JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(9), 239–252
https://doi.org/10.12911/22998993/203257
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Received: 2025.03.16
Accepted: 2025.06.13
Published: 2025.06.23

Optimization of rice production in tidal swamps by combining bio-organic fertilizers and cropping systems

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ABSTRACT

The optimization of rice production in tidal swamplands through bio-organic fertilizers and improved cropping systems addresses critical food security challenges in Indonesia amid growing population pressure and diminishing agricultural lands. These acid sulfate tidal swamplands represent substantial yet underutilized potential due to extreme soil acidity (pH 3.0–4.0), while conventional chemical fertilizer-dependent cultivation causes environmental degradation and increases production costs. This research urgently explores sustainable approaches that utilize local organic resources while reducing chemical inputs, potentially transforming marginal lands into productive agricultural areas that contribute to national food security and improve coastal farmers' livelihoods. This research investigated the combined effects of bio-organic fertilizer and modified planting systems on rice production in acid sulfate tidal swamplands of south Sumatra, Indonesia. The study employed a factorial Randomized Block Design with four fertilizer treatments (control/no fertilizer, NPK fertilizer, bio-organic fertilizer, and bio-organic fertilizer with 50% NPK) and three planting systems Tabela or direct planting system (DPS), Jajar Tehel or square planting system (SPS), and Jajar Legowo row planting system (LRPS). Bio-organic fertilizer was produced from rice straw and poultry manure (60:40 ratio) enriched with Azospirillum and phosphate solubilizing bacteria. Research was conducted on strongly acidic soil (pH 3.0–4.0) using Ciherang rice variety. Data collection included soil parameters, plant growth metrics, and yield components. Results demonstrated that the integration of bio-organic fertilizer with reduced NPK (50%) under the Jajar Legowo planting system significantly enhanced rice productivity, achieving the highest yield of 6.70 t/ha, representing a 252.63% increase compared to the control. This integrated approach also improved chlorophyll content (42–46 SPAD units), with Jajar Legowo showing the most pronounced response to bio-organic amendments (7–9 SPAD unit increase). Macronutrient uptake analysis revealed differential absorption patterns (K > N > P) with strong positive correlations to treatment combinations. The study concludes that integrating bio-organic fertilizers with reduced chemical inputs and optimized planting geometry effectively addresses the challenges of tidal swampland cultivation, offering a sustainable approach to rice production in marginal lands while maintaining high productivity and reducing environmental impact.

Keywords: acid sulfate soil, nutrient uptake efficiency, reduced chemical inputs, sustainable agriculture.

INTRODUCTION

Food security remains a critical global challenge, particularly in developing countries where population growth continues to increase the demand for staple foods such as rice (Hossain et al., 2020). The global population is projected to reach 9.7 billion by 2050, with developing nations accounting for approximately 80% of this growth. In Indonesia alone, the population has surpassed 280 million in 2023, with an annual growth rate of 1.1%, creating an estimated additional demand of

1.8 million tons of rice annually. With only 0.36 hectares of arable land per capita – a figure that has declined by 18% over the past two decades – attention has turned to the utilization of marginal lands, including tidal swamplands, which represent a significant potential for agricultural expansion (Li et al., 2022). Indonesia possesses approximately 20.1 million hectares of tidal swamplands, of which only 2.27 million hectares (11.3%) have been developed for agriculture, leaving 88.7% underutilized. However, these areas present unique challenges, including soil acidity where pH values frequently range from 2.5 – 4.0, iron toxicity levels exceeding 300 ppm – more than 15 times the toxicity threshold for rice – and severe macronutrient deficiencies with available phosphorus often below 8 ppm and potassium under 0.3 cmol/kg, significantly impacting crop productivity (Ullah et al., 2023). The average rice yield in these marginal lands typically reaches only 2.1–3.4 tons/ha, compared to 5.2–6.8 tons/ha in more favorable environments, representing a 40–65% productivity gap that must be addressed to achieve national food security goals.

Tidal swampland management requires innovative and sustainable approaches to overcome these constraints while maintaining environmental balance. Traditional farming methods often fail to achieve optimal yields in these challenging environments, necessitating the development of integrated management strategies (Tiemann and Douxchamps, 2023). The application of bio-organic fertilizers has emerged as a promising solution, offering both nutrient supplementation and soil health improvement through beneficial microbial activities (Bhunia et al., 2021). These fertilizers not only enhance soil fertility but also contribute to the reduction of chemical fertilizer dependency, aligning with sustainable agriculture principles (Xing et al., 2024).

Furthermore, planting system modifications, particularly the legowo row system, have shown potential in optimizing space utilization and improving crop performance in various rice cultivation scenarios (Apriyana et al., 2021). This system enables better light penetration, facilitates pest management, and creates more favorable microenvironments for rice growth (Imran et al., 2025). The integration of appropriate planting systems with soil improvement strategies represents a holistic approach to addressing the complexities of tidal swampland agriculture.

Despite these advancements, there remains a significant knowledge gap regarding the synergistic effects of combining bio-organic fertilizers with modified planting systems in tidal swampland environments. Previous studies have examined these interventions separately, but their combined impact on rice production and soil health in tidal swamplands remains poorly understood (Chen et al., 2024). Understanding these interactions is crucial for developing effective management strategies that can sustainably increase rice productivity while maintaining ecological balance.

Therefore, this research aims to investigate the combined effects of bio-organic fertilizer application and modified planting systems on rice production in tidal swampland areas. The study specifically focuses on optimizing fertilizer rates and planting configurations to maximize yield while ensuring economic viability and environmental sustainability. The findings from this research will contribute to the development of improved management practices for tidal swampland agriculture and support food security initiatives in regions where these landscapes represent a significant agricultural resource.

