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Review

Coastal Acid-Sulfate Soils of Kalimantan, Indonesia, for Food Security: Characteristics, Management, and Future Directions

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Abstract: Coastal acid-sulfate soils are crucial for producing crops and thus, for food security. However, over time, these soil resources experience degradation, leading to higher agro-input, lower yields, and environmental hazards that finally threaten food security. The optimal use of this fragile resource is only attained by implementing vigorous integrated water–soil–crop management technologies amid the climate change impact. This study aimed to review the distribution, properties, use, and management of acid-sulfate soils in Kalimantan, Indonesia. Acid-sulfate soils cover about 3.5 Mha of the coastal area in Kalimantan and have high acidity, high-risk iron and aluminum toxicity, and low fertility, requiring precise water management, amelioration and fertilizer application, crop variety selection, and rice cultivation technologies. Lime, biochar, organic fertilizer, compost, ash, and fly ash are ameliorants that raise pH, reduce iron and aluminum toxicity, and improve crop yield. Rice cultivation has developed from traditional to modern but needs re-designing to fit local conditions. Depending on the soil nutrient status, rice cultivation requires 80–200 kg ha^{-1} of urea, 50–150 kg ha^{-1} of SP36, 50–150 kg ha^{-1} of KCl, and 125–400 kg ha^{-1} of NPK compound fertilizer, but is affected by CH_4 and CO_2 emissions. Good water management impacts the effective implementation of amelioration and fertilizer application technologies. The remaining challenges and future directions for water management, amelioration, fertilizer application, crop varieties, cultivation techniques, land use optimization, climate change adaptation and mitigation, technology adoption and implementation, and resource conservation are outlined. Acid-sulfate soils remain a resource capital that supports food security regionally and nationally in Indonesia.

Keywords: acid-sulfate soil; rice; soil characteristic; soil management; tidal paddy field; wetland

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1. Introduction

Acid-sulfate soils (ASSs) contain a sulfidic layer at a 125 cm depth. In soil taxonomy [1,2], these soils include sulfa or sulfi prefixes in the suborder level, such as Sulfaquents, Sulfaquepts, and Sulfihemists, and sulfic prefixes in the great group levels, such as Sulfic Endoaquents and Sulfic Endoaquepts. ASS has unique characteristics that are controlled by its environmental conditions, such as parent materials, climate, hydro-topography, and climax vegetation, both on-site and upstream. The huge ASS area forms the center for rice production in Indonesia, Vietnam, Thailand, Bangladesh, and China, etc. In Indonesia, ASSs make up about 6.7 Mha [3], distributed mainly in coastal areas and around rivers in the big islands such as Sumatra, Kalimantan, and Papua.

In Indonesia, especially in Kalimantan, research on ASSs has been conducted since 1969, along with national development programs (Figure 1). The Indonesian government launched the Tidal Paddy Field Development Project from 1969 to 1984, where the government converted 0.005–0.2 Mha of tidal lands into paddy fields. Then, the government distributed them to farmers, who got 2.00–2.25 ha of paddy fields per head of household. The government reclaimed around 2.0 Mha of the tidal swamp for agriculture up to 1995, whereas the local people reclaimed 3.0 Mha. In addition, the government reclaimed 1.0 Mha of peatland in Central Kalimantan through the Peatland Development Project (PLG) to increase crop production from 1995 to 1999. The lessons learned from this research and development include (1) the high spatial variation in soil properties requires site-specific management technologies, (2) farmers still implement traditional farming techniques with limited infrastructure; thus, more technological dissemination and infrastructure improvements are needed, (3) production inputs for innovation technology adoption are lacking, and (4) youth interest in ASS-based agriculture is lacking, leading to land being abandoned. Managing ASSs in tidal areas is paramount for optimizing land utilization and crop productivity and reducing environmental hazards from soil and water acidification and iron toxicity.

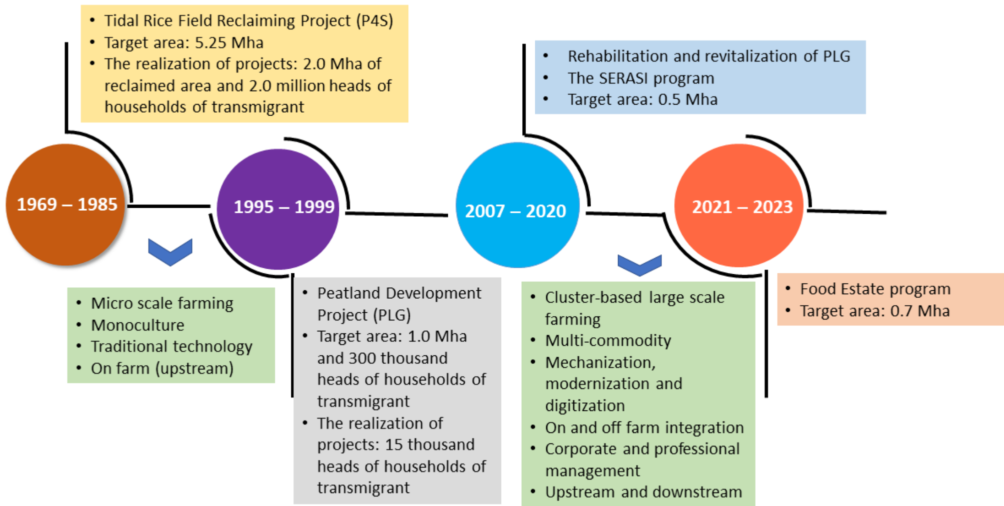


Figure 1. Progress on research and development on acid-sulfate soils, 1969–2023.

Formulating and implementing robust water and soil management technologies requires a better understanding of ASS characteristics. Mismanagement of these soils leads to land degradation, as indicated by soil pH dropping to 3 or less, and the release of organic acids and metals that are dangerous to water biota and human health [4,5]. During rice cultivation, in particular, these soils emit CH_4 under reduced soil conditions (Eh < −250 mV) and CO_2 under oxidized conditions. Tidal type influences CH_4 and N_2O emissions [6], while rice variety controls CH_4 emissions [7].

ASS is an essential wetland resource for producing food, feed, fiber, and fuel. Water management, amelioration, fertilizer application, and adaptive crop variety are among the technologies required to increase crop yield while maintaining good environmental quality. In Indonesia, Kalimantan is a crucial ASS-based agriculture production center. Nevertheless, publications elaborating on the state of ASSs in Kalimantan are still limited. Their unique characteristics, distribution, and existing management options are among the remaining questions, and future directions should be outlined accordingly. Therefore, this study aimed to review the distribution, properties, use, and management of ASSs in Kalimantan, Indonesia.

We surveyed articles in reputable journals and proceedings in digital databases (Google Scholar, Web of Science, Scopus, ScienceDirect, Dimensions, and Lens) using the keywords acid-sulfate soils, tanah sulfat masam, and Kalimantan, and collected relevant technical reports from previous projects. Then, we grouped articles into seven themes, i.e., distribution and properties, water management, soil amelioration, fertilizer application, rice varieties, farming system and technology adoption, and greenhouse gas emissions. Considering our experience and the recent information on these themes, we outlined challenges and future directions.

2. Acid-Sulfate Soil Distribution and Selected Properties

2.1. Distribution

In Kalimantan (Indonesia), the swampland is about 10.0 Mha [8], of which 2.9 Mha is tidal and about 7.1 Mha is inland. Figure 2 shows the indicative distribution of ASSs in the coastal area of Kalimantan, covering about 3.5 Mha. In the West Kalimantan province, this soil is found in the coastal area, from Sambas Regency in the north to Singkawang, Bengkayang, Mempawah, Pontianak, Kuburaya, and Ketapang Regency in the south. ASSs are mainly found in the estuary of the Kapuas River, the longest river in Indonesia (12 km long), and the Bengkayang River (2 km long).

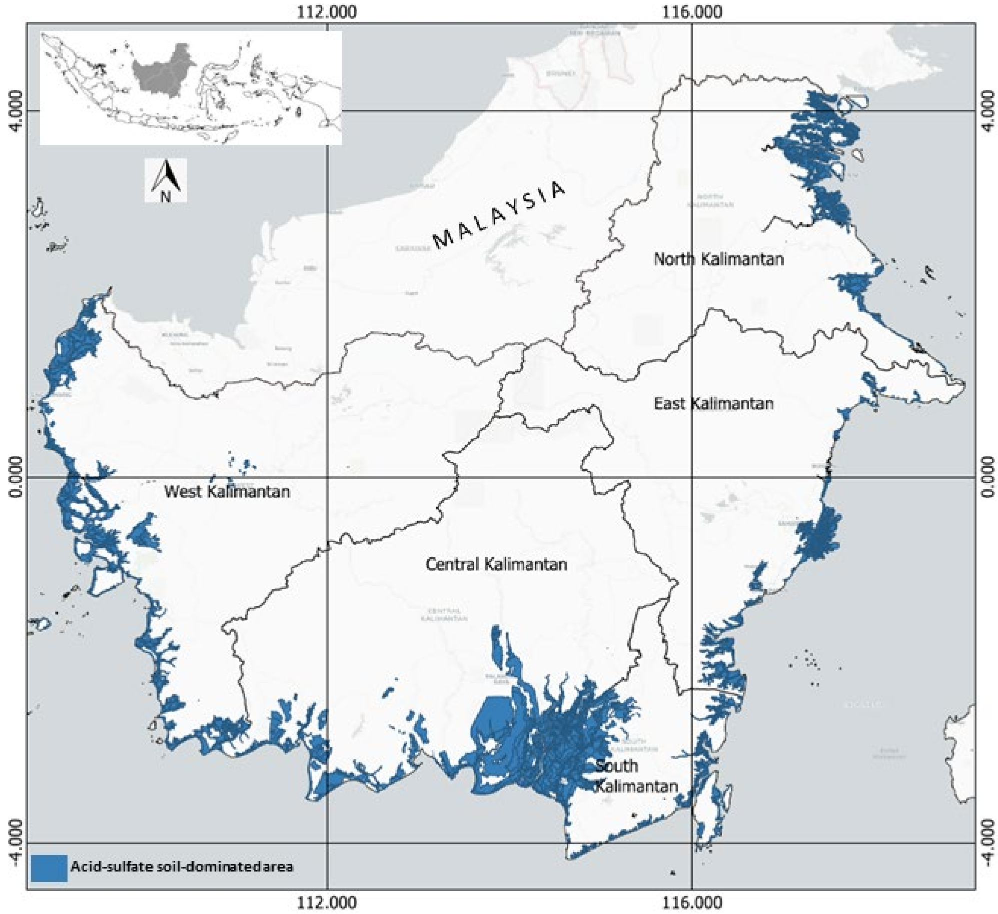


Figure 2. Indicative distribution of acid-sulfate soils in Kalimantan, Indonesia, plotted using OpenTopomap. Source: [9–12], re-drawn and updated.

