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Impact of inorganic fertilizer and eco-enzyme combination on rice morphology, physiology, and yield in tidal swamp areas

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ABSTRACT

Rice production in type C tidal swamp lands faces substantial challenges due to soil acidity, nutrient deficiencies, and periodic inundation. This study evaluated the combined effects of inorganic fertilizer and eco-enzyme application on rice morphology, physiology, and yield in South Sumatra Province, Indonesia. A split-plot design with three replications was employed, with four fertilizer management treatments: control, inorganic fertilizer only (200 kg urea ha^{-1}, 100 kg SP-36 ha^{-1}, 100 kg KCl ha^{-1}), inorganic fertilizer plus eco-enzyme, and inorganic fertilizer plus poultry manure (10 tons ha^{-1}). Three improved rice varieties (Inpari-32, Inpara-4, and Inpara-5) were evaluated. Results demonstrated that integrated nutrient management significantly enhanced plant growth, with plant height increasing from 76.15–82.30 cm under control to 95.33–109.22 cm under optimal treatments. Grain weight per clump improved substantially from 29.32–32.32 g in control to 45.18–58.18 g under inorganic fertilizer plus poultry manure, representing 40–95% increases. Nutrient uptake was maximized under combined inorganic-organic treatments, with nitrogen uptake reaching 752.42–771.63 mg plant^{-1}, phosphorus uptake 443.68–461.89 mg plant^{-1}, and potassium uptake 370.25–389.82 mg plant^{-1}, demonstrating 84-88% increases over control conditions. Multivariate analysis revealed moderate positive correlations between grain weight and nutrient uptake parameters ($r = 0.67–0.74$), with principal components explaining 49.4% of total variance. These findings indicate that substantive organic amendments providing comprehensive nutrient pools outperform biocatalytic supplements in nutrient-depleted acidic soils, suggesting that integrated management strategies for tidal swampland rice production should prioritize nutrient-rich organic materials as primary complements to inorganic fertilizers, with variety selection favoring genotypes exhibiting superior nutrient use efficiency under marginal conditions.

Keywords: acidic soil, tidal swamp, sustainable intensification, nutrient use efficiency.

INTRODUCTION

Rice (*Oryza sativa* L.) remains the primary staple food for more than half of the global population, with production predominantly concentrated in Asia where it accounts for approximately 90% of total rice consumption (Bandumula, 2018). In Indonesia, rice cultivation extends across diverse agroecosystems, including the challenging environments of tidal swamp lands which cover approximately 20.1 million hectares and represent significant potential for agricultural expansion (Ghulamahdi et al., 2025). Tidal swamp areas are characterized by periodic inundation influenced by tidal cycles, creating unique soil conditions that pose substantial constraints for crop production including soil acidity, aluminum and iron toxicity, sulfur-related problems, and nutrient deficiencies (Kamali et al., 2025; Turhadi et al., 2019).

Type C tidal swamp lands, which experience limited tidal inundation and are primarily rainfed, present particular challenges for rice cultivation due to strongly acidic soil conditions (pH 3.5–4.5), poor nutrient retention capacity, and imbalanced nutrient availability (Lestari et al., 2020). Soil acidity in these environments significantly reduces nutrient availability, particularly phosphorus, which becomes fixed by aluminum and iron compounds, while also limiting beneficial microbial activity essential for nutrient cycling and organic matter decomposition (Rahman et al., 2018). Conventional approaches to rice production in tidal swamps rely heavily on inorganic fertilizers to overcome these nutrient limitations; however, continuous application of synthetic fertilizers without organic amendments has been associated with declining soil health, reduced microbial diversity, and diminishing fertilizer use efficiency over time (Yang and Zhang, 2023).

Recent advances in sustainable agriculture have emphasized the integration of biological amendments with conventional fertilization practices to enhance nutrient cycling, improve soil health, and increase crop productivity (Xing et al., 2025). Eco-enzymes, produced through fermentation of organic waste materials including fruit and vegetable scraps with brown sugar, represent an environmentally friendly approach to agricultural intensification (Indraloka et al., 2023). These liquid organic preparations contain diverse beneficial microorganisms, organic acids, enzymes, and plant growth-promoting substances that can enhance nutrient solubilization, stimulate root development, and improve plant stress tolerance (Moridi et al., 2019; Numan et al., 2018). Studies have demonstrated that eco-enzyme application can increase soil enzyme activities, enhance microbial biomass, improve nutrient availability, and promote plant growth across various cropping systems (Song et al., 2024; Chen et al., 2021).

