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Analysis of the Biophysical Conditions of Type A Tidal Swamp on Production Results and the Development of Siam Pandak Rice Farming in Barito Kuala Regency

***Zulipah Mahdalena, M. Rifky Aditya**
Agribusiness Study Program, Faculty of Agriculture, Universitas Achmad Yani Banjarmasin Jl. Jend. Achmad Yani Km.5,5,Jalan Uvaya, Pemurus Baru, Banjarmasin, 70249, Indonesia.

*Corresponding Author e-mail: mahdalenazulifah@gmail.com

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Abstract

This study aims to evaluate the biophysical conditions of Type A tidal swamp lands in Barito Kuala Regency, South Kalimantan, and their impact on the productivity and economic sustainability of Siam Pandak rice farming. The biophysical data collected revealed that the soil conditions in the study area have a pH ranging from 4.5 to 5.0 (acidic), organic matter content ranging from 2.5% to 3.5%, and total nitrogen content between 0.18% and 0.25%. Average phosphorus availability was between 8 and 12 ppm, with potassium levels measured at 0.25 to 0.40 cmol/kg. Although the soil pH is low, leading to high solubility of toxic metals such as iron (Fe) and aluminum (Al), lime application (liming) can increase soil pH to more neutral levels, reducing Fe/Al toxicity, which in turn improves nutrient availability and supports rice growth. In terms of plant growth, the average height of Siam Pandak rice plants reached 135–150 cm, with 12 to 18 productive tillers per hill. Rice productivity was 3.5–4.5 tons of dry harvested grain (GKG) per hectare, which is still below the maximum potential (5–6 tons/ha). Regression analysis showed that soil pH, organic matter content, and potassium availability had a positive effect on productivity, while Fe/Al toxicity showed a significant negative effect. Effective water management strategies, including the alternating wetting and drying (AWD) system and proper drainage, helped reduce waterlogging risks and enhanced root growth. Economically, farmers who implemented effective soil and water management practices recorded a significant increase in net income, with an average income of IDR 33,968,750 per farmer per planting season. These findings emphasize that the application of proper soil amendments, good water management, and optimal biophysical conditions can increase rice yields and the economic sustainability of Siam Pandak rice farming in tidal swamp areas.

Keywords: Biophysical Management; Siam Pandak Rice; Tidal Swamp Lands; Iron and Aluminum Toxicity; Agricultural Economic Sustainability

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INTRODUCTION

Food security is a strategic issue facing almost every country in the world, including Indonesia. The continuous increase in population from year to year has serious consequences for food needs, especially rice, the staple food of the majority of Indonesians. Indonesia is the third-largest rice producer in the world after China and India, but national rice availability is still constrained by declining natural resource quality, reduced productive land on Java Island, declining farmer interest, and various obstacles to increasing production (Irwandi, 2015). Concurrently, the population growth continues to increase from year to year, increasing the need for staple foods, especially rice (Subekti & Umar, 2022). Population growth will drive increased demand for rice, so Indonesia's food self-sufficiency policy, particularly for rice, requires efforts to intensify and increase production sustainably (Ilham et al., 2023). Therefore, increasing rice production is a top priority for the government. One of the factors that plays a crucial role in agricultural productivity is the availability of agricultural land. One area with the potential to increase rice production is tidal swampland (Ardi et al., 2024). Rice is considered an economic commodity because it can stimulate the economy through the formation of various companies, such as seed, fertilizer, machinery, and pesticide companies (Masganti et al., 2020). Rice is the staple food of the Indonesian people and a strategic commodity because Indonesia is an agricultural country, meaning that agriculture plays an important role in the overall national economy (Rohansyah, 2020). Rice is the primary food source for more than half the world's population. Annually, global milled rice production reaches approximately 480 million metric tons, with China and India contributing approximately half of total global production and consumption. This commodity supplies up to 50% of the daily calorie needs of millions of people living below the poverty line (Muthayya et al., 2014).

However, the availability of rice fields is also decreasing due to conversion to residential and industrial areas, among other areas. One alternative with significant potential is tidal swampland, which is widespread outside Java, particularly in Kalimantan. Tidal swampland in Indonesia is estimated to cover approximately 20.1 million hectares, of which approximately 9 million hectares have the potential for developing food crops, particularly rice. Tidal swampland is marginal land with various biophysical limitations, such as being nutrient-poor, dominated by peat and acid sulfate soils, and vulnerable to potential acid sulfate, seawater intrusion, and salinity. Therefore, it is less than ideal for agricultural cultivation and results in low agricultural productivity, especially for rice (Zakirin et al., 2013). In addition to biophysical constraints, rice cultivation in tidal swampland also faces disturbances from Plant Pest Organisms (OPT). One of the most concerning problems for farmers is blast disease, as it can significantly reduce crop yields (Subekti et al., 2021). However, through wise, sustainable management and integrated technological support, this land has the potential to become a strategic alternative to address the decline in fertile land while supporting national food security (Susilawati et al., 2019). Each type of wetland has its own characteristics and potential as an agricultural resource. Tidal swamps have long been known to have the potential to develop various commodities, ranging from food (rice, secondary crops, vegetables, fruit), clothing (fiber crops), boards (wood), to biopharmaceuticals (medicinal plants such as ginger, and turmeric) (Noor & Rahman, 2015). Tidal swamps are considered suboptimal land but have great potential for developing rice farming (Koesrini et al., 2013). Tidal swamps have strategic potential for development as agricultural land and can become a new source of growth in food production. The advantages include a fairly large land area in the expanse, abundant water availability, relatively flat topography, easy distribution access via land and water routes, and a level of land and agronomic suitability which is generally classified as suitable to very suitable (Susilawati et al., 2016). Tidal swamps are one type of land currently being relied upon to increase rice production. Adapting rice plants to this ecosystem requires varieties with genetic resilience to extreme conditions, such as high soil acidity (low pH) and potential iron toxicity (Khairullah et al., 2021). Utilizing tidal swamps for agriculture is a strategic choice, both to meet food needs and to offset the shrinking of productive land (Suriadikarta, 2012).

South Kalimantan, particularly Barito Kuala Regency, is a region with significant tidal swamp potential. Tidal swamp land in South Kalimantan covers 17,828 ha, 80% of which is dominated by acid sulfate soil, spread across several regencies, including Barito Kuala (Kurniawan, 2012). Since the Peatland Project and Transmigration Program in the 1970s and 1980s, this area has been utilized for rice cultivation. However, utilizing tidal swamp land is challenging due to various biophysical constraints. Tidal swamp land is divided into several categories, one of which is Type A, which is land completely inundated by both large and small tides. Type A has the advantage of relatively secure water availability throughout the year but also presents significant management challenges. Tidal swamp with hydrotopography class A has a lower topography and can receive water from canals during the dry and rainy seasons, so this area has no problems with water availability (Imanudin et al., 2023).

