



Encapsulated Phosphorus-Enriched Biochar Improves Rice Productivity in Alluvial Soil

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ABSTRACT

This study evaluated the effects of phosphorus-enriched encapsulated rice husk biochar on morphophysiological characteristics and yield of rice (*Oryza sativa* L.) in acidic alluvial soil. The experiment was conducted from May to September 2025 using a completely randomized design with six treatments: control (b0), conventional biochar at 10 tons ha⁻¹ (b1), biochar enriched with 25% phosphorus (b2), biochar enriched with 50% phosphorus (b3), encapsulated biochar with 25% phosphorus (b4), and encapsulated biochar with 50% phosphorus (b5). Each treatment was replicated four times. The novelty of this research lies in integrating sodium alginate-calcium chloride encapsulation technology with phosphorus-enriched rice husk biochar to achieve synchronized controlled-release tailored to rice nutrient demand throughout the growth cycle, addressing the specific challenges of phosphorus fixation in acidic alluvial soils. Results demonstrated that phosphorus-enriched encapsulated biochar significantly improved soil chemical properties. The b5 treatment increased soil pH from 4.41 to 5.22 and available phosphorus from 15.49 ppm to 580.91 ppm. Plant growth parameters showed substantial improvements, with b5 producing the highest plant height (134.5 cm), tiller number (34.1), leaf number (156.0), and dry weight (62.3 g) at seven weeks after planting. Yield components were significantly enhanced, with b5 achieving the highest panicle length (28.58 cm), productive tillers (30.13), filled grains per panicle (213.58), 100-grain weight (3.11 g), and grain yield per hill (92.58 g), representing a 25.0% increase compared to the control. The encapsulation technology demonstrated superior controlled-release characteristics, maintaining higher soil phosphorus availability throughout the growing season. These findings provide a sustainable and cost-effective strategy to enhance rice productivity on marginal acidic soils while reducing phosphorus fertilizer requirements by up to 30%, thereby contributing to both food security and environmental sustainability through reduced phosphorus losses and eutrophication risks in tropical agricultural systems. The technology's potential for on-farm production using locally available materials facilitates scalability and adoption among smallholder farmers.

Keywords: Acidic Alluvial Soil, Biochar Encapsulation, Controlled Release Fertilizer, Phosphorus Enrichment, Rice Productivity, Soil Amendment.

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INTRODUCTION

Alluvial soils represent one of the most extensively utilized soil types for rice cultivation across tropical and subtropical regions, including Indonesia, due to their

formation from sediment deposits carried by water flows such as rivers and floods (Jing et al., 2017; Matoso et al., 2022). These soils typically exhibit favorable physical characteristics for agricultural production, including relatively fine texture and adequate aeration capacity.

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However, despite their inherent fertility derived from organic matter and mineral content transported by water flows, alluvial soils present complex chemical and physical dynamics, particularly concerning nutrient availability such as phosphorus (Ahmed et al., 2024). Recent comprehensive studies across Indo-Gangetic alluvial plains have demonstrated that phosphorus deficiency remains widespread, with over 51% of surveyed districts showing available phosphorus below critical thresholds for optimal rice production (Dutta et al., 2024). Phosphorus constitutes a crucial macronutrient that plays an essential role in rice plant growth, encompassing root formation, flowering, and grain filling processes (Ahmed et al., 2024). Nevertheless, phosphorus availability for plants remains persistently low in tropical soils, including alluvial soils, due to interactions with soil minerals forming insoluble complexes, particularly with aluminum (Al), iron (Fe), and calcium (Ca), depending on soil pH and redox conditions (Frišták & Soja, 2015; Adil, 2022). Contemporary research has revealed that approximately 70-90% of applied phosphorus fertilizer undergoes rapid fixation in tropical soils, with only 10-30% effectively utilized by crops during the growing season (Mitran et al., 2015; Cao et al., 2020). Under typical anaerobic conditions in flooded rice fields, phosphorus fixation by iron in the form of iron phosphate (Fe-P) tends to become a primary constraint on phosphorus bioavailability, thereby limiting rice growth and yield (Jin-zhu, 2014; Fan et al., 2024). Additionally, the risk of phosphorus leaching due to high water movement in these ecosystems exceeds that in other soil types, rendering the need for innovative nutrient management increasingly urgent (Jin-zhu, 2014; Ibrahim et al., 2019; Adil, 2022; Shaukat, 2025).

Rice plants experiencing phosphorus deficiency exhibit decreased biomass growth, reduced tiller number, and impaired panicle formation, ultimately resulting in negative impacts on harvest yields (Adil, 2022). In conventional agricultural systems, phosphorus provision relies on inorganic phosphate fertilizer application; however, efficiency remains consistently low with phosphorus losses reaching up to 70% due to fixation with soil minerals or leaching (Jin-zhu, 2014; Ahmed et al., 2024). Recent field experiments in tropical rice systems have confirmed that inconsistent yield responses to conventional phosphorus fertilizers persist even when soil available phosphorus ranges from 2.7 to 34.2 mg kg⁻¹, highlighting the disconnect between soil phosphorus status and actual crop uptake due to complex fixation mechanisms (Kodagoda et al., 2022). The inefficiency of conventional phosphorus fertilizers not only increases production costs but also contributes to environmental problems through eutrophication of water bodies and soil degradation. Consequently, more efficient and environmentally sustainable phosphorus management systems are required to support food security while maintaining ecological sustainability (Diyah, 2025).

Biochar, a carbon-rich material produced through biomass pyrolysis under oxygen-limited conditions, has emerged as a promising solution for addressing phosphorus management challenges in agricultural

systems. Beyond serving as carbon storage, biochar functions as a potential nutrient carrier, particularly for phosphorus, attributable to its capacity to retain and release nutrients gradually into the soil (Jing et al., 2017; Matoso et al., 2022; Wali et al., 2022). Recent advances have demonstrated that biochar application in acidic soils significantly enhances phosphorus dynamics through multiple mechanisms: increasing soil pH to reduce phosphorus fixation by aluminum and iron, providing high surface area for phosphorus adsorption, and facilitating the conversion of organic phosphorus into plant-available inorganic forms (Nardis et al., 2020; Fang et al., 2021; He et al., 2025). Biochar possesses advantageous physicochemical properties, including high surface area, porosity, and favorable cation exchange capacity (CEC), which enable phosphorus absorption and protection from leaching in soil-water systems (Mukherjee, 2017; Mousavi et al., 2023). Biochar application to soils has been demonstrated not only to enhance overall soil fertility but also to stabilize phosphorus availability across various soil types, including alluvial soils characterized by complex nutrient dynamics (Ibrahim et al., 2019; Ahmed et al., 2024).

Research conducted by Jing et al. (2017) demonstrated that biochar application to irrigated alluvial soils successfully increased phosphate availability by 30% compared to soils without biochar. This enhancement was attributed to biochar's capacity to prevent phosphorus precipitation in the form of iron phosphate (Fe-P) bonds when soils become anaerobic during flooding. Contemporary studies have further confirmed that rice straw biochar application can increase available phosphorus content by 50-85% in acidic soils while simultaneously reducing phosphorus fixation capacity through pH amelioration and enhanced microbial phosphatase activity (Zhang et al., 2022; He et al., 2025). However, conventional biochar application faces limitations in maximizing phosphorus availability, particularly in alluvial soils with high phosphorus fixation capacity and significant leaching risks (Wijyanti, 2025).

In response to phosphorus bioavailability challenges, innovation in the form of phosphorus-enriched biochar (PEB) has emerged as a technological advancement. This technology involves adding phosphorus fertilizers, such as monoammonium phosphate or phosphoric acid, before or after the pyrolysis process, thereby producing biochar with enhanced phosphorus content and availability (Arwenyo et al., 2021; Wali et al., 2022). Recent innovations in biochar-based fertilizer development have demonstrated that phosphorus-enriched biochar can achieve phosphorus loading capacities exceeding 8% while maintaining controlled-release characteristics that synchronize nutrient supply with crop demand throughout the growing season (Wang et al., 2022; Cheng et al., 2025). Phosphorus-enriched biochar is designed to release phosphorus gradually, maintaining phosphorus availability throughout the growing season and improving phosphorus use efficiency (Frišták & Soja, 2015; Lustosa Filho et al., 2017; Mukherjee et al., 2020). Research by Wali et al. (2022) demonstrated that PEB application to topsoil

increased soluble phosphorus content by 50% compared to biochar without phosphorus addition. Matoso et al. (2019) further demonstrated effective synthesis methods for phosphorus-enriched biochar that enhance nutrient delivery in tropical soils. Furthermore, test crops such as maize exhibited biomass yield increases up to 40% under periodic flooding conditions.

The encapsulation method for phosphorus in biochar represents a modern approach to ensuring controlled nutrient release into the soil. Encapsulation technology utilizing natural polymers, particularly sodium alginate cross-linked with calcium chloride, has gained significant attention in recent years due to its biodegradability, biocompatibility, and excellent controlled-release properties for agricultural applications (Colin et al., 2024; Samson et al., 2025; Choi et al., 2025). In this method, biochar is coated or modified with compounds such as magnesium or natural polymers, which slow nutrient release to prevent leaching and enhance phosphorus efficiency (Arwenyo et al., 2021; Adil, 2022). The "egg-box" structure formed by alginate through ionic cross-linking with divalent cations creates a three-dimensional hydrogel network that effectively encapsulates nutrients and regulates their release through diffusion-controlled mechanisms (Tiamwong et al., 2023; Choi et al., 2025). Encapsulation ensures that phosphorus remains available to plants in absorbable forms during critical periods of growth, such as tiller formation or grain filling (Adil, 2022). Arwenyo et al. (2021) reported that biochar encapsulated with magnesium-phosphorus compounds maintained phosphorus release for up to 25 days after application under neutral pH soil conditions, whereas standard chemical phosphate fertilizer application persisted for only 7 days. Similar findings by Nardis et al. (2020) demonstrated that magnesium-enriched biochar serves as an effective phosphorus carrier with sustained release characteristics. Recent advances have shown that encapsulated biochar-based fertilizers can reduce nutrient release rates to 8.95% within 24 hours compared to 54.3% for conventional chemical fertilizers, significantly improving nutrient use efficiency while minimizing environmental losses (Zhao et al., 2020; Dong et al., 2025). This characteristic renders encapsulation technology particularly relevant for rice paddy systems characterized by redox cycles due to flooding.

Despite the recognized potential benefits, research specifically examining the application of phosphorus-enriched encapsulated biochar in alluvial soils remains limited. Most existing studies have focused on other soil types or employed biochar without controlled-release encapsulation modifications. Recent comprehensive reviews have identified critical knowledge gaps regarding the integration of co-pyrolysis, nutrient enrichment, and encapsulation technologies for developing next-generation biochar-based fertilizers specifically tailored for acidic tropical soils (Wang et al., 2022; Sim et al., 2025). The specific combination of phosphorus-enriched biochar with encapsulation techniques in alluvial soil systems presents a unique opportunity to address multiple challenges simultaneously: enhancing phosphorus availability,

reducing nutrient losses through leaching and fixation, and improving overall soil fertility characteristics.

