CHILEAN JOURNAL of AGRICULTURAL RESEARCH

CHILEANJAR
CHILEAN JOURNAL of AGRICULTURAL RESEARCH

RESEARCH ARTICLE

Tidal inundation type and soil chemical properties determine rice productivity in tropical acid sulfate swamp ecosystems

Nukhak Nufita Sari[1], Masganti Masganti[2*], Andin Muhammad Abduh[3], Muhammad Rizky Romadhon[3], Rachmiwati Yusuf[4], Yanti Rina[5], Eni Maftu'ah[2], Khairil Anwar[2], Puspita Harum Maharani[2], Anna Hairani[2], Muhammad Alwi[2], Parlin Holomoan Sinaga[2], Nurhayati Nurhayati[4], Nurmili Yuliani[4], and Olvie Grietjie Tandi[4]

[1]Lambung Mangkurat University, Faculty of Agriculture, Department of Agroecotechnology, Banjarbaru 70714, South Kalimantan, Indonesia.
[2]National Research and Innovation Agency (BRIN), Research Center for Food Crops, Cibinong, Bogor 16911, West Java, Indonesia.
[3]Lambung Mangkurat University, Faculty of Agriculture, Department of Soil Science, Banjarbaru 70714, South Kalimantan, Indonesia.
[4]National Research and Innovation Agency (BRIN), Research Center for Horticultural and Estate, Crops, Food and Agricultural Research Organization, Cibinong, Bogor 16911, West Java, Indonesia.
[5]National Research and Innovation Agency (BRIN), Research Center for Behavioral and Circular Economics, Jakarta 12710, Indonesia.
[*]Corresponding author (masg001@brin.go.id)
Received: 9 April 2026; Accepted: 14 July 2026, Available online: 7 September 2026. doi:10.4067/S0718-58392026000600884

ABSTRACT

Ensuring sustainable rice (*Oryza sativa* L.) production in tidal swamp ecosystems is critical for strengthening food security in Indonesia. Soil chemical properties, tidal inundation type, and planting season strongly influence rice productivity in these systems. This study evaluated soil chemical characteristics and rice productivity across tidal swamp areas in Tanah Bumbu Regency, South Kalimantan, Indonesia, by inundation type and cropping season. Field surveys, soil analyses, and farmer interviews were conducted in five villages. Selimuran and Mudalang were classified as Type B tidal swamps. In contrast, Rantau Panjang, Api-api, and Segumbang were categorized as Type C. Type B soils were acidic, while Type C soils were very acidic. Although both types exhibited low organic C, total N, and exchangeable P, Type B soils had higher P and base cation availability and lower concentrations of exchangeable Al, Fe, sulfate, and pyrite. The pyritic layer was shallower in Type C soils, increasing oxidation risk. Rice productivity was significantly higher in Type B systems (5.43 t ha^{-1}) than in Type C systems (3.76 t ha^{-1}). Seasonal responses differed between tidal types. Yields in Type B fields declined by 0.95 t ha^{-1} from the dry to the rainy season, whereas yields in Type C fields increased by 0.45 t ha^{-1}. These findings highlight the importance of site- and season-specific nutrient and water management to enhance productivity and sustainability in acid sulfate tidal swamp ecosystems.

Key words: Acid sulfate soils, *Oryza sativa*, rice yield variability, seasonal water dynamics, soil chemical properties, tidal inundation, tidal swamp ecosystem.

INTRODUCTION

Rice (*Oryza sativa* L.) is the main staple food in Indonesia and must be available in increasing quantities due to rapid population growth, rising per capita energy requirements, declining rice production capacity, and the Government of Indonesia's commitment to becoming a global food granary by 2045. National rice production in 2024 declined by 3.75% compared with 2021 (Setiyanto et al., 2024). The limited diversification of carbohydrate sources and inefficient consumption patterns further exacerbate this decline. Rice shortages in the domestic market can trigger widespread public concern among consumers, industries, and traders. In response, the government frequently implements market intervention measures to stabilize rice prices.

However, such interventions are largely reactive and short-term. Over the long term, persistent supply instability poses a serious threat to national food independence and sovereignty. Ensuring a reliable and sustainable rice supply, therefore, remains a strategic priority for Indonesia.

Constraints on rice production capacity are closely linked to land availability, land quality, and land-use dynamics. Major challenges include (1) agricultural land conversion, (2) fragmentation and reduction of farm size, (3) declining soil fertility, and (4) increasing internal competition among land uses. Previous studies have emphasized that large-scale land conversion poses a significant threat to national food availability and food security (Novianty et al., 2025). Java Island, which has traditionally served as the backbone of the national rice supply, has experienced extensive conversion of irrigated paddy fields into residential areas, industrial zones, and transportation infrastructure, with nearly 90% of technical irrigation areas affected (Tirtalistyani et al., 2022). Additionally, rice farming is often perceived by farmers and rural youth as an unattractive and low-return sector, while pressing financial needs further encourage the sale of agricultural land.

Another factor reducing rice production capacity is the progressive shrinkage of cultivated landholdings, driven by land inheritance systems and increasing climate extremes. For example, a farmer owning 2.0 ha of rice land and having four children may, after 40-50 yr, pass on fragmented holdings such that eight grandchildren manage only about 0.25 ha each. Furthermore, the increasing frequency of extreme climatic events has discouraged rice cultivation in saline-affected areas, where farmers often abandon low-productivity fields and convert them into fishponds or salt ponds (Arifah et al., 2022). Declining rice production is also closely associated with reduced land productivity caused by soil degradation and declining soil fertility. Improper fertilization practices frequently result in nutrient imbalances, leading to specific nutrient deficiencies in rice plants and, in some cases, deterioration of soil structure, ultimately reducing fertilizer-use efficiency. Soil fertility degradation is further intensified by the application of non-site-specific fertilizer doses and the removal of rice straw from fields, practices that have led to widespread deficiencies of soil organic C, particularly in tidal swamp rice fields (Muliarta and Purba, 2020; Simarmata et al., 2025).

Government programs aimed at expanding planting areas and increasing production of selected commodities have also intensified competition for land resources. For instance, the expansion of *Jatropha curcas* and oil palm (*Elaeis guineensis* Jacq.) as alternative energy crops could reduce the area allocated to rice cultivation. Indonesia possesses approximately 8.92 million ha of tidal swamp land, of which about 3.45 million ha are considered suitable for agricultural development (Susilawati et al., 2023). Land suitability analyses indicate that around 2.81 million ha of tidal swamp land are suitable for rice cultivation, comprising 2.63 million ha of mineral soils and 0.18 million ha of peat soils. Nevertheless, the production capacity of tidal swamp rice systems remains relatively low, limiting their contribution to the national rice supply (Ilham et al., 2023).

Tanah Bumbu Regency is one of the major rice-producing regions in South Kalimantan, based on tidal swamp ecosystems. Rice production capacity in tidal swamp areas is strongly influenced by inundation types, as well as inherent soil properties such as soil acidity, deficiencies of essential nutrients and organic C, and toxicity of certain elements, including Fe, sulfate, Al, and pyrite (Susilawati et al., 2017; Fahmi et al., 2019; Merkohasanaj et al., 2025). Therefore, comprehensive characterization of the chemical properties of tidal swamp soils, along with an inventory of cultivation technologies and rice productivity across inundation types and planting seasons, is essential as a basis for developing site and season-specific nutrient and crop management recommendations.