In Central Kalimantan province, ASSs extend along the coastal areas of Kotawaringin Barat Regency, Seruyan Regency, Pulangpisau Regency, and Kapuas Regency. The soils also extend to South Kalimantan province, mainly in Barito Kuala, Barito Selatan, Hulu Sungai Selatan, Tapin, Tanah Laut, Tanah Bumbu, and Kotabaru Regency.

On the eastern coast of Kalimantan, ASSs are found from the coastal area of Paser Regency in the south to Kutai Kertanegara Regency in the north of East Kalimantan province. In North Kalimantan province, these soils are found in the coastal areas of Nunukan, Tana Tidung, and Bulungan Regency.

2.2. Soil Properties

ASSs in Kalimantan are dominated by silt and clay fractions and mostly have a clay texture (the clay fraction is more than 35%). The soils are also categorized as heavy clay soils (clay fraction of more than 60%), for example in Tapin and Nunukan. Table 1 provides the physicochemical properties of selected soils from Kalimantan.

Table 1. Physicochemical properties of selected profiles of acid-sulfate soils in Kalimantan.

	Depth cm	Sand	Silt (%)	Clay	pH	OC (%)	TN	P_2O_5 (mg 100 g^{-1})	K_2O	Exch.Ca	Exch.Mg	Exch.K (cmol kg^{-1})	Exch.Na	CEC	BS %
WG 86, Sambas Regency, West Kalimantan Province (1.457972°N, 109.221722° E)															
Ap	0–20	1	46	53	4.3	7.30	0.55	17	26	0.70	1.00	0.38	0.72	20.17	14
Cg1	20–40	1	46	53	4.3	5.99	0.36	9	19	0.67	1.63	0.23	1.42	20.11	20
Cg2	40–70 *	0	57	43	3.9	5.60	0.31	6	22	0.86	2.08	0.24	1.50	20.35	23
Cg3	70–120 *	1	31	68	2.6	5.40	0.26	5	42	1.73	3.51	0.17	1.81	23.10	31
LM5, Kotawaringin Barat Regency, Central Kalimantan Province (2.807222° S, 111.513417° E)															
A	0–20	7	68	25	4.4	15.79	0.74	34	22	1.39	0.73	0.05	0.49	29.61	9
Bg1	20–45 *	2	44	54	3.8	6.11	0.22	13	8	0.72	0.87	0.11	0.61	33.64	7
Bg2	45–70 *	4	62	34	2.6	5.61	0.30	12	10	0.76	1.66	0.05	0.41	13.19	22
Bg3	70–100 *	6	62	32	2.7	5.85	0.30	21	23	0.96	2.73	0.02	0.40	15.27	27
ZS9, Seruyan Regency, Central Kalimantan Province (3.173833° S, 112.393333° E)															
Ag	0–20	1	43	56	4.8	2.14	0.21	19	6	1.35	1.18	0.04	0.12	18.90	14
Cg1	20–55	1	48	51	4.3	4.27	0.41	17	5	1.11	1.27	0.05	0.17	20.63	13
Cg2	55–80 *	1	41	58	2.7	4.66	0.45	22	20	2.39	2.57	0.03	0.16	11.88	43
LM11, Tapin Regency, South Kalimantan Province (3.091833° S, 115.037694° E)															
Oa1	0–15 *	1	41	58	4.0	29.25	1.04	17	10	2.21	2.58	0.14	0.58	50.77	11
Oa2	15–50 *	0	38	82	4.3	42.17	2.24	15	12	3.93	3.58	0.28	0.44	83.47	10
Cg	50–150 *	0	20	80	3.6	3.66	0.33	4	11	1.67	3.01	0.31	0.02	21.86	23
UY60, Nunukan Regency, North Kalimantan Province (4.016389° N, 117.495250° E)															
AC	0–20	3	37	70	4.6	3.47	0.33	38	154	2.69	3.29	1.99	0.10	37.18	47
Cg1	20–40 *	1	38	61	4.8	5.14	0.17	40	167	5.99	3.61	3.08	0.11	19.17	67
Cg2	40–80 *	1	40	59	4.6	5.47	0.18	41	166	4.10	3.45	3.17	0.10	18.04	60
UY61, Nunukan Regency, North Kalimantan Province (4.014000° N, 117.517833° E)															
AC	0–20	1	33	66	4.6	26.68	0.87	24	90	5.13	3.92	1.66	0.10	32.40	33
Cg1	20–45 *	2	26	72	4.4	11.84	0.45	8	56	4.06	3.79	1.12	0.84	33.50	29
Cg2	45–80 *	8	38	54	4.0	5.39	0.35	7	47	2.88	3.27	0.73	0.73	18.77	41
UY63, Nunukan Regency, North Kalimantan Province (4.023361° N, 117.542611° E)															
AC	0–20 *	12	41	47	3.3	8.04	0.22	21	220	2.69	3.14	0.74	0.10	19.26	35
Cg1	20–60 *	1	49	50	3.4	7.49	0.21	21	217	2.54	3.30	0.82	0.11	19.16	35
Cg2	60–80 *	1	53	46	4.1	8.40	0.17	26	160	4.40	3.40	2.40	0.10	18.20	57
Cg3	80–100 *	18	41	41	4.7	7.43	0.17	30	142	5.08	3.80	2.71	0.09	22.72	51
CB 55, Tana Tidung Regency, North Kalimantan Province (3.552500° N, 117.203494° E)															
Ag	0–20	2	44	54	4.2	5.89	0.49	30	27	0.95	1.20	0.40	0.49	25.09	12
Cg	20–50 *	1	54	45	3.9	6.54	0.50	40	29	1.31	1.65	0.34	0.58	24.23	16
2Cg1	50–80 *	2	45	53	4.6	4.24	0.42	50	44	2.77	3.50	0.54	0.82	19.86	38
2Cg2	80–100 *	2	47	52	5.1	3.68	0.35	27	34	3.41	3.63	0.47	0.87	16.14	52
2Cg3	100–120 *	1	54	45	4.8	4.50	0.35	21	42	4.00	3.95	0.55	1.57	17.61	57

Note: pH = soil pH in the water extract, OC = organic carbon, TN = total nitrogen, P_2O_5 = potential P_2O_5, K_2O = potential K_2O, CEC = cation exchange capacity, BS = base saturation. * Layer containing sulfidic materials. Data in Table 1 are based on ref. [13,14].

As expected, the pH of the ASSs is low (acidic), ranging from 2.6 to 5.1. The soil pH is very low in the layer containing sulfidic materials (pH 2.6–4.8). Meanwhile, sulfidic materials are found 20 cm below the surface in Kotawaringin Barat and Tana Tidung Regency, and 55 cm below the surface in Seruyan Regency. Sulfidic materials are found near the surface in several sites, such as Nunukan Regency.

Information on the depth of the sulfidic material, pyrite, is crucial in managing this soil for agriculture because pyrite (FeS_2) is one of the primary sources of acidity [15,16]. Shamshuddin et al. [17] concluded that the oxidation of 1.0 moles of FeS_2 produces 4.0 moles of H_2SO_4. Several factors affect changes in soil acidity due to pyrite oxidation, i.e., oxygen and ferric (Fe^{3+}) availability, decomposable organic matter, the initial value of soil pH, base cation availability, pyrite content, and the hydrological condition of the land. However, soil moisture and the hydrological condition of the land are the main factors that determine soil acidity [18]. Variations in groundwater levels control pH and Eh. Decreased groundwater level or soil moisture during the dry season or due to drainage of the land leads to the oxidation of pyrite and other ferrous (Fe^{2+}) species [18,19]. Conversely, flooded soil leads to reduced soil conditions, increasing soil pH [18,20].

Soil organic carbon (SOC) content also varies, ranging from 2.14 to 8.40%. In some areas, the soils are covered with peat soils, called peaty ASSs, such as in Kotawaringin Barat, Tapin, and Nunukan Regency (Table 1). This organic matter is less than 50 cm thick, hence excluded from organic soils (Histosols). The peat material contains very high soil organic carbon ranging from 11.84 to 42.17%.