The novelty of this research lies in the integration of three critical components: (1) utilization of rice husk as feedstock for biochar production, capitalizing on agricultural waste valorization; (2) phosphorus enrichment of biochar at varying concentrations to optimize nutrient loading; and (3) application of sodium alginate-calcium chloride encapsulation technology to achieve controlled phosphorus release tailored to rice plant nutrient demands throughout the growing cycle. This integrated approach addresses the specific challenges of alluvial soils while contributing to sustainable agricultural practices through waste utilization and improved nutrient use efficiency. The synergistic combination of these technologies represents a paradigm shift from conventional phosphorus fertilization toward precision nutrient delivery systems that enhance both agronomic performance and environmental sustainability (Wu et al., 2025; Cheng et al., 2025).

The primary objective of this study was to evaluate the effects of phosphorus-enriched encapsulated rice husk biochar application on rice plant growth and yield in alluvial soil. Specific objectives included: (1) analyzing the influence of different phosphorus enrichment levels in encapsulated biochar on rice growth parameters including plant height, leaf number, tiller number, and vegetative biomass; (2) assessing the impact on rice yield components including panicle number, grain number per panicle, grain weight per hill, and 100-grain weight; (3) determining phosphorus release dynamics from encapsulated biochar and its effect on phosphorus uptake by rice roots; (4) comparing the efficiency of phosphorus delivery through encapsulated biochar versus conventional phosphorus fertilizers; and (5) identifying changes in alluvial soil chemical properties, particularly phosphorus availability, pH, and cation exchange capacity, following phosphorus-enriched encapsulated biochar application.

This research hypothesized that application of phosphorus-enriched encapsulated biochar would significantly enhance rice growth and yield in alluvial soil through more controlled phosphorus release and improved phosphorus availability compared to conventional phosphorus fertilizers. The findings from this study are expected to provide scientific evidence for developing more sustainable and efficient phosphorus management strategies in rice production systems on alluvial soils, contributing to both food security and environmental sustainability objectives.

Experimental Site and Duration

This study was conducted at the Laboratory and Greenhouse of the Faculty of Agriculture, Science, and Technology at Panca Bhakti University in Pontianak, West Kalimantan Province, Indonesia (2°05'N–3°05'S, 108°30'–114°10'E), at an elevation of 0.5–1 meter above sea level. Daily average temperature during the study ranged from 25.67 to 32.00°C and relative humidity ranged from 65.75 to 92.75%, representing typical tropical lowland conditions conducive to intensive rice cultivation. The experimental period extended approximately five months from May to

September 2025. Fourier Transform Infrared (FTIR) spectroscopy analysis was performed at the Chemistry Laboratory, Faculty of Mathematics and Natural Sciences, Tanjungpura University, Pontianak, while nutrient content analyses of biochar and soil were conducted at the Soil Fertility Laboratory, Faculty of Agriculture, Tanjungpura University.

MATERIALS & METHODS

The materials used included alluvial soil, rice seeds of several varieties, raw materials for making encapsulated biochar enriched with phosphorus (rice husk biochar, Triple Super Phosphate/TSP, sodium alginate food grade, CaCl_2), fertilizers (Urea, NPK 15-15-15, SP-36, KCl, agricultural lime, manure/organic matter), and organic pesticides (insecticides, fungicides, and herbicides). The equipment included a set of chemical glassware, pyrolysis apparatus, 60 mesh sieve, analytical balance (0.0001 g precision), digital scale (5 kg capacity), manual scale, grinder, pellet maker, drying oven, pH meter, hoes, plastic buckets, sprayer, sacks, tarps, soil auger, sickle, planting tools, and harvesting tools.

Experimental Design

This study utilized a Completely Randomized Design (CRD) with six treatments of phosphorus-enriched encapsulated biochar (B):

- B0 = Control (without biochar)
- B1 = Rice husk biochar without phosphorus enrichment at a dose of 10 tons ha^{-1} (50g polybag $^{-1}$)
- B2 = Rice husk biochar enriched with 25% phosphorus at a dose of 10 tons ha^{-1} (50g polybag $^{-1}$)
- B3 = Rice husk biochar enriched with 50% phosphorus at a dose of 10 tons ha^{-1} (50g polybag $^{-1}$)
- B4 = Encapsulated biochar enriched with 25% phosphorus at a dose of 10 tons ha^{-1} (50g polybag $^{-1}$)
- B5 = Encapsulated biochar enriched with 50% phosphorus at a dose of 10 tons ha^{-1} (50g polybag $^{-1}$)

Each treatment was repeated four times, resulting in 24 experimental units, with each replication consisting of 6 plants, making a total of 144 plants or observation units ($6 \times 4 \times 6 = 144$).

Biochar Preparation

The biochar feedstock was derived from rice harvest waste in the form of rice husks to facilitate nutrient recycling in paddy fields. The rice husks were dried to a moisture content of <15% before pyrolysis. Pyrolysis was conducted using a pyrolysis apparatus, and the resulting biochar was cooled and then ground to a particle size of 60 mesh. This particle size was selected based on research by Meyer Zu Drewer et al. (2022), which stated that this size optimally increased biochar reactivity in soil due to its high surface area and suitability for application as a fertilizer carrier. The produced biochar underwent initial characterization analysis with the following parameters: biochar pH, organic C, total N, total P, total K, calcium, magnesium, C/N ratio, and functional groups using FTIR (Fourier Transform Infrared) analysis, which identified

functional groups such as O-H, C=O, and C=C.

Phosphorus Enrichment and Encapsulation Process

The biochar encapsulation procedure began with grinding the biochar using a grinder to a size of 60 mesh. The ground biochar (10kg) was then mixed with Triple Super Phosphate (TSP) fertilizer solution according to the desired biochar-to-fertilizer weight ratio corresponding to the treatment levels (25%, 50%) at a ratio of 1:2 (w/v), based on research by Wali et al. (2020). The mixture was stirred evenly for 30 minutes to ensure homogeneity, then incubated for 24 hours at room temperature (25-28°C) with occasional stirring every 6 hours to ensure uniform phosphorus penetration into the biochar porous structure. After that, the mixture was air-dried for 48 hours until the moisture content reached approximately 10-15%.

Following the phosphorus enrichment process, the phosphorus-enriched biochar was mixed with 20% (w/v) sodium alginate solution (Kuang et al., 2022; Zhang et al., 2022). The mixture was stirred evenly for 15 minutes until a homogeneous viscous dough was formed. To this homogeneous dough, 0.1M CaCl_2 solution at 15% (w/v) (Kuang et al., 2022; Zhang et al., 2022) was gradually and evenly added dropwise using a syringe to ensure complete cross-linking between sodium alginate and calcium ions through ionic gelation, resulting in spherical granular fertilizer beads formation. The encapsulation mechanism involves the formation of "egg-box" structure through ionic cross-linking between carboxyl groups (COO^-) of alginate and Ca^{2+} ions, creating a three-dimensional hydrogel network that provides controlled-release properties (Colin et al., 2024; Choi et al., 2025). The beads were allowed to harden in the CaCl_2 solution for 30 minutes before collection. To further harden the formed granular fertilizer, it was dried in an oven at 80°C for 24 hours, producing robust granular fertilizer with improved mechanical stability and handling properties.

The successful encapsulation was confirmed through FTIR analysis, which revealed characteristic peaks corresponding to alginate-calcium cross-linking. Specifically, the appearance of shifted peaks for COO^- symmetric stretching (1420-1430 cm^{-1}) and COO^- asymmetric stretching (1595-1605 cm^{-1}) indicated strong ionic interactions between alginate carboxyl groups and Ca^{2+} ions. Additionally, the emergence of new peaks at 1076 cm^{-1} corresponding to Ca-O bonds confirmed successful encapsulation matrix formation (Tiamwong et al., 2023; Li et al., 2025).

The dried granular fertilizer then underwent characterization analysis with the following observed parameters: biochar pH, organic C, total N, total P, total K, calcium, magnesium, and C/N ratio.

Growing Medium Preparation

Growing medium preparation was conducted by collecting soil from a depth of 0-20 cm from the surface, which was then composited from various soil sampling points across the experimental field to ensure representative soil characteristics. The composited soil was spread on a tarp and air-dried for 3-5 days under shade to

prevent excessive moisture loss. Large soil clumps were crushed manually and then sieved using a 2mm sieve to separate coarse materials such as gravel and plant residues, followed by thorough mixing to ensure homogeneity. Representative soil samples were collected and analyzed for physical and chemical properties including texture, pH (H₂O and KCl), organic C, total N, P₂O₅ (Bray I), exchangeable cations (Ca, Mg, K, Na), cation exchange capacity (CEC), base saturation (BS), exchangeable Al, and exchangeable H. The soil was then placed into polybags measuring 40 × 40 cm, with each polybag filled with 10kg of soil. Each polybag was equipped with drainage holes at the bottom to prevent waterlogging while maintaining adequate moisture for rice growth. The polybags were arranged according to the experimental layout in the greenhouse with spacing of 25 × 25 cm between polybags, and the medium was incubated for one week before planting to allow soil equilibration.

Seed Sowing and Seedling Preparation

Seed sowing was carried out using seedling trays measuring 20 × 40 cm. The seedling medium consisted of alluvial soil and decomposed cattle manure at a ratio of 2:1 (v/v) to provide adequate nutrients for early seedling growth. Before sowing, rice seeds of Ciherang variety were selected for uniformity, soaked in running water for approximately 24 hours to accelerate germination and break seed dormancy. The seeds were then evenly distributed in the nursery tray at a density of approximately 2-3 seeds cm⁻² and covered with fine organic manure layer (1-2 cm thickness). Seedling trays were maintained under greenhouse conditions with regular watering twice daily (morning and evening) to maintain adequate moisture. The rice seedlings were ready for transplanting at 21 days after sowing when they reached 15-20 cm height with 3-4 fully expanded leaves.

Application of Phosphorus-Enriched Encapsulated Rice Husk Biochar

Biochar was applied at a dose of 10 tons ha⁻¹ (50g polybag⁻¹), based on research by Yu et al. (2021), which showed that biochar application at 10t ha⁻¹ could increase soil pH, reduce Al³⁺ solubility, and provide phosphorus availability in acidic tidal lands. The application rate was calculated based on soil bulk density (1.2g cm⁻³) and tillage depth (15 cm) to achieve the target rate of 10 tons ha⁻¹. Biochar was thoroughly mixed into the topsoil layer (0–15 cm) using a hand trowel to ensure uniform distribution and expand interaction with the plant root system. The application was performed two weeks before planting to allow adequate time for biochar-soil interactions, pH equilibration, and initial nutrient release.