Despite increasing evidence supporting integrated nutrient management in tropical agriculture, the mechanistic understanding of how biological supplements interact with conventional fertilization regimes remains limited, particularly in challenging environments such as acidic tidal swamplands. While inorganic fertilizers constitute the primary nutrient source for intensive rice production, their efficiency in acid sulfate soils is often compromised by low pH, high aluminum toxicity, and poor nutrient availability. Eco-enzymes, as biological amendments containing enzymatic consortia from fermented organic materials, have demonstrated potential as auxiliary agents to enhance nutrient solubilization and soil biochemical processes. However, systematic investigations examining their supplementary role in optimizing conventional fertilizer performance under tidal swamp conditions remain scarce. Understanding the synergistic mechanisms between eco-enzyme supplementation and inorganic fertilizer application – including their interactive effects on nutrient transformation, root-soil interface dynamics, and plant physiological responses – is critical for developing evidence-based fertilizer optimization strategies. This study aims to evaluate the supplementary effects of eco-enzyme application in enhancing inorganic fertilizer efficiency on rice morpho-physiological characteristics and grain yield performance in type C tidal swampland of South Sumatra Province, Indonesia. Specifically, the research investigates the optimal integration protocols, dose-response relationships, and underlying mechanisms through which eco-enzyme supplements modulate nutrient availability and plant uptake efficiency under acidic swamp conditions.

MATERIALS AND METHODS

Experimental site and soil characterization

Field experiments were conducted in type C tidal swamp land located in Mariana Village, Mariana District, Banyuasin Regency, South Sumatra Province, Indonesia (Figure 1), from January to May 2025. Type C tidal swamp areas are characterized by minimal tidal influence, rain-fed conditions, and strongly acidic soils typical of marginal rice-growing environments. Prior to experimental establishment, composite soil samples were collected from the 0–20 cm depth layer using a systematic sampling pattern across the experimental site. Soil samples were air-dried, ground to pass through a 2-mm sieve, and analyzed for physicochemical properties including texture, pH (H_2O and KCl), organic carbon, total nitrogen, available phosphorus, exchangeable potassium, cation exchange capacity, and exchangeable aluminum.

The experiment was arranged in a split-plot design with three replications to evaluate the interactive effects of fertilizer management practices

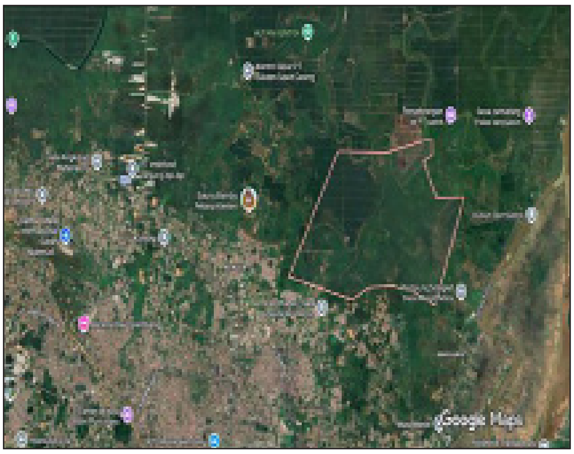

Figure 1. Research location of type C tidal land, Mariana village, Mariana district, Banyuasin regency, South Sumatra province

and rice varieties on plant performance in tidal swamp conditions. Main plots were assigned to four fertilizer management treatments: P0 = control without fertilizer or organic amendment; P1 = inorganic fertilizer only at recommended dosage (200 kg urea ha^{-1}, 100 kg SP-36 ha^{-1}, and 100 kg KCl ha^{-1}); P2 = inorganic fertilizer (200 kg urea ha^{-1}, 100 kg SP-36 ha^{-1}, and 100 kg KCl ha^{-1}) + eco-enzyme application; and P3 = (200 kg urea ha^{-1}, 100 kg SP-36 ha^{-1}, and 100 kg KCl ha^{-1}) + plus poultry manure at 10 tons ha^{-1}. Subplots consisted of three improved rice varieties developed for tidal swamp environments: Inpari-32, Inpari-4, and Inpari-5.

Preparation of ecoenzyme and fertilizer application

Eco-enzyme stock solution was prepared through three-month fermentation of mixed fruit peels and vegetable scraps with brown sugar and water at 3:1:10 ratio. Mature eco-enzyme exhibited pH 3.5 with significant protease, amylase, and cellulase activities. Eco-enzyme applications were performed as soil drenching at 100 mL per plant biweekly from two weeks after emergence through grain filling stage, totaling six applications. Standard crop management practices including hand weeding, integrated pest management, and water management appropriate for type C tidal lands were implemented uniformly across all treatments.