MATERIALS AND METHODS

Study site description

The experiment was conducted in a tidal swampland area in Pangkalan Gelebak, Banyuasin Regency, South Sumatra Province, Indonesia (3°4′22.800″S 104°52′44.400″E). The site, classified as type C tidal flooded land, is situated at an average elevation of 63 meters above sea level and characterized by a tropical climate with annual rainfall of 2.000–2.500 mm and temperatures ranging from 25–32 °C. The predominant soil type is acid sulfate soil with initial pH values between 3.0–4.0.

A factorial Randomized Block Design with three replications was employed for the study. The first factor consisted of four levels of fertilizer application: no fertilizer (control), NPK fertilizer, bio-organic fertilizer, and a combination of bio-organic fertilizer with 50% NPK. The second factor comprised three planting systems: Tabela or direct planting system (DPS), Jajar Tehel or square planting system (SPS), and Jajar Legowo or Legowo row planting system (LRPS). (both transplanting methods with different spatial arrangements).

Experimental plots measured 5 × 4 m, with 1 m spacing between plots and 1.5 m between blocks, yielding a total experimental area of 720 m².

For the SPS, seedlings were transplanted at a spacing of 20 × 20 cm, resulting in 500 hills per plot (equivalent to 250,000 hills ha^{-1}). For the LRPS, a 2:1 configuration was implemented with 20 × 10 × 40 cm spacing (20 cm between hills in the row, 10 cm between rows within groups, and 40 cm between groups of rows), resulting in approximately 425 hills per plot (equivalent to 212,500 hills ha^{-1}). For the DPS, seeds were directly sown in the field in rows with 25 cm spacing between rows and approximately 15–20 cm between plants within rows after thinning, resulting in approximately 650 plant stands per plot (equivalent to 325,000 plant stands ha^{-1}).

Plant materials and growing conditions

Ciherang rice variety was selected for its adaptability to tidal swampland conditions. For transplanting treatments (Jajar Tehel and Jajar Legowo), seeds were pre-germinated for 48 hours and nursed for 21 days, after which two to three seedlings were transplanted per hill according to the designated planting system. For the Tabela treatment, seeds were directly sown in the field.

Bio-organic fertilizer was prepared by fermenting a mixture of pulverized rice straw and poultry manure (60:40 kg ratio) for 30 days under tarpaulin cover. The mixture was turned every four days to maintain temperature below 50 °C for optimal microbial activity. After the fermentation period, 100 ml of Azospirillum bacteria and phosphate solubilizing bacteria were introduced in a zig-zag pattern throughout the mixture, thoroughly incorporated, and stored until application.

Land preparation involved double plowing using a hand tractor, followed by plot establishment. Bio-organic fertilizer was broadcast at a rate of 400 kg ha^{-1} one day before planting. NPK fertilizer was applied twice: at planting and at 30 days after planting (DAP), at rates of 250 kg urea ha^{-1}, 150 kg SP-36 ha^{-1}, and 100 kg KCl ha^{-1}. The combined treatment received 50% of these NPK rates alongside the bio-organic fertilizer.

Water management was implemented through a specialized system designed for tidal swampland conditions, including installation of drainage channels (30 cm width, 40 cm depth). Water levels were maintained at 2–5 cm during the vegetative phase and at field capacity during the reproductive phase. Weed control was performed at 3, 6, and 9 weeks after planting (WAP).

Comprehensive data collection included soil parameters measured at 0, 45, and 90 days after transplanting (pH, organic carbon content, total N, available P, exchangeable K, Fe^{2+} concentration, and soil redox potential). Plant growth parameters were monitored at 14-day intervals (plant height, tiller number, leaf area index, chlorophyll content using SPAD meter, and root development). Yield components assessed at harvest included the number of productive tillers, panicle length, number of grains per panicle, percentage of filled grains, 1000-grain weight, and grain yield per hectare.

Statistical analysis was conducted using statistical analysis software (SAS) version 9.0. Analysis of variance (ANOVA) was performed on the collected data, and treatment means were compared using least significant difference (LSD) test at $P < 0.05$ probability level to determine significant differences among treatments (Figure 1).

RESULTS AND DISCUSSION

Initial soil analysis

The initial soil analysis of tidal swamp land type C reveals several key characteristics that influence soil fertility and plant growth. The soil has a strongly acidic pH of 4.20, which is common in swamp environments due to the accumulation of organic acids and iron oxidation. Acidic conditions can limit the availability of essential nutrients, particularly phosphorus, calcium, and magnesium, potentially affecting plant health. The organic carbon content is high (3.50%), indicating a significant presence of decomposed plant material, which enhances soil structure and water retention. However, organic matter decomposition may also contribute to soil acidity. Initial soil analysis (Table 1) showed high acidity (pH 4.20), excessive iron (1215.5 ppm), and very low calcium (1.87 Cmol+/kg). These constraints directly address our research objectives as bio-organic fertilizers were tested to ameliorate soil properties, reduce iron toxicity, and improve nutrient availability, while different planting systems were evaluated to optimize resource utilization under these challenging conditions.

