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REVIEW

Water management and cropping pattern for rice cultivation in acid sulfate soils: A hydrological regimes and soil properties-based framework

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ABSTRACT

In tidal freshwater wetlands (TFW) dominated by acid sulfate soils (ASS), spatial variability in hydrological regimes and soil properties creates complex biogeochemical constraints that can reduce crop yield or lead to crop failure. Despite this heterogeneity, water management practices are frequently applied uniformly across TFW landscapes, overlooking the combined effects of hydrological and soil variability on crop growth and productivity. This paper synthesizes the scientific basis to develop a site-specific framework for water management and cropping patterns of rice (*Oryza sativa* L.), explicitly considering spatial variability in both hydrological regimes and soil properties. Our synthesis reveals that water management should be tailored to hydrological regimes and soil properties to enable optimal implementation of rice cropping patterns. In frequent flooding areas, water management aims to control excess water and saline intrusion by low dike construction equipped with stoplogs. In areas that are flooded only during spring tides, water management aims to maintain water quality through regular flushing by low dike construction equipped with channel networks with a one-way flow system, flap gates, and stoplogs. In non-flooded areas, water management aims to create sustained flooding by retaining rainfall and runoff through the construction of low dikes and the installation of stoplogs. These water management systems are designed to improve soil properties while respecting inherent site conditions, thereby supporting double cropping with superior rice varieties for increased production.

Key words: Acid sulfate soil, hydrological regime, rice, tidal freshwater wetland, water management.

INTRODUCTION

Wetlands represent a strategic land resource for agricultural expansion in many tropical countries, particularly as the availability of upland areas becomes increasingly limited. In Indonesia, wetlands cover approximately 34.12 million hectares (Mha), consisting of 8.92 Mha of tidal freshwater wetlands (TFW). Within this area, approximately 5.12 Mha have been identified as potentially suitable for rice (*Oryza sativa* L.) field development (Sulaiman et al., 2019). Consequently, wetland reclamation has become a key strategy to support national rice production and food security. However, such expansion may compromise essential ecological functions, creating trade-offs between immediate productivity gains and long-term environmental sustainability.

Most TFWs in Indonesia are dominated by acid sulfate soils (ASS), which are naturally subjected to alternating wetting and drying (AWD) cycles that create highly dynamic reduction-oxidation (redox) conditions.

These soils typically contain pyrite, which becomes unstable under aerobic conditions, leading to severe soil acidification (pH < 4.0), reduced nutrient availability, and elevated concentrations of ferric (Fe^{3+}) and Al. The intensity of these processes varies depending on inherent soil properties, ASS type, and hydrological regimes (Sukitprapanon et al., 2016; Fanning et al., 2017; Wang et al., 2022). In certain soils, particularly active ASS, seasonal flooding and strongly reducing conditions are associated with increased concentrations of potentially toxic elements, such as ferrous (Fe^{2+}), thereby inducing toxicity in rice plants (Minh et al., 2024; Firmino et al., 2025). Nugroho et al. (2021) reported that flooding increases Fe^{2+} concentration in actual ASS (AASS), but decreases it in potential ASS (PASS). Collectively, these interacting biogeochemical stresses may reduce rice yield by 15%-30% and, in severe cases, lead to crop failure, depending on stress intensity and duration (Zhang et al., 2025).

Given the strong influence of hydrological regimes on soil chemical processes, proper water management is therefore a critical determinant of successful rice cultivation in ASS-dominated TFW (Sulaeman et al., 2024). Various water management strategies have been proposed to mitigate these constraints, yet their effects on soil properties and rice yield remain inconsistent across different studies and TFW conditions. Intermittent irrigation has been reported to increase rice grain yield compared with continuous flooding (CF) (Kenichi et al., 2020), while AWD may enhance nutrient uptake and improve soil properties (Haque et al., 2021). In contrast, prolonged CF has been associated with increased soil pH (Bautista et al., 2023). However, re-flooding does not necessarily alleviate these conditions but may instead maintain or re-mobilize acidity and dissolved Fe^{2+} through dynamic redox interactions, potentially inducing toxicity in rice plants, with such contrasting responses largely governed by soil properties (Fitzpatrick et al., 2017). These contrasting findings underscore the complex interactions between water regimes and soil properties, indicating that the effectiveness of water management practices is highly site-specific and that no single water management practice is universally applicable across TFW environments.