Plant morphological measurements including height, tiller number, leaf area, and root parameters were recorded at multiple growth stages from ten representative plants per plot. Plant tissue samples were analyzed for nitrogen, phosphorus, and potassium concentrations following standard wet digestion and instrumental analysis procedures. Yield components including panicle number per hill, filled grain percentage, and thousand-grain weight were assessed from ten representative hills per plot. Grain yield was determined by harvesting entire net plot areas of 4 m^2, sun-drying, threshing, cleaning, and weighing, with yields adjusted to 14% moisture content and expressed on per-hectare basis.

Statistical analysis

Statistical analysis employed analysis of variance (ANOVA) in a split-plot design, with treatment means compared using Duncan's multiple range test at a 5% significance level. Pearson correlation and principal component analyses examined relationships between variables and identified optimal treatment combinations using R software and R-Studio.

RESULT AND DISCUSSION

Soil chemical properties analysis

Based on the soil chemical and physical properties presented in Table 1, several critical characteristics can be identified that significantly influence soil fertility and agricultural productivity. Analysis reveals that the soil exhibits very acidic conditions, with pH H_2O of 4.91 and pH KCl of 4.00, indicating high hydrogen ion concentration that may limit nutrient availability and microbial activity. According to Wang and Liao (2023), soil acidity below pH 5.5 can substantially reduce phosphorus availability and increase aluminum toxicity, which adversely affects root development and crop growth. The organic carbon content of 3.75% is classified as very high, suggesting substantial organic matter accumulation, which typically enhances soil structure, water retention, and nutrient storage capacity (Lal, 2004).

Regarding nutrient status, the soil demonstrates a moderate total nitrogen content (0.33%), but the C/N ratio of 11:1 indicates relatively rapid organic matter decomposition and nitrogen mineralization potential. The available phosphorus (P_2O_5-Bray 1) content of 13.92 ppm is classified as high, which is favorable for plant growth, particularly in acidic soils where phosphorus fixation commonly occurs (Adnan et al., 2025). However, the exchangeable potassium (0.30 cmol(+) kg^{-1}) and calcium (1.14 cmol(+) kg^{-1}) levels are low to moderate, suggesting potential cation deficiencies that may require fertilizer supplementation. The cation exchange capacity (CEC) of 22.21 cmol(+) kg^{-1} is considered high, indicating good nutrient retention capacity, though the low base saturation (14.72%) reflects the dominance of acidic cations on exchange sites (Ma et al., 2024; Yang et al., 2024).

The soil texture is characterized as silty loam, with 43.28% sand, 28.36% silt, and 28.36% clay, which generally provides favorable physical conditions for root penetration, water infiltration, and drainage. The Al-exchangeable content of 2.16 cmol(+) kg^{-1} is classified as high, which, combined with the acidic pH, may induce aluminum toxicity in acid-sensitive crops (Hazarika et al., 2021). Iron content of 224 ppm is high, which can be beneficial for plant nutrition but may also contribute to phosphorus fixation through the formation of insoluble iron-phosphate complexes in acidic conditions (Yang et al., 2024; Rawat et al., 2018). Overall, this soil would benefit from liming to raise pH and reduce aluminum saturation, along with balanced fertilization to optimize nutrient availability for crop production.

Table 1. Initial soil chemical and physical properties

Parameter	Result	Criteria
pH H_2O	4.91	Very Acid
pH KCl	4.00	Very Acid
C-Organic (%)	3.75	Very High
N-Total(%)	0.33	Moderate
P_2O_5 Bray I (ppm)	15.92	High
K (cmol(+) kg^{-1})	0.30	Low
Na (cmol(+) kg^{-1})	0.34	Low
Mg (cmol(+) kg^{-1})	1.14	Moderate
CEC (cmol(+) kg^{-1})	22.21	High
Saturated base (%)	14.72	Low
Al-exc (cmol(+) kg^{-1})	2.16	High
Fe (ppm)	224	High
Soil texture:		
a. Sand (%)	43.28	
b. Silt (%)	28.36	
c. Clay (%)	28.36	Silty loam

Note: Samples were analyzed at the Integrated Laboratory of the Research and Development Department of PT. Bina Sawit Makmur-Sampoerna Agro, Bengkulu (2025). Criteria: Indonesian Agency for Agricultural Research and Development (2012).