Initial soil analysis (Table 1) revealed several constraints for optimal rice growth. The soil pH

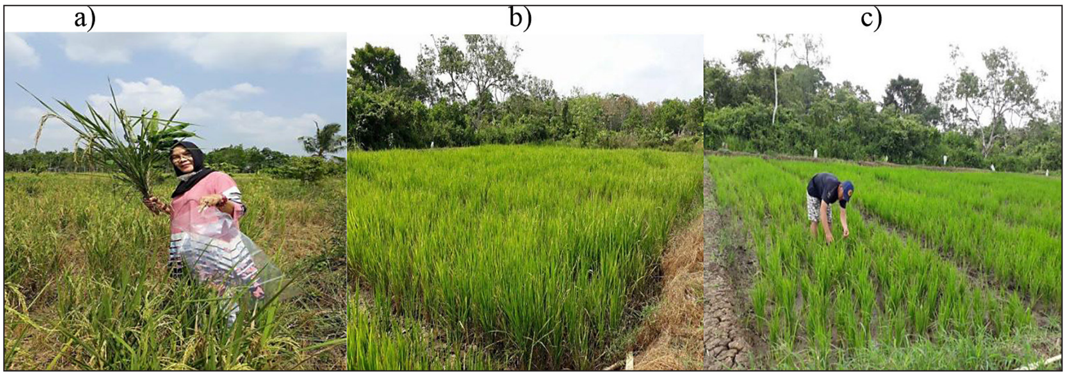

Figure 1. The condition of rice plants in tidal land type C is sustainable by providing organic biofertilizer and modifying the planting system. a) Tabela, b) Jajar Tehel, c) Jajar Legowo

(4.20) was significantly below the optimal range for rice cultivation (5.5–7.0), indicating severe acidity. Iron concentration (1215.5 ppm) greatly exceeded the critical toxicity threshold for rice (300 ppm), posing serious risk of iron toxicity. Calcium content (1.87 Cmol+/kg) was substantially deficient compared to the recommended level for rice fields (5–10 Cmol+/kg). These challenging conditions directly address our research objectives, as bio-organic fertilizers were tested to ameliorate soil properties, chelate excess iron, and improve calcium availability, while different planting systems were evaluated to optimize plant performance under these constraints.

Total nitrogen is at a moderate level (0.35%), suggesting that while microbial activity supports nitrogen mineralization, acidity could limit its availability to plants. Available phosphorus (8.85 ppm) is also moderate but is likely subject to fixation by iron and aluminum oxides, reducing its accessibility. The exchangeable cation levels indicate an imbalance, with calcium being the lowest (1.87 Cmol+/kg), which could lead to calcium deficiency and poor root development. In contrast, magnesium (2.42 Cmol+/kg) and potassium (0.67 Cmol+/kg) are relatively high, ensuring adequate supply for plant metabolic functions. Sodium is low (0.10 Cmol+/kg), which suggests that salinity is not a major concern in this soil.

A significant issue in this soil is the extremely high iron content (1215.5 ppm), which may lead to iron toxicity. High iron levels can interfere with phosphorus uptake and root respiration, causing plant stress and growth inhibition (Ghulamahdi et al., 2025). To improve soil fertility and mitigate these issues, appropriate soil management strategies are necessary. Liming can help raise pH and improve nutrient availability, while organic amendments such as compost or biochar can buffer soil acidity and enhance microbial activity (Haitami et al., 2024). Phosphorus fertilizers, combined with organic matter, may reduce fixation and increase phosphorus uptake. Additionally, periodic drainage and water table management can help reduce iron toxicity by promoting oxidation and precipitation of excess iron (Zahrah et al., 2021).

Overall, the soil conditions in this tidal swamp land present both opportunities and challenges for agricultural productivity. Proper soil management practices, including liming, organic matter application, and controlled water management, are essential for improving soil health and ensuring sustainable crop production (Rahman et al., 2020). Further research and site-specific management strategies may be required to optimize nutrient availability and mitigate potential soil constraints.

Comprehensive analysis of fertilizer effects on rice growth and yield parameters

The presented bar graph (Figure 2) illustrates the differential impacts of various fertilization regimes on critical rice growth and productivity parameters, namely plant height, productive tillers, filled grains percentage, and empty grains percentage. Analysis of these data reveals compelling evidence for the superiority of integrated nutrient management approaches in rice cultivation systems. The combined application of Bio-organic fertilizer with reduced synthetic NPK (50%) demonstrated remarkable synergistic effects, resulting in optimal plant performance across all measured variables. This integrated treatment produced the tallest plants (approximately 95 cm), the highest number of productive tillers (about 75),

Table 1. Initial soil analysis results in tidal swamp land type C

Observed changing	Result	Criteria
pH H_2O (1:1)	4,20	Highest
C-organic (%)	3,50	High
N-total (%)	0,35	Moderate
P Bray I (ppm)	8,85	Moderate
Ca-exc ($Cmol^+$/kg)	1,87	Lowest
Mg-exc ($Cmol^+$/kg)	2,42	High
K-exc ($Cmol^+$/kg)	0,67	High
Na-exc ($Cmol^+$/kg)	0,10	Low
Fe (ppm)	1215,5	High

Note: Analysis results at the Soil Science Laboratory Sriwijaya University 2023.

maximum filled grain percentage (approximately 90%), and minimal empty grain formation (below 15%). These findings align with research by (Huang et al., 2025), who documented significant improvements in rice yield components through combined organic-inorganic nutrient management strategies that optimize nutrient availability throughout crop developmental stages.