Tidal rice fields in Barito Kuala Regency are generally dominated by local rice varieties. However, one of the weaknesses of local rice varieties is their relatively long harvest period and low productivity. Local rice has certain advantages because it has been cultivated for generations and is well-adapted to various climates and soil conditions. However, local rice is currently being abandoned and threatened with extinction (Chaniago, 2019). For example, the Siam Unus, Pandak, Bayar Palas, Lemo Kwatik, and Lakatan Gadur varieties have harvest periods of 291, 305, 305, 272, and 295 days after sowing (Wahdah et al., 2012). Nevertheless, these local varieties still dominate agriculture in Barito Kuala Regency due to their high adaptability and ease of cultivation at the farmer level (Azis et al., 2024). One local rice variety widely cultivated by the community is Siam Pandak. This variety is known as a typical South Kalimantan rice with a fragrant aroma, soft taste, and high economic value. Siam Pandak rice is not only popular locally but also has a strong regional market. These organoleptic qualities make Siam Pandak still popular, despite its relatively lower productivity compared to superior national varieties. Siam Pandak yields only an average of 3–4 tons per hectare in tidal areas, while newer superior varieties can reach 6–7 tons per hectare in irrigated areas. Nevertheless, market preference and high selling price make this local variety a top choice for farmers.

The problem that arises is the absence of a study that directly analyzes the relationship between the biophysical conditions of Type A tidal swamps with the production yield of the Siam Pandak variety and the development of rice farming in such environments. A deep understanding of the interaction between local rice varieties and the biophysical factors of tidal swamps is crucial as a basis for developing strategies that enhance productivity while maintaining the distinctive qualities of the variety. Based on this problem, the present study is directed to analyze the biophysical conditions of Type A tidal swamps in Barito Kuala Regency in relation to the productivity of Siam Pandak rice and the development of rice farming, as well as to formulate recommendations for adaptive land management strategies. The results are expected to make a tangible contribution to the development of rice farming in tidal swamp areas, support regional food security, and preserve superior local varieties. This study provides an integrative analysis that simultaneously connects specific biophysical parameters of Type A tidal swamps with the performance of a local rice variety (Siam Pandak) and translates these relationships into practical, site-specific land management recommendations. Such a comprehensive linkage between biophysical characterization, varietal adaptation, and management implications has not been explicitly explored in previous research.

METHOD

Research Design

This study employed a quantitative, field-based observational design to assess the biophysical characteristics of Type A tidal swampland and their influence on the productivity and economic performance of Siam Pandak rice farming. The research was conducted in Tabunganen Pemurus Village, Tabunganen Subdistrict, Barito Kuala Regency, South Kalimantan Province. Fieldwork took place over one planting season from August to October 2024, corresponding to the second planting season under a transitional tidal phase (dry to wet). During this period, tidal amplitudes and canal operation strongly influence oxidation–reduction dynamics in acid sulfate soils, making it suitable for monitoring changes in soil chemistry and plant response in Type A hydrotopographic zones where land is regularly inundated by both high and low tides (Imanudin et al., 2023).

The study area was purposively selected based on its classification as Type A tidal swamp, the presence of a functioning tidal irrigation–drainage network, and the predominance of Siam Pandak rice. A sketch of Tabunganen Pemurus Village including the main canal system is presented in Figure 1, while Figure 2 shows the spatial distribution of sampling plots along the hydrotopographic gradient (upstream–midstream–downstream) within the village.

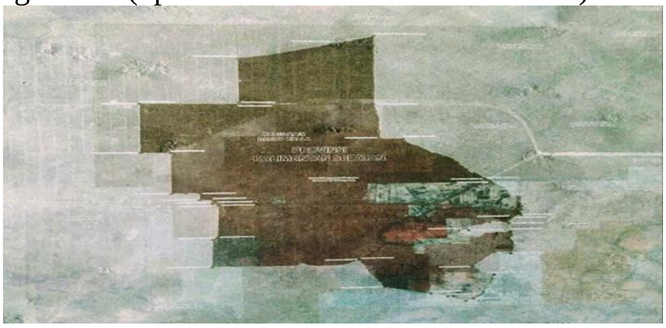

Figure 1. Sketch of the Village of Tabunganen Pemurus

Sampling Design and Field Measurements

Soil sampling and plot layout

Sampling design followed the principle that tidal wetlands and acid sulfate soils exhibit strong vertical and horizontal heterogeneity driven by elevation, inundation regime, and redox processes, so stratified and replicated sampling is needed to avoid pseudo-replication (Nahlik & Fennessy, 2016; Moon et al., 2018; Hulisz et al., 2020). Accordingly, six sampling plots (P1–P6) were established along the Type A hydrotopographic gradient, each measuring 20 × 20 m. Plot size was chosen as a compromise between capturing within-field heterogeneity and maintaining manageable field effort, consistent with plot-based designs used in wetland and agricultural landscapes (Lombardi et al., 2015).

The plots were positioned to represent upstream (near primary canals), midstream, and downstream (near outlets) positions (Figure 2). This layout reflects expected variation in drainage, tidal flooding intensity, sediment deposition, and Fe/Al mobilization along the canal network (Imanudin et al., 2021; Nurrahman et al., 2025).

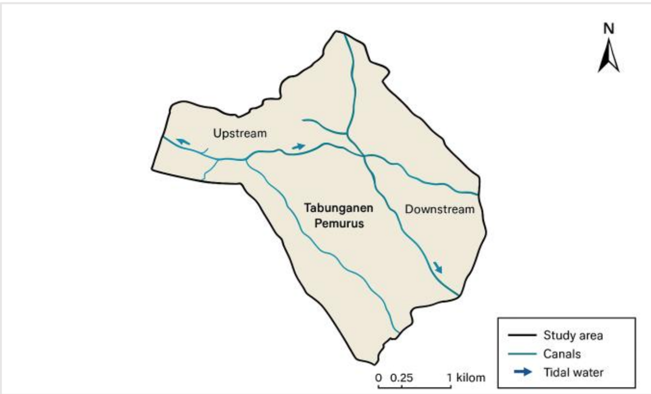

Figure 2. Study area showing the hydrotopographic gradient and sampling plots.