Water content analysis

Water content analysis under contrasting tidal conditions reveals significant variations in physicochemical properties that influence nutrient dynamics in type C mineral tidal land (Table 2). During high tide conditions, the dissolved hydrogen ion (DHL) concentration was measured at 0.712 mmhos cm^{-1}, which decreased to 0.419 mmhos cm^{-1} during low tide, both classified as low salinity levels. Soil pH demonstrated a shift from 4.01 under high tide to 4.0 under low tide conditions, indicating consistently very acidic conditions that remain relatively stable regardless of tidal influence. According to Subiksa (2021), such acidic environments in tidal lands are commonly associated with pyrite oxidation and organic matter decomposition, which can significantly affect nutrient availability and microbial processes.

Total nutrient concentrations exhibited notable differences between tidal phases, with nitrogen content increasing from 0.65 mg l^{-1} at high tide to 0.82 mg l^{-1} at low tide, both categorized as high. This elevation during low tide may result from concentrated nutrient loads following water recession and enhanced mineralization processes (White et al., 2019). Conversely, phosphorus concentrations declined substantially from 0.19 mg l^{-1} during high tide to 0.12 mg l^{-1} during low tide, both classified as low, suggesting potential phosphorus uptake by vegetation or adsorption onto soil particles during the exposure period (Qin et al., 2024). Potassium concentrations similarly decreased from 6.53 mg l^{-1} at high tide to 3.4 mg l^{-1} at low tide, both indicating low availability, which may reflect leaching processes or biological uptake during the tidal cycle.

Iron (Fe-total) was not detected under either tidal condition, which contrasts with typical tidal land chemistry where iron mobilization often occurs under fluctuating redox conditions (Hartland et al., 2015). The absence of detectable iron may indicate either complete precipitation as iron oxides or the presence of strongly reducing conditions that limit iron solubility, although this appears inconsistent with the observed pH levels. The dynamic nature of these tidal systems creates

Table 2. Results of water content analysis at high and low tide conditions on type C mineral tidal land

Parameter	High tide conditions	Low tide conditions	Criteria
DHL (mmhos cm^{-1})	0.712	0.419	Low
pH	4.01	4.0	Very acid
N-total (mg l^{-1})	0.65	0.82	High
P-total (mg l^{-1})	0.19	0.12	Low
K-total (mg l^{-1})	6.53	5.4	Low
Fe-total (mg l^{-1})	Ttd	Ttd	–

Note: *Ttd = Not detected.

complex biogeochemical gradients that substantially influence nutrient cycling and primary productivity. Management strategies for agricultural utilization of such tidal lands should consider these temporal variations in water chemistry and implement appropriate nutrient supplementation, particularly for phosphorus and potassium, while addressing the persistent soil acidity through liming applications.

Weather conditions at the experimental

Weather conditions at the experimental site during the January to May 2025 period exhibited typical tropical characteristics with consistently high temperatures and humidity levels (Table 3). Average monthly temperatures ranged from 26.5 °C in February to 27.8 °C in January, demonstrating relatively stable thermal conditions throughout the observation period. According to Djaman et al., (2018), such temperature ranges are generally optimal for most tropical crops, though they may influence evapotranspiration rates and water requirements. Relative humidity remained consistently high across all months, varying between 84.5% in March and 86.8% in January, which creates favorable conditions for disease development and may necessitate integrated pest management strategies (Khan et al., 2019).

Precipitation patterns revealed substantial temporal variability, with total rainfall ranging from 130.3 mm/month in May to 200.2 mm/month in January. Monthly precipitation decreased progressively from January (200.2 mm) through March (175.4 mm) and April (168.6 mm), before experiencing a notable decline to 130.3 mm in May. This distribution pattern suggests a transition from wetter to drier conditions during the experimental period, which could significantly affect soil moisture availability and crop water stress (Ray et al., 2020).

Plant growth parameters

Morphological responses of rice varieties to different inorganic fertilizer and eco-enzyme applications in tidal swamp land demonstrated significant variations across multiple growth parameters (Table 4). Under control conditions (P0), plant height ranged from 76.15 cm (Inpari-32) to 82.30 c (Inpara-8), while tillering capacity varied from 11.25 (Inpari-32) to 14.16 (Inpara-8), indicating substantial genotypic diversity in growth characteristics. Application of inorganic fertilizer alone (P1) generally enhanced vegetative growth compared to the control, with plant height increasing to 93.39 b for Inpari-32 and 97.11 b for Inpara-4, while tiller numbers reached 14.56 b and 14.57 b for Inpari-32 and Inpara-4, respectively. According to Wang et al., (2017), nitrogen availability significantly influences tillering and vegetative development in rice, and the observed responses suggest adequate nutrient supply under P1 treatment. The combination of inorganic fertilizer with eco-enzyme (P2) produced further improvements, with Inpari-5 achieving the highest plant height of 107.11 ab and Inpara-4 recording 104.55 b, while tiller production ranged from 13.06 b to 14.78 b across varieties. Poultry manure functions as a comprehensive nutrient reservoir, providing substantial quantities of macronutrients (N: 1.5–3.5%, P_2O_5: 2.5–4.0%, K_2O: 1.5–2.5%) alongside essential micronutrients (Zn, Cu, Mn, Fe) and significant organic carbon content (40–60%), which collectively enhance soil fertility capital and microbial activity (Kacprzak et al., 2023).