These biogeochemical dynamics are closely linked to the spatial and hydrological complexity of TFW. In these systems, hydrological regimes and soil properties are primarily governed by tidal dynamics, while micro-elevation regulates the extent of tidal influence and drainage intensity, leading to distinct spatial gradients in soil fertility (Liu et al., 2025; Jiang et al., 2025). Soils subjected to more frequent flooding tend to exhibit relatively higher fertility levels than those in elevated areas (Sulaeman et al., 2024). Despite this inherent heterogeneity, water management practices are often applied uniformly across TFW types. For instance, Sulaiman et al. (2019) described two water management systems: A one-way flow system (OWFS) for areas regularly flooded by tides and a stoplog water management system for areas not flooded by tides, reflecting a generalized approach without limitation based on soil type or other specific factors. However, this approach overlooks the fact that soil type plays a critical role in governing geochemical processes and ultimately rice productivity. We hypothesize that explicitly considering spatial variability in both hydrological regimes and soil properties will enable the development of site-specific water management strategies and cropping patterns that enhance rice productivity in ASS-dominated TFW. Therefore, this review aims to synthesize the scientific basis to develop a site-specific framework for water management and cropping patterns in rice cultivation, explicitly considering spatial variability in soil properties and hydrological regimes in ASS-dominated TFW.

RICE WATER REQUIREMENT IN WETLAND

Rice is typically a wetland crop. Historically, rice thrived in naturally flooded environments without requiring irrigation infrastructure. Adequate water availability is a key determinant of its productivity. Rice water requirements vary across growth stages, including the seedling, vegetative, reproductive, and ripening stages. Rice is most vulnerable to water stress during the reproductive stage, particularly from panicle initiation to early grain filling. Drought during the vegetative stage has been reported to reduce rice yield by 21%-51%, whereas drought during flowering can reduce yield by 42%-84%, and drought throughout the reproductive stage may result in yield losses of 51%-91% (Zhang et al., 2018). The following section explains the stage-specific water requirements and sensitivity to water stress of wetland rice:

Seedling stage. Water requirement during the seedling stage is relatively low. However, both flooded and drought conditions may cause mortality in rice seeds, with oxygen deficiency acting as the primary constraint on radicle development under hypoxic conditions (Kunwar et al., 2024).

Vegetative stage. Immediately after transplanting, sufficient water availability is essential to ensure rapid root establishment and recovery from transplant shock. During the vegetative stage, shallow flooding enhances tiller formation and improves plant stability. In contrast, excessive flooding suppresses biomass and grain yield (Alam et al., 2026).

Reproductive stage. Water consumption is high throughout most of this stage. Drought stress occurring between panicle initiation and flowering can lead to severe yield losses, primarily through increased panicle sterility arising from impaired panicle formation, heading, flowering, or fertilization. Conversely, excessive water during the booting stage may reduce culm strength and increase the risk of lodging.

Ripening stage. Water requirements decline substantially during this stage. Beyond the yellow-ripe phase, standing water is no longer necessary, and fields may be drained approximately 10 d prior to harvest to facilitate grain maturation and improve harvesting conditions.

Rice can be cultivated across diverse landscapes, provided that suitable temperatures and adequate water are available. Despite this broad ecological adaptability, effective water management remains a defining factor for successful rice cultivation, primarily in ASS-dominated TFW. Flooded rice cultivation in ASS is widely practiced because most rice varieties exhibit better growth and achieve higher grain yields compared with non-flooded systems (Da et al., 2024). Flooding improves soil properties while simultaneously suppressing weed competition (Paiman et al., 2022; Sulaeman et al., 2024).

While these general water requirements apply to rice cultivation across all ecosystems, their implementation becomes challenging in ASS-dominated TFW. Water management must simultaneously fulfil critical functions, i.e., ensuring the water needs of rice, while also enhancing soil quality and prevent land degradation. The following sections will examine how hydrological regimes and soil properties in ASS modify these general requirements and necessitate site-specific water management strategies.