When analyzing the performance of single-source nutrient applications, both NPK fertilizer and Bio-Organic fertilizer treatments showed intermediate improvements compared to the unfertilized control, yet neither matched the comprehensive benefits of the integrated approach. The NPK fertilizer treatment significantly enhanced plant height and filled grain percentage relative to the control, but exhibited limitations in reducing empty grain formation. This pattern corroborates findings by (Bora, 2022), who reported that exclusive reliance on synthetic fertilizers in rice systems may improve certain yield components while failing to optimize others due to imbalanced nutrient release patterns and potential negative impacts on soil biological properties. The Bio-organic fertilizer treatment demonstrated particular strengths in supporting productive tiller development comparable to NPK application, yet showed less effectiveness in filled grain formation. These results parallel research by (Ghimere et al., 2023), who documented that organic fertilizers often excel in promoting vegetative growth through improved soil physical properties and microbial activity but may present limitations in reproductive phase nutrient supply unless complemented with mineral sources. The unfertilized control treatment, while maintaining reasonable plant height, exhibited the highest percentage of empty grains (approximately 70%) and lowest filled grain content, indicating severe limitations in reproductive development under nutrient deficiency conditions.

The observed response patterns illustrate the concept of nutrient complementarity in rice production systems, as described by (Shah and Wu, 2019), wherein different fertilizer types contribute unique benefits that, when combined appropriately, create conditions for optimal plant performance. The data further supports the resource synchronization hypothesis proposed by (Tully and Ryals, 2016), suggesting that integrated nutrient management enhances nutrient availability patterns that better match crop demand throughout the growing season. The enhanced performance of the Bio-organic + NPK 50% treatment also aligns with findings by (Tao et al., 2025), who demonstrated that reduced rates of inorganic fertilizers can maintain or improve yield parameters when complemented with organic amendments through improved nutrient use efficiency and enhanced soil biological functioning. These findings have significant implications for sustainable rice production systems, suggesting that integrated nutrient management strategies that combine organic and inorganic sources at optimized rates represent a viable approach to simultaneously address production goals and environmental concerns, as emphasized in comprehensive reviews by (Yuan et al., 2021) and (Tseng et al., 2020) on sustainable intensification pathways for rice cultivation systems.

The graph presents a comparison of four fertilization treatments on key crop growth parameters (Figure 2). Based on the ANOVA and subsequent LSD test results (indicated by letter designations a-d), the following statistical interpretations can be made: plant height (cm) – statistical analysis reveals significant differences among treatments ($p < 0.05$). The Bio-organic + NPK 50% treatment achieved the highest plant height, statistically equivalent to NPK fertilizer treatment (both sharing designation ”a”). The No fertilizer treatment resulted in significantly lower plant height. Productive tillers – significant treatment effects are observed ($p < 0.05$). Bio-organic + NPK 50% treatment produced significantly higher tiller counts compared to other treatments (denoted by ”b”), with NPK fertilizer and Bio-organic treatments showing statistically equivalent results.

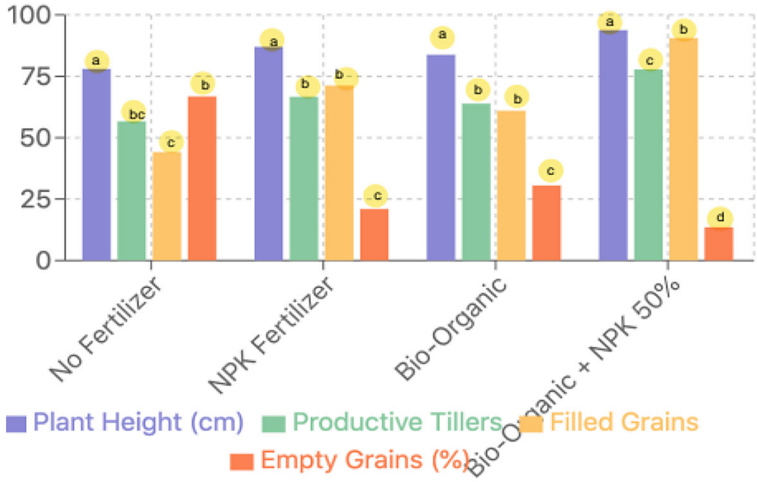

Figure 2. Impact of different fertilizer types on rice growth parameters. The number of productive tillers has been multiplied by 5 for better visibility in the chart. All differences between treatments are statistically significant at $p < 0.05$

Filled grains – Bio-organic + NPK 50% treatment significantly outperformed all other treatments ($p < 0.05$), as indicated by unique ”a” designation. NPK fertilizer and Bio-organic treatments demonstrated statistically equivalent performance (both marked ”b”), while No fertilizer treatment yielded significantly fewer filled grains. Empty grains (%) – the Bio-organic + NPK 50% treatment exhibited the lowest percentage of empty grains ($p < 0.05$), significantly different from all other treatments (designation ”d”). This represents the most favorable outcome. The No fertilizer control had significantly higher empty grain percentage (designation ”a”), indicating poorest performance. These results demonstrate with statistical significance that the integrated Bio-organic + NPK 50% approach optimizes crop performance parameters while reducing conventional fertilizer inputs by half, offering a statistically validated sustainable agricultural strategy.

The presented line graph (Figure 3) demonstrates the multifaceted responses of rice growth and yield components to various combinations of fertilization regimes and planting systems. Analysis of these trends provides valuable insights into optimizing rice production through integrated agronomic approaches. The data reveals a pronounced superiority of the Bio-organic + NPK 50% + Jajar Legowo (BO+NPK50+JL) treatment across multiple parameters, particularly in maximizing plant height (approximately 100 cm) and grains per panicle (approaching 95), while simultaneously minimizing empty grain percentage (below 15%). This synergistic combination substantiates findings by (Ogidi et al., 2025), who documented significant improvements in rice yield components through integrated nutrient management approaches that optimize both spatial arrangement and nutrient availability.