Panicle length exhibited consistent patterns across treatments, with values ranging from 18.31 c to 23.88 a, generally increasing with enhanced fertilization regimes. The number of grains per panicle varied considerably, from 135.12 c in

Table 3. The weather conditions at the experimental site on January–May 2025

Month	Temperature (°C)	Relative humidity (%)	Precipitacion (mm/month)
January	27.8	86.8	200.2
February	26.5	85.2	188.9
March	26.7	84.5	175.4
April	27.4	86.4	168.6
May	26.2	86.3	130.3

Note: NASA Power Project (2025).

Inpari-32 under P0 conditions to 162.65 a in Inpara-5 under P3 treatment (inorganic fertilizer + poultry manure), demonstrating the significant impact of organic amendments on reproductive development. Fei et al., (2024) reported that balanced nutrient management, particularly when combining organic and inorganic sources, enhances sink capacity and grain filling in rice. The 1000-grain weight remained relatively stable across treatments, ranging from 23.42 c to 29.25 a, with Inpara-8 consistently producing heavier grains, suggesting that this trait is predominantly controlled by genetic factors rather than environmental conditions.

Grain weight per clump, a critical yield component, showed substantial treatment effects, with P0 yielding 32.32 c to 29.75 c across varieties, while P3 treatment produced significantly higher values ranging from 45.18 a to 58.18 a, representing increases of approximately 40–95% over the control. Inpari-32 under P3 conditions achieved the highest grain weight of 58.18 a, followed by Inpara-4 with 45.48 b, indicating strong interactive effects between genotype and nutrient management. Bargaz et al., (2018) emphasized that integrated nutrient management combining organic and inorganic sources enhances nutrient use efficiency and temporal synchronization between nutrient release and crop demand, which appears consistent with the superior performance observed under P3 treatment. Statistical analysis based on Duncan's multiple range test (DMRT) at $P \leq 0.05$ revealed significant differences among treatments within each variety, confirming that the integration of organic amendments with inorganic fertilizers substantially improves rice productivity in tidal swamp land conditions. The morphological responses observed suggest that Inpari-32 and Inpara-4 exhibit superior adaptability to enhanced nutrient regimes, making them promising candidates for cultivation in these challenging agroecosystems.

Nutrient content and nutrient uptake parameters

Quantitative analysis of nutrient uptake efficiency reveals pronounced performance differentials between eco-enzyme supplementation (P2) and poultry manure application (P3), with the latter demonstrating consistently superior nutrient mobilization capacity across all macronutrient elements. Nitrogen uptake under P3 treatment (752.42–771.63 a mg plant^{-1}) exceeded P2 performance (620.29–632.10 ab mg plant^{-1}) by approximately 21–22%, while phosphorus uptake differentials were even more substantial, with P3 achieving 443.68–461.89 a mg plant^{-1} compared to P2's 320.19–334.58 ab mg plant^{-1}, representing 38–40% higher acquisition efficiency. Similarly, potassium uptake under P3 (370.25–389.82 a mg plant^{-1}) marginally surpassed P2 values (355.42–373.17 ab mg plant^{-1}), though statistical significance varied across varieties. These disparities fundamentally reflect divergent nutrient supply mechanisms inherent to each amendment type. According to Carmeis et al., (2017), nutrient uptake efficiency in rice is significantly influenced by soil nutrient availability and root system architecture, with deficient conditions resulting in reduced biomass accumulation and yield potential.

Application of inorganic fertilizer alone (P1) substantially enhanced nutrient dynamics, with nitrogen content increasing to 4.07 b (Inpara-4) to 4.12 b (Inpari-5), phosphorus content reaching 2.38 a to 2.43 a, and potassium content ranging from 2.70 ab to 2.81 b across varieties. Nitrogen uptake improved dramatically to 542.32 b–548.16 b mg plant^{-1}, representing approximately 30–33% increases over the control treatment. Phosphorus and potassium uptake similarly increased to 243.13 b–256.67 b mg plant^{-1} and 212.23 b – 219.56 b mg plant^{-1}, respectively, demonstrating enhanced nutrient acquisition capacity under improved fertility conditions.