Within each plot, soil was sampled at two depth intervals: 0–15 cm and 15–30 cm. These depths correspond to the active root zone of lowland rice and the zone where redox-sensitive processes and acid sulfate behavior are most pronounced (Gribaldi et al., 2016; Fulazzaky et al., 2022; Ahmad et al., 2024). The surface layer (0–15 cm) captures the zone most directly affected by surface-applied amendments and root activity, while 15–30 cm represents the upper part of the reduced subsoil and potential oxidation front in acid sulfate conditions (Hulisz et al., 2020; Kimiti et al., 2021).

For each depth in every plot, three subsamples were taken in a randomized pattern using an auger and combined into one composite sample per depth and plot. In total, this yielded 36 composite samples (6 plots × 2 depths × 3 composite replicates), which is consistent with composite sampling strategies recommended for heterogeneous acid sulfate and wetland soils to average microscale variability while controlling analytical costs (Ruiz et al., 2023; Nahlik & Fennessy, 2016).

Agronomic measurements and yield

Agronomic measurements of Siam Pandak rice were collected in farmer-managed fields located within the same hydrotopographic setting as the soil plots. Twenty farmer-managed fields were purposively selected to represent the range of soil conditions and water management practices in Type A tidal swamps. In each of these 20 fields, a 20 × 20 m observation plot was delineated using corner markers and tape.

Within each 20 × 20 m field plot, plant measurements followed a systematic five-point subsampling scheme (four corners and the center). At each point, two representative hills were sampled, resulting in 10 hills per field. On each sampled hill, the following variables were recorded at physiological maturity:

- Plant height (cm), measured from soil surface to the tip of the tallest panicle;
- Number of productive tillers per hill;
- Panicle length (cm), measured from panicle base to the tip of the longest spikelet;
- Number of grains per panicle;
- Weight of 1,000 grains (g) after oven drying to constant weight.

Grain yield was determined from a 5 × 5 m harvest subplot located in the center of each 20 × 20 m field plot. All hills within this 25 m² area were harvested, threshed, and weighed. Grain yield was adjusted to standard moisture content and converted to tons of dry harvested grain per hectare (GKG/ha). The growth and yield indicators used to characterize Siam Pandak performance and as background for regression analysis are summarized in Table 2 in the Results section.

Water management and drainage classification

Because water regime is a key driver of biogeochemistry and plant response in tidal swamps, water levels were visually monitored in each field throughout the season. Ponding depth and duration were recorded at key growth stages (tillering, panicle initiation, grain filling) using a simple ruler fixed in the plot. These observations, combined with farmer information on canal operation, were used to classify each plot into a drainage class reflecting overall seasonal water regime:

1 = prolonged shallow flooding (< 5 cm),
2 = optimal ponding for lowland rice (5–20 cm, intermittent),
3 = prolonged deeper flooding (> 20 cm).

This ordinal drainage classification was later included as predictor X_7 in the regression models. It is also reflected qualitatively in the "Drainage" row of Table 1, which summarizes the overall biophysical characteristics of the Type A tidal swamp in the study site.

Laboratory Analyses

All collected soil samples were air-dried, gently crushed, and passed through a 2-mm sieve prior to analysis. Laboratory analyses were performed at a certified soil testing laboratory following standard protocols for wetland and agricultural soils.

Physical properties included soil texture, determined by the hydrometer method, and qualitative assessment of soil structure and moisture retention to support interpretation of water movement and root development.

Chemical properties were determined as follows:

- Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter (Unagwu et al., 2023).
- Organic matter (OM) content was determined using the Walkley–Black wet oxidation method and converted from soil organic carbon using a standard factor, a widely used, cost-effective procedure for SOM estimation in agricultural and wetland soils (Różański & Stefaniuk, 2016; Xie et al., 2023).
- Total nitrogen (N) was analyzed using the Kjeldahl digestion method (Tebeje et al., 2024; Nguyen et al., 2024).

- Available phosphorus (P) was extracted using the Bray I method and analyzed colorimetrically, consistent with its routine use for acidic, highly weathered soils (Anago et al., 2021).
- Exchangeable potassium (K) was extracted using 1N ammonium acetate (NH_4OAc) and quantified by flame photometry, following standard exchangeable cation procedures (Arthur, 2017; Chabbi et al., 2024).
- Cation exchange capacity (CEC) was measured using NH_4OAc saturation and used together with exchangeable bases to calculate base saturation.

To characterize potential toxicity in this acid sulfate environment, available iron (Fe) and aluminum (Al) were extracted using DTPA and quantified with atomic absorption spectrophotometry (AAS), following procedures for bioavailable metals in soils (Pessoa-Filho et al., 2015; Leštan, 2015). The combined DTPA-extractable Fe + Al (mg kg^{-1}) was used as a continuous indicator of potential Fe/Al toxicity (X_8). Visual symptoms of Fe toxicity (leaf bronzing, chlorosis) and growth depression were also recorded in the field to support interpretation (Ye et al., 2018).

The main soil parameters used in subsequent analyses texture, pH, OM, total N, available P, exchangeable K, base saturation, drainage status, and potential Fe/Al toxicity are summarized with their ranges and qualitative interpretations in Table 1 of the Results section.

Farmer Survey and Economic Data

To link biophysical conditions to farm-level economic outcomes, primary economic data were collected from the same 20 farmers whose fields were monitored agronomically. A structured questionnaire was administered through face-to-face interviews to gather information on: landholding, input use (seed, fertilizer, lime, pesticides), labor (family and hired), machinery services, other variable costs, fixed costs (land tax, equipment depreciation), yield sold and consumed, and grain sale price.

Total revenue (TR) per season was computed as:

$$TR = Y \times P$$

where $Y$is rice yield (t GKG/ha) and $P$is the actual farm-gate grain price (IDR/kg). Total cost (TC) was calculated as the sum of all variable and fixed costs per hectare per season. Net income per hectare per season was then:

$$\text{Net income} = TR - TC$$

Farm profitability was evaluated using the Revenue–Cost Ratio (R/C):

$$R/C = \frac{TR}{TC}$$

An $R/C > 1$was interpreted as economically feasible. In addition to calculating income and R/C at the prevailing average price, a simple sensitivity analysis was carried out across three grain price scenarios (IDR 5,000; 5,200; and 7,143 per kg) to evaluate the robustness of farm profitability to price fluctuations. Summary descriptive statistics for production and income variables are reported in the Results section, and regression-based relationships between biophysical variables and farm income are presented in Table 4.

Data Analysis

Data analysis combined descriptive statistics and inferential modeling. Descriptive statistics (mean, standard deviation, minimum–maximum) were computed for all soil, plant, and economic variables to characterize the overall condition of the Type A tidal swamp and Siam Pandak performance. These descriptive summaries underpin Table 1 (soil biophysical conditions) and Table 2 (growth and yield characteristics).