The cation exchange capacity (CEC) of soil is between 15.27 and 83.47 cmol kg^{-1}, while base saturation (BS) varies between locations, ranging from 7% to 67%. High organic carbon and clay are responsible for this relatively high CEC. Variations in BS are closely associated with the variations in exchangeable Ca and exchangeable Mg. Soils from Sambas and Kotawaringin Barat Regency are low in exchangeable Ca and Mg, leading to lower BS. Meanwhile, the base cation content is alleviated and fertilizer application is required to support crop growth.

Nitrogen content varies from low to very high [15,21,22], with total nitrogen ranging from 0.17 to 1.04% (Table 1). Soil pH is essential when determining nutrient availability and toxicity in these soils; low soil pH causes aluminum and iron solubility to increase, and the capacity for fixing phosphorus is large [23]; phosphorus adsorption capacity may reach 800 mg kg^{-1} [24]. However, flooding in these soils decreases Eh and solubilizes Fe oxides, increasing P availability [25].

During ASS formation, the natural oxidation of sulfide-bearing minerals and sulfuric acid attack clay minerals, resulting in changes to the clay mineral structure. The sulfuric acid lowers pH, which makes nutrients less available; low soil pH causes aluminum and iron solubility to increase, displacing K, Ca, and Mg from the exchange complex. Furthermore, the exchange complex contains aluminum and iron. Therefore, ASS is likely deficient in Ca and K. Soil pH was positively and significantly correlated with exchangeable K, Ca, and Mg content in the soil [26]. However, flooding ASSs increases the availability of K, Ca, and Mg due to the increase in soil pH and the precipitation of aluminum and iron [27,28].

Iron (Fe) is abundant in ASSs. Fe concentrations in flooded ASSs can reach 4700 mg kg^{-1} [24]. Fe solubility depends on environmental conditions, such as Eh, pH, organic matter, soil moisture, microorganisms, anion presence [17,18,21], and land management systems. Fe solubility is also influenced by its characteristics, such as specific surface area and solubility [29].

Aluminum toxicity is the most critical limiting factor for plant growth in ASSs. A substantial amount of H^+ ions are supplied to the soil solution as a result of pyrite oxidation, and the acid reacts with soil minerals, dissolving Al in the soil solution. Al solubility is relatively higher at low pH [30]. Exchangeable Al in ASS ranges from 1.8 to 4.3 cmol kg^{-1}. These levels are toxic to plants and limit the availability of essential nutrient elements such as P, Ca, and Mg [17].

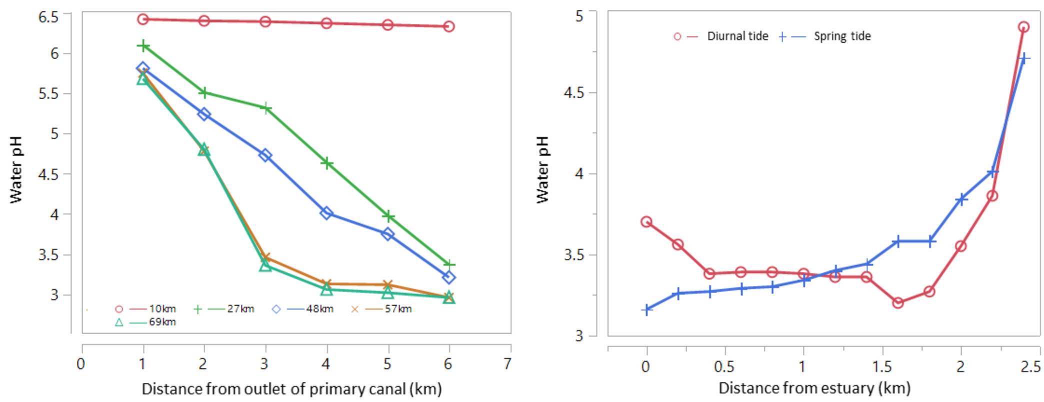
Salinity occurs in soils inundated by seawater daily. These areas are generally covered with mangrove forests and are not used for rice cultivation. During prolonged droughts (such as El Nino), salt concentrations in water increase [31]. The level of seawater increases from the tide to the upper stream, leading to an increase in the coverage of salt-affected soil obstructing crop growth [32]. During the rainy season, salt concentrations return to normal and rice can be planted on land in that area. Haloculture is another system for the sustainable use of saline water for crop production [33].

For rice cultivation, ASS has several constraints because pyrite oxidation increases acidity. In addition, this land has a low content of macro and micronutrients [34] and iron toxicity that can decrease rice yield from 30 to 100% depending on variety tolerance levels, toxicity intensity, and soil fertility status [35]. Managing water conditions is an option for controlling pyrite oxidation. In fact, insights into hydrological characteristics for water management technology are the key to successful crop production in ASS-dominated agricultural land.

3. Hydrological Characteristics and Water Management

Sea tide activities control the hydrological characteristics of ASSs. Pushing spring tide weakens with distance from the estuary (river or primary canal estuary), leading to lower water potency that inundates the ASS. Such a condition is caused by increasing topography upstream and water is pushed by the tide to balance the conditions in the water. The wave decreases moving energy, impacting the irrigation and drainage potency.

In areas that are routinely inundated by big tides and small tides (Type A), water floods ASSs every day. The potency of pyrite oxidation is very low and hence rarely found in acidic water (water pH < 4.0). In areas inundated only during big tides (Type B), irrigation water is always available; however, some big tides cannot reach the ASSs during small tides in the dry season (DS). Such conditions trigger pyrite oxidation in the soil layer, forming acids from leached soil that accumulate in the quarter/tertiary canal during the early wet season (WS) and move to secondary and primary canals. Some areas are not inundated by spring tides but only seepage below the soil surface (Type C or D); the only water source is rainfall. The potency of pyrite oxidation is high in these areas, primarily during the DS, resulting in acidic soils. Leached acidic compounds (organic acids, Fe, Al) lead to much lower water pH in the canals than in the Type B areas. The influence of the spring tide on water pH is presented in Figure 3, where water acidity increases with distance from the estuary.



(**a**) (**b**)

Figure 3. (**a**) Water pH at the peak of the spring tide based on distance from river/sea estuary in the primary canal along Barito River, South Kalimantan, measured at distances of 1, 2, 3, 4, 5 and 6 km from the canal estuary, and (**b**) water pH during the spring tide and the diurnal tide in the secondary canal of the Betaguh wetland irrigation region of Pulang Pisau Regency, Central Kalimantan, as measured on 10 June 2021. Source: primary data from Author/Khairil Anwar.

The depth of the pyrite layer also influences water quality in the ASS area. In the secondary canal (SC) edges with deep pyrite layers and more acidic irrigation water, the water pH will increase upstream of the SC. Mixing tidewater and drainage water in the SC leads to variations in water quality (Figure 3). In the SC, a regular pattern of water pH is more common during the diurnal tide than during the spring tide. The pH of the water in the primary canal (PC) is lower than that of the water in the SC during the diurnal tide; however, the pH of the water in the PC is higher than that of the water in the SC during the spring tide.

The water's acidity level is an indicator that pyrite has been oxidized. In Type B ASS areas with poor drainage, water acidity negatively correlates with the water's electrical conductivity (EC), Al^{3+}, Fe^{2+}, Mn^{2+}, $SO_2{}^{4-}$, Ca^{2+}, Mg^{2+}, Na^{+}, and SiO_2. Poor drainage in the PC leads to the accumulation of leached ions in the PC water body. Multazam et al. [36] confirmed that water pH is negatively correlated with the EC value. This correlation pattern differs from that in areas with better water circulation, as in the Type A area, where ions easily leach to the edge of the PC.

The sea surface is higher during the WS than during the DS [37]; therefore, the potency of tide overflow during the WS is higher than during the DS. Moreover, the volume of water in rivers, tributaries, and other water bodies in the upper region increases the tide overflow potency. Figure 4 shows the monthly rainfall patterns in South Kalimantan province, Indonesia, where the overflow potency is low from July to September. Overflow potency is associated with pyrite oxidation, the leaching of acids from the soil, and acidic compounds in the water canal. Therefore, pyrite oxidation occurs during the DS, and acids leach at the beginning of the WS. As a result, water pH is very low in areas with poor drainage at the start of the rainy season (October–December). Rainfall leaches acidic compounds and toxic ions from the ASSs and increases the acidic content and toxic ions in water bodies downstream [38]. Water pH increased in January along with the increasing rainfall intensity, leading to the dilution of acidic compounds. The fluctuation in standing water levels in the primary canal is influenced by rainfall [36].

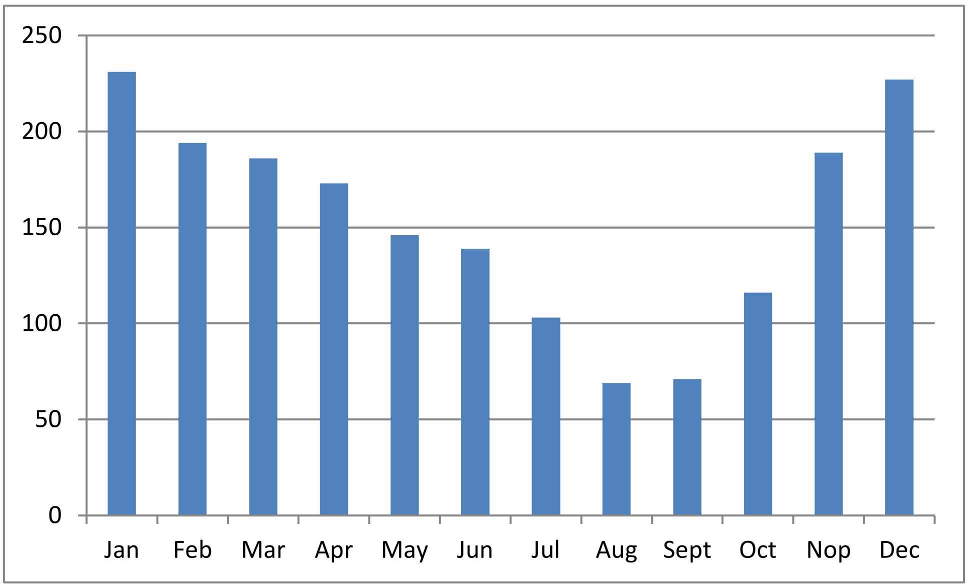


Figure 4. Monthly average rainfall (in millimeters) in South Kalimantan province, Indonesia. Source: https://dataonline.bmkg.go.id, accessed on 21 January 2024.