HYDROLOGICAL CHARACTERISTICS OF TROPICAL TIDAL FRESHWATER WETLANDS

Tidal freshwater wetland in tropical regions represents highly dynamic systems where hydrological regimes are governed by the bidirectional influence of marine and fluvial tidal oscillations. Within this broader system, a distinct subset occurs in TFW positioned between inland wetland areas and oligohaline reaches, where dynamic water level oscillations and periodic surface flooding lead to pronounced fluctuations in soil redox. Although salinity intrusion is minimal or episodic, hydrological regimes remain strongly governed by tidal exposure, while flooding frequency, drainage intensity, and water level are also largely determined by subtle variations in micro-elevation. Seawater intrusion generally occurs at the peak of the dry season. In the context of agricultural management, Noorsyamsi et al. (1984) classified TFW based on tidal exposure and drainage intensity into four types (A, B, C, and D):

Type A: Frequently flooded areas that experience flooding during both neap and spring tides and undergo daily drainage.

Type B: Areas that are flooded only during spring tides and undergo daily drainage.

Type C: A non-flooded area where surface flooding no longer occurs, but groundwater levels remain directly influenced by tidal dynamics through lateral inflow, with groundwater levels typically found less than 50 cm below the surface.

Type D: A non-flooded area where surface flooding no longer occurs, while groundwater levels continue to respond to tidal dynamics through lateral inflow, with the groundwater table typically deeper than 50 cm below the surface.

Tidal dynamics constitute the primary driver of hydrological processes in ASS within TFW. The hydraulic energy associated with oceanic tides progressively weakens with increasing distance from river mouths or estuaries as tidal flows move upstream against rising land elevation, resulting in reduced tidal amplitude and a more limited extent of flooding, which in turn constrains water level fluctuations. Consequently, these areas experience weaker flushing, lower flooding frequency, and diminished irrigation and drainage capacity, establishing a longitudinal hydrological gradient that regulates water level depth and soil saturation across the TFW landscape.

One of the dominant sulfide minerals in ASS is pyrite. Based on the oxidation status of sulfide minerals, ASS can be classified into PASS and AASS. The PASS is defined as soil or sediment containing Fe sulfides or other sulfide minerals that remain unoxidized, typically exhibiting a pH greater than 4.0 under undisturbed conditions. In contrast, AASS refers to soils or sediments in which sulfide minerals, including Fe sulfide, have undergone oxidation (Sarangi et al., 2022). The occurrence of pyrite or jarosite within the upper soil profile (< 50 cm) is also commonly used as a practical indicator of AASS, reflecting the development of sulfuric horizons. Therefore, the distinction between PASS and AASS is primarily determined by sulfide oxidation status, as reflected in soil pH and the occurrence of sulfidic or sulfuric materials in the soil profile. For instance, in practical terms, Typic Sulfaquents are generally associated with PASS conditions, whereas Sulfic Endoaquepts are commonly indicative of AASS due to the presence of sulfuric horizons or advanced sulfide oxidation. Meanwhile, other soil properties have not been consistently identified as reliable distinguishing factors, as evidenced by the variable and often inconsistent patterns of soil properties reported for both PASS and AASS (Sukitprapanon et al., 2015) and Typic Sulfaquents and Sulfic Endoaquepts (Anda and Subardja, 2013) (Table 1).

Table 1. Soil chemical properties of Typic Sulfaquents and Sulfic Endoaquepts in Indonesia (Anda and Subardja, 2013), and of potential acid sulfate soils (PASS) and actual acid sulfate soils (AASS) in Thailand (Sukitprapanon et al., 2015).

	Indonesia		Thailand	
Soils properties	Typic Sulfaquents	Sulfic Endoaquepts	PASS	AASS
pH H_2O	5.00	4.50	5.10	3.60
Organic-C, %	8.00	13.30	39.00	37.00
Total-N, %	0.20	0.15	-	-
P_2O_5, mg 100 g^{-1}	59.00	62.00	-	-
K_2O HCl, mg 100 g^{-1}	29.00	27.00	-	-
Exchangeable-Ca, cmol kg^{-1}	8.00	5.50	0.30	0.20
Exchangeable-Mg, cmol kg^{-1}	5.80	4.47	0.82	0.33
Exchangeable-K, cmol kg^{-1}	0.10	0.20	0.41	0.10
Exchangeable-Na, cmol kg^{-1}	0.78	0.20	0.11	2.46