To quantify the influence of biophysical conditions on Siam Pandak productivity, a multiple linear regression (MLR) model was specified with rice yield (tons GKG/ha; field-level mean per 20 × 20 m plot) as the dependent variable:

$$Y_{\text{yield}} = \beta_0 + \beta_1 \text{pH} + \beta_2 \text{OM} + \beta_3 N + \beta_4 P + \beta_5 K + \beta_6 BS + \beta_7 D + \beta_8 \text{FeAl} + \varepsilon$$

where pH = soil pH, OM = organic matter (%), N= total N (%), P= available P (ppm), K= exchangeable K (cmol kg⁻¹), BS= base saturation (%), D= drainage class (1–3), FeAl = DTPA-extractable Fe + Al (mg kg⁻¹), and $\varepsilon$is the error term. For each field, soil variables were represented by the mean of the 0–15 cm layer, which best reflects the active root zone.

A second MLR model examined the effect of the same biophysical variables on farm income (IDR/ha/season):

$$Y_{\text{income}} = \beta_0 + \beta_1\text{pH} + \beta_2\text{OM} + \beta_3 N + \beta_4 P + \beta_5 K + \beta_6 BS + \beta_7 D + \beta_8\text{FeAl} + \varepsilon$$

In both models, the number of observations was $n = 20$, corresponding to the 20 farmer-managed fields. With eight predictors plus the intercept, this implies 11 residual degrees of freedom, consistent with the F-statistics reported in Table 3 (yield model) and Table 4 (income model). Given the relatively small n-to-p ratio, the models are interpreted as exploratory, and emphasis is placed on effect sizes and confidence intervals rather than p-values alone.

All analyses were carried out using standard statistical software (SPSS version 26.0). An alpha level of 0.05 was used to judge statistical significance. Prior to interpreting the regression outputs, key assumptions were checked: linearity (scatterplots of predictors vs. residuals), normality of residuals (histograms and normal Q–Q plots), and homoscedasticity (residuals vs. fitted values). Multicollinearity was evaluated using the Variance Inflation Factor (VIF), with VIF < 10 taken as evidence of acceptable collinearity (Gómez et al., 2020; Shankar et al., 2019). Influential observations were identified using Cook's distance; cases with Cook's distance > 4/n were examined, but none were found to unduly influence model estimates (Baba et al., 2021).

The final regression coefficients (unstandardized and standardized), standard errors, t-statistics, p-values, and 95% confidence intervals for both models are reported in Table 3 (productivity model) and Table 4 (income model) in the Results section.

Ethical Considerations

The study protocol, including on-farm measurements and farmer interviews, was reviewed and approved by the Research Ethics Committee of the Faculty of Agriculture, Universitas Achmad Yani Banjarmasin. All participating farmers were informed about the objectives, procedures, potential risks, and benefits of the study and provided voluntary informed consent prior to data collection. Interview data were anonymized and used solely for research purposes. To enhance transparency and reproducibility, the overall workflow from field sampling, laboratory analysis, and data preprocessing to MLR modeling of productivity and income is summarized schematically in Figure 3, which highlights key decision points such as variable selection, multicollinearity screening (VIF), and the use of a baseline grain price scenario for economic analysis.

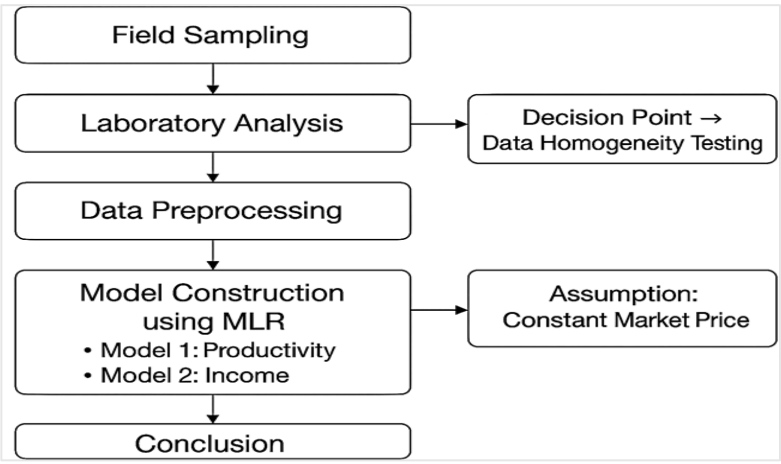

Figure 3. Workflow of data collection, laboratory analysis, preprocessing, and MLR modeling

RESULTS AND DISCUSSION

Result

Land biophysical conditions in Type A tidal swamp

The biophysical evaluation confirms that the Type A tidal swamp in Tabunganen Pemurus Village, Barito Kuala Regency, is physically suitable but chemically constrained for Siam Pandak rice. Across the six 20 × 20 m plots and two depth layers (0–15 cm and 15–30 cm), the soil is dominated by a silty clay loam texture on flat topography (slope <3%), which supports tidal water distribution and mechanical field operations, the data is presented in Table 1 below.

Table 1. Biophysical Data of Tidal swamp in Tabunganen Village

Biophysical Parameters	Criteria	Description
Topography	Flat (slope <3%)	Flat topography facilitates tidal distribution, land cultivation, and rice planting.
Tidal Type	Type A	Optimal for local rice varieties.
Soil Texture	Silty clay loam	This texture retains water and supports aeration, meeting the needs of lowland rice.
Soil pH	4.5–5.0 (acidic)	Acidity can reduce the availability of macronutrients (N, P, K) and increase the solubility of toxic Al and Fe.
Organic Matter Content	2.5–3.5%	Moderate content plays an important role in improving soil structure and providing nutrients.
Total N	0.18–0.25%	Requires additional N fertilizer.
Available P (Bray I)	8–12 ppm	Phosphorus is limited due to fixation by Fe and Al in tidal soils.
Exchangeable K (cmol/kg)	0.25–0.40	Limits grain filling, requiring additional K fertilizer.
Base Saturation	30–40%	Exhibits a predominance of acid ions, resulting in relatively low fertility.
Drainage	Seasonally flooded	Lowland rice requires shallow inundation; poor drainage is a positive for the Siam Pandak variety.
Tillage Depth	>100 cm	The soil is deep enough for rice rooting and water retention.
Potential Toxicity	High (Fe, Al)	Fe toxicity causes browning of leaves, while Al suppresses root growth.

Soil reaction in the root zone is consistently acidic, with pH values in the range of 4.5–5.0. Organic matter content is moderate (2.5–3.5%), reflecting decomposed residues and tidal inputs, whereas total N is low (0.18–0.25%), implying the need for supplementary N fertilization. Available P is 8–12 ppm and exchangeable K 0.25–0.40 cmol kg^{-1}, both low–moderate for lowland rice under acid sulfate conditions, and base saturation of 30–40% indicates a predominance of acidic cations.