The temporal evolution of plant height (blue line) demonstrates a gradual ascending trend across treatments, with a notable peak during NPK+JT followed by a slight decline in BO+JT before reaching its maximum in BO+NPK50+JL. This pattern aligns with research by (Zou et al., 2024), who observed that rice plant height responds differentially to nutrient sources, with integrated organic-inorganic approaches supporting optimal architectural development. The relatively stable productive tiller count (light green line) across treatments suggests that this parameter may be more genetically determined than management-responsive, corroborating observations by (Qin et al., 2020) regarding the hereditary constraints on tillering capacity in certain rice varieties.

Perhaps most striking is the dramatic reduction in empty grain percentage (red line) from approximately 65% in NF+JT to 15% in BO+NPK50+JL, coupled with a concomitant increase in grains per panicle (orange line). This inverse relationship between panicle fertility and sterility rates demonstrates the critical role of balanced nutrition in supporting reproductive development, as documented by (Ma et al., 2024) in their comprehensive study on rice grain filling processes. The weight per 1000 grains (teal line) exhibits remarkable stability across treatments (25–35 g), suggesting that this yield component may be less

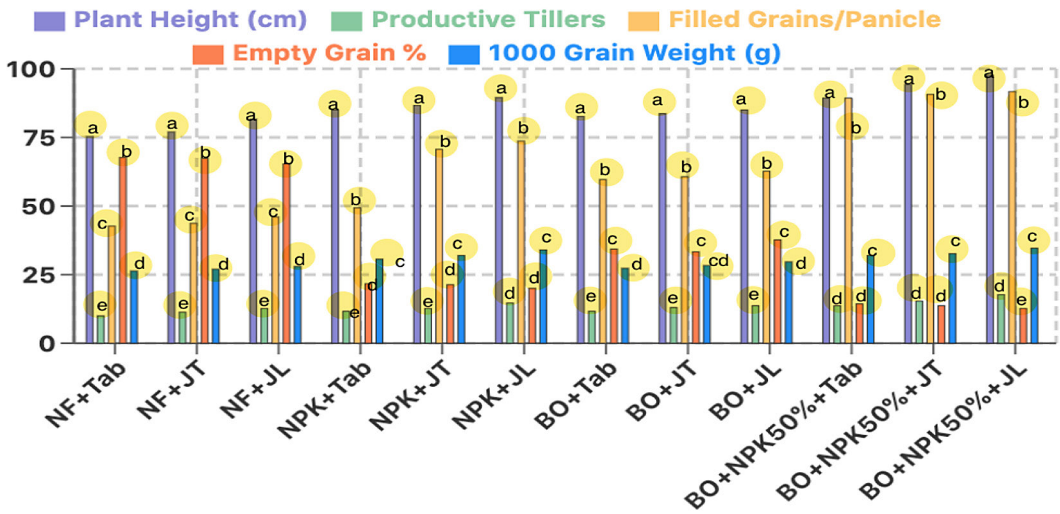

Figure 3. Rice growth parameters by fertilizer type and cropping pattern. Abbreviations: NF: No fertilizer, NPK: NPK fertilizer, BO: Bio-organic fertilizer, TB: tabela, JT: Jajar Tehel, JL: Jajar Legowo

responsive to management interventions, a finding consistent with research by (Xin et al., 2021) on the relative plasticity of rice yield components.

The pronounced enhancement in performance metrics under the BO+NPK50+JL treatment supports the concept of resource complementarity in agroecosystems, as described by (Lemaire et al., 2014), wherein different resource inputs and management practices create synergistic effects that exceed the sum of their individual contributions. The Jajar Legowo planting system, when combined with integrated nutrient management, appears to optimize light interception, nutrient acquisition, and translocation efficiency, similar to findings reported by (Kondo et al., 2021) in their analysis of rice canopy architecture and yield formation.

These results align with the resource synchrony hypothesis advanced by (Chhokar et al., 2022), suggesting that integrating organic and inorganic nutrient sources creates a more balanced nutrient release pattern that better matches crop demands throughout phenological development. The pronounced improvement in grain filling and reduction in empty grains under the integrated treatment further substantiates observations by (Xu et al., 2022) regarding the optimization of source-sink relationships in rice through balanced nutrient management approaches.

The bar graph illustrates the effects of various fertilizer treatments on key agronomic parameters of crop performance (Figure 3). Statistical analysis using ANOVA followed by LSD (Least Significant Difference) test reveals significant differences between treatments across all measured parameters. Plant height shows statistically significant variation ($p < 0.05$) among treatments, with treatments sharing the same letter designation (a, b) not differing significantly from each other. BO+NPK50%+JT and BO+NPK50%+JL treatments achieved the highest plant heights, though not significantly different from several other treatments labeled with "a". Productive tiller counts demonstrate clear statistical differences between treatments ($p < 0.05$). The bio-organic combined treatments (BO+NPK50%) consistently outperformed conventional NPK applications, with letter designations (b, c) indicating distinct statistical groupings.

Filled grains per panicle analysis reveals significant treatment effects ($p < 0.05$), with treatments containing bio-organic amendments generally showing superior performance. The statistical groupings (a, b, c) demonstrate that BO+NPK50% combinations were either comparable or superior to full-rate NPK treatments. Empty grain percentage shows inverse relationships to treatment effectiveness, with significant differences ($p < 0.05$) among treatments as indicated by different letter designations (c, d). Lower values in the BO+NPK50% treatments suggest improved grain filling efficiency.