Seasonal fluctuations in hydrological regimes play a key role in regulating the chemical properties of ASS. In tropical areas, soil pH in ASS typically follows a seasonal pattern driven by water-level dynamics, decreasing toward the end of the dry season and increasing at the peak of the wet season (Fahmi et al., 2023). A temporary decline in pH may also occur at the onset of flooding or the wet season, followed by a gradual increase in soil pH during prolonged flooding. These variations are closely associated with changes in soil redox potential, which control the precipitation, dissolution, and leaching of redox-sensitive minerals, such as sulfide-bearing and Fe minerals. Under aerobic conditions, oxidation of sulfide minerals lowers soil pH and induces weathering of clay minerals, resulting in structural degradations of the clay matrix, reduced nutrient availability, increased Al and Fe solubility, and loss of base cations from exchange sites (Agegnehu et al., 2021; Mendonça et al., 2021; Salo et al., 2023; Firmino et al., 2025). In contrast, reductive conditions following flooding tend to increase soil pH through the immobilization or precipitation of soluble components, often accompanied by significant changes in Fe concentrations (Wang et al., 2022). Consequently, the lowest soil pH generally occurs under oxidative conditions, whereas prolonged flooding promotes gradual pH recovery.

Tidal freshwater wetland characterized by spatial variations in the intensity and duration of flooding and drainage. Type A experiences more frequent flooding than types B and C, resulting in distinct hydrological regimes across TFW. Consistent with this pattern, water pH decreased with increasing distance from the estuary and distance from the canal outlet (Table 2). Soil pH in type A was higher than in types B and C, indicating the influence of water quality on the properties of ASS (Rasmusson et al., 2025). Similar patterns have also been reported by Proum et al. (2018). In addition, base cation concentrations increased with increasing distance from the canal outlet, likely associated with drainage processes that mobilize and redistribute solutes within the soil-water system (Maharani et al., 2025).

Table 2. Water pH observed in the canal based on distance from the estuary and from the canal outlet (Sulaeman et al., 2024).

Canal name	Distance from the estuary (km)	Distance from the canal outlet (km)					
		0	1	2	3	4	5
Tabunganen	10	6.42	6.4	6.39	6.37	6.35	6.33
Jelapat	27	6.10	5.51	5.32	4.64	3.98	3.37
Belawang	48	5.81	5.24	4.73	4.01	3.75	3.21
Barambai	57	5.75	4.78	3.46	3.13	3.12	2.96
Talaran	69	5.68	4.80	3.36	3.06	3.02	2.96

Under fluctuations of hydrological regimes, redox processes play a central role in regulating mineral transformation in ASS. For instance, drier or aerobic conditions favor the formation of more crystalline Fe minerals (Sukitprapanon et al., 2016). Consequently, frequently oxidized ASS tends to be dominated by crystalline Fe minerals such as jarosite and goethite, which are relatively resistant to reduction, thereby limiting increases in soil pH and constraining the release of sorbed P (Sukitprapanon et al., 2016) (Table 3). Oxidized layers of AASS typically exhibit greater abundances of these minerals compared with their reduced counterparts. In contrast, soil flooding lowers redox, increases soil pH, and induces the precipitation of Fe and Al, thereby enhancing the availability of base cations (Salo et al., 2023; Sulaeman et al., 2024). Additionally, soil flooding promotes Fe reduction and dissolution of Fe oxides, releasing previously bound P into the soil solution (Fahmi et al., 2023). The frequency and duration of flooding directly regulate soil redox dynamics and sulfide mineral stability, accordingly the hydrological regimes of TFW generate highly heterogeneous hydro-edaphic conditions across the landscape, influencing soil property gradients (Liu et al., 2025; Jiang et al., 2025). Therefore, water management strategies for rice cultivation in TFW cannot be uniformly applied but must be tailored to the degree of tidal influence and drainage intensity in each TFW type to minimize pyrite oxidation, mitigate soil acidity, and improve crop productivity.

Table 3. Range of Fe mineral concentrations and associated redox conditions across soil layers in potential acid sulfate soil (PASS) and actual acid sulfate soil (AASS) layers (Sukitprapanon et al., 2016).