Hydrotopographic observations confirm a seasonally flooded regime typical of Type A tidal swamps, with shallow inundation at high tide and temporary drawdown at low tide. Effective soil depth exceeds 100 cm, allowing deep root penetration and substantial water storage. However, high Fe and Al solubility at the beginning of the planting season generates visible toxicity symptoms (leaf bronzing, stunting) in low-lying micro-sites, identified as the main chemical constraint. Overall, the measured biophysical profile depicts a system that is structurally favorable for rice but limited by acidity, low macronutrient availability, and Fe/Al toxicity risk.

Growth and yield performance of Siam Pandak

Siam Pandak rice shows good vegetative adaptation under these tidal conditions. Across farmer-managed plots, plant height at maturity ranges from 135 to 150 cm, consistent with the varietal description for tall local aromatic rice. The number of productive tillers per hill varies between 12 and 18, a moderate-to-good level given the observed N and P status. Panicle length is 24–27 cm, supporting adequate sink capacity for grain formation, while grain number per panicle is 140–160, which is moderate to high for local lowland varieties.

The percentage of filled grain ranges from 75% to 82%; this is "fairly good" but still indicates some grain loss, plausibly linked to episodic Fe toxicity and nutrient limitations. Thousand-grain weight is stable at 26–28 g, indicating that filled kernels are close to the varietal potential. Harvest age is 145–155 days after transplanting, confirming Siam Pandak as a long-duration local variety. Plot-level productivity is 3.5–4.5 t GKG ha^{-1}, which is moderate and still below the potential of 5–6 t ha^{-1} with better soil chemical conditions and fertilization can be seen in Table 2 below.

Table 2. Growth and Yield of Siam Pandak Rice Variety

Growth & Production	Value Range	Status/Interpretation	Description
Plant Height (cm)	135 – 150	Normal	According to the Siam Pandak variety description:
Number of Productive Tillers (stems/clump)	12 – 18	Moderate – good	Limited by N and P availability
Panicle Length (cm)	24 – 27	Good	Panicle length sufficient to accommodate a large amount of grain
Number of Grains per Panicle	140 – 160 grains	Moderate – high	Influenced by nutrient availability, especially K for grain filling.
Percentage of Full Grain	75 – 82%	Fairly good	Influenced by Fe toxicity, which can cause empty grain.
Weight per 1000 Grains (g)	26 – 28	Stable	In accordance with the variety's potential, it shows fully filled grains.
Harvest Age (days after planting)	145 – 155 HST	Long	In accordance with the characteristics of superior local varieties with long maturation.
Productivity (tons of GKG/ha)	3.5 – 4.5	Moderate	Still below potential (5–6 tons/ha), due to soil biophysical limiting factors

Farm production, costs, and profitability

At the farm level, mean grain production per farmer in Tabunganen Pemurus is 4,755.63 kg of dry harvested grain (GKG) per planting season. With a prevailing farm-gate price of IDR 7,142.85 kg^{-1}, mean total revenue reaches IDR 33,968,750 per farmer per season. Total production costs, including fixed costs (land tax, equipment depreciation) and variable costs (seed, fertilizers, pesticides, hired labor), average IDR 11,313,981.77 per farmer per season.

These figures imply a Revenue–Cost ratio of roughly 3.0, indicating that gross revenue is about three times higher than total production costs under prevailing management and price conditions. In combination with the moderate yield range, this suggests that Siam Pandak rice farming in this Type A tidal swamp can be economically attractive for smallholders, largely because of the variety's price premium and strong local market demand. For the econometric analysis, all economic variables are subsequently expressed on a per-hectare-per-season basis to align with the yield data and ensure comparability across fields of different sizes.

Biophysical determinants of Siam Pandak productivity

The first multiple linear regression model quantified the relationships between eight biophysical variables and Siam Pandak productivity (t GKG ha^{-1}) across 20 field-level observations (Table 3). The dependent variable was plot-level yield; predictors were soil pH, organic matter, total N, available P, exchangeable K, base saturation, drainage status, and potential Fe/Al toxicity. The model fit is strong, with $R^2 = 0.82$ and $F(8,11) = 6.25$ ($p < 0.01$), indicating that 82% of observed yield variation is explained by the measured soil and hydrological factors.

Table 3. Multiple linear regression of biophysical land variables on rice productivity

Variable	Coefficient (β)	Std. Error	t-count	p-value	95% CI (Lower)	95% CI (Upper)
Constant	0.920	0.850	1.08	0.290	-0.951	2.791
Soil pH (X_1)	0.580	0.180	3.22	0.005	0.184	0.976
Organic Matter (X_2)	0.420	0.150	2.80	0.010	0.090	0.750
Total N (X_3)	0.250	0.120	2.08	0.050	-0.014	0.514
Available P (X_4)	0.180	0.090	2.00	0.060	-0.018	0.378
Exchangeable K (X_5)	0.090	0.040	2.25	0.040	0.002	0.178
Base Saturation (X_6)	0.050	0.020	2.10	0.050	0.006	0.094
Drainage (X_7)	0.400	0.200	2.00	0.060	-0.040	0.840
Potential Fe/Al Toxicity (X_8)	-0.015	0.006	-2.50	0.020	-0.028	-0.002

$R^2 = 0.82 \rightarrow$ 82% of the productivity variation is explained by biophysical variables.
F test: $F(8,11) = 6.25$; $p < 0.01 \rightarrow$ significant model

Soil pH has a positive, statistically significant coefficient (β = 0.580, SE = 0.180, t = 3.22, p = 0.005; 95% CI: 0.184–0.976), confirming that less acidic conditions are associated with higher yields. Organic matter is likewise positive and significant (β = 0.420, SE = 0.150, t = 2.80, p = 0.010), highlighting the role of soil organic status in supporting biomass production and grain filling. Total N (β = 0.250, SE = 0.120, t = 2.08, p = 0.050) contributes positively at the 5% threshold, while available P (β = 0.180, p = 0.060) is near-significant but still supportive in direction. Exchangeable K (β = 0.090, SE = 0.040, t = 2.25, p = 0.040) is significantly positive, and base saturation (β = 0.050, SE = 0.020, t = 2.10, p = 0.050) shows a modest but beneficial effect, reflecting the importance of balanced macronutrient supply and a higher proportion of basic cations.