MATERIALS AND METHODS

Study area and period

This study was carried out using an integrated approach combining field surveys and laboratory-based soil analyses over 5 mo, from November 2021 to March 2022. The research was conducted in five representative villages in Tanah Bumbu Regency, South Kalimantan, Indonesia (Figure 1). Selimuran and Rantau Panjang Villages in Kusan Hilir District, Mudalang and Api-api Villages in Kusan Tengah District, and Segumbang Village in Batulicin District. These sites were deliberately selected for their significance as major rice (*Oryza sativa* L.) producing areas within the region's tidal swamp agroecosystems. Selecting multiple locations across different districts was intended to capture spatial variability in soil characteristics and management practices, thereby ensuring a more comprehensive representation of the environmental conditions influencing rice cultivation in tidal swamp landscapes.

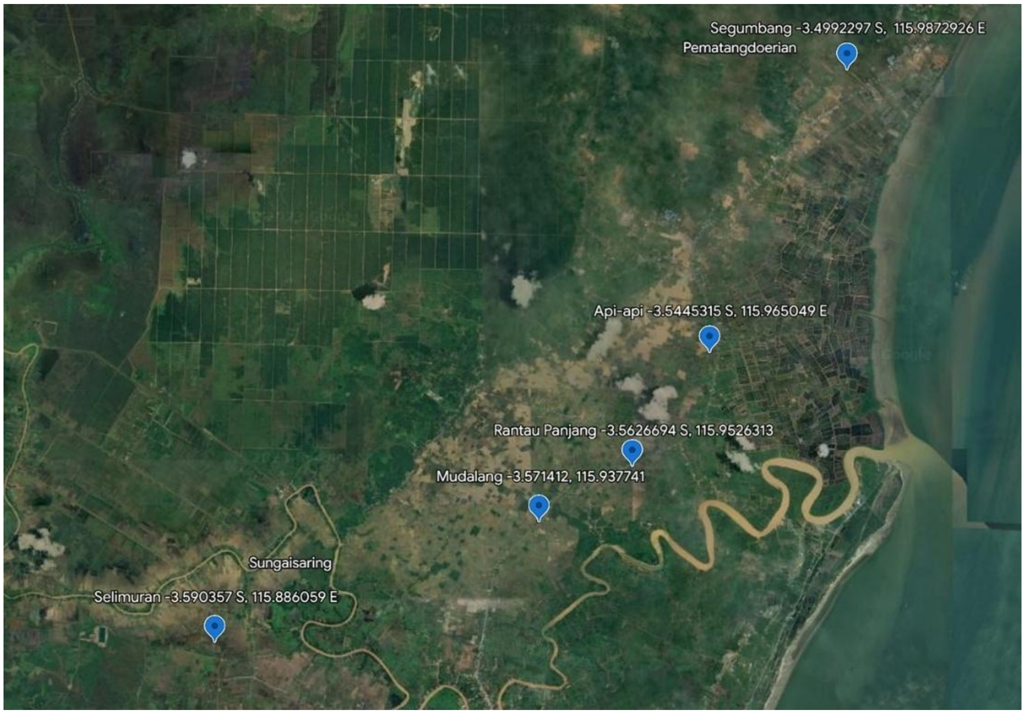

Figure 1. Soil sampling points in paddy fields of Tanah Bumbu Regency, South Kalimantan, Indonesia.

Preliminary survey and initial laboratory procedures

The collection and review of supporting data on administrative boundaries, rice cultivation practices, and rice productivity were conducted in each district within the study area. The selection of villages and soil sampling points was based on representativeness and relevance to achieving the study's objectives. Materials prepared for field activities included hydrogen peroxide (H_2O_2) for pyrite reaction testing, distilled water, litmus paper for in situ pH determination, and 0.5 kg soil sample bags. The equipment used included a Belgian auger with a minimum drilling capacity of 3.0 m, measuring tapes (50 and 2.5 m), and a global positioning system (GPS) unit. The research activities were conducted in two main stages: (1) Soil sampling and interviews with farmers, and (2) laboratory soil analysis and field measurement of water table depth. Soil sampling was carried out in November 2021, laboratory analyses were conducted in December 2021, and water table depth measurements were performed from November 2021 to March 2022.

Soil sampling

Soil samples for fertility analysis were collected in each village using a Belgian auger. Sampling depth was determined based on the depth of the uppermost pyritic layer, with samples taken from the soil layer extending 25 cm above the pyrite horizon. For example, when the pyrite layer occurred at a depth of 30 cm, soil samples were collected from the 5-30 cm depth interval. Each composite soil sample consisted of subsamples collected from five diagonal points established in the field. The subsamples were thoroughly mixed to obtain a representative composite sample for each location. The soil was then placed in plastic bags and labeled with information on location (village and district), sampling date, and sample code. The sample bags were compacted to minimize oxygen content and reduce oxidation. The spatial distribution of soil sampling points is shown in Figure 1. The depth of the pyrite layer was determined through augering at five observation points arranged diagonally and coinciding with the soil sampling locations. At each point, soil layers were exposed and tested using H_2O_2, followed by pH assessment with litmus paper. A visible reaction indicating the presence of pyrite was observed, and the depth at which it occurred was defined as the pyrite layer depth, expressed in centimeters.

Data analysis

Farmer interviews. Structured interviews were conducted with five representative farmers in each village to obtain detailed information on agronomic practices and production performance. The collected data included cultivated rice varieties, planting schedules, liming and fertilization practices, crop yields, and the cropping index (CI). To ensure consistency in varietal analysis, the rice variety selected for further evaluation in each village was defined as the most frequently cultivated variety among the five respondents. Quantitative variables, including fertilization rates, liming applications, and yield, were aggregated and expressed as mean values across the respondents to represent village-level practices. In addition, supplementary information related to land characteristics, water management, and cropping patterns was collected to support the classification and identification of the prevailing rice agroecosystem types in the study area.

Water table measurement. Water table depth was measured during the rainy season from November 2021 to March 2022. Measurements were conducted using a perforated PVC pipe (120 cm long, with perforations along the lower 60 cm) inserted vertically into the paddy field to a depth of 60 cm. Water table depth was recorded during single (major) tidal events, specifically at three observation times: Two days before the peak tide, at the peak tide, and 2 d after the peak tide. The mean value of these observations was expressed as water table depth in centimeters (cm).

Classification of tidal swamp rice agroecosystems. The classification of tidal swamp rice agroecosystems was based on water availability in paddy fields during the rainy season. Type A tidal swamps were defined as areas where tidal water enters the fields during both single (major) and double (minor) tides. Type B tidal swamps were characterized by inundation occurring only during single (major) tides. Type C tidal swamps were identified when tidal water did not enter the fields during either single or double tides, but the groundwater table depth was ≤ 50 cm. In contrast, Type D tidal swamps were defined by similar conditions to Type C, but with a groundwater table depth > 50 cm.

Soil chemical analysis. Soil chemical analyses were conducted at the Laboratory of the Swampland Agricultural Assembly and Testing Center. The parameters analyzed included soil pH (H_2O), organic C (C-organic), total N (N-total), available P (P-available), cation exchange capacity (CEC), exchangeable bases (Ca, Mg, K, Na), and exchangeable Al, pyrite (FeS_2), Fe, and sulfate (SO_4^{2-}). Analytical procedures for soil chemical properties followed the methods described by Eviati et al. (2023), as summarized in Table 1.