Standing water in the tidal region follows the sea tide dynamically, and changes by hour, day, and month depending on the moon's position relative to the earth and the sun. Such dynamics lead to different potencies in the overflow and drainage over time. Standing water can supply irrigated sources in paddy fields, adjust application time during rice cultivation, leach toxic ions, determine planting time, and select water management technologies [36]. In general, tide overflow supplies good quality water and is used to leach toxic ions into the land by the receding water.

Water management is critical to the sustainable management of ASSs because water management can prevent pyrite oxidation, the leaching of acidic and toxic elements and compounds from the soil, and the supply of water for crops. Water management is based on tidal overflow type, potency, and water table depth (Types A, B, C, and D) [39,40]. Water management can be tailored to the soil, hydrological characteristics, and rice needs and adjusted to the problems in each tidal overflow type.

Water management in ASSs fails because soil and water become more acidic, and crop productivity decreases [41]. This conclusion is supported by the results of research on water acidity [36]. Hence, water management must (i) be tailored to the hydrological characteristics, climate, and soil in each location, (ii) be supported by the government (central and local) and the farmer using the water, and (iii) conducted at macro scales (wetland irrigation regions) and micro-scales (paddy fields).

Type A tidal areas show high inundation during the rainy season, and the areas experience saltwater intrusion during the dry season. Therefore, water infrastructure, including periphery dikes and flapped water gates, is required to prevent overflow and saltwater intrusion (Figure 5a). Type B tidal areas with impeded drainage and poor water quality are a problem because leached acids in waterways cannot go out to river estuaries due to the push from the tide. This condition requires implementing a one-way direction of fork-like canals (macro water management) supported by implementation in paddy fields (micro-scale) for better water circulation. In addition, the primary, secondary, and tertiary canals are shorter than the existing ones and are tailored to each area's irrigated/drainage potency in such a way that acids move out from the site with the subsided water. A one-way directional system requires a swaying water gate and stop log (overflow) in the paddy fields. A swaying water gate is used to ascertain water circulation during the WS. During the DS, a stop log conserves water and prevents pyrite oxidation (Figure 5b).

Figure 5. Types of water gates: (**a**) flapped water gate, (**b**) swaying water gate, (**c**) stoplog water gate. Photo by Author/Khairil Anwar.

In Type C tidal areas, acids formed in soils during the DS are leached during the WS; paddy fields are inundated 5–10 cm to prevent pyrite oxidation by using overflow cascades starting from the paddy fields to tertiary and quarter canals (Figure 5c). Lowering inundation and the water table leads to pyrite oxidation, resulting in very acidic soils and water; hence, the water table requires better management.

The ASSs need leaching so that acids and toxic ions can leave the paddy field, but the water needs maintenance to prevent pyrite oxidation [42]. Precise water management, low prices, and economics are key factors in sustainable ASS management [43]. After implementing correct water management, ASSs need amelioration and fertilizers to support crop production [44].

4. Soil Amelioration

Soil amelioration improves soil properties so that the soil is favorable for crop growth and production. Table 2 lists the ameliorants used in ASSs in Kalimantan, including lime, organic fertilizers, biochar, compost, and fly ash. The efficacy of ameliorants on soil properties and rice yield depends on the type and dosage of ameliorant and the soil characteristics.

Table 2. Contributions of ameliorants to the improvement of the properties of acid-sulfate soils and rice growth and yield in Kalimantan.

Material	Location	Input	Outputs	Ref.
Lime	Central Kalimantan	Dolomite: 5 Mg ha^{-1}	• Raised soil pH from 3.2 to 4.0 • Decreased Fe^{2+} from 6000 to 900 mg kg^{-1}, Al^{3+} from 17 to 8 cmol kg^{-1}, and SO_4^{2-} from 8000 to 1000 mg kg^{-1}	[45]
	Semerak, Kelantan, Malaysia	Ground magnesium limestone (GLM) with biofertilizer: 4 Mg ha^{-1}	• Raised soil pH from 4.01 to 5.39, total N from 0.10 to 0.20%, available P from 16.33 to 34.38 mg kg^{-1}, Exchangeable Mg from 0.64 to 2.45 cmol kg^{-1}, Exchangeable Ca from 0.65 to 2.97 cmol kg^{-1}, and Exchangeable K from 0.16 to 0.35 cmol kg^{-1} • Decreased Fe^{2+} from 178 to 61 mg kg^{-1} • Increased grain yield from 3.2 to 5.24 Mg ha^{-1}	[46]
Biochar	West Kalimantan	Rice-husk biochar: 10 Mg ha^{-1}	• Raised soil pH from 3.75 to 4.4 • Decreased exchangeable Al from 1.42 to 1.09 cmol kg^{-1} • Increased the number of productive tillers from 9 to 17.3	[47]
Organic fertilizer	Central Kalimantan	Porre organic fertilizer: 2 Mg ha^{-1} Dolomite: 3 Mg ha^{-1}	• Raised soil pH from 3.2 to 4.3 • Decreased Fe^{2+} from 6000 to 1500 mg kg^{-1}, exchangeable Al from 17 to 6 cmol kg^{-1}, and SO_4^{2-} from 8000 to 900 mg kg^{-1}) • Increased grain yield by more than 17%	[45]
Compost	South Kalimantan	Compost: 3 Mg ha^{-1})	• Reduced Fe^{2+} from 709 to 600 mg kg^{-1}	[48]
	South Kalimantan	Compost: 2.7 Mg ha^{-1}	• Raised soil pH from m 3.67 to 3.70 • Decreased exchangeable Al from 8.82 to 7.05 cmol kg^{-1} • Increased grain yield by 48%	[49]
Ash	West Kalimantan	Rice-husk ash: 10 Mg ha^{-1}	• Raised soil pH from 3.75 to 3.98 • Decreased exchangeable Al from 1.42 to 1.32 cmol kg^{-1} • Increased the number of tillers from 9 to 15	[47]
	Central Kalimantan	Rice-husk ash: 2 Mg ha^{-1} Dolomite: 3 Mg ha^{-1}	• Raised soil pH from 3.2 to 3.8 • Decreased Fe^{2+} from 6000 to 1000 mg kg^{-1}, exchangeable Al from 17 to 8 cmol kg^{-1}, and SO_4^{2-} from 8000 to 1000 mg kg^{-1} • Increased grain yield by more than 7%	[45]
Fly ash	South Kalimantan	Fly ash: 5 Mg ha^{-1}	• Raised soil pH from 5.08 to 5.31 • Increased grain yield from 4 to 12 g pot^{-1}	[50]

Application of lime on ASSs raises soil pH, reduces Al and Fe content, and improves rice growth. Applying magnesium limestone plus biofertilizers increases soil nutrient content, i.e., total N, available P, exchangeable Ca, and exchangeable Mg [46]. Liming and application of organic fertilizer increased rice yields in acid-sulfate paddy soils [45].

Rice-husk biochar was better than ash at improving the chemical properties of ASSs (namely pH, SOC, available P, exchangeable K, exchangeable Na, exchangeable Mg, and CEC) and decreasing Al and Fe content [47]. Applying rice-husk biochar increased soil pH to 5.0 or more and rice yields by 20% [51]. Combining rice-husk biochar (5 Mg ha^{-1}) and chicken manure (0.5 Mg ha^{-1}) increased soil pH and P availability, decreased Fe and iron toxicity, and enhanced rice growth and yield [52]. Combining biochar (from empty fruit bunches of oil palm) increased rice yield from 141 to 472% and decreased Al toxicity [53].

Compost increases available P, whereas biochar is more effective at mitigating GHG by suppressing CO_2 emissions [54]. Compost increases soil pH and improves rice growth in ASSs [54]. Applying organic material (compost) to soil improves the pH of ASSs and its effect depends on the Eh and sulfate contents. Organic matter can temporarily replace liming in land management [55]. Adding organic matter can increase P availability in ASSs and P release from the soil [56]. Compost is potent in the arrangement of nematode communities by increasing biodiversity, trophic structure, and metabolic tract in ASS-based paddy fields [57].

Applying biofertilizers (microbes) improves the quality of ASSs. Phosphate-solvent bacteria secrete organic acids, which deactivate Al and Fe through chelation. It also increases soil pH, precipitating Al or Fe as inert hydroxide Al or Fe, decreasing Al and Fe availability [58]. Sulfate-reduction bacteria (*Desulfovibrio* sp.) are essential in reducing acid-sulfate soils, increasing soil pH and rice yield [52].

Soil amelioration is an essential treatment for ASSs. Ameliorants (lime, biochar, organic fertilizer, compost, ash, and fly ash) and their rates and effects on soil properties have been discussed. Nevertheless, crops still need nutrient input due to the low nutrient content of these soils; thus, fertilizer application is required.