Drainage status, coded to reflect relative water-level control within the Type A hydrotopographic class, has a positive coefficient (β = 0.400, SE = 0.200, t = 2.00, p = 0.060). Although slightly above the conventional 5% threshold, it indicates that fields with better-regulated seasonal flooding tend to attain higher yields. In contrast, potential Fe/Al toxicity has a negative, significant effect (β = −0.015, SE = 0.006, t = −2.50, p = 0.020; 95% CI: −0.028 to −0.002), confirming that higher Fe/Al stress reduces productivity.

Residual–fitted plots, Q–Q plots, and Cook’s distance were used to assess model assumptions. Residuals showed no strong deviations from linearity or homoscedasticity, and no highly influential observations were detected, supporting the adequacy of the linear specification for summarizing these biophysical–productivity relationships.

Biophysical determinants of farm income

A second multiple linear regression model linked the same biophysical variables to farm income from Siam Pandak rice, expressed as IDR ha^{-1} per season (Table 4). Using the same 20 observations, the income model exhibits high explanatory power, with $R^2 = 0.85$, adjusted $R^2 = 0.80$, and $F(8,11) = 7.55$ ($p < 0.001$). Thus, around 80–85% of the variability in per-hectare income is accounted for by the measured soil and drainage conditions.

Table 4. Multiple linear regression of biophysical land variables on farm income from Siam Pandak rice (IDR/ha/season)

Variable	Coefficient (β)	Std. Error	t-count	p-value	95% CI (Lower)	95% CI (Upper)
Constant	-4.500	2.100	-2.14	0.050	-9.122	0.122
Soil pH (X_1)	1.750	0.400	4.38	0.001	0.870	2.630
Organic Matter (X_2)	1.100	0.350	3.14	0.006	0.330	1.870
Total N (X_3)	0.600	0.250	2.40	0.030	0.050	1.150

Variable	Coefficient (β)	Std. Error	t-count	p-value	95% CI (Lower)	95% CI (Upper)
Available P (X_4)	0.300	0.120	2.50	0.020	0.036	0.564
Exchangeable K (X_5)	0.150	0.070	2.10	0.050	-0.004	0.304
Base Saturation (X_6)	0.080	0.030	2.67	0.020	0.014	0.146
Drainage (X_7)	0.700	0.250	2.80	0.010	0.150	1.250
Potential Fe/Al Toxicity (X_8)	-0.040	0.010	-3.20	0.005	-0.062	-0.018

$R^2 = 0.85$; Adjusted $R^2 = 0.80$
Uji F: $F(8,11) = 7.55$; $p < 0.001$

Soil pH again emerges as the dominant positive determinant (β = 1.750, SE = 0.400, t = 4.38, p = 0.001; 95% CI: 0.870–2.630), showing that less acidic soils generate substantially higher net returns per hectare. Organic matter (β = 1.100, SE = 0.350, t = 3.14, p = 0.006) and total N (β = 0.600, SE = 0.250, t = 2.40, p = 0.030) also exert significant positive effects, indicating that improved organic status and N supply raise both yield and income. Available P (β = 0.300, SE = 0.120, t = 2.50, p = 0.020) and exchangeable K (β = 0.150, SE = 0.070, t = 2.10, p = 0.050) contribute positively, underscoring the role of balanced macronutrient management in profitable production. Base saturation (β = 0.080, SE = 0.030, t = 2.67, p = 0.020) again appears as a supportive factor, reflecting the economic benefits of a more favorable cation balance.

Drainage status shows a positive and significant relationship with income (β = 0.700, SE = 0.250, t = 2.80, p = 0.010; 95% CI: 0.150–1.250), indicating that better-controlled water tables in the Type A regime are associated with higher per-hectare returns, likely via reduced yield risk and damage. Potential Fe/Al toxicity has a strong negative effect (β = −0.040, SE = 0.010, t = −3.20, p = 0.005; 95% CI: −0.062 to −0.018), showing that higher Fe/Al stress substantially reduces farm income by depressing yields and increasing the risk of partial crop failure. Diagnostics for this model similarly indicate acceptable residual behavior and no unduly influential points. Overall, the income analysis reinforces the productivity results: the same biophysical levers that most strongly affect yield particularly pH, organic matter, macronutrients, drainage, and Fe/Al toxicity also determine the economic viability of Siam Pandak rice farming in Type A tidal swamps.

Discussion

The biophysical conditions in Type A tidal swamps of Barito Kuala Regency play a significant role in influencing the productivity of Siam Pandak rice cultivation. This study highlights that while the soil properties and water management strategies are generally favorable for rice farming, challenges such as iron (Fe) and aluminum (Al) toxicity due to acidic soils pose considerable limitations to rice yields and overall farm productivity. These findings underscore the importance of understanding the intricate relationships between soil chemistry, hydrology, and crop management practices to improve rice farming sustainability in tidal swamp environments. This section synthesizes the key findings and discusses their implications in the context of the broader agricultural challenges and opportunities for smallholder rice farmers.

Biophysical Influences on Rice Productivity

The relationship between soil properties and rice growth has long been established, with several studies indicating that soil pH, organic matter, and nutrient availability are central to achieving high yields in lowland rice systems (Sari et al., 2018; Sonu et al., 2024). In the current study, soil pH was found to be a critical determinant of rice productivity, with levels below 5.0 resulting in increased solubility of toxic metals like iron and aluminum. As soil pH increases, it not only reduces metal toxicity but also improves nutrient availability. The positive effects of maintaining a slightly acidic to neutral pH are well documented, particularly for rice cultivation in acid sulfate soils, where low pH exacerbates Fe and Al toxicity (Napisah & Maftu'ah, 2024). As demonstrated in this study, even slight increases in pH achieved through practices such as liming have been shown to substantially improve yield by reducing metal toxicity while enhancing the availability of essential nutrients like nitrogen and phosphorus.

Organic matter also plays a pivotal role in enhancing soil fertility, particularly in wetland soils where soil structure can become compacted and poorly aerated. This study found that organic matter content in the range of 2.5–3.5% supported both improved nutrient availability and better water retention, which are crucial factors for rice growth in tidal environments. The dual role of organic matter improving both soil structure and nutrient supply is consistent with the findings of Kurnain et al. (2022), who highlighted that organic amendments can help mitigate the challenges posed by acidic and nutrient-poor soils by enhancing cation exchange capacity (CEC) and nutrient cycling.

Additionally, drainage is a critical factor that influences nutrient dynamics and rice productivity in tidal swamp systems. Adequate drainage helps maintain proper soil aeration, essential for root function and nutrient uptake (Setiawan et al., 2022). In contrast, poor drainage can lead to waterlogging, which is detrimental to rice growth and can exacerbate nutrient deficiencies. Effective water management not only improves nutrient availability but also reduces the risks associated with flooding and drought, which are frequent in tidal environments. The study highlights that improving drainage, along with other practices like alternate wetting and drying (AWD), can stabilize water levels, reduce nutrient losses, and improve farm productivity (Bwire et al., 2023).