Table 1. Methods for analysis of soil chemical properties. CEC: Cation exchange capacity.

N°	Type of analysis and unit	Method
1	pH H_2O	pH meter
2	Organic-C, %	Wakley & Black
3	Total-N, %	Kjeldahl
4	Available-P, µg g^{-1}	BrayII-spectrophotometer
5	CEC, $cmol_{(+)}$ kg^{-1}	NH_4OAc 1 N pH 7.0
6	Exchangeable-Ca, $cmol_{(+)}$ kg^{-1}	NH_4OAc 1 N pH 7.0
7	Exchangeable-Mg, $cmol_{(+)}$ kg^{-1}	NH_4OAc 1 N pH 7.0
8	Exchangeable-K, $cmol_{(+)}$ kg^{-1}	NH_4OAc 1 N pH 7.0
9	Exchangeable-Na, $cmol_{(+)}$ kg^{-1}	NH_4OAc 1 N pH 7.0
10	Exchangeable-Al $cmol_{(+)}$ kg^{-1}	KCl 1 N, titration
11	Pyrite (FeS_2), %	Destruction $HClO_4$
12	Fe, µg g^{-1}	NH_4OAc 1 N pH 4.8
13	SO_4^{2-}, µg g^{-1}	NH_4OAc 1 N pH 4.8

Statistical analysis

All laboratory-derived soil chemical data were systematically compiled, tabulated, and interpreted using the classification criteria proposed by Ritung et al. (2011). These criteria categorize soil chemical properties into five standardized classes, namely very low (VL), low (L), moderate (M), high (H), and very high (VH), thereby enabling consistent evaluation of soil fertility status across the study sites. The detailed thresholds and ranges for each parameter are presented in Table 2. This classification framework was applied to key soil variables to facilitate comparative assessment and to support the interpretation of soil constraints and nutrient availability within the tidal swamp agroecosystems.

Table 2. Criteria for assessing the results of soil chemical properties analysis. CEC: Cation exchange capacity; VL: very low; L: low; M: moderate; H: high; VH: very high.

	Values and categories				
Chemical properties and units	VL	L	M	H	VH
pH H_2O (1:5)	< 4.5	4.5-5.5	5.6-6.5	6.6-7.5	-
Acidity	Very acidic	Acid	Slightly acidic	Neutral	-
Organic-C, %	< 1.0	1.0-2.0	2.01-3.00	3.01-5.00	> 5.00
Total-N, %	< 0.1	0.1-0.2	0.21-0.50	0.51-0.75	> 0.75
C/N	< 5.0	5.0-10.0	11.0-15.0	16.0-25.0	> 25.0
Available-P, µg g^{-1}	< 4.4	4.4-6.6	6.7-11.0	11.1-15.3	> 15.3
CEC, $cmol_{(+)}$ kg^{-1}	< 5.0	5.0-16.0	17.0-24.0	25.0-40.0	> 40.0
Exchangeable-Ca, $cmol_{(+)}$ kg^{-1}	< 2.0	2.0-5.0	6.0-10.0	11-20	> 20.0
Exchangeable-Mg, $cmol_{(+)}$ kg^{-1}	< 0.4	0.4-1.0	1.1-2.0	2.1-8.0	> 8.0
Exchangeable-K, $cmol_{(+)}$ kg^{-1}	< 0.1	0.1-0.2	0.3-0.5	0.6-1.0	> 1.0
Exchangeable-Na, $cmol_{(+)}$ kg^{-1}	< 0.1	0.1-0.3	0.4-0.7	0.8-1.0	> 1.0
Exchangeable-Al, $cmol_{(+)}$ kg^{-1}	< 2.0	2-10	10-20	> 20	-
Fe, µg g^{-1}	< 1.0	1-3	3-9	> 9	-
Sulfate, µg g^{-1}	< 20.0	20-40	41-100	> 100	-
Pyrite, %	< 1.0	1-2	2-4	> 4	

In addition to descriptive classification, statistical analyses were conducted to enhance data interpretation. Descriptive statistics, including mean, standard deviation, and coefficient of variation, were calculated to summarize the distribution and variability of soil properties across sampling locations. Where appropriate, inferential statistical analyses were conducted to evaluate differences among sites, using ANOVA at a 95% confidence level. When significant differences were detected, post hoc tests were applied to identify pairwise differences among locations. Furthermore, correlation analysis was employed to examine relationships among soil chemical properties and their potential influence on rice yield and management practices. All statistical analyses were performed using standard statistical software to ensure accuracy, reproducibility, and robustness of the results.

RESULTS AND DISCUSSION

Agroecosystem characteristics

Based on field observations of water table depth and interviews with farmers, the agroecosystems in the five study villages were classified as tidal swamp types B and C. Selimuran and Mudalang Villages were categorized as Type B tidal swamps. In contrast, Rantau Panjang, Api-api, and Segumbang Villages were classified as Type C tidal swamps (Table 3). Farmers cultivating Type B tidal swamp fields generally achieved a cropping index (CI) of 180%-200%, whereas those farming Type C fields recorded a lower CI of 120%-140%. Nevertheless, all farmers at the soil sampling sites planted rice twice per year. Previous studies have consistently identified Type B tidal swamps as major rice production centers, where rice is commonly cultivated with a CI greater than 1 (Fahmi et al., 2019; Sulaeman et al., 2022). This higher cropping intensity is primarily attributed to greater water availability and easier water management (Noor and Sosiawan, 2019), as well as relatively higher soil fertility than in Type C tidal swamps (Fahmi et al., 2019).

Table 3. Groundwater depth and tidal inundation type of tidal swamp rice fields at the study sites. +: Above the soil surface; −: below the soil surface; B: inundated only during single tides; C: not inundated by either single or double tides, with groundwater table depth ≤ 50 cm.

N°	Name of village	Groundwater depth during single (major) tides in the rainy season (cm)		Tidal inundation type
		Interval	Average	
1	Selimuran	(+18)-(+30)	+24	B
2	Mudalang	(+14)-(+26)	+20	B
3	Rantau Panjang	(-06)-(-14)	-10	C
4	Api-api	(-10)-(-20)	-15	C
5	Segumbang	(-16)-(-30)	-23	C

Soil nutrient status

Overall, soils at the study sites exhibited acidic (A) to very acidic (VA) reactions. Available P, C/N ratio, and exchangeable Ca were classified as very low to low. Soil organic C and total N were generally low, while exchangeable K also fell within the low category. Cation exchange capacity (CEC) and exchangeable Al and Mg were classified as low to moderate. In contrast, exchangeable Na, sulfate (SO_4^{2-}), and pyrite contents were categorized as moderate to high, whereas Fe concentrations were high to very high, as presented in Table 4. Soil fertility in Type B tidal swamp fields was generally higher than that in Type C fields. This finding is consistent with previous studies reporting better soil chemical conditions and higher productive potential in Type B tidal swamps compared with Type C systems (Girsang and Raharjo, 2021).

Table 4. Soil nutrient status of tidal swamp rice fields in Tanah Bumbu Regency, South Kalimantan, Indonesia. CEC: Cation exchange capacity; A: acidic; VA: very acidic; VL: very low; L: low; M: moderate; H: high; VH: very high; Exch.: exchangeable.