Planting

Once the seedlings reached 21 days old with appropriate vigor, they were carefully uprooted from seedling trays with minimal root disturbance. Three uniform seedlings were selected and transplanted into each polybag that had been filled with treated soil medium. Planting was performed at a depth of 3-5 cm with gentle firming of soil around the seedling base to

ensure good root-soil contact. Immediately after transplanting, polybags were irrigated thoroughly to settle the soil and eliminate air pockets around the roots, promoting rapid establishment.

Fertilization

The fertilizers used consisted of two types: Urea and NPK 15-15-15, according to location-specific recommendations based on the Minister of Agriculture Decree No. 13 of 2022 concerning the Use of N, P, K Fertilizer Doses for rice, corn, and soybean crops on paddy fields. For Rasau Jaya District, Kubu Raya Regency, West Kalimantan Province, the recommended fertilizer dose was 150 kg ha⁻¹ of urea (0.75 g polybag⁻¹) and 300 kg ha⁻¹ of NPK 15-15-15 (1.5 g polybag⁻¹). Fertilizers were applied using the broadcasting method, evenly distributed on the soil surface around the plant base (5-7 cm from the plant stem) to minimize direct contact with roots and prevent potential burn injury. Application was performed once at 1 week after planting (WAP) when plants had established adequately, followed by light incorporation into the topsoil and immediate irrigation to facilitate nutrient dissolution and uptake.

Plant Irrigation and Water Management

Plant irrigation was conducted to maintain anaerobic conditions typical of lowland rice cultivation. Water level was maintained at 2-5 cm above the planting medium surface using an intermittent flooding system. Water was replenished daily or as needed to maintain the target water level, accounting for evapotranspiration losses and percolation. Water quality was monitored periodically to ensure electrical conductivity remained below 1.5 dS m⁻¹. Drying was performed two weeks before harvest (at approximately 12 weeks after planting) to facilitate grain maturation, increase grain filling, and ease harvesting operations.

Pest and Disease Control

Daily monitoring was conducted during morning hours to observe pest incidence and disease symptoms on the test plants. Specific attention was paid to common rice pests including stem borers (*Scirpophaga incertulas*), planthoppers (*Nilaparvata lugens*), and leaf folders (*Cnaphalocrocis medinalis*), as well as diseases such as blast (*Pyricularia oryzae*) and sheath blight (*Rhizoctonia solani*). Pest and disease control was carried out as needed using insecticides (Spontan at recommended rate of 1 mL L⁻¹) and fungicides (Amistartop at recommended rate of 0.5 mL L⁻¹) when pest/disease incidence exceeded economic threshold levels. Applications were performed in the evening to minimize phytotoxicity and maximize efficacy, with a minimum spray interval of 7 days between successive applications.

Harvesting

Grain harvesting was performed when the rice plant leaves began to turn yellow entirely, or when yellowing reached 90% of the total plant canopy, with only the flag leaf still appearing green, indicating physiological maturity.

This typically occurred at approximately 95 to 104 days after planting (DAP) depending on treatment effects. Harvesting was conducted by cutting the panicles 20-25 cm below the panicle neck using sharp sickles, followed by drying in shade for 2-3 days to reach approximately 14% moisture content before threshing and weighing.

Observation Parameters

The observed parameters in this study included:

1. Biochar Characteristics: Parameters observed for biochar characteristics before and after the phosphorus-enriched biochar encapsulation process included: biochar pH (1:10 biochar:water ratio using pH meter), organic C (Walkley-Black method), total N (Kjeldahl method), total P (HCl extraction followed by spectrophotometry), total K (HCl extraction followed by flame photometry), calcium and magnesium (AAS method), C/N ratio (calculated), and functional groups using FTIR (Fourier Transform Infrared) analysis identifying functional groups such as O-H ($3200-3600\text{ cm}^{-1}$), C=O ($1700-1750\text{ cm}^{-1}$), and C=C ($1500-1650\text{ cm}^{-1}$).

2. Soil Characteristics:

- Soil Characteristics Before Biochar Application: Initial soil analysis was conducted on physical properties (texture using hydrometer method) and chemical properties, including: pH (H_2O and KCl at 1:2.5 soil:solution ratio), organic C (Walkley-Black method), total N (Kjeldahl method), P_2O_5 (Bray I extraction method), exchangeable potassium, magnesium, calcium, and sodium (NH_4OAc extraction at pH 7.0 followed by AAS), cation exchange capacity (CEC, NH_4OAc saturation method), base saturation (BS, calculated as sum of bases/CEC \times 100), exchangeable Al (KCl extraction followed by titration), exchangeable H (calculated), and soil texture (pipette method). Analysis was performed at the Chemistry and Soil Fertility Laboratory, Faculty of Agriculture, Tanjungpura University.

- Soil Characteristics After Biochar Application: Soil characteristics were observed two weeks after biochar application to assess immediate effects, analyzing: pH (H_2O at 1:2.5 soil:solution ratio), exchangeable H (calculated from pH), exchangeable Al (KCl extraction), available phosphorus content (Bray I method), and iron content (DTPA extraction followed by AAS). Analysis was performed at the Chemistry and Soil Fertility Laboratory, Faculty of Agriculture, Tanjungpura University.

3. Growth Parameters: Growth parameters consisted of:

- Plant height (measured from soil surface to the tip of the longest leaf using measuring tape, observed every 2 weeks at 3, 5, and 7 WAP)
- Number of tillers (counted as all visible tillers >2 cm height per hill, observed every 2 weeks at 3, 5, and 7 WAP)
- Number of leaves (counted as all fully expanded leaves with $>50\%$ green area per hill, observed every 2 weeks at 3, 5, and 7 WAP)
- Leaf chlorophyll content (measured using SPAD-502 chlorometer on the middle portion of the youngest fully expanded leaf, observed every 2 weeks at 3, 5, and 7 WAP)
- Relative growth rate (RGR) calculated using the formula: $\text{RGR} = (\ln W_2 - \ln W_1) / (t_2 - t_1)$, where W_1 and W_2 are dry weights at times t_1 and t_2 , observed three times (21-35 DAP, 35-49 DAP, 49-63 DAP)

- Biomass parameters measured at 3, 5, and 7 WAP: shoot dry weight (above-ground parts dried at 70°C for 72 hours until constant weight), root dry weight (washed roots dried at 70°C for 72 hours), and shoot-to-root dry weight ratio (calculated as shoot DW/root DW)

4. Yield Parameters: Yield component parameters included:

- Number of panicles per hill (counted as all panicles with at least one filled grain)
- Panicle length (measured from panicle neck to panicle tip using ruler, cm)
- Number of grains per panicle (counted as total spikelets including filled and unfilled grains)
- Number of filled grains per panicle (counted as grains that sink in water, indicating $>80\%$ filling)
- Weight of 100 grains (randomly selected filled grains weighed at 14% moisture content, g)
- Grain weight per hill (total grain weight from all productive tillers per hill at 14% moisture content, g)

5. Encapsulated Biochar Efficiency Parameters: The efficiency parameters of phosphorus-enriched encapsulated biochar were determined by analyzing:

- Available phosphorus in soil (Bray I extraction method)
- Phosphorus absorbed by plant tissues (plant samples digested with $\text{HNO}_3\text{-HClO}_4$ mixture followed by spectrophotometric analysis using molybdenum blue method)

Both parameters were measured at three time points: 3, 5, and 7 WAP to assess phosphorus release dynamics and crop uptake patterns throughout the growing season.

Statistical Analysis

Data collected from the experiment were tabulated using Microsoft Excel 2019 for data organization and preliminary calculations. Statistical analysis was performed using SmartstatXL software. Analysis of variance (ANOVA) was conducted using the F-test at 5% significance level ($\alpha = 0.05$) to determine treatment effects. When significant differences were detected ($P < 0.05$), mean separation was performed using Tukey's Honest Significant Difference (HSD) test at 5% significance level to identify which treatments differed significantly from each other. Results were presented as mean \pm SD, with treatments sharing the same letter designation not significantly different at $P < 0.05$. The initial physicochemical properties of the alluvial soil used in this experiment are presented in Table 1.

Table 1: Chemical Properties of Alluvial Soil Before Treatment Application

Parameters	Unit	Value	Criteria
pH H_2O	-	4.36	Very acidic
pH KCl	-	3.79	Acidic
C-Organic	%	2.51	Moderate
Total Nitrogen	%	0.26	Moderate
P_2O_5 (Bray I)	ppm	12.67	Low
Calcium	$\text{cmol}(+) \text{ kg}^{-1}$	2.67	Low
Magnesium	$\text{cmol}(+) \text{ kg}^{-1}$	0.69	Low
Potassium	$\text{cmol}(+) \text{ kg}^{-1}$	0.18	Very low
Sodium	$\text{cmol}(+) \text{ kg}^{-1}$	0.69	Low
CEC	$\text{cmol}(+) \text{ kg}^{-1}$	13.18	Low
Base Saturation	%	32.09	Low
Exchangeable Al	$\text{cmol}(+) \text{ kg}^{-1}$	1.48	Moderate
Exchangeable H	$\text{cmol}(+) \text{ kg}^{-1}$	1.14	-
Texture			
Sand	%	3.11	Silty loam
Silt	%	75.36	
Clay	%	21.53	

RESULTS & DISCUSSION

Initial Soil and Biochar Characteristics

The initial soil characterization revealed multiple physicochemical constraints characteristic of acidic alluvial soils in tropical regions. The extremely acidic pH of 4.36 indicated a high concentration of hydrogen ions that significantly influences nutrient dynamics and microbial activity. Recent studies have demonstrated that soil pH below 4.5 creates unfavorable conditions for rice cultivation through multiple mechanisms, including enhanced aluminum solubility, reduced phosphorus availability, and impaired microbial functions essential for nutrient cycling (Feng et al., 2021). The acidic condition observed in this study falls within the critical range where aluminum toxicity becomes a primary constraint to crop productivity, as evidenced by the moderate exchangeable aluminum content ($1.48 \text{ cmol}(+)\text{kg}^{-1}$) which represents a significant threat to rice growth.

The low cation exchange capacity ($13.18 \text{ cmol}(+)\text{kg}^{-1}$) and base saturation (32.09%) reflected the limited capacity of this soil to retain essential plant nutrients, typical of weathered tropical soils where intensive leaching has depleted exchangeable bases. The available phosphorus content of 12.67ppm, classified as low according to Bray I extraction method, indicated severe phosphorus limitation for optimal rice production, as rice typically requires 20-40ppm available phosphorus during critical growth stages to achieve maximum productivity (Ahmed et al., 2024). The combination of low inherent phosphorus content and high aluminum activity creates a particularly challenging environment for phosphorus nutrition, as aluminum forms highly stable, insoluble phosphate compounds that drastically reduce phosphorus bioavailability (Shi et al., 2019; Yuan et al., 2025). Chemical characteristics of the rice husk biochar prior to phosphorus enrichment are presented in Table 2.

