AF-834
[1-11]

REVIEW ARTICLE Indian Journal of Agricultural Research,

Constraints of Acid Sulfate Soils and Practical Use for the Improvement of Farming in the Mekong Delta, Vietnam: A Review

Vo Quang Minh[1], Tran Van Hung[1], Pham Thanh Vu[1]

10.18805/IJARe.AF-834

ABSTRACT

Vietnam's Mekong Delta region contains a sizable amount of acid-sulfate soil, which has properties that harm plants, such as low pH, aluminum and iron toxicity, hydrogen sulfide and sulfate acid. The study aims to gather helpful information about the problems with acid sulfate soils' chemical makeup so that suggestions can be made for improving these soils in the Mekong Delta. These methods mainly review studies and projects on the properties, constraints and management improvement of acid-sulfate soils and recommend the proper methods for sustainable use. The Mekong Delta contains many sulfidic or acid-sulfate-producing materials. Soils that contain acid sulfate are especially vulnerable to the consequences of climate change. Therefore, evaluating and predicting how acidic soil impacts soil quality and the affected factors such as drought, water scarcity, rainstorms, floods and saltwater intrusion are essential. Selecting cultivars that can withstand acid sulfate or salt is easy and inexpensive. Designing appropriate farming models is necessary in the interim. To correctly manage and exploit acid sulfate soils in the current situation, one must also be aware of their distribution, physicochemical makeup and biological properties.

Key words: Active, Aluminum, Iron, Jarosite, Potential, Pyrite, Toxicity.

Where acid sulfate soils (ASS) are present, firm acidity is commonly found, which (N. van Breemen and Pons, 1978) characterized as soils with a pH below 3.5 (for Entisols) or 4 (for Inceptisols) at a depth of 50 cm. Pyrite, a mineral with the chemical formula FeS_2, is oxidized to produce sulfuric acid, directly or indirectly contributing to acidity. Lousy water conditions, low pH, the dangers of aluminum and iron, a lack of phosphorus and nitrogen and not enough nutrients are the main things that make it hard for plants to grow in ASS (Breemen and Pons, 1978; Dent, 1986).

Terrestrial sulfidic sediments, commonly associated with agricultural usage and removal, lead to ASS discharge (Brady, 1981; Breemen, 1980; Dent, 1986; Dent and Pons, 1995; Tuong, 1993), innovative water management techniques can be successful strategies and can improve soil conditions for agricultural output. These techniques include controlling groundwater levels, decreasing capillary rise, managing soil nutrients appropriately and leaching and flushing toxins. Microorganisms change these sulfates into sulfides, which react with iron to form iron sulfide (FeS_2) (Sammut *et al.*, 1996).

Many marine magnetotactic bacteria (MB) can produce magneto-containing iron sulfide crystals. All information regarding iron-sulfide-producing MB is based on cells isolated from their natural habitats because pure cultures of these organisms are not accessible. MB may contain the mineral greigite, an iron sulfide. The ancestors of greigite may have been in temporary nonmagnetic iron sulfide phases (Pósfai and Buseck, 2010). When iron sulfide MB is present in highly reducing, sulfidic circumstances at neutral pH, greigite should transform into pyrite.

While ASSs are stable in anoxic environments, exposure to air renders them toxic. The pyrite in the sulfides oxidizes at this point, releasing sulfuric acid (Stumm and Morgan, 1981). The potential contaminant, sulfuric acid, can escape into estuarine systems, particularly during intense rainfall.

According to Van and Putu (1992), roughly 12 million hectares of acid-sulfate soil are worldwide. Vietnam's soils cover 1,866,500 ha, or 5.5% of its total land area, with around 1.6 million ha (or 40%) of that area concentrated in Dong Thap Muoi (EIA), the Long Xuyen Quadrangle (TGLX), the Hau River Valley (TSH) and a portion of the Ca Mau Peninsula (CC). Mekong Delta Saline and acid-sulfate-saline soils comprise 0.74 million ha or roughly 19% of the total land area (Xuan and Matsui, 1998). Saline soils are thought to sent the most significant difficulties for cultivating rice. The soil got salty during the shrimp season due to people breaking the dyke to prevent salt water from entering shrimp farming in recent years as the movement of shrimp farming increased (a substantial barrier to lowering the salt water region).