Characteristics	Villages at the soil sampling sites				
	Selimuran	Mudalang	Rantau Panjang	Api-api	Segumbang
pH H_2O	5.23 (A)	4.75 (A)	4.39 (VA)	4.27 (VA)	4.29 (VA)
Organic-C, %	1.93 (L)	1.84 (L)	1.34 (L)	1.54 (L)	1.31 (L)
Total-N, %	0.26 (M)	0.22 (M)	0.10 (L)	0.13 (L)	0.12 (L)
C/N	7.42 (L)	8.36 (L)	13.40 (M)	11.85 (M)	10.92 (M)
Available-P, µg g^{-1}	6.82 (L)	4.56 (L)	4.43 (L)	2.78 (VL)	2.59 (VL)
CEC, $cmol_{(+)}$ kg^{-1}	23.62 (M)	20.71 (M)	16.47 (L)	13.71 (L)	15.28 (L)
Exch. Ca, $cmol_{(+)}$ kg^{-1}	5.36 (L)	4.97 (L)	2.64 (L)	1.95 (VL)	1.78 (VL)
Exch. Mg, $cmol_{(+)}$ kg^{-1}	1.83 (M)	1.97 (M)	0.88 (L)	1.10 (M)	1.25 (M)
Exch. K, $cmol_{(+)}$ kg^{-1}	0.29 (L)	0.25 (L)	0.19 (L)	0.23 (L)	0.20 (L)
Exch. Na, $cmol_{(+)}$ kg^{-1}	0.96 (H)	0.87 (H)	0.58 (M)	0.62 (M)	0.48 (M)
Exch. Al, $cmol_{(+)}$ kg^{-1}	5.20 (L)	6.00 (L)	11.27 (M)	12.02 (M)	12.97 (M)
Fe, µg g^{-1}	38.20 (H)	40.40 (H)	66.20 (VH)	70.00 (VH)	74.20 (VH)
SO_4, µg g^{-1}	82.70 (M)	98.70 (M)	112.00 (H)	135.10 (H)	146.20 (H)
FeS_2 (pirit), %	1.70 (M)	1.90 (M)	3.20 (H)	3.80 (H)	3.70 (H)

Soil acidity and organic C

Laboratory analyses indicated that soils in Type B tidal swamp fields were generally A, whereas soils in Type C fields were VA. Murjani (2024) reported that tidal swamp ecosystems are characterized by poor drainage, with prolonged flooding during the rainy season that may persist for several months. Such conditions promote the accumulation of toxic substances leached by rainfall and generated by the decomposition of organic compounds, which, in turn, influence soil and water acidity. Elevated soil acidity reduces nutrient availability, thereby limiting rice productivity (Marlina et al., 2025). The relatively lower soil acidity observed in Type B tidal swamps is likely due to differences in organic matter decomposition processes among agroecosystem types. In Type C tidal swamps, more oxidative conditions favor intensive decomposition of organic materials, resulting in higher concentrations of organic acids and hydrogen ions, which contribute to increased soil acidity. This interpretation is supported by the higher soil organic C content observed in Type B fields. Soil organic C content across the study sites was classified as low, ranging from 1.31% to 1.93%. Farmers in the study area commonly utilize rice straw as supplementary feed for cattle and goats. The widespread practice of removing rice straw from fields, rather than returning it to the soil, contributes to low soil organic C levels (Muliarta and Purba, 2020). Previous studies have demonstrated that returning rice straw to the field enhances nutrient retention, improves soil chemical properties, and increases rice productivity in tidal swamp ecosystems (Alwi et al., 2021).

Nitrogen and phosphorus status

Nitrogen availability in tidal swamp soils has generally been reported to range from moderate to low (Widowati et al., 2022). This is consistent with the present laboratory results, which showed that soil N availability at the study sites was predominantly classified as low (Table 4). One of the primary sources of N in tidal swamp soils is soil organic C (Yao et al., 2022). As shown in Table 4, soil organic C content in the study area was low, indicating that organic matter decomposition contributed only marginally to increasing N availability in these soils. Phosphorus is an essential nutrient for rice growth, playing a critical role in tiller formation and reducing the proportion of unfilled grains. However, P availability in tidal swamp soils is generally classified as low to moderate (Qin et al., 2024). The present analysis revealed that available P in Type B tidal swamps was categorized as low, whereas in Type C tidal swamps it was classified as very low.

The P availability in soil is strongly influenced by its interactions with reactive metal elements, particularly Al and Fe, which function as dominant P-fixing agents in acidic environments. Elevated concentrations of Al and Fe enhance the formation of insoluble Al-P and Fe-P compounds through adsorption and precipitation processes, thereby reducing the proportion of plant-available P in the soil solution. This inverse relationship indicates that increasing levels of exchangeable or soluble Al and Fe are associated with a decline in P availability for plant uptake. Such mechanisms provide a plausible explanation for the comparatively higher P availability observed in Type B tidal swamp agroecosystems relative to Type C systems (Table 4), where the intensity of P fixation is likely lower due to reduced concentrations or activity of these metal ions. This finding is consistent with previous studies (Fahmi et al., 2023), which reported that elevated Al and Fe availability significantly contribute to P immobilization in tidal swamp soils. Consequently, the interaction between P and metal ions constitutes a critical factor governing nutrient dynamics and fertilizer efficiency in these environments.

Exchangeable base cations

Soil chemical analyses indicated that two base cations, K and Ca, were present at low availability levels, with Ca availability in Type C tidal swamp soils classified as very low. Farmers in the study area commonly address these limitations by applying soil amendments and ameliorants, as reported in previous studies (Alwi et al., 2021; Marlina et al., 2022). The low availability of K and Ca is primarily associated with high soil acidity, which reduces the exchangeable fraction of these cations. As shown in Table 4, the availability of both K and Ca was relatively higher in Type B tidal swamp soils, corresponding to their lower acidity levels. Potassium deficiency in tidal swamp rice fields has been shown to increase plant susceptibility to pests and diseases, reduce tiller formation and the number of grains per panicle, and result in poorly filled grains, ultimately limiting rice productivity (Gribaldi et al., 2023). Table 4 further indicates that exchangeable Mg was classified as low to moderate, whereas exchangeable Na varied from moderate to high. High Na concentrations were observed only in Type B tidal swamp soils, likely due to their closer proximity to coastal areas, a major source of Na inputs.

Elements and compounds

Rice cultivation in tidal swamp ecosystems requires careful and integrated nutrient and water management to mitigate the adverse effects of toxic elements and compounds, particularly pyrite, Fe, and Al. Under inappropriate water management, oxidation of pyritic layers can produce sulfuric acid, leading to a sharp decline in soil pH and increased solubility of Fe and Al to toxic levels. These conditions not only inhibit root development and nutrient uptake but also induce physiological stress, limiting plant growth and productivity. Effective water management, such as maintaining appropriate water levels to prevent pyrite oxidation, combined with balanced fertilization and soil amendments (e.g., liming and application of organic matter), is therefore essential for improving soil conditions. Without proper management, the accumulation of toxic elements and nutrient imbalances can substantially reduce rice yield potential and, consequently, negatively affect farmers' income and the overall sustainability of rice production in tidal swamp agroecosystems (Jumakir et al., 2024).