5. Fertilizer Application

The nutrient (N, P, and K) content of ASSs in Kalimantan is generally low to medium, while that of exchangeable Ca is very low to low and the soil pH is 4.5 or lower. Thus, fertilizer application is a priority in soil management and the rate and application depend on the crop, tidal type, and land typology. Field studies assessed dose and production at selected rice production centers, as presented in Table 3.

Table 3. Rice yields and fertilizers for selected acid-sulfate soils-based tidal paddy fields in Kalimantan.

No.	Location (Village, District, Regency, Province)	Fertilizer Rate (kg ha^{-1})				Rice Yield (Mg ha^{-1})	Ref.
		Urea	SP-36 *	KCl	NPK **		
1.	Karang Indah, Mandastana, Barito Kuala, South Kalimantan	100	-	50	-	2.70	[59]
2.	Karang Indah, Mandastana, Barito Kuala, South Kalimantan	100	50	-	-	2.92	[59]
3.	Karang Indah, Mandastana, Barito Kuala, South Kalimantan	-	50	50	-	3.06	[59]
4.	Karang Indah, Mandastana, Barito Kuala, South Kalimantan	100	50	50	-	3.40	[59]
5.	Danda Jaya, Rantau Badauh, Barito Kuala, South Kalimantan	-	-	-	400	2.95–5.55	[60]
6.	Kanamit Jaya VII, Maliku, Pulang Pisau, Central Kalimantan	200	100	150	-	4.0–5.0	[61]
7.	Matang Danau, Paloh, Sambas, West Kalimantan	100	-	-	250	4.0–6.0	[62]
8.	KP. Belandean, Alalak, Barito Kuala, South Kalimantan	200	150	150	-	4.0	[63]
9.	Karang Bunga, Wanaraya, Barito Kuala, South Kalimantan	100	-	-	300	4.5–6.2	[64]
10.	Sido Mulyo, Kutai Kartanegara, East Kalimantan	100	-	-	300	4.5–6.2	[64]
11.	Danda Jaya, Rantau Badauh, Barito Kuala, South Kalimantan	80	-	-	125	4.40	[65]
12.	Terusan Karya, Bataguh, Kapuas, Central Kalimantan	100	-	-	250	5.0–6.0	[66]
13.	Belanti Siam, Pandih Batu, Pulang Pisau, Central Kalimantan	150	-	-	250	6.0–7.0	[66]
14.	KP. Belandean, Alalak, Barito Kuala, South Kalimantan	167	104	62.5	-	2.67–4.13	[67]
15.	Danda Jaya, Rantau Badauh, Barito Kuala, South Kalimantan	167	104	62.5	-	2.95–5.31	[67]
16.	Karang Buah, Belawang, Barito Kuala, South Kalimantan	150	-	-	300	4.39–6.62	[68]

* P fertilizer containing 36% P_2O_5, ** NPK compound fertilizer. Rice yield was unmilled grain.

Levels of N input and N loss in N cycles determine soil nitrogen content variations. Low N content occurs because N is taken up by crops, leached, and volatilized [69]. On average, nutrient loss for every ton of superior rice variety at harvest is about 17.5 kg ha^{-1} of N, 3.0 kg ha^{-1} of P, and 17.0 kg ha^{-1} of K [70]. ASSs with low N status need N fertilizer application. Applying 90 kg ha^{-1} of N to ASSs containing a total N of 0.25% yielded 4.1 Mg ha^{-1} of rice while adding 135 kg ha^{-1} of N showed no increase in yield [71]. Farmers commonly apply urea at more than the recommended rate.

The content of available P in ASSs is low, although the total P content may be high. In the ASSs in South Kalimantan, the available P is very low to medium [72] because Al and Fe fix P [73] in very acidic soil reactions (pH of 2.5–3.9). The effect of P fertilizer application on rice yield depends on P status in the soils; in low P status, fertilizer application significantly increases rice yield. Applying 22.5 kg ha^{-1} of P_2O_5 increases rice yield from 3.23 to 4.40 Mg ha^{-1}. Statistically, there were no differences in rice yields between using 22.5 and 45–67.5 kg ha^{-1} of P_2O_5 [74].

The availability of K in ASSs is mainly low to very low. For instance, the available K in ASSs in South Kalimantan ranges from 0.09 to 0.25 cmol kg^{-1}, and is categorized as low to very low [72]. K is an essential macronutrient that regulates stomata movement, energy transfer, anion balance, and stress resistance [75]. K is crucial to photosynthesis, carbohydrate distribution, and starch synthesis, leading to higher rice yields [76]. Applying 25 to 37.5 kg ha^{-1} of K_2O under low K status increases grain weight and influences seed quality. However, using a higher K fertilizer rate does not affect yield increase.

Balanced fertilizer application to ASSs has better yield than partial application of only N fertilizer, P fertilizer, or K Fertilizer. Balanced fertilizer can also be applied to local rice varieties. Adding 60 kg ha^{-1} of N, 60 kg ha^{-1} of P_2O_5, and 50 kg ha^{-1} of K_2O to ASSs increased local rice yield by 42%–77% [77]. Application of NPK compound fertilizer and urea are other options for increasing crop production.

In ASSs, liming can increase the effectiveness of the fertilizer. Liming and N, P, and K fertilizer addition increased rice yield from 0.64 Mg ha^{-1} to 4.24 Mg ha^{-1}. The contributions of lime, N fertilizer, P fertilizer, and K fertilizer to this yield increase were 33.9%, 33.3%, 22.7%, and 10.1%, respectively. For one hectare of this soil, the fertilizer rates for superior varieties are 67.5–135 kg N, 45–70 kg P_2O_5, 50–75 kg K_2O, and 1–3 Mg lime [78].

Results of other studies suggest that increasing crop production in ASSs requires the application of chemical fertilizers (N, P, K), organic fertilizers, and biofertilizers. Biofertilizers contain microbes such as decomposers (*Trichoderma* sp.), P solvents (*Bacillus* sp.), and N fixers (*Azospirillium* sp.). Biofertilizers increase N and P availability, accelerate organic residue decomposition, and promote crop growth. Applying 25 kg ha^{-1} of Biotara (a biofertilizer), 400 kg ha^{-1} of NPK compound fertilizer, and in-situ organic matter increased rice yield by 35%–48% [64,74]. Applying 25 kg ha^{-1} of Biotara and 300 kg ha^{-1} of NPK compound fertilizer to ASSs increased total N, available P, and available K in Barito Kuala Regency, South Kalimantan province [64].

Organic fertilizer decomposition increased macro and micronutrients in the soil [79]. In tidal paddy soils, applying organic fertilizers, compost from manure, compost from rice straw, and compost from *Salvinia* sp. increased rice yield by 3.60 Mg ha^{-1}, 3.73 Mg ha^{-1}, and 3.54 Mg ha^{-1} compared to not applying organic fertilizers (3.15 Mg ha^{-1}) [67]. Adding organic matter increased rice yield and reduced the use of inorganic fertilizers in tidal paddy fields [65]. Thus, for a given rice variety, fertilizer application is site-specific.

6. Adaptive Varieties and Gene Conservation

6.1. Adaptive Varieties

When selecting rice varieties for planting, farmers consider market demand and preference, plant age, high yield, plant height, tolerance to abiotic stress, and resistance to pests and diseases. The local rice variety is adaptive to environmental growth but has a low yield; thus, improving rice varieties for ASSs requires creating a rice variety that is adapted to high soil acidity, iron toxicity, and water stress (flooding and dryness). Iron toxicity limits rice growth and reduces rice yield by 30–60% [80]. The decrease in yield differs in iron-tolerant varieties [81]; the decline is up to 30% for an iron-tolerant variety but 75% for an iron-sensitive one. Iron-tolerant rice varieties absorb and translocate less iron from roots to leaves compared with iron-sensitive varieties.

Improved varieties recommended for acid-sulfate paddy soils in Indonesia include Inpara, Mekongga, and Ciherang. There are nine varieties of Inpara, from Inpara 1 to Inpara 9 [82]. The adaptation test in the tidal paddy field in Barito Kuala Regency (South Kalimantan province) showed that five of nine varieties (Inpara 3, Inpara 4, Inpara 6, Inpara 8, and Inpara 9) were adapted to local conditions. They yielded more than 3 Mg ha^{-1} of unmilled rice (Table 4). Inpara 4, Inpara 6, Inpara 8, and Inpara 9 may be introduced to farmers as alternatives to Inpara 2 and Inpara 3. Farmers in Barito Kuala Regency (South Kalimantan province) have planted Inpara 2 and Inpara 3 since 2012, while farmers in Hulu Sungai Selatan Regency (South Kalimantan province) have planted Inpara 4. Inpara 2 and Inpara 3 gave a yield of about 4.12–6.20 Mg ha^{-1} [83,84].

Table 4. Adaptive and farmers' preferred rice varieties in Barito Kuala Regency (South Kalimantan province) in the 2016 dry season.