[1]Department of Land Resources, Environment and Natural Resources College, Can Tho University, Can Tho, 90000, Vietnam.

Corresponding Author: Tran Van Hung, Department of Land Resources, Environment and Natural Resources College, Can Tho University, Can Tho, 90000, Vietnam.Email: tvanhung@ctu.edu.vn

How to cite this article: Minh, V.Q., Hung, T.V. and Vu, P.T. (2024). Constraints of Acid Sulfate Soils and Practical Use for the Improvement of Farming in the Mekong Delta, Vietnam: A Review. Indian Journal of Agricultural Research.
DOI: 10.18805/IJARe.AF-834

Submitted: 03-11-2023 **Accepted:** 12-01-2024 **Online:15-02-2024**

The effects of climate change, through variations in rainfall intensity, rising temperatures, floods, droughts and river flow, devastate homes, infrastructure, crops and fisheries. Vulnerable populations are forced to deal with food shortages and limited livelihoods due to inadequate knowledge of how to use and develop acid sulfate and salty soils and the extent of acid sulfate and saline-contaminated soil in the Mekong Delta is expanding. These two types of soil are unfavorable regarding plant growth and yield. After harrowing and plowing, the soil is known as acid soil. The pH of the field water is below 4.0, as transparent as acid sulfate and acid soils (Xuan, 1997). According to Pons (1973), acid-sulfate soils can be prospective or active. Extensive research has been done on the crucial pH targets and the incubation period for sulfidic soil materials (Andriesse, 1993). After incubation, several researchers recommended a crucial pH target of 3.5 (Breemen *et al.*, 1982), while others recommended a pH of 4.0 (Dent, 1986; Thomas and Varley, 1982).

Because of the acid-sulfate soil limitation, the soil is contaminated, degraded and acidic. Ecosystems and rice production both suffer as a result. Understanding and evaluating the constraints for proper soil use and advice is crucial, especially for acid-sulfate soils. The study aims to collect pertinent information regarding the shortcomings of acid sulfate soils to suggest appropriate changes for these soils in Vietnam's Mekong Delta.

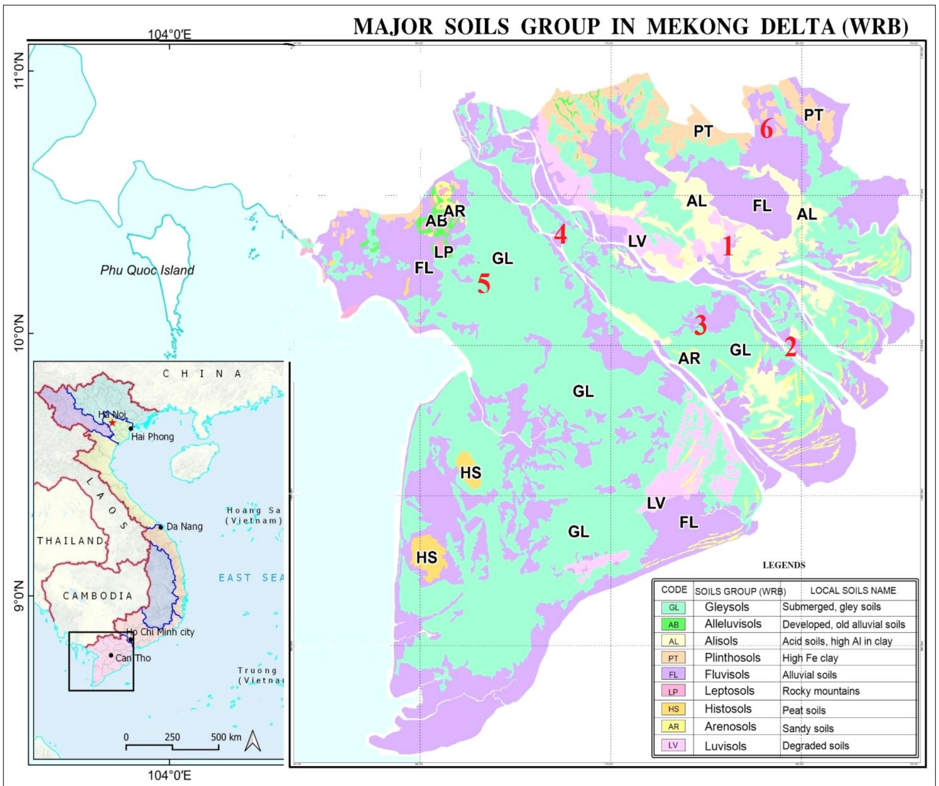
The Mekong Delta in Southern Vietnam is in the tropical monsoon zone between the Tropic of Cancer and the equator. The Mekong Delta lies between 8°40′ and 10°40′ N atitudes and 104°10′ and 107°10′ E longitude.