Pyrite. Pyrite is a major source of soil acidity in tidal swamp soils and can inhibit rice growth and reduce productivity. When the groundwater table drops below the pyritic layer, pyrite oxidation occurs, generating hydrogen ions and increasing soil acidity (Anda et al., 2024). Therefore, two key aspects must be considered in pyrite management: Pyrite concentration and the depth of the pyritic layer relative to the soil surface. Oxidation of pyrite during the dry season produces organic and inorganic acids, enhances the solubility of toxic elements, and increases P fixation, all of which negatively affect rice growth and yield. During the rainy season, the organic acids formed may be leached and subsequently deteriorate water quality in drainage channels. As shown in Table 4, pyrite concentrations at the study sites ranged from moderate to high, from 1.70% to 3.80%. Pyrite concentrations were lower in Type B tidal swamp soils than in Type C soils. Pyrite (FeS_2) formation is strongly influenced by sulfate availability, which likely explains the lower pyrite concentrations observed in Type B tidal swamps (Table 5).

Table 5. Pyrite depth and concentration in tidal swamp rice fields at the study sites. B: Inundated only during single tides; C: not inundated by either single or double tides, with groundwater table depth ≤ 50 cm.

N°	Village and tidal inundation type	Depth of the pyrite layer		Pyrite concentration
		Interval	Average	
		cm	cm	%
1	Selimuran (B)	90-135	113	1.7
2	Mudalang (B)	86-120	103	1.9
Mean value for Type B tidal inundation		86-135	108	1.8
3	Rantau Panjang (C)	38-47	43	3.2
4	Api-api (C)	30-42	36	3.8
5	Segumbang (C)	28-37	33	3.7
Mean value for Type C tidal inundation		28-47	37	3.6

In addition to concentration, pyrite depth is a critical factor determining its risk to rice cultivation. Soils with relatively low pyrite concentrations but shallow pyrite layers are more susceptible to rapid oxidation. Measurements of pyrite depth indicated that the potential risk posed by pyrite was lower in Type B tidal swamps than in Type C systems (Table 5). The observed differences are likely attributable to more intensive surface soil transport and erosion in Type C tidal swamps, resulting in shallower pyrite layers. Another contributing factor may be land preparation practices, particularly burning, which are more likely to occur in Type C tidal swamps due to limited water availability. These conditions suggest that tillage depth in Type C tidal swamp soils should be carefully managed and should not exceed 25 cm to minimize the risk of pyrite oxidation.

Iron toxicity. Iron toxicity is a major constraint to rice cultivation in tidal swamp ecosystems, as it can reduce rice yields by 30%-90% and, under severe conditions, may result in complete crop failure (Khairullah et al., 2021). Several factors, including varietal tolerance, toxicity intensity, plant growth stage, soil fertility status, and the effectiveness of water and nutrient management, influence the severity of Fe toxicity effects on rice production. High concentrations of ferrous iron (Fe^{2+}) in soil lead to excessive uptake by rice plants, causing toxicity and inhibiting the absorption of other essential nutrients (Dilhani et al., 2026). This condition is commonly triggered by poor drainage, high soil acidity, and low availability of key nutrients such as N, P, K, and Ca. These factors explain why Fe concentrations were lower in Type B tidal swamp soils than in Type C soils. The mean Fe concentration in Type B soils was 39.3 $\mu g\ g^{-1}$, classified as high, whereas in Type C soils it reached 72.5 $\mu g\ g^{-1}$, classified as very high. Such differences in soil Fe status have important implications for input requirements and rice productivity across tidal swamp types.

Aluminum toxicity. Another soil constituent that poses toxicity risks to rice in tidal swamp ecosystems is exchangeable Al (Al^{3+}). High concentrations of exchangeable Al can strongly bind P, thereby reducing its availability to plants and limiting the potential for rice production in tidal swamp soils (Bai et al., 2017). Exchangeable Al concentrations were lower in Type B tidal swamp soils than in Type C soils. In Type B soils, exchangeable Al ranged from 5.20 to 6.00 $cmol_{(+)}$ kg^{-1}, classified as low, whereas in Type C soils it ranged from 11.27 to 12.97 $cmol_{(+)}$ kg^{-1}, classified as moderate (Table 4). As a consequence, the lime requirement for Type C tidal swamp soils was higher than that for Type B soils (Table 6). These results further confirm that soil fertility status in Type B tidal swamp fields is generally superior to that in Type C fields. Consequently, differences in soil chemical constraints lead to varying requirements for production inputs, such as fertilizers and soil amendments, which ultimately result in differences in rice productivity across tidal swamp types and planting seasons (Gribaldi et al., 2023).

Table 6. Dolomite lime application rates for rice cultivation by planting season in Tanah Bumbu Regency, South Kalimantan, Indonesia. B: Inundated only during single tides; C: not inundated by either single or double tides, with groundwater table depth ≤ 50 cm.

		Planting season		
N°	Village and tidal inundation type	Rainy season	Dry season	Average
		kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1	Selimuran (B)	500	750	625
2	Mudalang (B)	750	1000	875
Mean dolomite application rate in Type B tidal swamps		625	875	750
3	Rantau Panjang (C)	1000	1250	1125
4	Api-api (C)	1000	1250	1125
5	Segumbang (C)	1250	1500	1375
Mean dolomite application rate in Type C tidal swamps		1083	1333	1208
Mean dolomite application rate by planting season		854	1104	979

Rice cultivation practices

Rice farmers in tidal swamp areas of Tanah Bumbu Regency typically practice year-round rice cultivation (Table 7), with two principal planting seasons: The rainy season (December-April) and the dry season (May-September). This bimodal cropping pattern reflects the strong influence of seasonal hydrological dynamics on agricultural activities in tidal environments. However, the timing of planting differs between tidal inundation types. In Type B tidal swamp systems, planting generally begins earlier than in Type C systems, primarily due to more favorable and stable water availability. Type B fields benefit from more controlled inundation and better water retention, which allows farmers to initiate land preparation and transplanting at an earlier stage. In contrast, Type C systems often experience a less predictable water supply and greater exposure to soil constraints, such as higher acidity and potential oxidation of pyritic layers, which can delay planting. These differences in planting schedules highlight the critical role of water regime and soil conditions in shaping cropping calendars and ultimately influencing rice productivity in tidal swamp agroecosystems.

Table 7. Rice planting calendar according to planting season and tidal inundation type in Tanah Bumbu Regency, South Kalimantan, Indonesia. B: Inundated only during single tides; C: not inundated by either single or double tides, with groundwater table depth ≤ 50 cm.

		Planting season	
N°	Village and tidal inundation type	Rainy season	Dry season
1	Selimuran (B)	Dec-Mar	May-Aug
2	Mudalang (B)	Dec-Mar	May-Aug
3	Rantau Panjang (C)	Jan-Apr	Jun-Sep
4	Api-api (C)	Jan-Apr	Jun-Sep
5	Segumbang (C)	Jan-Apr	Jun-Sep
Planting time		Dec-Apr	May-Sep

Varieties. The use of improved, adapted rice varieties is one of the most cost-effective and efficient strategies for overcoming soil fertility constraints and enhancing productivity in tidal swamp ecosystems. These environments are characterized by multiple biophysical limitations, including soil acidity, salinity, and toxicity from Fe and Al, which can severely restrict plant growth and nutrient uptake. The selection of rice varieties tolerant of such stresses plays a critical role in mitigating these constraints, improving crop resilience, and optimizing yield under suboptimal soil conditions. At the study sites, farmers predominantly cultivated two improved rice varieties, Inpari-32 and Mekongga. Both varieties have been widely recognized for their adaptability to tidal swamp environments, particularly their tolerance to acidic soils and toxic metal stress. Their ability to maintain stable growth and yield under fluctuating water regimes and chemical constraints makes them suitable choices for these agroecosystems. Consequently, the adoption of stress-tolerant, high-yielding varieties, combined with appropriate soil and water management practices, represents a key strategy for sustainably increasing rice production in tidal swamp areas (Ratmini et al., 2021). In addition to their high yield potential, these varieties have also been associated with relatively low methane emissions, making them agronomically and environmentally favorable options for rice production in tidal swamp ecosystems (Abduh et al., 2026).