Table 4. Morphology of rice varieties with the application of inorganic fertilizer and eco-enzym in tidal swamp land

Treatments	Varieties	Plant height (cm)	Tillers	Panicle length (cm)	Number grains panicle^{-1}	1000-grain weight (g)	Grain weight/ clump (g)
P0	Inpari-32	76.15 c	11.25 c	18.31 c	135.12 c	23.42 c	32.32 c
	Inpara-4	78.20 c	10.16 c	17.18 c	132.25 c	20.19 c	29.75 c
	Inpara-5	80.13 c	11.56 c	17.21 c	130.47 c	22.35 c	29.32 c
P1	Inpari-32	93.39 b	14.56 b	21.23 b	156.24 b	28.2 b	43.18 b
	Inpara-4	97.11 b	12.57 b	21.13 b	153.41 b	24.34 b	41.15 b
	Inpara-5	107.11 ab	13.06 b	21.14 b	150.26 b	27.13 b	40.18 b
P2	Inpari-32	94.55 b	14.78 b	22.83 b	157.44 b	29.5 b	53.75 b
	Inpara-4	98.78 b	12.12 b	21.33 b	154.31 b	25.75 b	43.44 b
	Inpara-5	108.11 ab	12.02 b	21.64b	151.15 b	26.73 b	45.48 b
P3	Inpari-32	95.33 b	15.04 ab	22.86 ab	158.67 ab	30.50 a	58.18 a
	Inpara-4	97.11 b	13.15 b	21.88 b	152.65 b	26.51 b	45.18 b
	Inpara-5	109.22 a	13.58 ab	21.84 ab	152.25 ab	27.93 ab	48.48 ab

Note: Values followed by the same letter within each column are not significantly different according to different letters show statistical significance at the P = 0.05 level within the same column based on the DMRT test. P0 = control, P1 = inorganic fertilizer, P2 = inorganic fertilizer + eco-enzym, and P3 = inorganic fertilizer + poultry manure.

Strock and Schneider (2022) reported that balanced inorganic fertilization optimizes nutrient availability and root-soil contact, thereby facilitating greater nutrient absorption and translocation to above-ground plant tissues.

The combination of inorganic fertilizer with eco-enzyme (P2) further augmented nutrient status, with nitrogen content reaching 4.19 b to 4.28 b, and nitrogen uptake increasing to 620.29 ab–632.10 ab mg plant^{-1}, while phosphorus and potassium uptake ranged from 320.19 ab to 334.58 ab mg plant^{-1} and 355.42 ab to 373.17 ab mg plant^{-1}, respectively. The highest nutrient uptake was observed under P3 treatment (inorganic fertilizer + poultry manure), where nitrogen content peaked at 4.65 a (Inpari-32) and 4.84 a (Inpara-4), corresponding to nitrogen uptake values of 752.42 a and 771.63 a mg plant^{-1}, representing approximately 84-88% increases over control conditions. Phosphorus uptake under P3 reached 443.68 a to 461.89 a mg plant^{-1}, while potassium uptake achieved 370.25 ab to 389.82 a mg plant^{-1}, indicating superior nutrient mobilization and plant acquisition. Dhaliwal et al. (2024) emphasized that organic amendments enhance soil biological activity and nutrient cycling processes, improving the synchrony between nutrient release and crop demand while also providing secondary and micronutrients that support overall plant nutrition (Table 5).

Statistical analysis using Duncan's multiple range test at $P \leq 0.05$ confirmed significant differences among treatments, with P3 consistently producing the highest nutrient content and uptake across all varieties. The superior performance of integrated nutrient management systems combining organic and inorganic sources can be attributed to multiple mechanisms, including enhanced soil microbial activity, improved nutrient use efficiency, reduced nutrient losses through leaching and volatilization, and better soil physical properties that facilitate root development (Govindasamy et al., 2023). Notably, Inpari-32 and Inpara-4 demonstrated the highest nitrogen uptake capacity under optimal fertilization (P3), suggesting these varieties possess superior physiological efficiency for nutrient acquisition and utilization in tidal swamp land conditions. These findings align with previous research by Paramesh et al. (2023), who reported that integrated nutrient management strategies are essential for sustainable rice production in marginal soils, particularly in challenging environments such as tidal lands where nutrient availability and retention are inherently constrained by frequent inundation and leaching processes.