The study mostly looks at research papers, project reports and books about the properties, problems, management methods, improvement models and suggestions for sustainably using acid-sulfate soils. It also looks at the newest research and journal articles about acid-sulfate soil in different parts of the world. The study gathers references from various sources, such as the Department of Agricultural and Rural Development of many Vietnamese provinces in the Mekong Delta and the Ministry of Agricultural and Rural Development.

The study's search criteria include the definition and implementation of standards, benefits, drawbacks and suggestions for the sustainable improvement of acid-sulfate soils in the Mekong Delta.

The acid sulfate soils in the Mekong Delta

The ten major soil groups of the Mekong Delta, based on the World Reference System (FAO, 1998), are depicted on the revised and updated 2009 soil map. The major soil groups of Fluvisol and Gleysol occupied the most significant area. A large area with a complicated distribution of acid sulfate soil is covered in this region. However, acid sulfate is most concentrated in soil groups like Fluvisols and Gleysols, as shown in Table 1 and Fig 1 (Minh and Vu, (2015).



Note: Locations of soil analysis were shown in red number color.

Fig 1: Map of the distribution of major soil groups in the Mekong Delta, Vietnam.

Table 1: Major soil group (WRB-FAO, 2007) in the Mekong Delta, Vietnam.

Major soil groups	Code	Area (ha)
Albeluvisols	AB	19,212.1
Alisols	AL	189,890.0
Arenosols	AR	56,492.0
Fluvisols	FL	1,078,169.1
Gleysols	GL	1,914,561.1
Histosols	HS	33,074.2
Leptosols	LP	15,335.4
Luvisols	LV	155,195.6
Plinthosols	PT	133,300.4
Solonchaks	SC	250,377.1
Total		3,845,606.8

The Mekong Delta acid sulfate soil is the most extensive and intricately differentiated, focusing on soil types like Fluvisol and Gleysols. The presence of sulfidic material or sulfuric horizons in the profile determines how acid-sulfate soils are classified. The sulfidic or acid-sulfate-generating horizon is a layer often covered in clay or organic matter that is in the reduced conditon. It contains acid sulfate and this thicknessis typically over 25 cm when oxidizing at pH = 3.5, with acidity created while oxidizing acid sulfate beds. As the sulfuric horizon becomes active and produces jarosite minerals with yellow mottling, it also forms and oxided the potential acid-sulfate soils It is the soil indicator horizon for active acid-sulfate soil (Fig 2).

The constraints and improvement of acid sulfate soil in the Mekong Delta

Constraints of acid-sulfate soil for farming

The Mekong Delta contains a sizable area of acid-sulfate soil and the closer it is to the surface layer, the more it prevents plant growth. According to Dent (1986), in acidic soils with low pH levels, excessive concentrations of harmful chemicals like iron and aluminum hinder the growth of plant roots, produce an uneven nutrient content, particularly a phosphorus deficiency and result in reduced yield. Having too much toxicity damage plants. Different forms of acid-sulfate soil are categorized according to the presence of the acid-sulfate layer at various depths (Kyuma, 1976; Monre, 2016; Sammut *et al.*, 1996). According to Hung *et al*. (2019) and Olk and Cassman (2002), active acid sulfate soils are moist, poorly drained soils in well-drained locations with seasonally shifting soil layers that have lost Fe, Al and bases but still include weathered minerals. The most direct effects of active acid sulfate are on acidic soil and water, so the requirement of active acid sulfate soil classification is the absence of sulfidic material within 50 cm of the topsoil, a low soil pH, typically less than 3 or 4 and an n-value equal to or less than 0.7 in one or more sub-layers at a depth of 20-50 cm (Dent, 1986; Pons, 1973; Sen, 1988). Rainfall has decreased soil acidity during the dry season in the Mekong Delta.