Liming. Results of the soil chemical analyses indicate that the paddy soils at the study sites require improved fertility to create a more favorable environment for crop growth. One effective measure is applying lime and soil amendments. Liming not only alleviates soil acidity and mitigates toxic elements and compounds, but also increases the availability of base cations such as Ca and Mg, as well as P. Liming in tidal swamp rice fields has been reported to: (1) Reduce the risk of Fe, Al, Na, and sulfate toxicity; (2) improve the soil environment for plant growth; (3) enhance fertilizer efficiency and effectiveness; (4) increase rice productivity; (5) improve grain quality; and (6) increase farmers' income (Sulaeman et al., 2022). Accordingly, rice farmers in the tidal swamp areas of Tanah Bumbu commonly apply dolomite lime, as the availability of Ca and Mg in these soils is generally low.

The amount of dolomite applied in Type B tidal swamp fields was lower than that used in Type C fields (Table 7). This difference reflects the more favorable chemical properties of Type B soils, characterized by lower acidity, lower concentrations of toxic elements, and greater availability of essential nutrients. In contrast, soils in Type C tidal swamps are more prone to pyrite oxidation during the dry season, leading to increased soil acidity and a greater requirement for dolomite application. Type B tidal swamp soils generally maintain sufficient water supply even during the dry season, which helps prevent pyrite oxidation and sustains more reductive soil conditions. These conditions dilute toxic elements and compounds and maintain a relatively higher soil pH, thereby reducing the amount of lime required. Therefore, water conservation toward the end of the rainy season is a critical management strategy for rice cultivation during the dry season in tidal swamp ecosystems.

Fertilization. Soil nutrient availability across the study sites was characterized by generally low levels of N and K. In contrast, P availability ranged from very low to low, indicating pronounced constraints on soil fertility. Nitrogen deficiency limits vegetative growth and chlorophyll formation, K deficiency affects plant water regulation and resistance to environmental stress, and insufficient P restricts root development and energy transfer. Collectively, these limitations reduce the soil's overall capacity to support optimal rice growth and yield. Such nutrient imbalances are typical of tidal swamp ecosystems, where soil acidity, leaching, and fixation processes further reduce nutrient availability and efficiency. Under these conditions, improving rice productivity requires implementing balanced, site-specific soil fertility management strategies. This includes the adequate and proportionate application of N, P, and K fertilizers, adjusted to soil conditions and crop requirements. In addition, integrated nutrient management practices—such as incorporating organic amendments, liming to reduce soil acidity, and improving water management—can enhance nutrient availability and uptake efficiency. These approaches are essential not only to increase rice yields but also to sustain long-term soil fertility and ensure environmentally sound agricultural practices in tidal swamp agroecosystems.

Rice farmers in the tidal swamp areas of Tanah Bumbu apply N primarily using compound fertilizers and urea, with compound fertilizers also serving as sources of P and K. Better water availability in Type B tidal swamp fields results in more favorable soil fertility conditions than in Type C fields. In addition, higher concentrations of toxic elements and compounds in Type C soils impose greater constraints on production. Consequently, nutrient requirements in Type B soils are relatively lower than those in Type C soils (Table 8). Fertilizer requirements for rice cultivation in tidal swamp areas were higher during the dry season (Table 8). This increase is associated with higher evapotranspiration rates and enhanced pyrite oxidation, both of which reduce fertilizer efficiency and effectiveness. These findings highlight the importance of adjusting fertilizer rates according to tidal inundation type and planting season to optimize nutrient use efficiency in tidal swamp rice systems.

Table 8. Application rates of NPK compound fertilizer and urea for rice cultivation according to tidal inundation type and planting season in Tanah Bumbu Regency, South Kalimantan, Indonesia. B: Inundated only during single tides; C: not inundated by either single or double tides, with groundwater table depth ≤ 50 cm.

	Fertilizer type and planting season					
	NPK			Urea		
Village and tidal inundation type	Planting season-1	Planting season-2	Average	Planting season-1	Planting season-2	Average
	kg ha^{-1}			kg ha^{-1}		
Selimuran (B)	250	300	275	50	100	75
Mudalang (B)	300	400	350	50	100	75
Mean value for Type B	275	350	313	50	100	75
Rantau Panjang (C)	350	500	425	100	150	125
Api-api (C)	350	400	375	100	150	125
Segumbang (C)	350	400	375	100	150	125
Mean value for Type C	350	433	392	100	150	125
Mean chemical fertilizer application rate by planting season	313	382	348	75	125	100

Rice productivity

The crop-growing environment strongly influences rice productivity; improved nutrient supply generally results in higher yields. Data from the Provincial Statistics Office of South Kalimantan indicate that the average rice productivity in South Kalimantan Province was 3.99 t ha^{-1} in 2019 and 3.69 t ha^{-1} in 2020 (Badan Pusat Statistik Kalimantan Selatan, 2021). In comparison, average rice productivity in Tanah Bumbu Regency during the same years was slightly higher, at 4.16 and 4.14 t ha^{-1}, respectively. Field data collected in this study showed that the average rice productivity across the five study villages during the dry season (DS) 2021 and the rainy season (RS) 2021/2022 exceeded the regency-level averages. Mean rice productivity reached 4.72 t ha^{-1} in DS and 4.48 t ha^{-1} in RS. Rice productivity in Type B tidal swamp fields was substantially higher than that in Type C fields, averaging 5.43 and 3.76 t ha^{-1}, respectively. This represents a productivity difference of 1.67 t ha^{-1}, equivalent to an increase of 37.13% in Type B systems. These findings are consistent with results reported in previous studies, summarized in Table 9, which reported average rice yields of 5.23 t ha^{-1} in Type B tidal swamps and 3.61 t ha^{-1} in Type C systems. The higher productivity observed in Type B tidal swamps highlights the combined effects of more favorable water regimes, lower soil acidity, reduced toxicity, and improved nutrient availability compared with Type C systems.

Improved land quality resulted in higher rice productivity in Type B tidal swamp fields. The superior productivity observed in Type B systems is also attributed to greater nutrient uptake efficiency by rice plants cultivated under these conditions (Fahmi et al., 2019). Table 10 further indicates that the effect of planting season on rice productivity differed between tidal inundation types. In Type B tidal swamps, the transition from DS to RS led to a productivity decline of 0.95 t ha^{-1} (16.07%). In contrast, Type C tidal swamps experienced a productivity increase of 0.45 t ha^{-1} (12.71%) during the same seasonal transition. The reduction in rice productivity during the RS in Type B tidal swamps is understandable, as the DS provides higher solar radiation, which supports plant physiological processes and promotes better growth and yield. Conversely, rice production in Type C tidal swamps is subject to more severe constraints during DS, including (1) limited water availability, (2) higher concentrations of toxic elements and compounds, and (3) stronger P fixation. Under RS conditions, increased water availability partially alleviates these constraints, thereby improving rice productivity.