Rice Variety	Yield (Mg ha^{-1})	Potential Yield (Mg ha^{-1})	Productive Tiller Number	Score of Tolerance to Iron Toxicity *	Resistance to Pests and Diseases **
Inpara 3	3.70	5.60	11.7	1.0	• Moderate resistance to BPH biotype 3 • Resistant to leaf blast ras 101, 123, 141, and 373
Inpara 4	4.30	7.60	15.9	1.7	• Susceptible to BPH biotype 3 • Susceptible to BLB pathotypes IV and VIII
Inpara 6	3.83	6.00	12.2	1.0	• Susceptible to BPH • Resistance to leaf blast • Slightly resistant to BLB pathotype IV
Inpara 8	3.60	6.00	11.1	1.0	• Moderate resistance to BPH biotypes 1 and 2 • Susceptible to BPH biotype 3 • Resistant to BLB pathotype III • Moderate resistance to BLB pathotypes IV and VIII • Moderate resistance to leaf blast ras 133.
Inpara 9	3.48	5.60	13.4	1.0	• Moderate susceptible to BPH biotypes 1,2 and 3 • Resistance to BLB pathotype III • Resistance to rice tungro virus

Note: * lower score indicates that a variety adapts better to iron toxicity. ** BPH = brown plant hopper, BLB = bacterial leaf blight. Source: [85].

In the tidal paddy fields of Sambas Regency (West Kalimantan province), Inpara yielded 5.43 Mg ha^{-1} of rice [62], higher than in South Kalimantan province, which yielded 3.09 Mg ha^{-1} of rice [85]. The yield difference was due to soil fertility and iron toxicity levels. In West Kalimantan, the soil pH was 5.3 and the iron content was 150 mg kg^{-1} (showing no symptoms of iron toxicity), whereas in South Kalimantan, the soil pH was 4.62 and the iron content was 439 mg kg^{-1} (showing symptoms of iron toxicity). Low soil fertility and iron toxicity are responsible for the low productivity of superior varieties, ranging from 3.0 to 4.0 Mg ha^{-1} [85], much lower than the potential yield of about 5.0–7.6 Mg ha^{-1} [82].

6.2. Conservation of Genes of Local Rice Varieties

Several local tidal rice varieties are available, and some are grown by farmers. Conservation of these local varieties is crucial for safeguarding biodiversity and as materials for improving rice varieties. The indigenous agriculturalists residing in South Kalimantan acknowledged and designated indigenous tidal rice cultivars contingent upon the visual characteristics of the lemma and palea husk coloration. From a genetic standpoint, the dissimilarity in husk coloration could signify genetic or phenotypic adaptability, precisely the capacity of individual genotypes required to generate diverse phenotypes in response to alternative environmental circumstances [86]. Conserving local rice varieties is vital to preventing genetic erosion [87–89].

Genebanks, exemplifying ex-situ conservation, guarantee the accessibility, thorough characterization, and documentation of stored materials, thus safeguarding them considerably from external risks [90]. It ensures germplasm preservation when plants are obliterated from their original habitats. Additionally, from the user's perspective, it can consolidate materials from diverse and dispersed locations into a single site that is readily accessible for utilization [91].

Indonesia is an archipelago distinguished by various climatic conditions, ecological geography, and agricultural practices that sustain extensive rice diversity. With Indonesia's vast biodiversity, the abundance of genetic resource variability is considerable, encompassing diverse geographical areas. Each specific area in Indonesia possesses numerous distinct genetic resources, often dissimilar to those found in other regions [92]; these are primarily local varieties, and thus immensely different cross islands. Local rice varieties in South Kalimantan exhibit distinctive characteristics. These varieties range in plant height from 105 to 180 cm, with 10–24 tillers. The panicle is prominently exposed and grain threshing is moderate (6%–25%). The leaf angle is horizontal and the flag leaf angle is intermediate and flat, lacking the upright angle in high-yielding varieties. Similarly, the stem angle is generally moderate, falling between upright and open. More than 3300 rice accession numbers are stored in the Indonesian Gene Bank [93].

In the history of rice breeding, numerous studies have shown that rice landraces are the progenitor lines of promising new varieties. The development of IR8 [94], the identification of genes for submergence tolerance [95], and the improvement of rice yield [96] are noteworthy among these studies. IR8 is a hybrid of two landraces, Peta, an active and tall rice variety from Indonesia, and Dee-geo-woo-gen, a Chinese semi-dwarf rice type [94]. In Indonesia, the development of superior rice varieties through cross-breeding began in the 1900s using germplasm originating from various sources. Until 1965, rice breeding was directed at establishing varieties suitable for multiple land conditions, including land with medium and low fertility levels [97]. The most significant increase in production occurred from the 1970s to the 1980s with the introduction of new high-yielding varieties that were more responsive to fertilizers and matured early, for example, IR36, Cisadane, IR64, and IR66, with a growth rate of 3.3% each year [98].

Genetic diversity is also valuable in the gene conservation of natural resources [99]. Several essential genes were discovered and significantly contributed to the rice breeding process. Regarding submergence tolerance, submergence 1 quantitative trait locus (SUB1 QTL) is the origin of the rice landrace FR13A [95]. The narrow leaf 1 (NAL1) allele in the Tropical Japonica rice landrace Daringan is responsible for the substantial enhancement of the yield of contemporary rice varieties [96]. Yustisia et al. [100] reported that the levels of iron and zinc in brown rice varied across five high-yielding varieties (Ciherang, Widas, IR64, Cisokan, and Cimelati) that were cultivated in Inseptisols, with Fe ranging from 10.84 to 19.80 mg kg^{-1}, and Zn ranging from 19.64 to 24.55 mg kg^{-1}. The Widas variety possessed the highest Fe concentration whereas the Cisokan variety had the lowest.

The above information significantly contributed to the development of rice varieties and increased rice production in Indonesia over the years. During the pre-green revolution period, there was a notable enhancement in rice productivity in Indonesia. Notably, the mean yield per hectare, as recorded by FAOStat, went up from 1.76 Mg ha^{-1} in 1961 to 2.25 Mg ha^{-1} in 1969, subsequently increasing to 2.38 Mg ha^{-1} in 1970. This increase can be primarily attributed to the extensive adoption of high-yielding varieties [101]. During the Green Revolution decade, rice varieties with excellent yields and tolerance to numerous pests and plant diseases were released. One of these was IR-64, which has dominated rice fields in Indonesia since its introduction in 1986 due to its high yield and resistance to brown planthoppers. Superior cultivars boosted national rice productivity from 3.96 Mg ha^{-1} $year^{-1}$ on average during the 1980–1990 period to 4.35 Mg ha^{-1} $year^{-1}$ during the 1990–2000 period, an average gain of 0.23% yearly [101].

In addition to water conditions, soil management, adaptive rice varieties, farming systems, and technology adoption are other essential factors required for successful crop production in coastal acid-sulfate soils. Human resource characteristics and conditions (farmers and other stakeholders) also play crucial roles.

7. Farming Systems and Technology Adoption

In Kalimantan, ASSs predominate tidal paddy fields, mainly in Sambas Regency (West Kalimantan province), Pulangpisau and Kapuas Regency (Central Kalimantan province), and Barito Kuala Regency (South Kalimantan province). These soils are also used in oil palm plantations and swamp forests. Most rice production centers in Indonesia have acid-sulfate paddy soils. Hence, the discussion will focus on the rice cultivation system.

Figure 6 shows the schedules for the cultivation of the local rice variety (A) and the high-yielding rice variety (B) in tidal paddy fields in South Kalimantan province. The local rice is planted once a year, while superior rice is cultivated twice a year, especially in tidal paddy fields with good water management. For local rice, sowing begins from October to November, at the start of the rainy season; from December to January, 30-day-old rice plants are transplanted to the area near the paddy fields as the first seedlings. Then, 45–60-day-old rice plants are transplanted again to the edge of paddy fields as the second seedlings (from February to March). Finally, these plants are transplanted to entire fields (from March to May). For the first seedlings, farmers prepare land from January to February. The farmers harvest the rice from July to September. Seedling adjustment is conducted to tailor inundation in the paddy fields. For high-yielding varieties, farmers cultivate rice twice. The first rice cultivation begins in October, where seedling generation, land preparation, and transplanting are performed from October to November. Then, farmers harvest the rice from February to March. The second rice cultivation period begins in April, where seedling generation, land preparation, and transplanting are performed from March to May. The farmers then harvest rice from August to September. Understanding rice cultivation schedules in ASS-dominated areas is crucial to rice production and farmer-related activities.

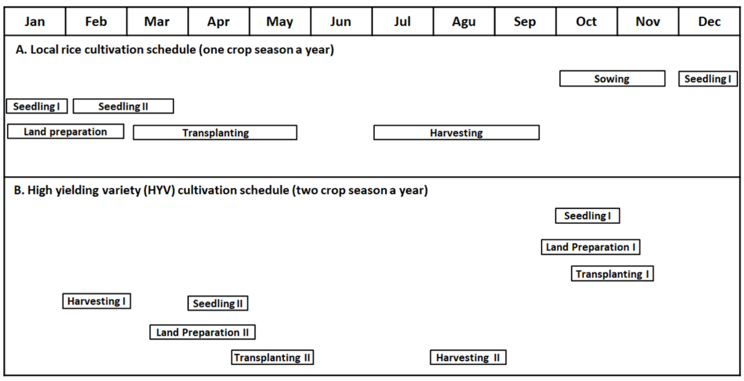


Figure 6. Schedule for the cultivation of local and superior varieties of rice in South Kalimantan province. Reused with permission from [66]; copyright owned by the MDPI.