Fig 2: Active acid sulfate soil with mottles of jarosite.

The acid-sulfate soil has also limited widespread cultivation in the Mekong Delta. Only a few crops-cassava, cashew and pineapple-can be produced on acidic soils. In highly acidic soils, traditional and modified rice cultivars deliver subpar crops. According to Kyuma (1976), Nedeco (1993) and Sen (1988), acid sulfate soil hurts plants by inhibiting nutrient uptake, inducing phosphorus fixation and lowering base cation ion exchange. In addition to altering ecosystems, acid-sulfate soils can also lower biodiversity. Acid-sulfate soil conditions frequently support acid-tolerant plants, such as *Melaleuca spp.* and *Eleocharis spp.* Additionally, acid sulfate soil is washed into the aquatic environment at the start of the rainy season, lowering water quality and hurting aquatic species (Callinant *et al.*, 1996).

The constraints of active acid sulfate soil

Low pH indirectly affects the availability and solubility of Al^{3+}, Fe^{2+}, Fe^{3+} and phosphorus while directly harming plants. Any acid soil with such a pH value will be found at pH 4.5–5 for seedlings and at pH 3.5-4.2 for older crops, according to Breemen and Pons (1978). Low pH levels will directly hurt plants and impact the solubility of Al^{3+}, Fe^{2+} and Al^{3+} and phosphorus availability. At pH 3.5-4, the concentration of H^+ directly affects the growth of rice in the solution; however, in the field, this pH range is mainly characterized by the toxicity of Al^{3+} (Breemen and Pons, 1978; Ponnamperuma, 1972). However, other elements, like the level of phosphorus in the soil, will affect the potential for toxicity. Additionally, it uses inorganic fertilizers, particularly those from the acidic physiological group (K_2SO_4, $(NH_4)_2SO_4$, KCl), which always turn the soil acidic. In the Mekong Delta, rice farming plants only use a portion of this fertilizer, according to Ren, (1999), because inorganic nitrogen, phosphorus and potassium are added to boost crop output. Many H^+ ions are released when nitrogen nitrate converts to NO_3^- and NO_2^-, or NH_4^+, converts to NO_3^-, making the soil acidic. The remainder is either retained in the soil or washed away. Fertilizers with a low free acid content raise the soil's acidity when applied.

High aluminum (Al) concentration

Because phosphate is precipitated at the roots and residues in the soil when a high aluminum concentration builds up in the root cells, it impairs cell division, inhibits the action of enzymes in cell wall formation and obstructs phosphorus uptake. Dent, (1986) noted the Al^{3+} poisoning symptoms of brown patches following yellow-orange leaves at the tips of the leaf margins, according to Rorison, (1972). Since aluminum is usually harmful before this symptom appears on the leaves, it is rare to see it in the field. In addition, a high aluminum concentration results in a significant phosphorus deficiency.

High iron (Fe) concentration

Rice is hazardous at dissolved Fe^{2+} values exceeding 300-400 ppm. It is unusual to see this quantity on Mekong Delta-flooded active acid sulfate soils. Despite the high Fe^{2+} concentration, the rate of pH increase was modest on acid-sulfate soils. It could be that these soils have robust buffering abilities and require a lot of reduced Fe oxide to elevate pH considerably. According to Breemen (1976), dissolved Fe^{2+} values above 300-400 ppm are harmful. According to Ponnamperuma (1972), the "bronzing" of the leaves of rice plants growing in acid-sulfate soils is a clear sign of iron toxicity (Fig 3). In flooded Sulfaquept soils, this concentration is infrequently encountered (Breemen, 1976). Despite the high Fe^{2+} concentration, the rate of pH increase in acid-sulfate soils was modest. It could be that these soils have excellent buffering abilities and require a lot of reduced Fe oxide to boost pH levels considerably. Due to the low concentrations of free (amorphous) Fe (0.08%) and $Fe(OH)_2$ they do not develop in Vietnamese soil. All of the Fe^{2+} was consumed after 6–10 weeks of flooding, but the pH did not rise enough to result in $Fe(OH)_2$ precipitation. The concentration of Fe^{2+} can also decrease when sulfide is present due to SO_4^{2-} reduction. However, because there is little reduction of SO_4^{2-} at pH 5, the Fe^{2+} level only starts to fall after extensive flooding.