Table 9. Variability of rice productivity in tidal swamp rice fields according to tidal inundation type and planting season. RS: Rainy season; DS: dry season.

N°	Province	Season	Productivity (t ha^{-1})		Source
			Type B	Type C	
1	South Sumatra	RS 2018/2019	5.83	4.70	Ratmini and Hendra (2019)
2	Bengkulu	DS 2020	5.35	2.13	Chozin et al. (2023)
3	South Sumatra	RS 2020/2021	4.50	4.00	Gribaldi et al. (2023)
	Average		5.23	3.61	-

Table 10. Rice productivity of tidal swamp rice fields at the study sites according to tidal inundation type and planting season. RS: Rainy season; DS: dry season; B: inundated only during single tides; C: not inundated by either single or double tides, with groundwater table depth ≤ 50 cm.

N°	Village and tidal inundation type	Planting season		
		DS 2021	RS 2021/2022	Average
1	Salimuran (B)	6.03	5.12	5.58
2	Mudalang (B)	5.78	4.80	5.29
Mean productivity of Type B		5.91	4.96	5.43
3	Rantau Panjang (C)	3.74	4.16	3.95
4	Api-api (C)	3.55	3.97	3.76
5	Segumbang (C)	3.32	3.84	3.58
Mean productivity of Type C		3.54	3.99	3.76
Mean productivity by planting season		4.72	4.48	4.60

CONCLUSIONS

This study demonstrates distinct agroecosystem differentiation across tidal swamp rice systems, with Selimuran and Mudalang classified as Type B, and Rantau Panjang, Api-api, and Segumbang as Type C. Type B soils were acidic, whereas Type C soils were very acidic, reflecting more severe chemical constraints. Although both systems exhibited generally low levels of organic C, total N, and exchangeable K, Type B soils were characterized by higher availability of essential nutrients (P, Ca, Mg, K, and Na) and lower concentrations of toxic elements, including exchangeable Al, Fe, sulfate, and pyrite. The deeper pyritic layer in Type B further reduced the risk of oxidation and associated soil acidity problems. Rice cultivation was dominated by 'Inpari-32' and 'Mekongga', which are well adapted to tidal swamp conditions. Planting time and input requirements varied between systems, with earlier planting and lower fertilizer inputs observed in Type B due to more favorable water regimes and soil conditions. Rice productivity was significantly influenced by both tidal type and season, with Type B achieving higher yields (5.43 t ha^{-1}) compared to Type C (3.76 t ha^{-1}), indicating a substantial productivity advantage. Seasonal yield responses also differed, highlighting the interaction between water availability, soil acidity, and toxic element dynamics. Overall, these findings underscore the importance of site-specific and season-specific management strategies. Tailored nutrient and water management based on tidal inundation characteristics are essential to enhance productivity, improve input efficiency, and mitigate soil toxicity risks, thereby supporting sustainable rice production in tidal swamp ecosystems.

Author contribution

Conceptualization: N.N.S., M.M., A.M.A., R.Y. Methodology: N.N.S., M.M., A.M.A., M.R.R., R.Y., Y.R., E.M., K.A. Validation: M.M., E.M., K.A. Formal analysis: N.N.S., M.M., .A.M.A., E.M., K.A. Investigation: N.N.S., M.M., A.M.A. Resources: M.M., K.A., A.H. Data curation: M.M., P.H.M., A.H., M.A. Writing-original draft: N.N.S., M.M., A.M.A., M.R.R., R.Y., Y.R., E.M., K.A., P.H.M., A.H., M.A., P.H.S., N.N., N.Y., O.G.T. Writing-review & editing: N.N.S., M.M., A.M.A., M.R.R., K.A. Visualization: N.N.S., A.M.A., M.R.R. Supervision: M.M., K.A., R.Y. Project administration: N.N.S., A.M.A., N.Y. Funding acquisition: M.M. All co-authors reviewed the final version and approved the manuscript before submission.

References

Abduh, A.M., Masganti, Sari, N.N., Khairullah, I., Fahmi, A., Anwar, K., et al. 2026. Rice crop management to increase productivity and reduce methane emissions in Indonesia. Chilean Journal of Agricultural Research 86:140-153. doi:10.4067/S0718-58392026000100140.

Alwi, M., Yusuf, W.A., Fahmi, A. 2021. Improving productivity of rice yield on tidal swampland using soil amendment. IOP Conference Series Earth and Environmental Science 648(1):012141. doi:10.1088/1755-1315/648/1/012141.

Anda, M., Sukarman, S., Yatno, E., Hikmat, M., Heryanto, R.B., Gani, R.A., et al. 2024. Mapping the spatial distribution of pyrite and evaluating soil and water properties in idle swamp land: A strategy to promote sustainable paddy field establishment and prevent land degradation. CATENA 241:107985. doi:10.1016/j.catena.2024.107985.

Arifah, Salman, D., Yassi, A., Bahsar-Demmallino, E. 2022. Climate change impacts and the rice farmers' responses at irrigated upstream and downstream in Indonesia. Heliyon 8(12):e11923. doi:10.1016/j.heliyon.2022.e11923.

Badan Pusat Statistik Kalimantan Selatan. 2021. Provinsi Kalimantan Selatan Dalam Angka 2020. Badan Pusat Statistik Kalimantan Selatan, Banjarmasin (in Indonesian)

Bai, J., Ye, X., Jia, J., Zhang, G., Zhao, Q., Cui, B., et al. 2017. Phosphorus sorption-desorption and effects of temperature, pH and salinity on phosphorus sorption in marsh soils from coastal wetlands with different flooding conditions. Chemosphere 188:677-688. doi:10.1016/j.chemosphere.2017.08.117.

Chozin, M., Sumardi, S., Sudjatmiko, S., Gusmiatun, G. 2023. Grain yield stability of swamp rice lines across swampland agroecosystems in Bengkulu Province of Indonesia. SABRAO Journal of Breeding and Genetics 55(4):1183-1192. doi:10.54910/sabrao2023.55.4.14.

Dilhani, N.T., Nawarathna, K., Wickramasinghe, V., Chandrasekara, C., Chandrajith, R., Suriyagoda, L. 2026. Iron toxicity-related morphological and biochemical variations of selected rice (*Oryza sativa* L.) varieties in Sri Lanka. Discover Agriculture 4(1):5. doi:10.1007/s44279-026-00481-y.

Eviati, Sulaeman, Herawaty, L., Anggria, L., Usman, Tantika, H.E., et al. 2023. Analisis Kimia, Tanah, Air, dan Pupuk. Ministry of Agriculture, Bogor, Indonesia (in Indonesian)

Fahmi, A., Alwi, M., Nursyamsi, D. 2019. The role of inundation types of tidal swampland on the chemical properties of potentially acid sulphate soils under fertilizer and lime application. Journal of Tropical Soils 23(2):55-64. doi:10.5400/jts.2018.v23i2.55-64.