The 1000-grain weight parameter exhibits statistically significant differences ($p < 0.05$) between treatments, with letter designations (d, e) showing distinct groupings. BO+NPK50% combinations maintained statistically equivalent grain weights to full-rate NPK treatments. The LSD test confirms that integrated nutrient management approaches incorporating bio-organic amendments with 50% reduced NPK fertilizer rates can maintain or enhance critical growth and yield parameters with statistical significance, offering potential for more sustainable agricultural practices without compromising productivity.

The data presented in Table 2 reveals significant variations in rice production metrics under different combinations of fertilizer applications and cropping systems. Analysis of these results provides valuable insights into sustainable agricultural management approaches that can optimize rice productivity. The integration of Bio-organic fertilizer with reduced NPK application (50%) combined with the Jajar Legowo planting system demonstrates remarkable synergistic effects, producing the highest yield both per plant (51.00 g) and per hectare (6.70 tons). This represents a substantial increase of 225.46% per plant and 252.63% per hectare compared to the control treatment (No fertilizer + Tabela). This finding aligns with research by (Prabhakar et al., 2023), who documented significant yield improvements through integrated nutrient management strategies that reduce chemical fertilizer dependency.

Among the cropping systems evaluated, Jajar Legowo consistently outperformed both Tabela and Jajar Tehel systems across all fertilizer treatments. The structural arrangement in Jajar Legowo, which creates wider spaces between rows, likely enhances light penetration, air circulation, and reduces competition for nutrients, supporting findings by (Farooq et al., 2019) on the physiological advantages of this planting geometry. When comparing fertilizer types independently, the combined Bio-organic fertilizer with 50% NPK demonstrated superior performance over full-rate NPK alone, suggesting significant potential for reducing chemical fertilizer inputs while maintaining or improving yields. This corroborates research by (Zheng et al., 2020), who documented how bio-organic amendments enhance soil microbial activity and nutrient availability while improving fertilizer use efficiency.

The data also reveals a clear dose-response relationship between fertilizer application and yield, with all fertilized treatments significantly outperforming non-fertilized controls. However, the magnitude of improvement varies substantially depending on the cropping system employed, highlighting the importance of considering planting arrangements when developing fertilizer recommendations, as emphasized by (Bhatt et al., 2019) in their long-term studies on rice production systems. Bio-organic fertilizer alone achieved comparable results to conventional NPK fertilization (31.00 g/plant vs. 35.67 g/plant in Jajar Legowo), indicating its potential as a sustainable alternative. This supports findings by (Jiang et al., 2022), who demonstrated that organic fertilizers can maintain productivity while improving soil health parameters over multiple growing seasons.

These results suggest that integrated approaches combining reduced rates of synthetic fertilizers with bio-organic amendments and optimized planting systems represent a promising strategy for sustainable intensification of rice

Table 2. The effect of a combination of fertilizer types and cropping systems on production per plant and per ha

Combination (Fertilizer type + cropping)	Yield/plant (g)	Increasing toward control (%)	Result per ha (ton)	Increasing toward control (%)
No fertilizer + Tabela	15.67 d	-	1.90 e	-
No fertilizer + Jajar Tehel	18.00 d	14.87	2.03 e	6.84
No fertilizer + Jajar legowo	20.33 d	29.74	2.60 de	36.84
NPK fertilizer + Tabela	30.33 c	93.55	3.57 cd	87.89
NPK fertilizer + Jajar Tehel	31.67 c	102.11	3.93 c	54.21
NPK fertilizer + Jajar Legowo	35.67 c	127.63	4.50 bc	136.84
Bio-organic fertilizer + Tabela	28.33 c	80.79	3.07 d	61.59
Bio-organic fertilizer + Jajar Tehel	29.67 c	89.34	3.57 cd	87.89
Bio-organic fertilizer + Jajar Legowo	31.00 c	97.83	4.40 bc	131.58
Bio-organic fertilizer + NPK 50% + Tabela	44.00 b	180.79	5.20 b	173.68
Bio-organic fertilizer + NPK 50% + Jajar Tehel	47.00 ab	199.94	6.27 a	230.00
Bio-organic fertilizer + NPK 50% + Jajar Legowo	51.00 b	225.46	6.70 a	252.63

Note: Different letters denote statistically significant differences at the $p < 0.05$ level.

production, as proposed in comprehensive reviews by (Sharma et al., 2023) and (Bhunia et al., 2021). Furthermore, this approach aligns with concepts of ecological intensification described by (Timsina et al., 2018), which aims to enhance crop productivity while reducing environmental impacts through biological processes and optimized resource utilization.

Analysis of macronutrient uptake patterns in plants

These Figure 4 presents significant correlations between an independent variable (x-axis) and the uptake of essential macronutrients (N, P, and K) by plants. The linear relationships displayed provide valuable insights into nutrient absorption dynamics under varying conditions.

Nitrogen uptake analysis: (Graph a) illustrates nitrogen uptake with a highly significant linear relationship ($R^2 = 0.8477$), represented by the equation $y = 0.1777x + 0.991$. This robust coefficient of determination indicates that approximately 85% of the variation in N uptake can be explained by the independent variable. The slope coefficient (0.1777) suggests a moderate but consistent increase in N uptake with each unit increase of the independent variable. This aligns with findings by (Govindasamy et al., 2023), who demonstrated that nitrogen uptake efficiency follows predictable patterns when influenced by appropriate environmental and management factors. For N uptake: The slope of 0.1777 indicates that for every unit increase in (independent variable), nitrogen uptake increases by 0.1777 units. This suggests a moderate response, highlighting the importance of sustained N availability to support crop growth.