Fe and Al Toxicity: Constraints and Mitigation Strategies

Iron and aluminum toxicity continue to be major constraints to rice cultivation in acid sulfate soils, particularly in tidal swamp environments where the soils are naturally acidic and prone to periodic flooding. The study confirms the findings of Murphy et al. (2018), who reported that Fe and Al toxicity are exacerbated in waterlogged conditions, leading to reduced root function, chlorosis, and stunted growth. This study observed that high concentrations of soluble Fe^{2+} and Al^{3+} in the soil, typical of acidic conditions, hindered grain filling and resulted in lower rice yields. These findings align with those of Rodriguez (2020), who emphasized the negative impact of Fe toxicity on grain number and overall yield in flooded rice systems.

To mitigate Fe and Al toxicity, soil amendments such as lime have proven effective in raising soil pH and reducing the solubility of these toxic metals. Liu et al. (2020) found that liming effectively neutralizes soil acidity, thereby reducing Fe and Al solubility and enhancing nutrient availability. The current study observed similar results, where the application of lime raised the soil pH from below 5.0 to around 5.5, significantly reducing Fe toxicity and improving nutrient uptake. This aligns with the work of Hamid et al. (2018), who reported that liming not only reduced metal toxicity but also enhanced microbial activity and nutrient cycling, which are vital for rice growth in tidal swamp environments.

Additionally, organic amendments such as compost and biochar have shown promise in mitigating Fe toxicity by chelating Fe and reducing its availability in the soil. Biochar, particularly rice husk biochar, has been shown to improve soil pH, increase nutrient availability, and reduce soluble Fe concentrations in flooded soils (Annisa et al., 2021; Perwira et al., 2023). The application of biochar in the current study improved soil chemical properties, enhanced nutrient retention, and contributed to better rice growth and higher yields. Biochar's ability to reduce Fe toxicity through pH modification and metal immobilization supports its use as a sustainable amendment in tidal swamp rice farming (Panjaitan et al., 2024).

While lime and biochar have been demonstrated to mitigate Fe toxicity, their effectiveness depends on proper application rates and the specific characteristics of the soil. Future research should focus on optimizing the application rates of these amendments for maximum efficacy in different tidal swamp contexts. Furthermore, combining liming with organic amendments may offer a more comprehensive approach to soil health and rice productivity in these challenging environments.

Water Management: Enhancing Nutrient Uptake and Reducing Toxicity

Water management practices are crucial in tidal swamp rice farming, where fluctuating water levels can exacerbate nutrient deficiencies and metal toxicity. The study highlighted the role of water management strategies, such as AWD and effective drainage, in mitigating the negative effects of waterlogging and iron toxicity. AWD, which alternates between wet and dry periods, has been shown to enhance root development, increase nutrient uptake, and reduce the solubility of toxic metals such as Fe (Panhwar et al., 2020). The findings of this study support the work of Setiawan et al. (2022), who demonstrated that AWD improved rice growth by promoting better oxygen availability in the soil, which in turn facilitated better nutrient absorption and reduced Fe toxicity.

In tidal environments, where water levels are heavily influenced by tidal cycles, controlling the flow of water through one-way flow systems and gated channels is essential for managing salinity and preventing the backflow of contaminated water (Mawardi & Khairullah, 2022; Setiawan et al., 2022). These systems can help regulate freshwater ingress, leach excess salts, and manage soil acidity, all of which are crucial for improving rice yield in tidal swamp conditions. The use of one-way flow systems and tidal control structures in the study area contributed to better water quality and more stable growing conditions, which ultimately enhanced rice productivity.

Moreover, the study highlights the importance of water-table management, especially in acid sulfate soils, where improper water management can lead to the mobilization of toxic ions. Effective water-table management through controlled flooding and drainage has been shown to promote the oxidation of iron, reducing its solubility and alleviating toxicity (Carmona et al., 2021; Lestari et al., 2025). In this study, water management practices that maintained a stable water table and facilitated periodic drainage were associated with improved rice yields, reinforcing the role of water control in enhancing both rice growth and nutrient dynamics in tidal swamp environments.

Economic Implications of Biophysical Improvements

The economic analysis in this study reveals that implementing effective biophysical management practices, particularly liming, organic amendments, and efficient water management, can lead to significant increases in rice productivity and farm income in tidal swamp regions. The study found that farmers who adopted such practices recorded not only higher rice yields but also greater profitability. These results are consistent with a growing body of literature showing that soil health improvements and optimal water management have a direct, positive impact on economic outcomes in rice farming, particularly in vulnerable areas such as tidal swamps (Mawardi et al., 2020; Panjaitan et al., 2024; Setiawan et al., 2022).

One of the major economic benefits of these biophysical improvements is the reduction in the need for expensive fertilizers and pesticides. Traditional rice farming in areas with acid sulfate soils often requires high inputs of chemical fertilizers to compensate for soil deficiencies, particularly nitrogen, phosphorus, and potassium. However, with the incorporation of organic amendments, such as compost and biochar, and the application of lime to raise soil pH, the availability of these nutrients is naturally enhanced, reducing the need for chemical inputs (Helmi, 2015; Kurnain et al., 2022). By improving soil structure, organic amendments enhance the cation exchange capacity (CEC) of the soil, which increases its ability to retain essential nutrients and reduces nutrient leaching, especially during the wet season. The use of lime, particularly, raises soil pH, reducing metal toxicity from Fe and Al, which are known to impair rice growth in acidic conditions. The combined benefits of these amendments mean that farmers can achieve better yields with fewer external inputs, ultimately lowering production costs and improving profitability.

In addition to reducing input costs, these practices increase the resilience of rice farming systems, helping farmers to better manage the risks posed by environmental challenges such as flooding and drought. Tidal swamps are prone to extreme water fluctuations, and efficient water management practices, such as alternate wetting and drying (AWD), are crucial for controlling water levels, improving soil aeration, and optimizing nutrient availability (Bwire et al., 2023; Panhwar et al., 2020). This study found that effective water management not only enhanced rice productivity but also reduced the negative impacts of waterlogging, which is a common problem in tidal swamps. By improving water control and integrating it with soil health practices, farmers are able to stabilize their production systems, making them more resilient to fluctuating climatic conditions and less vulnerable to losses caused by water stress.