Fahmi, A., Hairani, A., Alwi, M., Nurzakiah, S. 2023. Fe-P pools as phosphorus source for rice in acid sulfate soils. Chilean Journal of Agricultural Research 83:626-634. doi:10.4067/s0718-58392023000500626.

Girsang, S.S., Raharjo, B. 2021. Factors affecting rice yield productivity in tidal swamp of South Sumatra. IOP Conference Series Earth and Environmental Science 648(1):012164. doi:10.1088/1755-1315/648/1/012164.

Gribaldi, G., Nurlaili, N., Novriani, N. 2023. Strategy of rice productivity increment through agronomical treatment at two flooding types of tidal swampland. Journal of Agriculture and Crops 92:199-204. doi:10.32861/jac.92.199.204.

Ilham, N., Sumaryanto, Azis, M., Syahyuti, Anwar, K., Sudaryono, T., et al. 2023. Technical efficiency of local rice farming in tidal swamp areas of Central Kalimantan, Indonesia: Determinants and implications. International Journal of Design and Nature and Ecodynamics 18(5):1235-1245. doi:10.18280/ijdne.180526.

Jumakir, Meilin, A., Adri, Waluyo, Suparwoto, Bobihoe, J., et al. 2024. Productivity and feasibility analysis of rice farming in tidal swamps land Jambi Province. E3S Web Conferences 595:01003. doi:10.1051/e3sconf/202459501003.

Khairullah, I., Saleh, M., Alwi, M., Masganti. 2021. Increasing productivity of rice through iron toxicity control in acid sulfate soils of tidal swampland. IOP Conference Series Earth and Environmental Science 648(1):012151. doi:10.1088/1755-1315/648/1/012151.

Marlina, N., Aryani, I., Khodijah, K., Marlina, M., Rompas, J.P., Yulianto, D., et al. 2022. Potential rice straw as biofertilizer in rice (*Oryza sativa* L.) in tidal soils. Journal of Global Sustainable Agriculture 2(2):69. doi:10.32502/jgsa.v2i2.4772.

Marlina, N., Haitami, A., Gusmiatun, G., Meidelima, D., Aluyah, C., Gribaldi, et al. 2025. Optimization of rice production in tidal swamps by combining bio-organic fertilizers and cropping systems. Journal of Ecological Engineering 26(9):239-252. doi:10.12911/22998993/203257.

Merkohasanaj, M., Garbanzo, G., Cortez, N., Peinado, F.J.M., Andreetta, A., Cunha-Queda, C., et al. 2025. Soil physicochemical characterization and suitability assessment for the coastal mangrove swamp rice production system in Guinea-Bissau. CATENA 256:109131. doi:10.1016/j.catena.2025.109131.

Muliarta, I.N., Purba, J.H. 2020. Potential of loss of organic fertilizer in lowland rice farming in Klungkung District, Bali. Agro Bali Agricultural Journal 3(2):179-185. doi:10.37637/ab.v3i2.567.

Murjani. 2024. Physical and chemical characteristics of wet soil in swamp ecosystems: Implications for sustainable agriculture of tidal swamps in South Kalimantan. Hidroponik Jurnal Ilmu Pertanian dan Teknologi dalam Ilmu Tanam 1(3):1-11. doi:10.62951/hidroponik.v1i3.124.

Noor, M., Sosiawan, H. 2019. Water management in tidal swamps farming: From indigenous knowledge to improved technology. p. 83-88. In Sulaeman, Y., Poggio, L., Minasny, B., Nursyamsi, D. (eds.) Tropical wetlands – Innovation in mapping and management. CRC Press, Boca Raton, Florida, USA.

Novianty, P.C., Soemarno, Efani, A. 2025. Analyzing land conversion rate and conversion farmer household food security in Bakalan Village, Pasuruan Regency. Jurnal Penelitian Pendidikan IPA 11(1):415-424. doi:10.29303/jppipa.v11i1.7583.

Qin, J., Yang, J., Zhang, J., Liu, X., Yu, J., Wang, Z., et al. 2024. Effects of tidal hydrology on soil phosphorus forms in the Yellow River estuary wetland: A field study of soil core translocation. Science of the Total Environment 922:171360. doi:10.1016/j.scitotenv.2024.171360.

Ratmini, N.P.S., Hendra. 2019. Produktivitas varietas padi lahan rawa pasang surut pada berbagai tipe luapan air pasang. Smart Farming yang Berwawasan Lingkungan untuk Kesejahteraan Petani. p. 559-566. Universitas Sriwijaya, Palembang, Indonesia (in Indonesian)

Ratmini, N.P.S., Herwenita, Irsan, F. 2021. Climate change mitigation through superior varieties use to increase rice production in tidal swamp land. IOP Conference Series Earth and Environmental Science 824(1):012019. doi:10.1088/1755-1315/824/1/012019.

Ritung, S., Nugroho, K., Mulyani, A., Suryani, E. 2011. Technical guidelines for land evaluation for agricultural commodities (revised edition). Center for Agricultural Land Resources Research and Development, Bogor, Indonesia (in Indonesian)

Setiyanto, A., Suryadi, M., Azis, M., Effendi, M.W. 2024. Predicting national rice production 2023-2024 under rising food and energy prices and global climate change. BIO Web Conferences 119:01012. doi:10.1051/bioconf/202411901012.

Simarmata, T., Hibatullah, F.H., Khumairah, F.H., Irwandhi, Ambarita, D.D.M., Nurbaity, A., et al. 2025. Advancing climate-resilient rhizomicrobiome engineering for enhancing productivity and sustainability of strategic crop farming in Indonesia’s problematic soils. Environmental and Sustainability Indicators 27:100821. doi:10.1016/j.indic.2025.100821.

Sulaeman, Y., Maftu’ah, E., Mukhlis, M., Anwar, K., Karolinoerita, V., Wakhid, N., et al. 2022. Tidal rice yield assessment in Central Kalimantan, Indonesia, under different cultural practices. Resources 11(12):116. doi:10.3390/resources11120116.

Susilawati, A., Nursyamsi, D., Syahbuddin, H. 2017. Physical properties of soils from several land uses in a tidal swampland area applied with a fork irrigation system. Journal of Tropical Soils 22(3):167-174. doi:10.5400/jts.2017.v22i3.167-174.

Susilawati, S., Surdianto, Y., Erythrina, E., Bhermana, A., Liana, T., Syafruddin, et al. 2023. Strategic, economic, and potency assessment of sorghum (*Sorghum bicolor* L. Moench) development in the tidal swamplands of Central Kalimantan, Indonesia. Agronomy 13(10):2559. doi:10.3390/agronomy13102559.

Tirtalistyani, R., Murtiningrum, M., Kanwar, R.S. 2022. Indonesia rice irrigation system: Time for innovation. Sustainability 14(19):12477. doi:10.3390/su141912477.

Widowati, L.R., Hartatik, W., Setyorini, D., Santri, J.A., Hatta, M. 2022. Validating fertilizer recommendation of swamp soil test kit. IOP Conference Series Earth and Environmental Science 1025(1):012031. doi:10.1088/1755-1315/1025/1/012031.

Yao, X., Yan, D., Li, J., Liu, Y., Sheng, Y., Xie, S., et al. 2022. Spatial distribution of soil organic carbon and total nitrogen in a ramsar wetland, Dafeng Milu National Nature Reserve. Water 14(2):197. doi:10.3390/w14020197.