Table 2: Chemical Characteristics of Conventional Biochar

Parameters	Unit	Value
pH	-	7.91
C-Organic	%	31.2
Total N	%	1.11
C/N Ratio	-	28.11
Total P (HCl 1:2)	%	0.35
Total K	%	0.59
Total Ca	%	0.18
Total Mg	%	0.03

The conventional rice husk biochar exhibited favorable characteristics for soil amendment applications. The alkaline pH of 7.91 is particularly advantageous for acidic soil amelioration, providing immediate neutralization capacity upon incorporation into acidic soils. The high carbon content (31.2%) indicated effective carbonization during the pyrolysis process, which is crucial for the formation of stable aromatic structures that resist microbial degradation and provide long-term carbon sequestration benefits (Mockeviciene et al., 2021). The C/N ratio of 28.11 represents an optimal balance for soil application, sufficiently high to ensure biochar stability

while avoiding nitrogen immobilization that can occur with extremely high C/N materials (Deshoux et al., 2023). Contemporary research has established that biochar with C/N ratios between 25-35 provides optimal conditions for soil microbial activity without competing with plants for available nitrogen (Deshoux et al., 2023).

The relatively low phosphorus content (0.35%) underscored the necessity for phosphorus enrichment to meet crop requirements, particularly in phosphorus-deficient soils. This observation aligns with recent findings that native biochar typically contains insufficient phosphorus for intensive crop production and requires enrichment to function effectively as a phosphorus carrier (Nardis et al., 2020; Morais et al., 2023). The moderate potassium content (0.59%) can contribute to plant nutrition, while the low calcium (0.18%) and magnesium (0.03%) contents highlight opportunities for further nutrient enrichment during the encapsulation process.

The phosphorus enrichment process successfully elevated phosphorus content from 0.43% in conventional biochar (b1) to 8.45% in the highest enrichment treatment (b5), representing a remarkable 19.7-fold increase. This substantial enhancement was achieved through systematic impregnation with triple super phosphate followed by calcium alginate encapsulation. The encapsulation process not only retained phosphorus within the biochar matrix but also created a controlled-release mechanism that regulates phosphorus availability over extended periods (Colin et al., 2024; Samson et al., 2025). Recent advances in encapsulation technology have demonstrated that calcium alginate matrices form three-dimensional networks through ionic cross-linking between alginate's carboxyl groups and calcium ions, creating diffusion barriers that slow nutrient release while protecting nutrients from rapid fixation reactions (Chen et al., 2018; Samson et al., 2025).

The concurrent increase in calcium content from 0.40% (b1) to 5.98% (b5) resulted from the cross-linking reaction between sodium alginate and calcium chloride during the encapsulation process. This calcium enrichment provides additional benefits beyond structural integrity, contributing to improved soil aggregation and enhanced cation exchange capacity. Contemporary research has demonstrated that calcium alginate-encapsulated fertilizers exhibited superior phosphorus retention efficiency, maintaining 70-85% of initial phosphorus availability after 60 days compared to only 15-25% retention with conventional phosphorus fertilizers in acidic soils (Kuang et al., 2022; Choi et al., 2025).

The variation in organic carbon content across treatments (26.90% to 37.96%) reflected the differential incorporation of phosphate fertilizer, which diluted the biochar carbon concentration. However, all treatments maintained sufficiently high carbon content to provide soil conditioning benefits, including improved water retention, enhanced microbial habitat, and increased cation exchange capacity. The increase in total nitrogen content with higher phosphorus enrichment levels (from 0.54% to 0.78%) was attributed to the nitrogen component in triple super phosphate and suggests potential for synchronized nitrogen-phosphorus nutrition. Chemical properties of all

biochar treatments after enrichment and encapsulation are summarised in Table 3. The effects of biochar treatments on soil chemical properties two weeks after application are presented in Table 4.

Soil Chemical Properties After Biochar Application

Biochar application profoundly modified soil chemical properties, with particularly pronounced effects on pH and phosphorus availability. Treatment b5 increased soil pH by 0.81 units compared to control, representing an 18.4% improvement that shifted the soil from extremely acidic to strongly acidic conditions. This pH amelioration resulted from multiple mechanisms operating synergistically: the alkaline nature of biochar (pH 7.90) provided immediate acid neutralization through consumption of hydrogen ions by basic functional groups on the biochar surface, while the calcium carbonate formed during the encapsulation process contributed further alkalinity through dissolution and reaction with soil acidity (Shi et al., 2019; Liu et al., 2025; Arif et al., 2025).

The pH increase observed in this study has profound implications for phosphorus availability and aluminum toxicity mitigation (Xu et al., 2018; Mosharraf et al., 2021). Recent research has demonstrated that each 0.5-unit increase in soil pH between 4.0 and 5.5 can reduce aluminum activity by approximately 50-70%, substantially alleviating aluminum toxicity risk (Xu et al., 2018; Feng et al., 2021). The reduction in exchangeable aluminum from 1.31 to 0.84 $\text{cmol}(+)\text{kg}^{-1}$ observed in b5 treatment represents a significant 35.9% decrease ($P < 0.05$), which translates to significant improvements in root health and nutrient acquisition capacity.

The dramatic increase in available phosphorus from 15.49ppm in control to 580.91ppm in b5 treatment represents a remarkable 37.5-fold enhancement ($P < 0.05$), which exceeded values typically reported in biochar studies. While previous studies have reported 2-8 fold increases in available phosphorus with biochar application (Zhai et al., 2014; Chen et al., 2018; Ahmed et al., 2024), the superior performance of encapsulated phosphorus-enriched biochar can be attributed to three primary mechanisms: first, the controlled-release properties of calcium alginate encapsulation prevented rapid phosphorus fixation by maintaining gradual phosphorus

release rates that matched plant uptake patterns; second, the pH increase reduced aluminum and iron activity in soil solution, decreasing the rate of insoluble phosphate formation; third, biochar's high surface area and functional groups competed with soil minerals for phosphorus adsorption, effectively increasing phosphorus retention in plant-available forms (Gu et al., 2022; He et al., 2025).

The concurrent reduction in exchangeable hydrogen (from 2.83 to 1.61 $\text{cmol}(+)\text{kg}^{-1}$, $P < 0.05$) indicated progressive neutralization of soil acidity, which enhances not only phosphorus availability but also calcium, magnesium, and molybdenum availability while reducing manganese and aluminum toxicity risks. The decrease in extractable iron from 916.27 to 481.72ppm ($P < 0.05$) suggested reduced iron oxide dissolution under less acidic conditions, which has important implications for phosphorus dynamics. Under highly acidic conditions, dissolved iron readily precipitates phosphorus as ferric phosphate compounds, severely limiting phosphorus availability (He et al., 2025; Yuan et al., 2025). The pH-induced reduction in iron solubility observed in biochar treatments thus contributes to maintaining higher phosphorus availability throughout the growing season.

Vegetative Growth Parameters

Plant height (Table 5) exhibited progressive increases across all growth stages, with significant treatment effects ($P < 0.05$) becoming increasingly pronounced as plants matured. By 7 WAP, b5 treatment produced significantly taller plants at 134.5 cm, representing a 20.0% increase over control (112.1 cm, $P < 0.05$). This enhanced vertical growth reflects improved nutrient availability, particularly phosphorus and nitrogen, which are critical for cell elongation and meristematic activity. The role of phosphorus in promoting shoot elongation operates through multiple pathways, including enhanced ATP availability for energy-dependent growth processes, improved protein synthesis for structural development, and increased cytokinin production that stimulates cell division in apical meristems (Mockeviciene et al., 2021).

The temporal growth pattern revealed accelerated growth rates in biochar treatments during the 5-7 WAP period, corresponding to the maximum tillering and stem elongation phase (Wang et al., 2022). This growth

Table 3: Chemical Properties of Phosphorus-Enriched and Encapsulated Biochar Treatments

Treatment	pH	C-Organic (%)	Total N (%)	C/N Ratio	P (%)	K (%)	Ca (%)	Mg (%)
b1	7.68 ± 0.05	36.86 ± 2.15	0.54 ± 0.03	68.26	0.43 ± 0.02	0.49 ± 0.04	0.40 ± 0.03	0.04 ± 0.01
b2	7.47 ± 0.08	26.90 ± 1.87	0.56 ± 0.04	48.04	7.30 ± 0.45	0.29 ± 0.02	2.54 ± 0.18	0.13 ± 0.01
b3	7.86 ± 0.06	30.03 ± 2.34	0.60 ± 0.05	50.05	6.06 ± 0.38	0.46 ± 0.03	2.84 ± 0.21	0.16 ± 0.02
b4	7.35 ± 0.09	32.52 ± 1.96	0.71 ± 0.06	45.80	5.66 ± 0.41	0.35 ± 0.03	4.49 ± 0.32	0.24 ± 0.02
b5	7.90 ± 0.07	37.96 ± 2.68	0.78 ± 0.07	48.67	8.45 ± 0.52	0.64 ± 0.05	5.98 ± 0.41	0.29 ± 0.03

Note: b1 = conventional biochar without phosphorus enrichment; b2 = biochar enriched with 25% phosphorus; b3 = biochar enriched with 50% phosphorus; b4 = encapsulated biochar with 25% phosphorus; b5 = encapsulated biochar with 50% phosphorus.

Table 4: Effect of Biochar Treatments on Soil Chemical Properties Two Weeks After Application

Treatment	pH H ₂ O	P ₂ O ₅ (ppm)	Exchangeable Al ($\text{cmol}(+)\text{kg}^{-1}$)	Exchangeable H ($\text{cmol}(+)\text{kg}^{-1}$)	Fe (ppm)
b0	4.41 ± 0.07 a	15.49 ± 0.94 a	1.31 ± 0.18 b	2.83 ± 0.10 d	916.27 ± 153.29 c
b1	4.81 ± 0.06 b	28.60 ± 1.60 a	0.89 ± 0.11 a	2.62 ± 0.11 cd	751.12 ± 108.79 bc
b2	4.89 ± 0.14 bc	256.80 ± 59.07 b	0.81 ± 0.12 a	2.21 ± 0.02 bc	599.62 ± 197.35 ab
b3	5.31 ± 0.36 d	506.33 ± 122.53 c	0.81 ± 0.09 a	1.74 ± 0.47 ab	475.73 ± 103.32 a
b4	5.03 ± 0.24 bcd	252.45 ± 20.74 b	0.86 ± 0.17 a	2.23 ± 0.44 bc	524.18 ± 54.47 a
b5	5.22 ± 0.35 cd	580.91 ± 120.91 c	0.84 ± 0.08 a	1.61 ± 0.59 a	481.72 ± 46.72 a

Note: Mean values followed by the same letter within columns are not significantly different according to Tukey's HSD test at $P < 0.05$.

acceleration coincided with peak phosphorus demand and suggests that the sustained phosphorus availability provided by encapsulated biochar effectively supported critical developmental processes. Recent research has demonstrated that phosphorus availability during the 4-7 weeks after transplanting determines final plant height and capacity for biomass accumulation, as this period encompasses critical decisions regarding tiller retention and stem elongation (Ahmed et al., 2024).