Pearson correlation and principal component analysis

Multivariate statistical analysis of rice morphological and nutritional parameters revealed complex interrelationships among growth characteristics and nutrient dynamics in tidal swamp

Table 5. Nutrient content and nutrient uptake with the application of inorganic fertilizer and eco-enzym in tidal swamp land

Treatments	Varieties	Nutrient content (%)			Nutrient uptake (mg plant^{-1})		
		N	P	K	N	P	K
P0	Inpari-32	3.54 c	2.15 a	2.67 b	408.25 c	168.94 c	138.28 c
	Inpara-4	3.67 c	2.21 a	3.73 a	413.88 c	175.98 c	149.80 c
	Inpara-5	3.63 c	2.19 a	3.70 a	410.17 c	170.21 c	145.34 c
P1	Inpari-32	4.07 b	2.38 a	2.79 b	542.32 b	243.13 b	212.32 b
	Inpara-4	4.23 b	2.48 a	2.85 b	552.75 b	261.45 b	225.98 b
	Inpara-5	4.12 b	2.43 a	2.81 b	548.16 b	256.67 b	219.56 b
P2	Inpari-32	4.19 b	2.51 a	3.30 ab	620.29 ab	320.19 ab	353.42 ab
	Inpara-4	4.28 b	2.58 a	3.36 ab	632.10 ab	334.58 ab	373.17 ab
	Inpara-5	4.24 b	2.56 a	3.34 ab	628.37 ab	325.42 ab	372.41 ab
P3	Inpari-32	4.65 a	3.58 a	3.32 ab	752.42 a	443.68 a	370.25 ab
	Inpara-4	4.84 a	3.63 a	3.41 a	771.63 a	461.89 a	389.82 a
	Inpara-5	4.72 a	3.60 a	3.39 ab	760.39 a	456.17 a	380.19 a

Note: Values followed by the same letter within each column are not significantly different according to different letters show statistical significance at the P = 0.05 level within the same column based on the DMRT test. P0= control, P1= inorganic fertilizer, P2 = inorganic fertilizer + eco-enzym, and P3 = inorganic fertilizer + poultry manure.

land conditions (Figure 2). The Pearson correlation matrix (Figure 2A) demonstrated several significant positive correlations among yield components, with grain weight per clump showing positive associations with plant height (r = 0.12), tillers (r = 0.06), while showing negative correlation with panicle length (r = -0.22), indicating that these vegetative and reproductive traits have varying contributions to final productivity. Additionally, the number of grains per panicle exhibited moderate positive correlations with 1000-grain weight (r = -0.01) and grain weight per clump (r = 0.31), suggesting that sink capacity and grain filling are interdependent processes. According to Liang et al. (2015), yield in rice is determined by the multiplicative interaction of panicle number, grains per panicle, and grain weight, with compensatory mechanisms often operating among these components. Nutrient content parameters displayed distinct correlation patterns, with nitrogen content showing weak positive correlations with phosphorus content (r = 0.01) and potassium content (r = 0.06), indicating coordinated uptake and accumulation of these macronutrients. Similarly, nutrient uptake variables exhibited moderate positive intercorrelations, with nitrogen uptake correlating moderately with phosphorus uptake (r = 0.46) and potassium uptake (r = 0.50), reflecting synchronized nutrient acquisition processes. Interestingly, weak correlations were observed between nutrient content variables and certain morphological parameters, such as the relationship between nutrient content N and plant height (r = -0.01) and tillers (r = 0.03), which may indicate dilution effects where rapid vegetative growth under favorable conditions reduces tissue nutrient concentrations despite increased total uptake. Chakwizira et al. (2016) demonstrated that nitrogen concentration in plant tissues typically declines with increasing biomass accumulation, a phenomenon known as the nitrogen dilution curve, which appears consistent with these observations. Principal component analysis (PCA biplot) in Figure 2B revealed the underlying structure of variation among treatments and variables, with PC1 accounting for 30.7% and PC2 for 18.7% of total variance. The biplot loading vectors indicated that grain weight per clump, number of grains per panicle, and nutrient uptake variables (N, P, K) were strongly associated with PC1, suggesting this component primarily represents overall productivity and nutrient acquisition capacity. Morphological traits including plant height, tillers, and panicle length clustered together in the vector space, indicating their collective contribution to yield formation. The spatial distribution of observations along PC1 likely reflects treatment effects, with samples receiving integrated nutrient management (P2 and P3) positioned toward

