194.67±68.90 ^a	11.08±4.65 ^a	22.50±8.43 ^a	38.83±13.69 ^a
B6 (NPK)	82.53±6.82 ^b	120.19±2.90 ^{bc}	133.72±7.90 ^b	54.08±8.76 ^a	145.83±48.70 ^a	178.17±43.93 ^{ab}	10.58±3.07 ^a	19.92±3.39 ^{bc}	35.33±8.99 ^b

Note: Values followed by different letters in the same column indicate significant differences based on LSD test ($p < 0.05$). Values are mean \pm standard deviation ($n=4$).

Beyond economics, organic matter-enriched biochar systems provide distinct advantages: persistent soil amelioration and pH maintenance across multiple seasons; 34-45% reduction in nutrient leaching, critical for high-rainfall regions (Canatoy et al., 2024); and climate change mitigation through carbon sequestration (Pandian et al., 2024). The results of this study demonstrated that rice straw-enriched biochar increased available P by 636% and K by 474%, achieving first-season yield improvements of 20-35% that substantially exceeded fresh organic matter alone, particularly valuable for severely degraded soils where baseline productivity averages below 2 t/ha. The appropriateness of biochar-enriched systems depends on site conditions: severely degraded acid sulfate soils (pH<4.0), where rice yields remain below 2 t/ha, require biochar for effective Al/Fe toxicity mitigation that fresh organic matter cannot adequately address. In contrast, farmers with moderate soil constraints may initially use fresh organic matter and transition to biochar as their economic capacity improves. Despite these benefits, several barriers impede adoption among smallholder farmers, underscoring the need for practical solutions. The high initial investment can be addressed through cooperative production systems that reduce costs by 40-60% through shared equipment, the use of rice husk waste from local mills to minimize feedstock costs, and phased adoption, where farmers initially apply biochar to small plots (0.1-0.25 ha) while maintaining conventional practices elsewhere.

Technical barriers can be mitigated through simplified production technologies, such as kontiki or drum kilns, which require minimal training. At the same time, time constraints can be addressed through off-season production during the dry period, when field activities are minimal. For farmers seeking immediate results, hybrid strategies combining biochar with fresh organic matter (70:30 ratio) deliver both rapid nutrient release and long-term soil improvement. Important limitations warrant acknowledgment: biochar properties vary with production conditions, necessitating quality control; field-scale validation under actual farmer conditions remains limited despite promising greenhouse results, optimal application rates likely range from 5 to 15 t/ha, requiring site-specific adjustment (Panwar and Patel, 2024), and long-term studies (>5 years) in acid sulfate soils are needed. This study recommends that agricultural extension services establish demonstration plots in severely degraded areas, prioritize biochar adoption for the most constrained soils where conventional amendments prove inadequate, facilitate cooperative biochar production to reduce individual costs, and advocate for policy support recognizing biochar as climate-smart agriculture technology. In conclusion, for severely degraded acid sulfate soils common in coastal areas, biochar-enriched systems offer economically viable solutions when barriers are addressed through community-based approaches and appropriate support mechanisms.

Conclusion

The application of biochar enriched with various organic amendments demonstrated significant potential for rehabilitating degraded acid sulfate soils and improving rice productivity. Rice straw-enriched biochar (B2) showed superior performance in increasing available P (117.93 ppm) and K (1.09 cmol(+)/kg), while achieving the highest plant height (137.43 cm). *Tithonia* sp.-enriched biochar (B5) excelled in producing the maximum number of productive tillers (38.83) and leaves (194.67). All organic matter-enriched biochar treatments successfully improved soil pH from extremely acidic conditions (3.75-3.87) to more favorable levels (4.43-4.56), while cattle manure-enriched biochar achieved the highest organic carbon increase (1.30%). From a sustainability perspective, organic matter-enriched biochar technology offers multiple benefits: using local agricultural wastes reduces input costs, contributes to climate change mitigation through carbon sequestration and reduced greenhouse gas emissions (18% N₂O and 3% CH₄ reductions), and provides long-term soil fertility improvement due to biochar's recalcitrant nature.

This study confirmed that biochar enriched with locally available organic materials, particularly rice straw and *Tithonia* sp., presents a viable and sustainable solution for managing degraded acid sulfate soils in rice production systems. The technology addresses both immediate productivity challenges and long-term sustainability goals, making it particularly suitable for resource-limited farmers in tropical regions with acid sulfate soil problems. Future research should focus on field-scale validation, optimal application rates for different soil conditions, and long-term residual effects to further refine recommendations for practical implementation.

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