The economic benefits of integrated soil and water management strategies also go beyond yield improvements. As these practices help to create more sustainable farming systems, they ensure long-term farm income stability. For instance, by enhancing soil fertility and minimizing the need for external chemical inputs, farmers are able to reduce the risks of rising production costs, which are a major concern in resource-constrained environments (Mawardi & Khairullah, 2022; Setiyono & Rahayu, 2018). This is particularly important for smallholder farmers in tidal swamps, who often operate with limited resources and face financial uncertainty due to unpredictable climatic conditions.

In terms of financial returns, the study showed that smallholder farmers who adopted these biophysical practices had significantly higher net incomes, ranging from IDR 15 to 18 million per hectare per season, compared to farmers who did not implement the recommended practices. These findings align with the work of Kurnain et al. (2022), who found that soil fertility improvements and integrated nutrient management (INM) could increase farm income by improving nutrient-use efficiency and reducing the need for costly external inputs. Similarly, the work of Panjaitan et al. (2024) highlights how biochar and organic amendments can contribute to both higher yields and cost reductions, further supporting the economic case for biophysical improvements in tidal swamp rice systems.

Ultimately, the economic analysis of this study highlights the potential for smallholder farmers to significantly benefit from integrating soil health improvements and efficient water management practices. These strategies provide a cost-effective means of enhancing productivity, reducing production costs, and stabilizing farm income, ensuring the sustainability and profitability of rice farming in the long term. Future research should continue to explore the economic impact of these biophysical practices in different tidal swamp contexts, examining how they can be scaled up and adapted to varying environmental and socio-economic conditions.

Limitations and Future Directions

While this study provides valuable insights into the biophysical and economic aspects of rice farming in tidal swamps, several limitations need to be addressed in future research. One limitation is the relatively short duration of the study, which may not capture the full range of variability in water and soil conditions across multiple seasons. Long-term field studies are necessary to assess the consistency and sustainability of biophysical improvements over time, especially in the context of changing climatic conditions. Additionally, the study primarily focused on a single variety of rice (Siam Pandak), and future research should explore the response of other rice varieties to the same biophysical interventions. Different rice varieties may have varying tolerance to Fe and Al toxicity, and understanding these variations can help tailor management practices for different cultivars. Finally, while the study focused on the impact of biophysical conditions on rice productivity, future research should also consider the social and economic aspects of rice farming in tidal swamps. This includes examining the socio-economic factors that influence the adoption of improved management practices, such as access to credit, market opportunities, and farmer education.

CONCLUSION

This study emphasizes the critical role of biophysical conditions in influencing the productivity and economic sustainability of Siam Pandak rice farming in Type A tidal swamps of Barito Kuala Regency. Key biophysical factors such as soil pH, organic matter content, nutrient availability, and the presence of iron (Fe) and aluminum (Al) toxicity have significant effects on rice growth, yield, and overall farm productivity. Managing soil properties and optimizing farming practices are essential strategies for improving rice yields and ensuring the long-term viability of farming in tidal swamp environments.

Soil pH, in particular, was found to significantly affect nutrient availability and the solubility of toxic metals like Fe and Al, which can hinder rice growth and reduce yields. Raising soil pH through practices like liming or dolomite application can mitigate the adverse effects of Fe and Al toxicity, thereby improving nutrient uptake and promoting root development. This study confirms that liming can enhance soil conditions, contributing to higher rice productivity. Maintaining an optimal pH range of 5.0 to 6.5 is crucial for maximizing nutrient bioavailability and minimizing the negative impact of metal toxicity on rice cultivation.

The study also highlights the importance of effective water management, essential for controlling fluctuating water levels and preventing waterlogging in tidal swamp ecosystems. Water management practices, such as alternating wetting and drying (AWD) and efficient drainage, help maintain proper soil aeration, reduce toxic metal solubility, and promote root growth, leading to higher yields.

Furthermore, organic matter content plays a key role in improving soil structure and enhancing water retention in tidal swamp conditions. The application of organic amendments like rice husk ash (RHA) or biochar, along with liming, improves soil health, nutrient cycling, and microbial diversity. These combined practices result in a more resilient and productive farming system, capable of withstanding environmental challenges.

Economically, these biophysical management practices reduce the need for expensive inputs like fertilizers and pesticides, lowering production costs and enhancing farm profitability. Increased farm productivity and better management practices lead to greater income for farmers, improving food security and economic stability in the region.

RECOMMENDATION

Based on the findings of this study, several recommendations can be made to enhance the sustainability and productivity of Siam Pandak rice farming in Type A tidal swamps of Barito Kuala Regency. First and foremost, improving soil management through the application of liming or dolomite is highly recommended. Given the significant impact of soil pH on nutrient availability and metal toxicity, maintaining an optimal pH range of 5.0 to 6.5 is essential for improving rice yield. Regular soil testing should be conducted to monitor pH levels and other soil properties, allowing farmers to make informed decisions about when and how to apply lime or dolomite. This practice not only helps mitigate the harmful effects of Fe and Al toxicity but also enhances nutrient uptake, promoting better plant growth and higher yields.

In addition to soil pH management, the use of organic amendments such as rice husk ash (RHA) and biochar should be encouraged. These organic inputs have been shown to improve soil structure, increase water retention, and enhance microbial activity. By integrating organic amendments with traditional farming practices, farmers can further boost soil fertility and support sustainable farming systems in tidal swamp environments. This combination of chemical and organic approaches can also help enhance the long-term health of the soil, making it more resilient to environmental stressors such as flooding and drought.

Water management plays a pivotal role in the success of rice farming in tidal swamps, and thus, it is crucial to implement effective water control systems. Practices such as alternating wetting and drying (AWD) and efficient drainage are recommended to prevent waterlogging and reduce the solubility of toxic metals. Farmers should be trained on the benefits of these water management strategies and how to apply them effectively, especially in areas prone to fluctuating water levels. The use of one-way flow systems and well-designed drainage networks should be promoted to improve water quality, soil aeration, and nutrient availability in rice paddies.

Lastly, the adoption of integrated soil and water management strategies is essential for ensuring the long-term economic sustainability of rice farming in tidal swamps. Farmers should be encouraged to adopt a holistic approach that includes optimizing soil conditions, improving water management, and utilizing organic amendments. Government support, including access to affordable inputs like lime, biochar, and other organic fertilizers, should be provided to smallholder farmers. Additionally, further research and extension services are needed to continue developing and disseminating best practices tailored to the specific biophysical challenges of tidal swamp environments. These measures will not only improve farm profitability but also contribute to greater food security and economic stability in the region.

AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Zulipah Mahdalena	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
M. Rifky Aditya		✓				✓		✓	✓	✓	✓	✓		

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author.

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