Phosphorus uptake analysis: (Graph b) depicts phosphorus uptake dynamics with a moderately a highly significant linear relationship ($R^2 = 0.7741$) and regression equation $y = 0.0273x + 0.065$. The relatively smaller slope coefficient compared to N and K uptake indicates that P

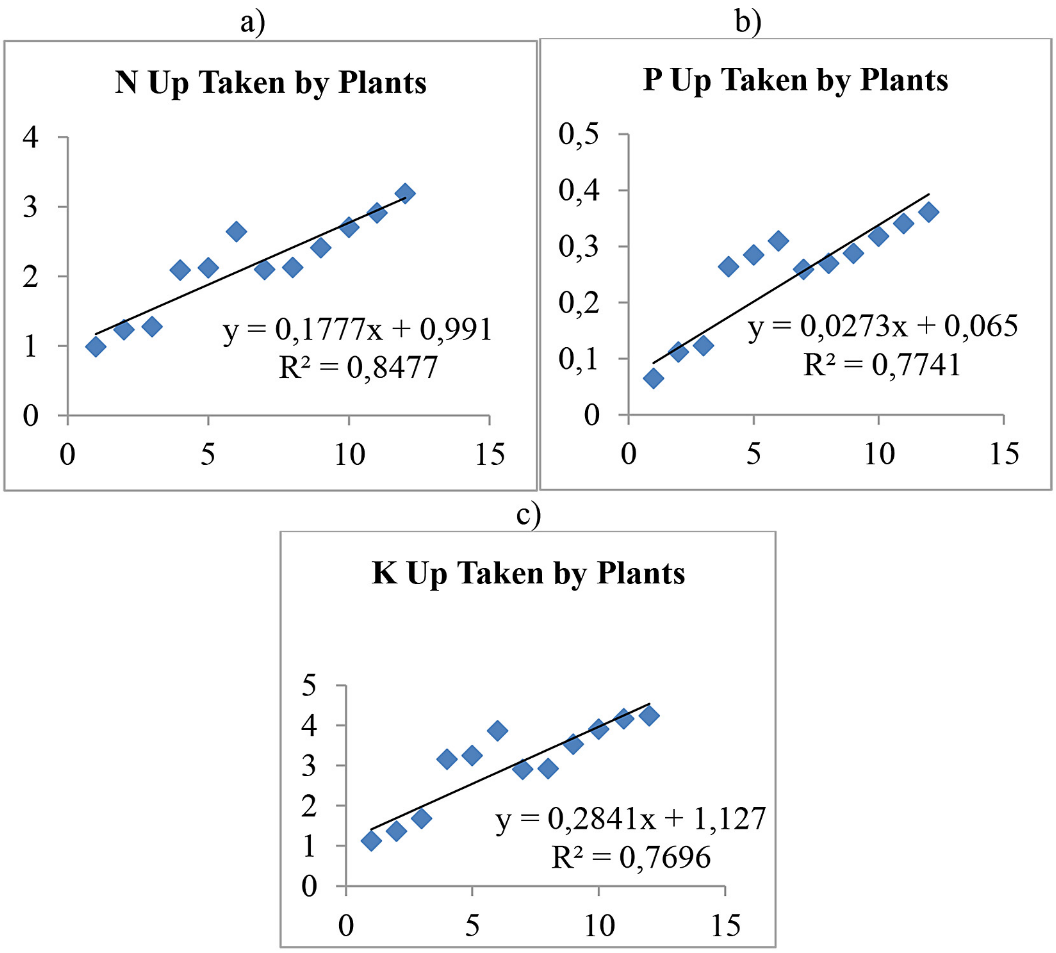

Figure 4. The relationship between NPK uptake, the type of fertilizer, and the cropping system on the plant: a) N uptake, b) P uptake, c) K uptake

uptake increases at a slower rate per unit of the independent variable. This reduced uptake efficiency is consistent with research by (Amadou et al., 2021), who documented the challenges in phosphorus availability and acquisition due to its tendency to form insoluble complexes in soil. The baseline P uptake (y-intercept = 0.065) is notably lower than for other nutrients, reflecting the typically limited bioavailability of phosphorus in most agricultural soils.

Potassium uptake analysis: (Graph c) shows potassium uptake with a highly significant linear relationship ($R^2 = 0.7696$) and equation $y = 0.2841x + 1.127$. The steeper slope coefficient for K compared to N and P suggests that potassium uptake responds more sensitively to changes in the independent variable. Additionally, the higher y-intercept (1.127) indicates greater baseline K uptake even at low values of the independent variable. This pattern corresponds with research by (Appiah et al., 2024), who found that potassium demonstrates different uptake kinetics than nitrogen and phosphorus, often showing luxury consumption patterns when available.

Comparative analysis – the relative uptake rates (slopes) follow the order K > N > P (0.2841 > 0.1777 > 0.0273), which aligns with typical plant nutritional requirements and uptake patterns documented by (Wiesler, 2012) in comprehensive studies on mineral nutrition of higher plants. The baseline uptake values (y-intercepts) follow the same pattern (K > N > P), suggesting inherent differences in the plants' ability to access these nutrients independent of the manipulated variable.

These findings suggest that management practices that enhance the independent variable will have proportionally greater effects on K and N uptake than on P uptake. This differential response must be considered when formulating balanced fertilization strategies, particularly in integrated nutrient management systems as documented by (Kuila and Ghosh, 2022) in their analysis of nutrient uptake and partitioning in modern crop varieties. The observed relationships provide a quantitative basis for predicting nutrient uptake responses and could serve as valuable parameters in crop modeling or for developing site-specific nutrient management recommendations, supporting the precision agriculture approaches advocated by (Schröder et al., 2022) in their work on sustainable intensification of crop production systems.