Soil	Layers	Minerals		
		Pyrite	Jarosite	Goethite
		%	%	%
Potential acid sulfate soil	Top soil	-	-	< 5
	Reduced	5-20	-	-
Actual acid sulfate soil	Top soil	-	5-20	< 5
	Oxidized	-	5-20	< 5
	Reduced	5-20	-	-

WATER MANAGEMENT AND CROPPING PATTERN

The occurrence of a sulfuric horizon or jarosite minerals in the surface layer necessitates careful management of AASS. Under aerobic conditions, pyrite oxidation adversely affects soil fertility through acid generation. The PASS is generally more fertile and easier to manage, as they are periodically replenished with sediment from river overflows (Maharani et al., 2025) and as deeper pyrite layer permits the implementation of relatively simple water management strategies, as long as it remains unoxidized. However, this is not the case for AASS. Upon drying and rewetting, jarosite in AASS may transform into more stable Fe oxides under oxidative conditions or be reduced to Fe^{2+} under reducing conditions, leading to further alterations in soil chemical properties. During these processes, acidity is released into the soil solution. These processes indicate that the degree of soil development and associated soil properties govern the geochemical reactions. The effectiveness of water management interventions is fundamentally governed by the soil's sulfurization level (Firmino et al., 2025).

Water management in type A areas

In general, soils in type A exhibit higher fertility than the other TFW types, as they are periodically replenished with sediment from river overflows (Maharani et al., 2025). However, high flood levels and frequent flooding restrict the effective cropping season. Consequently, without proper water management, rice cultivation is typically limited to a single cropping season using local rice varieties that are tolerant to salinity but have relatively low productivity. Improved water management can enhance cropping intensity by enabling better control of water levels. This is achieved by constructing a low dike around the rice field and installing a stoplog in the channel (Figure 1), which regulates water levels and prevents excessive inflow. Stoplogs function as overflow weirs, designed to regulate water levels. During the peak of the dry season, when saline water intrusion occurs, the stoplogs are raised by installing the barrier panels as high as possible to prevent tidal water from entering the rice fields. Conversely, during the wet season, the overflow weir is lowered (i.e., the barrier panels are only partially installed), allowing both spring and neap tides to enter the fields. This water management system enables the adoption of superior rice varieties with double rice-cropping seasons per year. Similar water management practices have been widely implemented in the Mekong Delta, Vietnam.

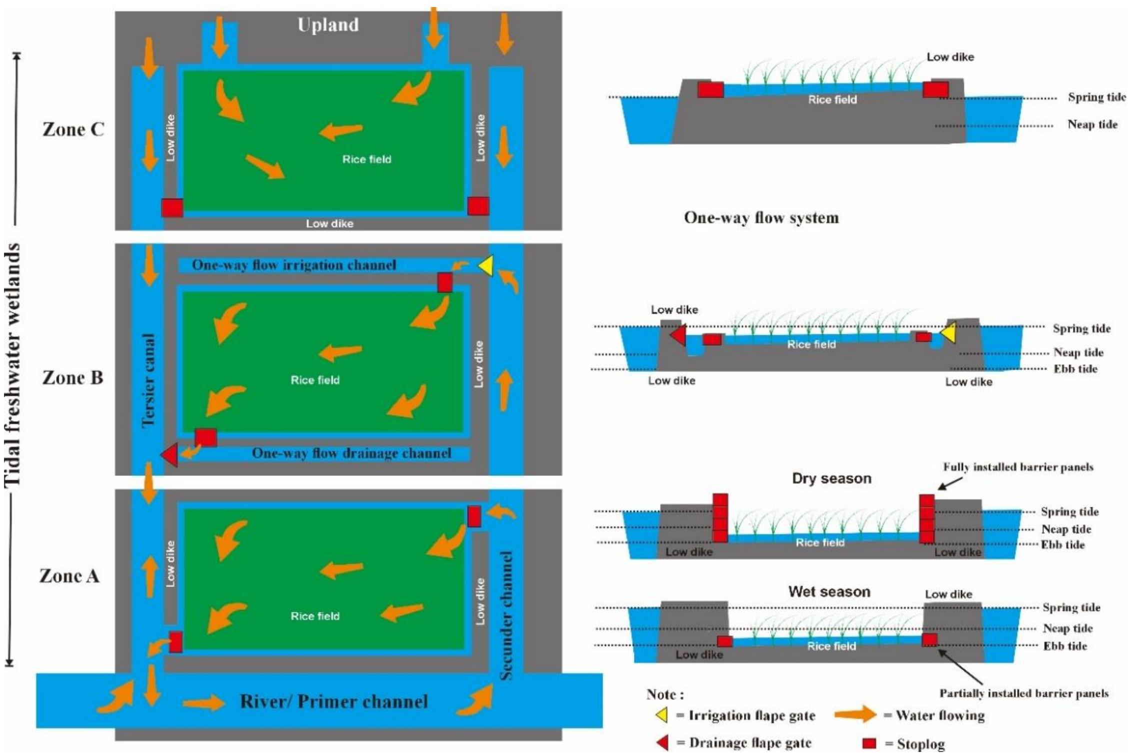

Figure 1. Illustration of water management systems in tidal freshwater wetlands (TFW). Top view of the water management system for types A, B, and C (left); side view of each system (right).