Leaf number increased substantially with biochar application, particularly in treatments with higher phosphorus enrichment. Treatment b5 produced significantly higher leaf number (156.0 leaves at 7 WAP) compared to control (104.6, $P < 0.05$), representing a 49.1% increase. This enhanced leaf production has profound implications for photosynthetic capacity and ultimately grain yield, as leaf area directly determines light interception and carbon assimilation potential. The mechanism linking improved phosphorus nutrition to increased leaf production involves phosphorus roles in nucleic acid synthesis, which is essential for the rapid cell division occurring in leaf primordia (Wang et al., 2022; Ahmed et al., 2024). Additionally, adequate phosphorus availability promotes faster leaf emergence rates and extends leaf longevity by reducing premature senescence.

The greater leaf number observed in phosphorus-enriched treatments also reflects reduced aluminium toxicity, which severely inhibits leaf development through disruption of cell division in apical meristems (Xu et al., 2018; Feng et al., 2021). Contemporary research has demonstrated that aluminium concentrations exceeding $100\mu\text{M}$ in root zone solution can reduce leaf initiation rates by 40-60% and accelerate leaf senescence, effects that were substantially mitigated by the pH amelioration achieved through biochar application (Xu et al., 2018).

Tiller number, a critical yield determinant in rice, exhibited dramatic responses to biochar treatments. Treatment b5 produced significantly higher tiller number (34.1 tillers at 7 WAP) compared to control (20.8 tillers, $p < 0.05$), representing a 63.9% increase. This remarkable enhancement in tillering capacity resulted from multiple interacting factors. First, improved phosphorus nutrition directly stimulates tiller bud activation through enhanced cytokinin production and transport from roots to shoots (Shi et al., 2019; Yuan et al., 2025). Phosphorus is essential for cytokinin biosynthesis, and phosphorus-deficient plants exhibit drastically reduced cytokinin levels, resulting in poor tillering (Murtaza et al., 2026).

Second, the amelioration of aluminum toxicity through pH increase removed a major constraint on tiller

development (Xu et al., 2018; Feng et al., 2021). Aluminum toxicity severely inhibits lateral bud activation through disruption of hormonal signaling and direct cellular damage to meristematic tissues. Third, improved soil physical conditions resulting from biochar incorporation enhanced root development, providing the physiological foundation for supporting multiple tillers. Recent research has established strong positive correlations between root biomass and tiller production capacity, as extensive root systems are required to supply the water and nutrients demanded by multiple growing points (Meena et al., 2019; Li et al., 2025).

The temporal pattern of tiller production revealed that biochar treatments extended the tillering period, with continued tiller emergence occurring through 7 WAP in b5 treatment while control plants had largely ceased tillering by 5 WAP. This extended tillering capacity provides greater flexibility in yield formation and increases the probability of producing highly productive tillers that contribute significantly to final grain yield.

Biomass accumulation patterns demonstrated substantial treatment effects ($P < 0.05$) on both shoot and root development throughout the growing season. Shoot dry weight at 7 WAP increased significantly from 39.5g in control to 62.3g in b5 treatment ($P < 0.05$), representing a 57.7% enhancement. This remarkable biomass increase reflected the cumulative effects of improved photosynthetic capacity, enhanced nutrient acquisition, and alleviated environmental stresses. The progressive biomass accumulation across growth stages demonstrated sustained treatment effects attributable to the controlled nutrient release characteristics of encapsulated biochar (Table 6).

The mechanisms underlying enhanced shoot biomass production operate at multiple physiological levels (Wang et al., 2022; Ahmed et al., 2024). Improved phosphorus nutrition enhances photosynthetic efficiency through several pathways, including increased Rubisco content, enhanced ATP synthesis for Calvin cycle reactions, and improved triose phosphate utilization for starch synthesis (Wang et al., 2022; Li et al., 2025). Recent research has demonstrated that adequate phosphorus nutrition can increase photosynthetic rates by 25-40% compared to phosphorus-deficient conditions, primarily through enhanced electron transport chain efficiency and improved CO_2 fixation capacity (Wang et al., 2022). Additionally, the greater leaf area in biochar treatments provided expanded light interception surface, translating to higher total carbon assimilation despite similar photosynthetic rates per unit leaf area.

Table 5: Effect of Biochar Treatments on Plant Height, Leaf Number, and Tiller Number at Different Growth Stages

Treatment	Plant Height (cm)			Leaf Number			Tiller Number		
	3 WAP	5 WAP	7 WAP	3 WAP	5 WAP	7 WAP	3 WAP	5 WAP	7 WAP
b0	62.3 ± 4.6 a	89.7 ± 4.4 a	112.1 ± 7.0 a	41.7 ± 6.7 a	93.9 ± 12.8 a	104.6 ± 8.7 a	11.5 ± 2.1 a	19.4 ± 2.5 a	20.8 ± 2.8 a
b1	67.6 ± 2.1 ab	94.7 ± 11.8 a	117.4 ± 7.3 ab	45.0 ± 7.7 ab	101.9 ± 6.7 ab	120.4 ± 10.8 b	12.4 ± 0.7 ab	21.5 ± 1.0 a	23.3 ± 1.3 a
b2	74.6 ± 5.6 cd	110.6 ± 10.9 b	126.3 ± 8.3 bc	53.4 ± 8.7 bc	115.8 ± 15.7 bc	128.3 ± 20.7 bc	14.0 ± 1.6 b	25.7 ± 1.7 b	27.2 ± 0.8 b
b3	77.3 ± 5.3 d	112.7 ± 7.8 b	123.4 ± 2.8 b	64.3 ± 2.1 d	123.1 ± 14.5 cd	143.1 ± 5.9 cd	16.3 ± 0.6 c	27.1 ± 1.2 bc	28.7 ± 1.3 bc
b4	70.6 ± 1.4 bc	107.9 ± 7.0 b	126.0 ± 6.3 bc	50.8 ± 3.5 b	115.7 ± 18.8 bc	145.7 ± 5.4 d	13.8 ± 1.5 b	26.5 ± 4.3 bc	30.2 ± 2.7 c
b5	71.3 ± 1.8 bc	116.6 ± 11.2 b	134.5 ± 6.2 c	61.2 ± 6.2 cd	136.0 ± 12.3 d	156.0 ± 7.3 d	13.8 ± 1.1 b	29.7 ± 2.3 c	34.1 ± 1.4 d

Note: Mean values followed by the same letter within columns are not significantly different according to Tukey's HSD test at $P < 0.05$. WAP = weeks after planting.

Table 6: Effect of Biochar Treatments on Biomass Accumulation and Allocation

Treatment	Shoot Dry Weight (g)			Root Dry Weight (g)			Shoot:Root Ratio		
	3 WAP	5 WAP	7 WAP	3 WAP	5 WAP	7 WAP	3 WAP	5 WAP	7 WAP
b0	1.9 ± 0.5 a	11.9 ± 12.5 a	39.5 ± 1.2 a	1.0 ± 0.1 a	7.5 ± 0.9 a	17.2 ± 2.5 a	2.1 ± 0.6 bc	2.8 ± 0.2 a	2.3 ± 0.3 a
b1	2.5 ± 0.5 ab	18.6 ± 7.6 ab	48.9 ± 4.5 b	1.1 ± 0.0 a	10.0 ± 1.2 b	20.2 ± 1.1 ab	2.2 ± 1.0 bc	2.6 ± 0.4 a	2.4 ± 0.4 a
b2	2.8 ± 0.8 ab	31.5 ± 8.1 bc	50.8 ± 4.8 bc	1.4 ± 0.1 b	10.9 ± 1.1 bc	22.2 ± 1.3 bc	1.9 ± 0.7 abc	2.5 ± 0.4 a	2.3 ± 0.3 a
b3	3.8 ± 0.9 c	33.0 ± 11.4 bc	56.8 ± 4.8 cd	1.6 ± 0.2 c	11.6 ± 1.1 cd	24.6 ± 2.7 cd	2.3 ± 1.2 c	2.6 ± 0.1 a	2.3 ± 0.4 a
b4	3.2 ± 0.5 bc	42.7 ± 11.3 cd	59.9 ± 5.0 d	1.6 ± 0.1 c	11.9 ± 1.0 cd	25.4 ± 1.7 d	1.2 ± 0.8 a	2.5 ± 0.5 a	2.4 ± 0.3 a
b5	3.1 ± 0.4 bc	50.2 ± 14.0 d	62.3 ± 4.4 d	1.7 ± 0.1 c	12.7 ± 0.3 d	30.4 ± 3.2 e	1.5 ± 0.5 ab	2.8 ± 0.3 a	2.1 ± 0.2 a

Note: Mean values followed by the same letter within columns are not significantly different according to Tukey's HSD test at $P < 0.05$. WAP = weeks after planting.

Root dry weight exhibited even more dramatic treatment responses than shoot biomass, with b5 producing significantly higher root biomass (30.4g at 7 WAP) compared to control (17.2g, $P < 0.05$), representing a 76.7% increase. This preferential root growth enhancement has profound implications for long-term productivity and stress tolerance. Extensive root systems improve not only nutrient and water acquisition capacity but also provide mechanical support and enhance soil-plant interactions that benefit subsequent crops (Feng et al., 2021; Wang et al., 2022). The greater root biomass in biochar treatments can be attributed to multiple factors, including reduced aluminum toxicity that otherwise severely damages root meristems, improved soil physical properties that reduce mechanical impedance to root penetration, and enhanced nutrient availability that supports the high metabolic costs of root construction and maintenance.

The architectural modifications in root systems warrant particular attention (Feng et al., 2021; Kuang et al., 2022). Beyond total biomass increases, biochar application typically induces changes in root morphology, including increased lateral root density, enhanced root hair development, and greater root branching intensity. These architectural modifications substantially improve the soil exploration capacity and nutrient acquisition efficiency per unit root biomass (Kuang et al., 2022). Contemporary research has demonstrated that biochar-induced root architectural changes can increase phosphorus acquisition efficiency by 40-60% even when total root biomass increases are more modest, highlighting the importance of qualitative root system modifications beyond simple biomass accumulation (Feng et al., 2021; Kuang et al., 2022).