Low Fe^{2+} content, prolonged reduction, high H_2S concentrations, waterlogging and pH increases above 5 are the causes of high H_2S concentrations. Because there is insufficient Fe^{2+} to induce FeS to precipitate, the reduction of SO_4^{2-} under submerged conditions causes an increase in H_2S. At concentrations as low as 0.1 ppm, H_2S can harm plants and lead to iron poisoning. In the Mekong Delta, rice crops are grown continuously due to the need to prevent floods throughout the year. Rice cultivation soil is nearly always in a reduced state, particularly in areas where three harvests are grown annually. Tri (1998) states that plants are vulnerable to organic acid toxicity. It also agrees with the findings of Olk and Cassman (2002), who found that not giving the soil enough time to rest between two rice crops causes the soil to become mineralized, depleted of oxygen and slow to degrade lignin, phenol and lignin. Increased phenolic compound buildup is not beneficial for soil N mineralization or plant growth. Furthermore, Takai and Kamura (1966) reported that it was discovered that the amount of H_2S in the surrounding solution of the rice root zone increased significantly in fields with a bottom mud layer that accumulates a lot of organic matter, fields with a lot of manure and sour fields. Increased sulfite in anaerobic conditions leads to a rise in H_2S concentration, which is hazardous to rice plants.

Fig 3: A rice plant with the "bronzing" sign of Fe toxicity.

Change in soil phosphorus (P)

According to Ren (1999), phosphate ions react with iron, aluminum and perhaps silicate clay minerals to retain phosphorus in acidic soils' mineral compositions. After 15 days of flooding, phosphate fertilizers added to acid sulfate soils are primarily transformed into Fe-P and Al-P forms, making up 80-90% of the total phosphate fertilizers among the four inorganic P groups. After 15 to 20 days, the soil's iron and aluminum content declines rapidly. In oxidizing conditions, soils fix more P than in reducing conditions.

The crop removes more phosphorus from the soil each year than it puts back into it. The fertilizing rice experiment in the Mekong Delta revealed that 1 ton of rice grain contains 10.8 kg of nitrogen, 4.4 kg of phosphorous oxide and 3.3 kg of potassium dioxide. Annual alluvium also contributes to the phosphorus supply for plants in wet areas. The 1 cm-thick alluvial layers will contain 19 kg of P_2O_5 per ha. Farmers frequently apply the same amount of phosphate fertilizer during the Winter-Spring and Summer-Autumn seasons. Although unacceptable, P_2O_5 must be decreased by 20% r the Winter-Spring season and increased by 20% for the Summer-Autumn season. However, farmers only need to apply P to one crop; they do not need to apply P to the following crop, according to research findings on the leftover P in rice soil (Tan, 2001, 2005).

Acidic environment

The generation of sulfuric acid creates an acidic environment that makes other hazardous metals more likely to be mobilized and become soluble, increasing their concentrations in receiving water bodies (Astrom, 2001; Astrom and Astrom, 1997). The pH of the flooded layer above acid sulfate soil can drop as low as 3.5 when combined with dissolved Al^{3+} of 0.3-2.6 moles per m^3 (acid sulfate soil in the Long Xuyen quadrilateral area). One Long Xuyen. During the dry season, acidic salts may form when acidity, frequently brought on by pyrite oxidation at a depth in the soil, moves toward the topsoil (Fig 4). When these salts are dissolved in water, acids are produced. The following sulfate ion balances the soil's conversion to Fe^{2+}. Cook *et al.* (2000) found that aluminum hydrolysis can release acidity. However, the oxidation of Fe^{2+} to Fe^{3+} acidifies the water and eliminates dissolved oxygen. Most aquatic species steer clear of conditions with high acidity and low quantities of dissolved oxygen.

Minh and Vu (2015) claim that the Mekong Delta's acid sulfate contamination in the canals came from three sources at the start of the rainy season:

- The quantity of free acid that pyrite oxidation during the dry season.
- The amount of acid sulfate water that the $Al_2(SO_4)_3$ breakdown solidified on the ground during the dry season.
- $FeSO_4$ diffuses into the canal water as it travels from the soil to the channel's bottom.