Chlorophyll content using SPAD meter

The SPAD meter readings presented in Table 3 reveal significant variations in chlorophyll content across three rice planting systems: Tabela, Jajar Tehel, and Jajar Legowo. The data demonstrates a clear pattern where the Jajar Legowo system exhibits the highest chlorophyll content (42–46 SPAD units on average), followed by Jajar Tehel (40–44 SPAD units), and Tabela showing the lowest values (38-42 SPAD units). This gradient suggests that planting configuration substantially influences chlorophyll development in rice plants, with Jajar Legowo offering potentially optimal conditions for chlorophyll synthesis and accumulation. The variation ranges indicate that Jajar Legowo not only produces higher mean chlorophyll content but also demonstrates greater plasticity (39–49 SPAD units), compared to narrower ranges in Jajar Tehel (37–47 SPAD units) and Tabela (35–45 SPAD units). This observation aligns with findings from (Adijaya et al., 2021), who reported that optimized spacing in Jajar Legowo systems enhances light interception, potentially explaining the elevated chlorophyll measurements. The wider variation in the Jajar Legowo system may indicate greater adaptability to micro-environmental conditions, a phenomenon also noted by (Islam et al., 2022) in their comparative analysis of rice cultivation systems.

Perhaps most compelling is the differential response to bio-organic amendments across the three systems. Jajar Legowo showed the most pronounced improvement (7-9 SPAD units), while Jajar Tehel and Tabela demonstrated more modest increases of 6–8 and 5–7 SPAD units, respectively. This gradient of responsiveness suggests that the spatial arrangement in Jajar Legowo may facilitate more efficient nutrient uptake and utilization when supplemented with bio-organic inputs. This synergistic effect between planting configuration and organic amendments corresponds with research by (Paramanik et al., 2024, who documented enhanced physiological responses in rice under integrated management practices.

The observed SPAD values across all systems fall within the optimal range (35–45) suggested by Zhang et al., (2019) for high-yielding rice varieties during reproductive stages. However, the consistently higher values in Jajar Legowo, particularly after bio-organic application, suggest potential for photosynthetic optimization. Biradar

Table 3. SPAD meter for chlorophyll content

Planting system	Average SPAD	SPAD variation	SPAD Increase after Bio-organic
Tabela	38–42	35–45	5–7 point
Jajar Tehel	40–44	37–47	6–8 point
Jajar Legowo	42–46	39–49	7–9 point

et al., (2025) similarly reported that SPAD readings above 42 during critical growth phases correlate strongly with improved grain filling and yield components. The enhanced chlorophyll content in Jajar Legowo might be attributed to improved ventilation and reduced competition for light and nutrients, as suggested by (Kartika et al., 2018) in their comprehensive analysis of modern rice cultivation techniques. These findings have significant implications for sustainable rice production. As Zhang et al. (2021) demonstrated, higher chlorophyll content directly influences photosynthetic efficiency and correlates with improved nitrogen use efficiency – a critical factor in reducing environmental impacts of rice cultivation. Further research by (Zhang et al., 2022) confirmed that SPAD readings can serve as reliable proxies for photosynthetic capacity and nitrogen status when calibrated appropriately for specific rice varieties and growing conditions.

CONCLUSIONS

This research investigated the integrated effects of bio-organic fertilizer applications and modified planting systems on rice production in acid sulfate tidal swamplands of South Sumatra, Indonesia. The findings provide substantial evidence that the combination of bio-organic fertilizer with reduced synthetic inputs (50% NPK) under the Jajar Legowo planting system significantly enhances rice productivity in these challenging environments.

The integration of bio-organic fertilizer with 50% NPK under the Jajar Legowo planting system achieved the highest rice yield (6.70 t/ha), representing a 252.63% increase compared to the control treatment. This integrated approach demonstrated significant improvements across multiple agronomic parameters, including plant height, productive tiller formation, filled grain percentage, and reduced empty grain formation. The Jajar Legowo system consistently outperformed both Tabela (direct planting system) and Jajar Tehel (square planting system) across all fertilizer treatments, with enhanced chlorophyll content (42–46 SPAD units) and greater responsiveness to bio-organic amendments (7–9 SPAD unit increase).

Macronutrient uptake analysis revealed differential absorption patterns (K > N > P), with strong correlations to the combined treatments. The bio-organic fertilizer demonstrated potential to replace conventional fertilizers, achieving comparable results to full-rate NPK fertilization while improving soil conditions in these acid sulfate environments. These findings confirm that integrating bio-organic fertilizers with reduced chemical inputs and optimized planting geometry effectively addresses the challenges of tidal swampland cultivation. This approach offers a sustainable pathway to transform marginal lands into productive agricultural areas while maintaining high productivity and reducing environmental impacts. The research provides empirical evidence for developing improved management practices for tidal swampland agriculture that can contribute significantly to food security initiatives in regions where these landscapes represent a substantial but underutilized agricultural resource.

The study demonstrates that sustainable intensification of rice production in marginal lands is achievable through ecologically sound approaches that optimize resource utilization and reduce dependency on conventional chemical inputs, thereby supporting both productivity goals and environmental sustainability in challenging agroecosystems.

Acknowledgements

The author would like to express his gratitude to the LPPM of Universitas Muhammadiyah Palembang for providing research funding assistance and to the farmers of Pangkalan Gelebak village in type C tidal land.

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