In the Mekong Delta, two dike systems have been developed to facilitate intensified rice cultivation. High dike systems are designed to exclude annual flooding and therefore enable triple rice-cropping seasons per year. In contrast, low dike systems allow controlled or partial flooding and typically support double rice-cropping seasons per year. However, several studies have shown that high dike systems may increase production costs, intensify reliance on synthetic fertilizers, and contribute to the long-term degradation of soil and water quality (Tran et al., 2019; Da et al., 2024). Based on these considerations, we propose the implementation of a low dike combined with a stoplog to limit excessive flooding while still allowing periodic sediment enrichment (Figure 1).

Water management in type B areas

In type B, soil flooding occurs mainly during spring tides. Based on their biophysical characteristics, these areas are most suitable for rice cultivation. Improving the productivity of ASS in type B requires the adoption of superior rice varieties combined with enhanced biophysical properties. Controlled flooding improves the chemical properties of ASS, but optimal productivity depends on adequate water quality and quantity (Multazam et al., 2022). To meet rice water quantity requirements, rice fields are typically maintained under flooded conditions for most of the growing season by constructing perimeter low dikes. To ensure water quality, the OWFS must be implemented (Sulaeman et al., 2024). The OWFS regulates irrigation and drainage through separate channels, enabling periodic unidirectional water movement and replacement (Figure 1). During spring tides, fresh water is used for soil leaching and flooding, after which the water is discharged through a dedicated drainage channel. Following tidal inflow, water is retained until the next tidal cycle, allowing fresh water to replace stagnant water and sustain favorable soil conditions. Previous studies have demonstrated that OWFS improves both soil quality and rice yield (Hidayat and Fahmi, 2020). For instance, in the Mekong Delta, controlled flooding at 10-15 cm water depth in ASS (pH 3.7-4.5) minimizes pyrite oxidation, reduces sulfuric acid release by 50%-60%, stabilizes soil pH at 4.8-5.2, and increases yield by 12%-18% (Minh et al., 2024).

The underlying chemical mechanism in OWFS involves flooding-induced reduction processes, which increase Fe^{2+} concentration and mobilize soil nutrients. Thereby facilitating the removal of acidity and dissolved Fe^{2+} through the drainage channel. To regulate water level and maintain water quality, the OWFS requires a stoplog and a one-way flap gate. The stoplog is installed in a channel connecting a rice field to an irrigation and drainage network to control the water level within the rice field. The one-way flap gate is placed at the mouth of the irrigation channel (referred to as an irrigation flap gate) and at the end of the drainage channel (referred to as a drainage flap gate) (Figure 2). An Irrigation flap gate opens automatically inward during spring tides to allow inflow and closes during ebb tides, while those on drainage channels operate oppositely.

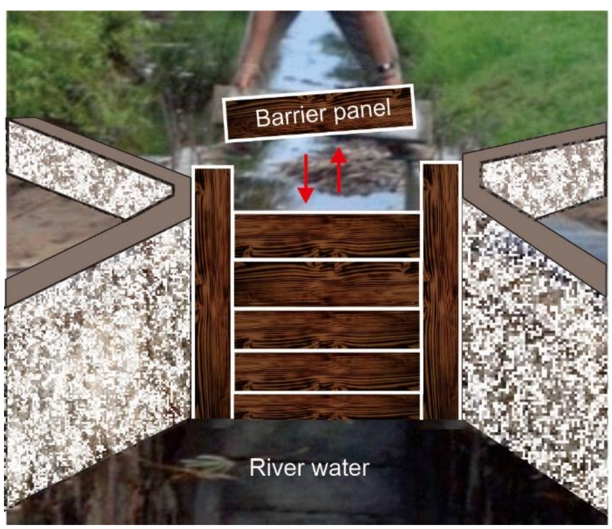

Figure 2. Illustration of stoplogs with barrier panels in a channel.