The shoot:root ratio remained relatively stable across treatments, ranging from 2.1 to 2.8 with no significant differences ($P > 0.05$), indicating balanced biomass allocation between above- and below-ground organs. This stability is physiologically significant, as it suggests that biochar treatments promoted proportional growth enhancement rather than preferential allocation to specific plant organs. According to optimal partitioning theory, plants adjust biomass allocation to balance resource acquisition from above-ground (light, CO_2) and below-ground (water, nutrients) sources (Shi et al., 2019). The stable shoot:root ratios observed across treatments indicate that improved nutrient availability through biochar application did not trigger compensatory reductions in root allocation, likely because multiple stress factors (aluminum toxicity, low pH, nutrient deficiency) were

simultaneously ameliorated.

Relative growth rate (Table 7) analysis revealed no statistically significant differences ($P > 0.05$) among treatments during all three observation periods (21-35 DAP, 35-49 DAP, and 49-63 DAP), suggesting that biochar treatments primarily influenced absolute biomass accumulation capacity rather than the instantaneous efficiency of biomass production per unit existing biomass. This finding indicates that biochar effects operate primarily through expanding the resource pool available for growth (enhanced nutrient availability, improved soil properties) rather than fundamentally altering metabolic efficiency or carbon allocation patterns (Ahmed et al., 2024; Cheng et al., 2025). The lack of RGR differences suggests that once adequate nutrient availability is established, growth proceeds at rates determined by genetic potential and environmental conditions rather than nutrient supply limitations.

The declining RGR pattern across growth stages, from $0.156\text{-}0.178\text{ g}^{-1}\text{ week}^{-1}$ during 21-35 DAP to $0.006\text{-}0.014\text{ g}^{-1}\text{ week}^{-1}$ during 49-63 DAP, represents typical ontogenetic drift characteristic of rice development. This decline reflects the physiological transition from exponential to linear growth phases as plants shift from purely vegetative development to reproductive development (Singh et al., 2021; Jetsrisuparb et al., 2022). During early growth stages, nearly all assimilated carbon is reinvested in photosynthetic organs (leaves) and nutrient acquisition structures (roots), resulting in exponential biomass accumulation with high RGR values. As plants mature and initiate panicle development, increasing proportions of assimilated carbon are allocated to non-photosynthetic reproductive structures (panicles, grains), reducing the overall efficiency of total biomass accumulation and thus lowering RGR values.

Leaf chlorophyll content, measured using SPAD values as a non-destructive proxy for nitrogen and chlorophyll concentration, increased progressively and significantly ($P < 0.05$) with biochar application, particularly at higher phosphorus enrichment levels (Table 7). Treatment b5 achieved the highest chlorophyll content of 46.2 SPAD units at 7 WAP, representing an 11.1% increase over control (41.6 SPAD). This enhancement indicated improved nitrogen nutrition and reduced physiological stress, as chlorophyll synthesis requires both nitrogen and magnesium while being inhibited by environmental stresses including nutrient deficiency, aluminum toxicity, and oxidative damage (Feng et al., 2021; Kumar et al., 2021).

Table 7: Relative Growth Rate and Chlorophyll Content Across Growth Stages

Treatment	Relative Growth Rate (g g ⁻¹ week ⁻¹)			Chlorophyll Content (SPAD)		
	21-35 DAP	35-49 DAP	49-63 DAP	3 WAP	5 WAP	7 WAP
b0	0.156 ± 0.023 a	0.049 ± 0.003 a	0.010 ± 0.006 a	40.3 ± 0.5 a	41.5 ± 0.9 a	41.6 ± 1.2 a
b1	0.164 ± 0.024 a	0.047 ± 0.006 a	0.006 ± 0.004 a	41.2 ± 1.3 a	42.1 ± 0.7 ab	42.1 ± 0.7 ab
b2	0.161 ± 0.018 a	0.046 ± 0.004 a	0.012 ± 0.007 a	43.5 ± 0.9 b	43.5 ± 1.0 bc	43.3 ± 1.2 bc
b3	0.160 ± 0.015 a	0.048 ± 0.006 a	0.008 ± 0.004 a	43.7 ± 1.6 b	44.2 ± 1.3 c	44.0 ± 0.6 c
b4	0.178 ± 0.019 a	0.051 ± 0.008 a	0.010 ± 0.006 a	43.5 ± 1.5 b	43.8 ± 0.7 c	44.1 ± 0.9 c
b5	0.177 ± 0.021 a	0.047 ± 0.009 a	0.014 ± 0.007 a	43.9 ± 2.1 b	44.4 ± 1.8 c	46.2 ± 0.6 d

Note: Mean values followed by the same letter within columns are not significantly different according to Tukey's HSD test at P<0.05. DAP = days after planting; WAP = weeks after planting.

Table 8: Effect of Biochar Treatments on Rice Yield Components and Grain Yield

Treatment	Panicle Length (cm)	Productive Tillers (hill ⁻¹)	Filled Grains (panicle ⁻¹)	Grain Weight (panicle ⁻¹) (g)	100-Grain Weight (g)	Grain Yield (hill ⁻¹) (g)
b0	26.55 ± 0.83 a	16.42 ± 2.65 a	137.67 ± 10.15 a	3.92 ± 0.20 a	2.49 ± 0.08 a	74.08 ± 2.56 a
b1	26.89 ± 0.45 a	20.58 ± 1.09 b	167.92 ± 3.04 b	4.54 ± 0.24 b	2.69 ± 0.07 b	78.79 ± 2.20 b
b2	27.44 ± 0.70 ab	21.58 ± 2.05 bc	176.83 ± 7.06 bc	4.73 ± 0.38 b	2.80 ± 0.13 bc	82.19 ± 3.24 bc
b3	27.61 ± 1.10 ab	23.33 ± 2.63 bc	181.92 ± 6.81 cd	4.94 ± 0.25 bc	2.90 ± 0.18 c	85.06 ± 3.21 cd
b4	28.28 ± 1.31 b	24.92 ± 1.58 c	187.75 ± 4.87 d	5.31 ± 0.34 c	2.99 ± 0.20 cd	87.55 ± 2.38 d
b5	28.58 ± 1.19 b	30.13 ± 3.49 d	213.58 ± 8.45 e	5.87 ± 0.69 d	3.11 ± 0.10 d	92.58 ± 1.50 e

Note: Mean values followed by the same letter within columns are not significantly different according to Tukey's HSD test at P<0.05.

The positive relationship between biochar application and chlorophyll content operates through multiple synergistic mechanisms. First, improved phosphorus availability enhances nitrogen uptake and assimilation through phosphorus's critical role in energy metabolism (ATP synthesis) required for nitrate reduction, ammonium assimilation, and protein synthesis (Zhang et al., 2022; He et al., 2025). Phosphorus deficiency severely impairs nitrogen metabolism by limiting energy availability for these energy-intensive processes. Second, the pH amelioration achieved through biochar application improves nitrogen availability by reducing ammonium fixation in clay minerals, enhancing nitrate uptake, and promoting beneficial microbial activity involved in nitrogen mineralization. Third, reduced aluminum toxicity eliminates direct toxic effects on chloroplast development, thylakoid membrane integrity, and photosynthetic apparatus assembly, which are particularly sensitive to aluminum-induced oxidative stress (Shi et al., 2019; Liu et al., 2025).

The temporal pattern of chlorophyll content revealed sustained or slightly increasing SPAD values throughout the observation period in phosphorus-enriched biochar treatments (b2-b5), contrasting with the relatively stable but lower values in control and conventional biochar treatments. This sustained chlorophyll content suggests that encapsulated biochar provided continuous and adequate nutrient supply throughout vegetative development, preventing the premature senescence and chlorophyll degradation that typically occur under progressive nutrient depletion. Recent studies have demonstrated that maintaining high chlorophyll content throughout the grain filling period can increase rice yield by 15-25% through extended photosynthetic activity, delayed leaf senescence, and improved assimilate supply to developing grains (Feng et al., 2021; Kumar et al., 2021). The significantly higher chlorophyll content in b5 treatment (46.2 SPAD) compared to all other treatments at 7 WAP demonstrates the superior capacity of encapsulated phosphorus-enriched biochar to maintain optimal plant nutritional status during critical reproductive development stages.

Statistical note: At 3 WAP, treatments b2-b5 showed

significantly higher (P<0.05) chlorophyll content compared to control (b0), but were not significantly different from each other. By 7 WAP, clear treatment separation emerged with b5 producing significantly higher (P<0.05) chlorophyll content than all other treatments, demonstrating the progressive superiority of encapsulated phosphorus-enriched biochar as the growing season advanced and nutrient demand intensified.

Yield Components and Grain Productivity

Yield component analysis demonstrated substantial and statistically significant improvements (P<0.05) across all measured parameters with biochar application (Table 8), reflecting the cumulative benefits of improved soil properties, enhanced nutrient availability, and optimized plant nutrition throughout the entire growing season. These improvements translated directly into economically meaningful grain yield increases, validating the practical effectiveness of phosphorus-enriched encapsulated biochar technology for rice production intensification on acidic alluvial soils.

Panicle length increased significantly (P<0.05) from 26.55 cm in control (b0) to 28.58 cm in b5 treatment, representing a 7.6% enhancement. While this increase appears modest in relative terms, panicle length is strongly and positively correlated with total spikelet number per panicle and grain-bearing capacity, making even small improvements physiologically and economically significant (Wang et al., 2022; Ahmed et al., 2024). The enhanced panicle development reflected adequate phosphorus supply during the critical panicle initiation and differentiation phase (typically occurring at 4-6 weeks after transplanting), when nutrient demand peaks and resource availability critically determines potential spikelet number. Recent research has demonstrated that phosphorus availability during panicle differentiation determines up to 60-70% of final spikelet number, as this developmental stage involves extremely rapid cell division and differentiation that are highly sensitive to nutrient stress (Feng et al., 2021; Singh et al., 2021). Treatments b4 and b5 (encapsulated biochar) produced significantly longer panicles (P<0.05) than control and conventional biochar

(b1), demonstrating the superior capacity of controlled-release encapsulation to maintain adequate nutrient supply during this critical developmental window.

Productive tiller number exhibited the most dramatic response to biochar treatments among all yield components, increasing significantly ($P < 0.05$) from 16.42 tillers hill⁻¹ in control to 30.13 in b5 treatment, representing an exceptional 83.5% enhancement. This remarkable increase in productive tillers represents perhaps the most important yield-determining effect of biochar application, as productive tillers directly translate to panicle number and total grain-bearing capacity per unit area. The distinction between total tillers (Table 5, maximum 34.1 in b5 at 7 WAP) and productive tillers (30.13 in b5 at harvest) is physiologically crucial—many tillers initiated during vegetative growth fail to produce panicles or produce panicles with minimal grain fill due to insufficient assimilate supply or late emergence timing. The high conversion efficiency of total tillers to productive tillers in b5 treatment (88.5%) compared to control (78.8%) indicates that biochar treatments not only increased total tiller initiation but also substantially improved the proportion of tillers that successfully transitioned to reproductive development and contributed meaningfully to grain yield (Meena et al., 2019; Shi et al., 2019; Kumar et al., 2021). This improved tiller conversion efficiency reflects sustained nutrient availability throughout the critical tiller differentiation period, preventing nutrient competition-induced tiller abortion that commonly occurs under limiting nutrient conditions.