Farmers apply several rice cultivation technologies ranging from indigenous knowledge to modern ones. Banjarese farmers, for instance, use indigenous knowledge, termed the tajak-puntal-balik-ampar system, for land preparation. Tajak means cutting paddy stubble and other grasses using a tajak (long sword) (Figure 7a). These stubbles and others are collected in spots, forming a ball-like, mixed organic matter called puntal (Figure 7b) and then stored for about one month. These balls are turned up and down at specific times (balik) so that decomposition occurs evenly. After sufficient composting, the organic matter stack is cut off, separated, and spread evenly on the soil surface (called ampar), as shown in Figure 7c [102]. This system prevents soil acidification, increases the pH from 3.0–3.9 to 5.80–6.20 [103], and the yield of the local rice variety from 2.5 Mg ha^{-1} to 3.0 Mg ha^{-1}.

Figure 7. Traditional Banjarese land preparation for rice cultivation: (**a**) Tajak is used for land clearing, (**b**) the residue is arranged into Puntal, and (**c**) compost residues are applied on the land (ampar). Photo by Author/M. Saleh.

Some farmers prefer to grow local varieties rather than superior ones because local varieties tolerate high iron content and very low acidity. The local varieties have photoperiod characteristics, namely, they blossom depending on solar radiation. The generation of seedlings of local varieties follows three steps: taradak, ampak, and lacak [104]. Taradak refers to sowing at the beginning of the wet season. After 40 days, the plants are moved to the second seedling area (ampak). After 40 days in ampak, the plants are transferred to the third seedling area (lacak). The duration of plants in the lacak depends on the inundation level in the planting area.

Other farmers use superior varieties combined with transplanting techniques. Rice transplanting is a common practice of farmers who grow superior varieties, where 25-day-old plants are planted. Farmers who use local varieties grow 60–90-day-old plants after sowing tailored to water inundation [105]. However, the transplanting technique requires more labor and time.

The seedlings can be grown in wet or dry media. In dry seedlings, seeds are distributed in the dry bed, usually in a bund, roadside, or yard, for ease of plant transport. In wet seedlings, seeds are spread in moist beds. The farmer applies 0.1–0.2 kg of dolomite, 5 g of urea, and 5 g of KCl for a one-meter square seedling medium. Each square meter needs 6.25 g of seeds; hence, one ha needs 25 kg. Seeds are submerged for about one night, air-dried, and stored for 24 h before sowing [105]. Sowing is conducted at the beginning of the wet season.

Rice seeds grow well under muddy conditions; hence, the soil tillage method and equipment selected should take into account pyrite depth during land preparation. Land with a pyrite depth of 0.5 m or more offers more opportunity to use the tillage method due to the low risk of pyrite oxidation. However, land with a shallow pyrite layer needs conservation tillage techniques [106]. Meanwhile, the one-way water management system creates better planting conditions because this system can reduce the accumulation of toxic substances.

Besides the tegel system, the Jajar Legowo planting system is used to increase the crop population (Figure 8a). Using jajar legowo 2:1 (Figure 8b), the population increased by 33%, and the yield of superior varieties increased by 43% compared to farmer techniques [107]. The jajar legowo method can be implemented manually or using a transplanter. In flat and 27-cm-deep mud with 3–4 seeds per hole, machinery increases the yield by about 9.89% compared to manual techniques [108]. The challenge of using transplanters is the requirement for a no-flat planting area and mud, resulting in no straight plant strip. Inundation is also a challenge when using a transplanter.

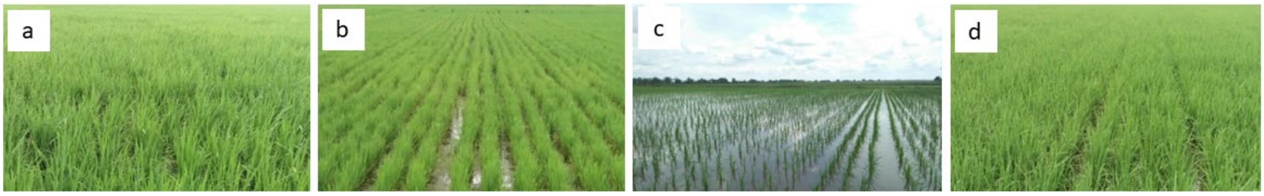


Figure 8. Rice planting systems and planting distances for optimizing space use, solar radiation, and crop populations: (**a**) Tegel system, (**b**) Jajar Legowo 2:1 system, (**c**) Jajar legowo 3:1 system, and (**d**) Jajar Legowo 4:1 system. Photo by Author/M. Saleh.

Some farmers use direct seeding, spreading seeds by hand, or using a seedier. Direct seeding requires soil tillage, good water management, a flat planting area, and 0.5–1.0 cm inundation. This technique can save labor and time but requires more seeds—from one-half to twice—compared to the transplanting practice. Other weaknesses include the possibility of seed loss in water due to increasing inundation, loss due to pests (rats, fish), and competition for solar radiation, water, and nutrients by weeds. A pre-growth herbicide is recommended for weed control [109].

A farmer may use a seeder for sowing seeds. Different types of seeders are available. Some farmers manually operate a pipe seeder–a 3-inch-diameter PVC (polyvinyl chloride) pipe with two wheelies. Using this pipe seeder, a farmer distributes seeds evenly following the planting distance set by the equipment. Other seeders include drum seeders, power seeders, and drones. Drones are more effective than drums and power seeders but are not currently used by farmers.

Some farmers use combined rice harvesters to harvest rice, whereas others still use traditional rice harvesters due to the small sizes of their paddy fields. In ASSs, operators should ascertain that paddy fields have good accessibility, no muddy areas, and low inundation so that they can run the combined harvester properly. In addition to the application of machinery, greenhouse gas (GHG) emissions are an emerging issue in rice cultivation on coastal ASSs.

8. Emerging GHG Emission Issues

ASS inundation (due to tides, rainfall, and extreme monsoons) controls soil biochemical processes that impact changes in soil oxidation–reduction (Eh) and influence soil behavior. During flooding, sulfate acid (H_2SO_4) is released from the sulfuric horizon, leading to deoxygenation and/or water acidification [18,110] and triggering environmental degradation. When sulfate acid reacts with carbonate minerals, H^+ converts inorganic carbonate to CO_2 because of the dilution of the acid [111]. CO_2 production stops if Fe (II) or inorganic carbon over CO_2 emission from the soil system results from a biological process, namely soil respiration. Microbe abundance and activity and organic carbon availability determine CO_2 emissions [112,113].

Rice cultivation in tidal paddy fields releases CO_2, N_2O, and CH_4 into the atmosphere. CO_2 emission is controlled by carbon source availability (organic matter), microbe activity, and soil characteristics (mainly moisture content, pH, and redox potential) [112,113]. The emission of CH_4 is correlated with physical properties of soil associated with soil–water movement [6]. Methanogenesis, the process responsible for CH_4 production, occurs when 70–80% of the pore spaces are filled with water. Time is needed to reduce molecular oxygen and electron acceptors trapped in the soil pores [114]. Methanogenesis involves methane-producing bacteria in anaerobic zones and methane-oxidizing bacteria in aerobic zones [115,116]. Methane-oxidizing bacteria can oxidize more than 50% of CH_4.

The interaction between soil pH and Eh is essential for CH_4 emission. The critical determinant of CH_4 emission occurs after ASSs are submerged, starting from Eh of −150 mV and pH of 6.5–7.5 [117,118]. During submersion, soil acidity determines the methanogenic microbes. The activity of methanogenic microbes in the soil is controlled by soil Eh, pH, organic matter content, and temperature. The low pH is responsible for the effect of organic matter on CH_4 emissions. Microbes mineralize organic matter, resulting in biochemical changes in the soil that decrease redox potential. CH_4 production is influenced by soil and nutrient management systems and the rice growth stage [119,120]. The tight requirement for an anoxic condition to produce CH_4 shows the importance of precise water management.

Good management practices to minimize CH_4 emission during rice cultivation in ASSs include (i) selection of rice variety, (ii) amelioration, (iii) fertilization, and (iv) water management. CH_4 emissions vary greatly, depending on water conditions, soil characteristics, cultivation system, rice variety, amelioration, and fertilization (Table 5).

Table 5. CH_4 emission during rice cultivation in acid-sulfate paddy soils of Kalimantan.

Location	Rice Variety	Type and Rate of Soil Ameliorant	Added Fertilizer (kg ha^{-1})	Emission	Ref.
South Kalimantan	Inpara 3, Inpari 30	compost (rice straw): 5 Mg ha^{-1}	Urea: 200 SP-36:100 KCl: 100	CH_4 flux (mg m^{-2} day^{-1}) - Inpara 3 = 0.192 - Inpari 30 = 0.571	[121]
South Kalimantan	Inpara 1	Compost (rice straw, purun, cattle dung): 5 Mg ha^{-1} Biochar (rice husk): 5 Mg ha^{-1}	Intensive rice cultivation: Urea: 200 SP-36: 100 KCl: 100	CH_4 Flux (kg ha^{-2} season^{-1}) - Compost = 12.94 - Biochar = 11.5	[122]
		Compost (rice straw, purun, cattle dung): 5 Mg ha^{-1} Biochar (rice husk: 5 Mg ha^{-1}	Traditional rice cultivation: Urea: 150 SP-36: 75 KCl: 75	CH_4 flux (kg ha^{-2} season^{-1}) - Compost = 7.75 - Biochar = 6.65	
South Kalimantan	Inpara 3	50% compost and 50% rice-husk biochar Control	Urea: 200 SP-36: 100 KCl: 100	CH_4 flux (kg ha^{-2} season^{-1}) - Compost + biochar = 105 - Control =210	[123]

N_2O emission is closely associated with denitrification, namely, changing N depending on microbe activity, environmental conditions, and N and C sources. Denitrification occurs under anaerobic conditions [124] and is influenced by several factors, including soil aeration, moisture content, NO_3 and C availability, and soil pH [125–127]. Denitrification is closely associated with organic carbon dissolved in the soil [126]. In ASSs, nitrates oxidized the reduced Fe, resulting in N_2O and other N gasses [127].