Water management in type C areas

Rice cultivation typically requires soil flooding for almost the entire cropping season. However, in type C, surface soils remain predominantly aerobic under natural conditions. To address this constraint, low dikes are constructed to elevate the field water level, thereby enabling the successful cultivation of wetland rice (Maharani et al., 2025). The function of a low dike is to retain rainwater and runoff from higher elevations, ensuring sustained soil flooding throughout the growing period. In areas with limited rainfall, water management strategies must be precisely designed to ensure sufficient water supply during phenologically critical stages of rice (e.g., tillering, panicle initiation, and flowering). Accordingly, controlled flooding should be regarded as a strategic agronomic and physiological intervention for wetland rice systems in type C.

In addition, similar to type B, soil flooding is required not only to support rice growth and development but also to maintain anaerobic soil conditions that prevent pyrite oxidation. The water level is maintained as high as and as long as possible (providing that it does not interfere with rice growth) to ensure water availability, particularly during critical stages of rice growth. Accordingly, controlled flooding should be regarded as a strategic agronomic and physiological intervention for wetland rice systems in type C. Furthermore, similar to type B, maintaining soil flooding serves a dual purpose: It not only supports optimal rice growth and development but also preserves anaerobic conditions that suppress pyrite oxidation. Therefore, water level should be maintained as high and as persistently as possible, provided that flooding does not compromise crop performance, particularly during the most sensitive growth stages.

Cropping pattern

Traditionally, TFW is used for local rice cultivation that are characterized by a long growth duration, photoperiod sensitivity, and relatively high tolerance to soil acidity and Fe toxicity (Khairullah, 2020). The rice cultivation process on TFW commences with seedling preparation at the onset of the wet season. Seedlings are raised on elevated seedbeds, a strategic measure to protect them from flooding and to avoid exposure to extremely low soil pH and high Fe^{2+} levels in the rice fields (Maharani et al., 2025). At 30-40 d of age, the seedlings undergo initial transplanting to the edges of flooded rice fields (T 1). Approximately 40 d later, a second transplant moves them to the peripheral parts of the flooded rice fields. After a further 55-60 d (T 2), rice seedlings are finally planted in the main rice field. Harvesting is typically conducted during the dry season. Spatial variation of the timing of the initiation of cultivation processes for each type of TFW is presented in Figure 3. Type C commences earlier than types A and B, reflecting that groundwater recession occurs sooner in type C than in the other two types.

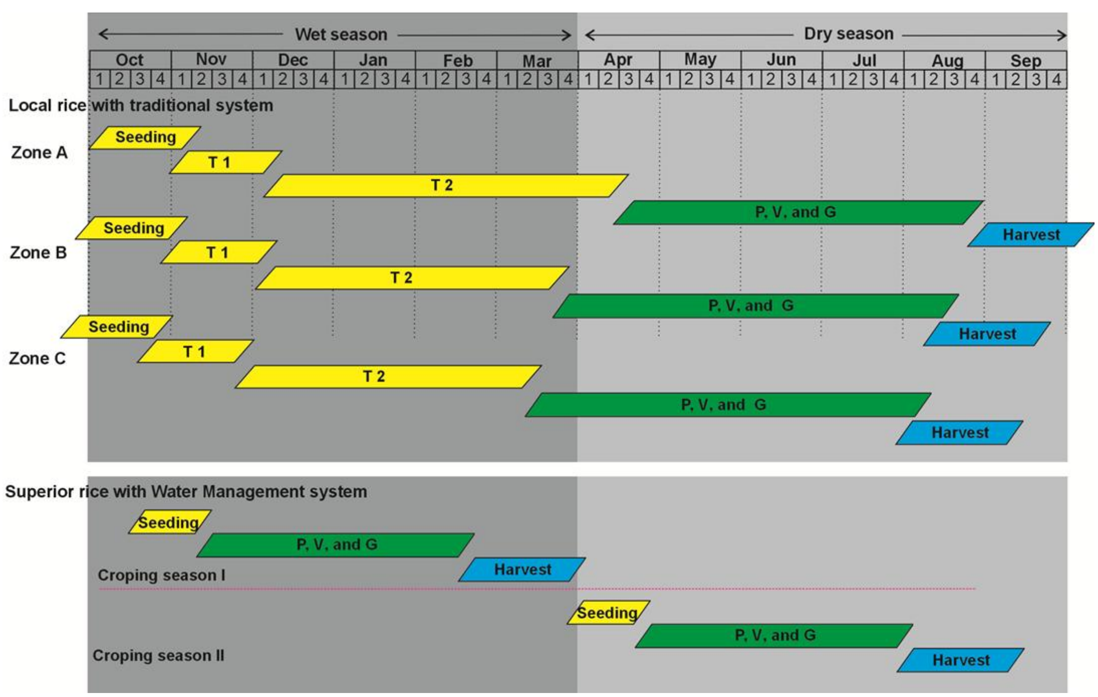

Figure 3. Local rice planting calendar for each tidal freshwater wetland (TFW) and a single superior rice planting calendar for all three TFW types. T 1: Transplanting 1; T 2: Transplanting 2; P: Planting; V: Vegetative; G: Generative.