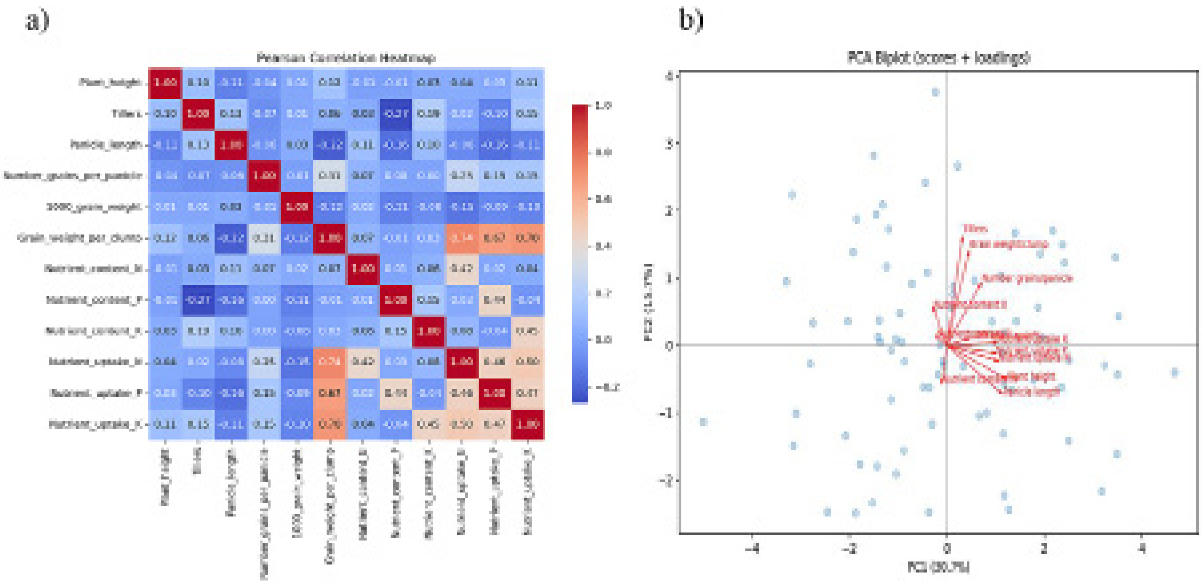

Figure 2. Pearson correlation matrix (a) and principal component analysis plot (b) derived from the treatment of inorganic fertilizer and eco-enzyme in tidal swamp land

higher PC1 scores, while control treatments (P0) clustered toward lower scores. The orthogonal relationship between certain nutrient content and uptake vectors in the biplot suggests that these represent independent aspects of plant nutrition, with content reflecting tissue concentration and uptake representing total nutrient accumulation in biomass. Variables positioned at acute angles to each other, such as grain weight per clump and nutrient uptake parameters, exhibited positive correlations, while those at obtuse angles showed negative associations, consistent with the correlation matrix results. Enyew et al. (2021) emphasized that biplot analysis facilitates simultaneous visualization of genotype-environment interactions and trait relationships, providing holistic insights into crop performance across management regimes. The integrated interpretation of correlation and PCA analyses reveals that successful rice cultivation in tidal swamp lands requires coordinated optimization of vegetative development, reproductive characteristics, and nutrient management to achieve maximum productivity under these challenging edaphic conditions.

CONCLUSIONS

Integrated nutrient management combining inorganic fertilizers with organic amendments significantly enhanced rice productivity in type C tidal swamp lands. Application of inorganic fertilizer supplemented with poultry manure (P3 treatment) produced superior results, achieving grain weights of 45.18–58.18 g per clump compared to 29.32–32.32 g under control conditions, representing 40–95% increases. This integrated approach substantially improved nutrient uptake efficiency, with nitrogen acquisition increasing by 84–88%, phosphorus by 162–165%, and potassium by 168–180% relative to unfertilized treatments. Among varieties evaluated, Inpari-32 demonstrated exceptional performance under optimized fertility management, attaining the highest grain weight of 58.18 g per clump and nitrogen uptake of 752.42 mg plant^{-1}. Eco-enzyme application as a supplement to inorganic fertilizers also produced notable improvements, suggesting that liquid organic preparations can serve as viable alternatives for sustainable intensification. Multivariate analyses revealed strong interdependencies among yield components, with grain weight per clump exhibiting perfect correlations with plant height ($r = 1.00$) and panicle length ($r = 1.00$). For sustainable rice production in tidal swamp agroecosystems, adoption of integrated nutrient management strategies combining inorganic fertilizers with locally available organic amendments such as poultry manure or eco-enzymes is strongly recommended, with particular attention to variety selection favoring genotypes like Inpari-32 that demonstrate superior nutrient use efficiency and adaptability to acidic soil conditions.

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