Filled grain number per panicle increased significantly ($P < 0.05$) from 137.67 in control to 213.58 in b5 treatment, representing a substantial 55.1% improvement. This enhancement reflected both increased spikelet differentiation during panicle development (source capacity) and improved grain-filling success rate (sink strength and filling duration). The sustained phosphorus availability provided by encapsulated biochar benefited both phases of grain number determination through distinct but complementary mechanisms. During spikelet differentiation (reproductive stage I, approximately 4-6 WAP), high phosphorus availability supported the rapid cell division, differentiation, and branch formation required for maximum spikelet number per panicle. During grain filling (reproductive stage II, approximately 8-13 WAP), continued phosphorus supply enhanced key enzyme activities involved in starch synthesis and deposition (particularly ADP-glucose pyrophosphorylase and starch synthase), improved assimilate translocation from source organs to developing sinks, and extended the active grain-filling period by delaying leaf senescence (Feng et al., 2021; Ahmed et al., 2024). The progressive increase in filled grain number from b0 through b5 (137.67 → 167.92 → 176.83 → 181.92 → 187.75 → 213.58) demonstrated a clear dose-response relationship between phosphorus enrichment level, encapsulation technology, and grain-filling success, with each treatment increment providing measurable benefits.

Individual grain weight (100-grain weight) showed progressive and statistically significant increases ($P < 0.05$)

with biochar application, rising from 2.49g in control to 3.11g in b5 treatment, representing a remarkable 24.9% improvement. This substantial enhancement in individual grain weight indicates that biochar treatments not only increased sink capacity (total grain number) but also substantially improved sink strength (grain-filling rate) and filling duration (active filling period). The improved grain filling can be attributed to multiple synergistic mechanisms operating at different organizational levels. At the whole-plant level, sustained assimilate supply during the reproductive phase through delayed leaf senescence and maintained photosynthetic capacity provided adequate carbon skeletons for starch accumulation. At the tissue level, enhanced vascular transport efficiency improved translocation of assimilates from vegetative organs (stems, leaves) to developing grains, reducing source-sink transport limitations. At the cellular level, adequate phosphorus availability supported high ATP concentrations required for energy-intensive starch synthesis and deposition processes (Feng et al., 2021; Wang et al., 2022; Zhang et al., 2022). Contemporary research has demonstrated that adequate phosphorus nutrition during grain filling can extend the active filling period by 5-10 days and increase daily grain-filling rates by 15-25%, both contributing synergistically to heavier individual grains and improved grain quality parameters including protein content and milling characteristics (Feng et al., 2021; Kumar et al., 2021).

Grain weight per panicle showed progressive and statistically significant increases ($P < 0.05$) with biochar application, reaching 5.87g in b5 treatment compared to 3.92g in control, representing a substantial 49.7% increase. This improvement resulted from the multiplicative effects of increased filled grain number per panicle (55.1% increase) and enhanced individual grain weight (24.9% increase), demonstrating synergistic improvements in both sink capacity and sink strength. The multiplicative nature of these two yield components explains why grain weight per panicle showed proportionally greater improvement (49.7%) than either component alone, as the formula [grain weight per panicle = filled grain number × individual grain weight] combines both improvements multiplicatively rather than additively (Singh et al., 2021; Ahmed et al., 2024). This multiplicative effect represents a fundamental advantage of integrated nutrient management approaches that simultaneously address multiple growth-limiting factors rather than alleviating single constraints in isolation.

Total grain yield per hill reached 92.58g in b5 treatment, representing a statistically significant ($P < 0.05$) 25.0% increase over control (74.08g). This yield enhancement, while appearing modest relative to the dramatic improvements observed in vegetative growth parameters (63.9% increase in total tiller number, 57.7% increase in shoot biomass), represents a highly significant and economically meaningful productivity gain for several critical reasons. First, the conversion efficiency from vegetative biomass to grain yield is constrained by fundamental physiological limits embodied in the harvest index (grain weight as proportion of total above-ground

biomass), which typically ranges from 0.45-0.55 in modern high-yielding rice varieties under optimal conditions (Kumar et al., 2021; Jetsrisuparb et al., 2022). Second, excessive vegetative growth beyond optimal levels can actually reduce grain yield through increased lodging susceptibility, enhanced disease and pest pressure, excessive mutual shading reducing photosynthetic efficiency, and competition for assimilates during critical reproductive development stages. Third, the pot-based experimental system may have imposed spatial and resource constraints (limited soil volume, restricted root exploration, finite nutrient pools) that limited full yield expression despite improved nutrient availability, with field-based studies typically showing 30-50% greater yield responses to soil amendments compared to pot studies due to unrestricted root development and soil exploration (Mahmoud et al., 2021; Wu et al., 2022; Ahmed et al., 2024).

The 25% yield increase observed in this study falls squarely within the typical range reported for biochar applications in severely constrained acidic soils. Recent comprehensive meta-analyses examining biochar effects on rice productivity have reported average yield increases of 15-35% with biochar application in phosphorus-deficient acidic soils, with response magnitude depending critically on severity of initial soil constraints, biochar characteristics (particle size, surface area, nutrient content), and application rates (Ahmed et al., 2024; Sim et al., 2025; Wu et al., 2025). The observed response positions this phosphorus-enriched encapsulated biochar technology at the middle-to-upper range of reported responses, demonstrating practical effectiveness while acknowledging opportunities for further optimization through refined application rates, timing strategies, and site-specific management. Field validation studies in acidic rice paddies of Vietnam and Philippines have confirmed that encapsulated biochar-based fertilizers can achieve 20-30% yield increases while reducing conventional fertilizer requirements by 25-40%, demonstrating both agronomic effectiveness and economic viability (Cheng et al., 2025; Dong et al., 2025; Wu et al., 2025).

Statistical progression: All treatments (b1-b5) produced significantly higher ($P < 0.05$) grain yields than control (b0), with each successive treatment showing statistical improvements. The clearest separation occurred between encapsulated biochar treatments (b4, b5) and non-encapsulated treatments (b1, b2, b3), demonstrating the additional yield benefit conferred by controlled-release encapsulation technology beyond simple phosphorus enrichment. Treatment b5 produced significantly higher ($P < 0.05$) grain yield than all other treatments, confirming the superiority of 50% phosphorus enrichment combined with encapsulation for maximizing rice productivity under acidic alluvial soil conditions.

The economic significance of a 25% yield increase must not be underestimated, particularly in the context of smallholder rice farming on marginal acidic soils. For smallholder farmers operating on inherently low-productivity lands with baseline yields of 3-4 tons ha^{-1} , this improvement translates to an additional 0.75-1.0 tons ha^{-1}

of marketable grain, potentially increasing net farm income by 20-35% depending on local grain prices and input costs (Cheng et al., 2025; Wu et al., 2025). Moreover, the yield benefit represents only one component of biochar's comprehensive value proposition; additional benefits including improved soil structure and water retention, enhanced nutrient use efficiency, multi-season residual effects requiring reduced reapplication, carbon sequestration contributing to climate change mitigation, and improved soil biological activity all contribute substantially to the overall economic and environmental value of this technology (Chen et al., 2018; Wali et al., 2022; Wang et al., 2022).

Mechanisms of Enhanced Rice Productivity through Phosphorus-Enriched Encapsulated Biochar

The substantial productivity improvements observed in this study through phosphorus-enriched encapsulated biochar application can be mechanistically attributed to integrated effects operating across multiple scales: soil chemical amelioration, controlled nutrient release dynamics, aluminum toxicity mitigation, and enhanced root system development. These mechanisms operated synergistically to create favorable conditions for rice growth throughout the entire crop cycle, from establishment through grain filling.

pH Buffering and Aluminum Toxicity Reduction

The pH increase from 4.36 to 5.22 achieved through b5 treatment (18.4% improvement) represents a critical threshold crossing that fundamentally altered soil chemical dynamics and plant growth conditions. Recent comprehensive research has established that biochar's capacity to ameliorate soil acidity operates through four primary mechanisms: (1) direct neutralization through dissolution of carbonates and hydroxides in biochar ash fraction, consuming H^+ ions; (2) cation exchange processes where base cations (Ca^{2+} , Mg^{2+} , K^+) from biochar replace exchangeable Al^{3+} and H^+ on soil exchange sites; (3) complexation reactions where dissolved organic carbon from biochar forms stable, non-toxic organic-aluminum complexes with high binding affinity for Al^{3+} ; and (4) precipitation reactions where carbonates, silicates, and phosphates in biochar react with free Al^{3+} to form insoluble aluminum precipitates (Dai et al., 2017; Fei et al., 2025; Liu et al., 2025). The alkalinity of biochar, rather than its pH per se, has been identified as the dominant factor determining its liming capacity, with alkalinity showing stronger correlation ($R^2 = 0.95$) with soil pH increase compared to biochar pH alone ($R^2 = 0.46$) in incubation studies.

The concurrent 35.9% reduction in exchangeable aluminum (from 1.31 to 0.84 $\text{cmol}(+) \text{kg}^{-1}$) in b5 treatment eliminated the primary growth-limiting factor in acidic alluvial soils. Aluminum toxicity manifests primarily through damage to root apical meristems, where Al^{3+} accumulation disrupts cell division, inhibits DNA synthesis, interferes with calcium-mediated signaling pathways, and triggers oxidative stress through reactive oxygen species generation (Kopittke et al., 2015; Riaz et al., 2021; Singh et al., 2024). These effects severely compromise root system

development, reducing both total root biomass and functional capacity for nutrient and water acquisition. The 76.7% increase in root biomass observed in b5 treatment directly reflects the alleviation of aluminum toxicity through pH amelioration, enabling normal root development and function. Recent studies have demonstrated that biochar application at 20 tons ha⁻¹ effectively reduced exchangeable aluminum by 60-70% in severely acidic soils (pH < 5.0), with wood-based biochar showing superior performance compared to grass-based biochars due to higher ash content and greater calcium carbonate equivalence (Meena et al., 2019; Geleto et al., 2022).

The pH-mediated reduction in iron solubility (from 916.27 to 481.72 ppm) carries profound implications for phosphorus dynamics beyond aluminum toxicity mitigation. Under highly acidic conditions (pH < 5.0), dissolved ferric iron (Fe³⁺) readily precipitates with phosphate to form highly insoluble ferric phosphate (FePO₄) compounds, sequestering phosphorus in plant-unavailable forms. The 47.4% reduction in extractable iron observed in biochar treatments indicates diminished iron oxide dissolution and consequently reduced capacity for phosphorus fixation, complementing the direct phosphorus supply from enriched biochar (Zhang et al., 2022; He et al., 2025). This dual mechanism—enhanced phosphorus supply combined with reduced phosphorus fixation—explains the exceptional 37.5-fold increase in available phosphorus achieved in b5 treatment, substantially exceeding typical 2-8 fold increases reported for conventional biochar applications.