Despite this, the cultivation system has persisted for centuries and is considered relatively environmentally friendly (Fahmi et al., 2024). Nevertheless, its yield remains low (Maharani et al., 2025). Therefore, to increase rice production, ASS-dominated TFW should be managed following scientific guidelines to prevent adverse environmental impacts and crop failure.

Each type of TFW requires a water management system specifically tailored to its soil properties, as these properties govern geochemical dynamics under different hydrological regimes (Multazam et al., 2022; Fitzpatrick et al., 2025). Appropriate water management can mitigate extreme flooding and severe drought, which otherwise restricts effective cropping. Under normal weather conditions, implementing a tailored water management system enables simultaneous rice cultivation across TFW types (Figure 3), as hydrological processes directly influence rice growth and grain yield.

However, the optimal implementation of a planting calendar depends on weather conditions. During extreme weather events, the calendar must be adjusted according to hydrological regimes. If water levels drop more rapidly in higher-elevation areas, planting should be prioritized in type C, followed by type B, and finally type A to anticipate the risk of extreme flooding and severe drought. Thus, a planting calendar that is flexible and responsive to environmental conditions is essential for achieving sustainable productivity across TFW types under both normal and extreme flooding or drought.

In fact, a planting calendar with water management based on soil type and TFW type is insufficient to ensure optimal productivity under normal or extreme weather conditions, as each soil type has a limited capacity to support plant growth and grain production. An important factor in increasing rice production is the use of superior varieties. Therefore, rice varieties adapted to soil acidity and other environmental constraints are required (Khairullah et al., 2026). The cultivation of different rice varieties across TFW and soil types is recommended, following agronomic and economic principles. Specifically, type A should adopt varieties tolerant to salinity and flooding. In type B, varieties should be selected for tolerance to moderate salinity, high soil acidity, and Fe toxicity. In type C, varieties must be adapted to extreme soil acidity, Fe and Al toxicity, and drought. Consequently, an integrated framework combining site-specific water management, a flexible planting calendar, and land type-adapted rice varieties is essential to achieve sustainable productivity across TFW types.

CONCLUSIONS

In acid sulfate soils of tidal freshwater wetlands, maintaining or creating reductive conditions through flooding is an effective water management strategy for rice cultivation. However, its effectiveness in improving soil conditions is strongly governed by the presence and characteristics of sulfide minerals. Therefore, site-specific water management strategies, tailored to tidal freshwater wetland types and soil properties, are required to optimize rice productivity. In the frequently flooded areas (type A), water management focuses on controlling excess water through the construction of low dikes and the installation of stoplogs to regulate water levels, facilitate sediment deposition, and prevent saline intrusion during the dry season. In type B areas, which are flooded only during spring tides, water management focuses on maintaining flooding while facilitating the removal of acidity and dissolved Fe, using a combination of low dikes and channel networks equipped with a one-way flow system, flap gates, and stoplogs. In the non-flooded areas (type C), water management focuses on creating and maintaining flooded conditions during the rice cropping season by constructing low dikes and installing stoplogs to retain rainfall and runoff. Collectively, these approaches ensure sufficient water quantity and adequate quality to support double cropping with superior rice varieties.

Author contribution

Conceptualization: A.F., M.Am., A.N., K.A., M.M. Methodology: A.F., K.A., A.H., D.C. Data curation: I.K., M.A., A.N. Formal analysis: A.F., I.K., A.N. Resources: S.N., S.N., R.D.N. Writing-original draft: A.F., A.N. I.K. Writing-review & editing: A.F., M.Am., P.H.M., M.A., D.C., S.N., I.K., M.M., A.R.S., R.D.N. Visualization: A.F., A.H., D.C., R.D.N. All co-authors reviewed the final version and approved the manuscript before submission.

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