Submerging accelerates the utilization of electron acceptors (e.g., NH_4^+, Mn^{4+}, Fe^{3+}, and SO_4^{2-}). N_2O emission occurs due to the addition of N sources (e.g., urea, manure), microbe activity, and environmental conditions supporting the growth of nitrification bacteria (i.e., pH, temperature, and aeration). Denitrification occurs in submerged ASSs; that is, NO_3 and/or NO_2 are reduced to NO, NP, and N gases, catalyzed by denitrifying microorganisms [128,129].

Measuring GHG emissions during rice cultivation in paddy fields uses the close chamber technique from the International Atomic Energy Agency [130]. In this method, samples are collected with a syringe for laboratory analysis. The closed chamber method provides estimates of GHG fluxes at the observation plot level of less than 1.0 m^2 (small scale). The technique is used to study processes that occur in the soil, including microbial activity. GHG emissions from paddy fields are from complex interactions between environmental conditions, soil properties, and management practices. Implementing appropriate land management will minimize GHG emissions.

9. Challenges and Future Directions

Specific and unique tidal land ecosystems need particular care for production or conservation purposes. Disturbing its natural condition changes soil and water properties, and even rice productivity decreases due to mismanagement and degradation. Therefore, the use of tidal land and ASSs for agricultural production should consider the land's characteristics and crops selected based on suitability. Keys to successful and sustainable agricultural production include soil and water management, adaptive variety selection, amelioration, and fertilizer application tailored to crop needs and soil nutrient status. Based on our experience of more than 30 years in research, development, and offering technical assistance to farmers, we list the remaining challenges and proposed future directions in Table 6.

Table 6. List of challenges and future directions for successful and sustainable rice production in coastal acid-sulfate paddy soils.

Aspect	Goal	Main Challenges	Future Directions
A. Water management	• To improve soil fertility • To fulfill water crop requirements • To increase land productivity • To adapt to climate change • To mitigate GHG emissions	• Water management technology is still, in general, not detailed • Water management infrastructure is not yet optimal • Stakeholders' coordination is not yet optimal • Water farmers' institution is not properly run • Implementation at the farmer level is still poor	• Creating site-specific water management technologies • Optimizing water infrastructure management • Increasing coordination between stakeholders • Strengthening the water users' association • Implementing precise water management by farmers
B. Amelioration	• To improve soil quality • To increase land productivity • To increase crop yield • To maintain land and environmental quality • To suppress GHG emissions	• Diverse land conditions • Limited amelioration technologies • Limited ameliorant availability • Amelioration technology is not yet considered of financial benefit • Low farmer's interest in technology	• Strengthening research to create standard amelioration • Exploring local materials for soil ameliorants • Creating cheaper soil amelioration technologies • Socialization of soil amelioration technologies
C. Fertilizer application	• To improve soil fertility • To improve land and crop productivity • To improve the effect and efficiency of fertilizer application • To maintain land and environmental quality	• Various soil nutrient status spatially and vertically • Generalized fertilizer recommendation • High dependent on chemical fertilizers • The high price of chemical fertilizers • Environmental damage • Land resource degradation • Limited farmer knowledge of fertilizer technology	• Creating easy and practical tools for detecting soil nutrient status • Developing site-specific balanced fertilizer applications (inorganic, organic, and biofertilizer) • Genetical engineering of superior microbe strains for accelerating soil nutrient provision • Revitalizing the extension working system to promote the provision of fertilizer technology to farmers

Table 6. *Cont.*

Aspect	Goal	Main Challenges	Future Directions
D. Crop varieties	• To create adaptive, high-yielding varieties • To create multi-tolerant varieties (saline, acid-sulfate, pests, and diseases) • To create low GHG emission varieties • To create low-input varieties (fertilizer-efficient, water-efficient)	• Climate change increases saline land area, drought duration, flooding, and pest and disease attacks • Soil nutrient status varies • Scarce fertilizer availability and the high price of fertilizers • Environmental issues (Greenhouse effects) • Issues of stagnant rice production	• Creating high-yielding and adaptive varieties that can withstand climate change impact (multi-tolerant) • Creating low-input and low-GHG emission varieties using precision and advanced methods such as genome editing and marked selection
E. Cultivation techniques	• To increase crop and land productivity • To formulate precision crop cultivation systems • To formulate a low-emission crop cultivation system	• High environmental stress in many locations. • Farmers may still use local varieties as they are highly adapted and cost less than superior varieties. • Still high pest and disease attack • Available crop cultivation technologies tend to increase GHG emissions • Farmers' low adoption of low-emission varieties	• Formulating site-specific crop cultivation technologies • Formulating more efficient and effective control technologies for pests and diseases • Increasing research collaborations on low-emission rice cultivation technologies for acid-sulfate soils • Promoting low-emission, high-yielding varieties
F. Land use optimization	• To increase land productivity • To increase added value/income • To increase the planting area • To increase crop intensity and diversity • To reduce the risk of crop and land failure	• Crop and land productivity are still low • Fragile land characteristics and easy decline in land quality • Inefficient use of production inputs • High crop production costs	• Creating suitability maps for selected crops • Creating a very detailed site-specific recommendation for the technology map at a scale of 1:25.000 or bigger • Diversification of crop cultivation • Developing mechanization technologies tailored to local land conditions
G. Climate change adaption and mitigation	• To improve land resiliency to the impact of climate change • To maintain land productivity and optimal crop growth • To suppress GHG emissions	• Rice cultivation also results in GHG emissions • Flooding and drought • An increase in pest and disease attacks due to surface temperature changes and rainfall pattern changes • Conversion of forests into more intensive and extended uses • Decline in crop productivity	• Creating superior varieties adapted to extreme climate events • Mapping risk zones of flooding and drought • Implementing technologies for land resource conservation and technologies for organic fertilizers, biofertilizers, and biopesticides • Improving the capacity and capability of extension workers and farmers to understand climate prediction data and information

Table 6. *Cont.*

Aspect	Goal	Main Challenges	Future Directions
H. Technology adoption and implementation	• To increase crop productivity and production • To improve technology adoption • To increase farmers' income	• Diverse land and environmental characteristics • High production costs • Low knowledge of advanced technologies	• Developing agricultural crop cultivation tailored to land resource characteristics • Increasing productivity using efficient production, value-added products, and sustainable production systems • Social and institutional engineering based on farmers' needs and interests • Policy for high rice prices for farmers to intensify rice production
I. Resource conservation	• To preserve wetland resources • To optimize the use of agricultural resources • To develop new economic growth areas	• Land and water resource degradation • Remote and fragmented agricultural land • Limited infrastructure (roads, markets, storehouses, banks, electricity) and water infrastructure • Climate change impact	• Re-inventory and re-delineate characteristics of land and water resources • Formulating a roadmap and action plan for agriculture resource and infrastructure management • Implementing sustainable farming to be adaptive to climate change impacts • Prohibiting agricultural land use conversion • Reforming regulations and laws on land use and land tenure systems

For more efficient implementation, at least four activities are required: (i) re-inventory of soil and water and farmer characteristics, (ii) developing and rehabilitating infrastructure, (iii) developing agribusiness models from upstream to downstream using a holistic and integrated implementation of technology innovation, and (iv) social and institutional engineering.

10. Conclusions

The coastal acid-sulfate soils of Kalimantan cover about 3.5 Mha and remain an invaluable resource for paddy fields and other wetland agriculture. The area has become the national agricultural production center but faces high acidity, a high iron and aluminium toxicity risk, and low soil fertility. Water management for better water circulation is crucial in controlling iron and aluminium toxicity and providing good water quality for crop growth. Water management, soil amelioration, fertilizer application, crop variety selection, and site-specific rice cultivation techniques are keys to high crop production.

Soil ameliorants that raise soil pH, decrease iron and aluminium toxicity and improve crop yield include lime, biochar, organic fertilizer, compost, ash, and fly ash. Fertilizer application for rice requires 80–200 kg ha^{-1} of Urea, 50–150 kg ha^{-1} of SP36, 50–150 kg ha^{-1} of KCL, and 125–400 kg ha^{-1} of NPK compound fertilizer. The rate and time for ameliorants and fertilizer applications depend on crop variety, soil properties, and soil nutrient status.

Farmers implement traditional or modern rice cultivation technologies, with cultivation schedules adjusted based on rice variety, available resources, water inundation, and water management conditions. Rice varieties are continuously improved to provide tolerant but high-yielding varieties. High CH_4 and CO_2 emissions challenge rice cultivation but could be minimized by rice variety selection, amelioration, fertilization, and water management.

The remaining challenges are technology development and transfer in water management, soil amelioration, fertilizer application, crop varieties, cultivation technology, land use optimization, climate change adaptation and mitigation, technology adoption and implementation, and resource conservation. Each aspect has specific goals and exit strategies. Four activities are required for effective implementation: (i) re-inventory of soil, water, and farmer characteristics, (ii) developing and rehabilitating infrastructure, (iii) developing agribusiness models from upstream to downstream using holistic and integrated implementation of technology innovation, and (iv) social and institutional engineering.

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Abbreviations

ASSs = acid-sulfate soils; DS = dry season; WS = wet season; PC = primary canal; SC = secondary canal; PVC = polyvinyl chloride; GHG = greenhouse gas.

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