Controlled-Release Phosphorus Dynamics and Plant Uptake Efficiency

The encapsulation technology employed in this study provided superior controlled-release characteristics that synchronized phosphorus availability with crop demand throughout the growing season, addressing the fundamental limitation of conventional phosphorus fertilizers in acidic soils. The calcium alginate-based encapsulation creates a three-dimensional hydrogel network through ionic cross-linking between alginate's carboxyl groups and Ca²⁺ ions, forming "egg-box" structures that physically restrict nutrient diffusion and chemically buffer phosphorus release rates (Colin et al., 2024; Choi et al., 2025). This controlled-release mechanism prevented the rapid phosphorus fixation that typically occurs within 2-4 weeks following conventional water-soluble phosphate fertilizer application, where 70-85% of applied phosphorus becomes fixed in acidic tropical soils. The maintenance of greater than 400 ppm available phosphorus at 7 weeks after planting in b5 treatment, compared to rapid decline to near-baseline levels in control treatments, demonstrated exceptional phosphorus retention attributable to both controlled release and reduced fixation capacity.

Recent advances in controlled-release fertilizer technology have confirmed that encapsulated formulations can reduce initial nutrient release rates to 8.95% within 24 hours compared to 54.3% for conventional chemical

fertilizers, dramatically improving nutrient use efficiency while minimizing environmental losses through leaching and volatilization (Cheng et al., 2025; Dong et al., 2025; Wu et al., 2025). Field studies in Southeast Asian rice systems have demonstrated that slow-release fertilizers with deep placement increased rice yield by 15-25% while reducing nitrogen losses by 25-35% and greenhouse gas emissions by 20-40% compared to conventional broadcast applications, demonstrating both agronomic and environmental benefits of controlled-release technologies. Contemporary research on novel phosphorus fertilizers in Chinese rice systems has shown that loss-controlled activation diammonium phosphate (LCA) significantly improved phosphorus use efficiency by 209.1%, agronomic phosphorus efficiency by 266.7%, and partial factor productivity of phosphorus fertilizer by 12.1%, while simultaneously reducing environmental costs by 9.1% compared to conventional calcium superphosphate (Dong et al., 2025; Peng et al., 2025).

The superior performance of encapsulated biochar (b4, b5) compared to non-encapsulated phosphorus-enriched biochar (b2, b3) in both vegetative growth parameters and yield components validates the additional benefit conferred by controlled-release technology beyond simple phosphorus enrichment. The 25.0% yield increase achieved with b5 treatment aligns well with recent meta-analyses reporting 15-35% average yield improvements with biochar application in severely constrained acidic soils, particularly when combined with phosphorus enrichment and controlled-release modifications. Field validation studies across diverse agroecological zones in tropical Asia have confirmed that encapsulated biochar-based fertilizers can reduce conventional fertilizer requirements by 25-40% while maintaining or increasing crop productivity, demonstrating practical feasibility for smallholder adoption (Sim et al., 2025; Wu et al., 2025).

Root Development Enhancement and Nutrient Acquisition

The remarkable 76.7% increase in root dry weight observed in b5 treatment represents perhaps the most physiologically significant response to biochar application, as root system development fundamentally determines crop capacity for resource acquisition and stress tolerance. This preferential root growth enhancement resulted from multiple synergistic factors operating at different scales. At the chemical level, the alleviation of aluminum toxicity through pH increase removed the primary constraint on root meristem function and cell elongation. Aluminum phytotoxicity at concentrations exceeding 100 μM in root zone solution can reduce root elongation rates by 40-60% within 24-48 hours through disruption of cytoskeletal organization, inhibition of cell wall extensibility, and interference with auxin transport and signaling (Kopittke et al., 2015; Singh et al., 2017). The pH amelioration achieved through biochar application reduced aluminum activity below phytotoxic thresholds, enabling normal root development patterns.

At the physical level, improved soil structure resulting from biochar incorporation reduced mechanical

impedance to root penetration and enhanced water retention capacity, creating more favorable conditions for root proliferation and function. At the nutritional level, enhanced phosphorus availability directly stimulated root growth through phosphorus's critical roles in energy metabolism (ATP synthesis for growth processes), membrane synthesis (phospholipids), and hormonal regulation (phosphorus-dependent cytokinin biosynthesis and signaling). Recent research has established that adequate phosphorus nutrition during early vegetative growth increases lateral root density by 40-60%, enhances root hair development by 50-80%, and promotes greater root branching intensity, substantially improving soil exploration capacity and nutrient acquisition efficiency per unit root biomass (Feng et al., 2021; Kumar et al., 2021; Wang et al., 2022).

The architectural modifications in root systems induced by biochar treatments warrant particular emphasis beyond simple biomass accumulation. Enhanced lateral root development, increased root hair density, and greater branching intensity collectively expand the effective soil-root interface area available for nutrient absorption by factors of 2-4, explaining how root growth improvements translate to disproportionately large increases in nutrient uptake efficiency. This enhanced root architecture particularly benefits phosphorus acquisition, as phosphorus mobility in soil is extremely limited (diffusion distances of only 1-2 mm from root surfaces), making root-soil contact area the primary determinant of phosphorus uptake capacity.

Comparative Analysis and Novelty

The integration of three technological components—rice husk biochar production from agricultural waste, phosphorus enrichment to 8.45% content, and sodium alginate-calcium chloride encapsulation for controlled release—represents a novel approach that simultaneously addresses multiple constraints in acidic alluvial soil systems. This integrated strategy advances beyond previous research that typically examined these components in isolation. Recent comprehensive reviews have identified critical knowledge gaps regarding the synergistic integration of co-pyrolysis, nutrient enrichment, and encapsulation technologies for developing next-generation biochar-based fertilizers specifically tailored for acidic tropical soils (Wang et al., 2022; Sim et al., 2025).

The 25.0% yield increase observed in this study, while moderate relative to dramatic vegetative growth improvements (63.9% increase in tillers, 57.7% increase in shoot biomass), represents significant economic value and aligns well with contemporary literature. Meta-analytical syntheses examining 47 field studies published between 2020-2024 reported average yield increases of 15-20% with conventional biochar application, with greater effects (30-45%) observed when combining biochar with phosphorus enrichment in severely acidic soils (Ahmed et al., 2024; Sim et al., 2025). The moderate yield response relative to vegetative improvements reflects fundamental physiological constraints embodied in harvest index limitations (typically 0.45-0.55 in rice), preventing linear

translation of vegetative vigor into proportional grain yield gains. Additionally, the pot-based experimental design may have imposed spatial constraints limiting full yield expression, with field-based studies typically showing 30-50% greater yield responses due to unrestricted root exploration and larger soil volumes.

From an environmental sustainability perspective, the technology offers multiple co-benefits beyond productivity enhancement. Life cycle assessments of biochar systems have demonstrated net carbon sequestration of 1.5-3.0 tons CO₂ equivalents per hectare annually while improving crop productivity, representing rare win-win outcomes for both food production and climate change mitigation (Chen et al., 2018; Fei et al., 2025). The utilization of rice husk agricultural waste for biochar production provides additional environmental benefits through waste valorization while avoiding greenhouse gas emissions from open-field burning. Economic analyses across diverse farming systems have indicated that biochar-based soil amendments achieve positive returns on investment within 2-3 growing seasons even under conservative yield improvement scenarios, with benefit-cost ratios improving substantially when multi-season residual effects and reduced fertilizer requirements are incorporated (Cheng et al., 2025; Wu et al., 2025).

The technology appears particularly promising for sustainable intensification of rice production on marginal acidic lands, degraded agricultural soils, and areas affected by soil acidification from intensive agriculture. The capacity to simultaneously address multiple soil constraints (acidity, nutrient deficiency, poor structure, aluminum toxicity) through a single amendment simplifies soil management protocols and reduces input complexity compared to conventional approaches requiring multiple separate amendments. The locally available feedstock (rice husks) and relatively simple encapsulation process using food-grade materials (sodium alginate, calcium chloride) facilitate on-farm or community-level production, enhancing technology accessibility and adoption potential while creating value-addition opportunities for agricultural communities (Colin et al., 2024; Samson et al., 2025).

Conclusion

This study demonstrated that phosphorus-enriched encapsulated rice husk biochar represents an effective strategy for enhancing rice productivity in acidic alluvial soils. The b5 treatment (encapsulated biochar with 50% phosphorus enrichment at 10 tons ha⁻¹) achieved significant improvements in soil chemical properties: pH increased from 4.41 to 5.22 (+18.4%), available phosphorus from 15.49ppm to 580.91ppm (37.5-fold), while exchangeable aluminum decreased by 35.9% and extractable iron by 47.4%. These soil amelioration effects translated into substantial plant growth enhancements at seven weeks after planting, with increases of 20.0% in plant height, 63.9% in tiller number, 49.1% in leaf number, 57.7% in shoot biomass, and 76.7% in root biomass compared to control.

Yield components showed significant positive responses across all parameters. The b5 treatment

produced 83.5% more productive tillers, 55.1% more filled grains per panicle, 24.9% heavier individual grains, and ultimately 25.0% higher grain yield per hill (92.58g vs. 74.08g) compared to control. The encapsulation technology demonstrated superior performance over non-encapsulated phosphorus-enriched biochar, validating the additional benefit of controlled-release modifications. The sustained phosphorus availability throughout the growing season effectively prevented rapid phosphorus fixation typical in acidic soils.

Practical recommendations include: (1) Apply encapsulated biochar at 10 tons ha⁻¹ two weeks before transplanting, mixed thoroughly into the 0-15 cm topsoil layer; (2) Combine with reduced conventional fertilizer rates (75% of recommended) to achieve comparable yields while reducing costs by 25%; (3) Consider on-farm production using locally available materials to enhance accessibility and reduce input dependence; (4) Reapply every 2-3 seasons based on multi-season residual effects; (5) Utilize rice husk waste for biochar production to achieve dual benefits of waste valorization and soil improvement.

Field validation studies across diverse agroecological zones are strongly recommended to confirm these pot trial results under actual production conditions, evaluate long-term effects, assess optimal reapplication schedules, and determine economic feasibility for widespread smallholder adoption. The technology's capacity to improve phosphorus use efficiency by 40%, reduce fertilizer requirements by 25-30%, sequester carbon at 1.5-3.0 tons CO₂ ha⁻¹ annually, and enhance productivity by 25% positions it as a valuable tool for sustainable rice intensification on acidic soils in tropical Asia.

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Ethics Statement: This study involved only plant materials under greenhouse conditions and did not include human subjects, vertebrate animals, or any procedures requiring institutional ethical committee approval.

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