Tri (1998) also pointed out that the acidity and salinity of the soil might increase to levels that are harmful to crop growth. Although some soil issues in specific regions restrict but do not impede agricultural usage, it is still possible. The depth of the sulfuric horizon (pH below 3.5, with or without jarosite mottles) determines the toxicity of the land quality. After 50 cm, the soil is considered "severely acidic", then "moderately acidic", then "slightly acidic" and finally "not acidic" below 120 cm.

The constraints of potentially acid-sulfate soil

Rice growing faces many difficulties due to the acid-sulfate soils of the Mekong Delta, including soil acidity, subsurface salinity, iron and aluminum toxicity, high phosphorus fixation, *etc.* Brackish or saline water, according to Xuan (1986), can now be utilized to lessen soil acidity or stop acidification, which can solve many problems brought on by the possible development of acid-sulfate soils.

According to Dent (1986) pyrite (FeS_2), which typically accounts for 2-10% of the soil, is the significant component that creates potentially acidic soils. Potential acid-sulfate soils turn acidic due to drainage; pyrite is only stable under anaerobic circumstances. Drainage makes it possible for oxygen to enter the soil, where it oxidizes pyrite and generates sulfuric acid that most possible soils are around the shore, according to (Dent, 1986; Shamshuddin *et al.*, 2014). The main issues with possible acid-sulfate soil include high salinity, unstructured soil, limited mechanical tolerance, high absorbency and difficulty keeping water away from the tide. When seawater levels are low, the soil is also severely oxidized, causing acidity.

The typical of properties of some acid sulfate soil in the Mekong Delta are shown in Table 2.

Table 2: Soil properties of some acid sulfate soil in the Mekong Delta.

Location	Depth (cm)	pH_{H2O} (1:5)	pH_{KCl} (1:5)	Organic matter (%)	CEC (cmol/kg)	N (%)	P ($\%P_2O_5$)	Avai P (mg/100g)	Exch K (cmol/kg)	Exch Al (cmol/kg)	Clay (%)	Bulk density (g/cm^3)	Density (g/cm^3)	Texture
Cai Lay	0-20	5.6	4.7	2.9	24.4	0.35	0.099	2.5	0.43	0.46	66.39	0.9	2.2	Clay
(Alluvial soils)	20-50	7.9	6.0	0.5	26.2	0.06	0.063	0.0	0.25	0.03	61.57	1.3	2.3	Clay
Cau Ke	0-20	5.0	3.6	3.5	9.8	0.19	0.057	1.1	0.11	1.78	31.47	1.3	2.1	Clay loam
(Acid sulfate soils)	20-50	7.4	5.1	0.3	13.3	0.05	0.042	0.0	0.37	0.02	38.05	1.5	2.5	Silt clay loam
Tam Binh	0-20	5.1	3.9	1.4	19.1	0.10	0.052	0.6	0.14	0.05	36.67	1.3	2.4	Clay loam
(Alluvial soils)	20-50	5.3	4.8	0.4	5.2	0.06	0.015	0.0	0.02	0.15	26.42	1.6	2.5	Sandy clay loam
Vinh My	0-20	5.3	4.4	3.4	17.3	0.16	0.078	1.5	0.19	0.33	58.59	0.6	2.4	Clay
(Acid sulfate soils)	20-50	5.6	4.8	0.9	23.9	0.11	0.061	0.7	0.14	0.01	71.98	1.3	2.5	Clay
Vinh Nguon	0-20	5.5	4.7	3.7	17.3	0.13	0.059	0.7	0.14	0.07	55.42	0.8	2.6	Silty clay
(Aluvial soils)	20-50	5.9	5.2	1.6	22.4	0.09	0.044	0.3	0.13	0.02	63.80	1.3	2.6	Clay
Moc Hoa	0-20	4.7	3.7	2.0	3.8	0.11	0.042	2.0	0.02	2.52	15.42	1.3	2.3	Silt loam
(Acid sulfate soils)	20-50	5.4	3.8	0.5	5.6	0.04	0.017	0.0	0.02	5.76	33.86	1.6	1.3	Silt clay loam

Note: Locations of study sites, in red color number, are shown on the map.

Fig 4: Acid sulfate water in brown color.

Fig 5: Model of the ditches for washing acid sulfate toxicity.

The improvement and management solutions of acid sulfate soils in the Mekong Delta

Water management solution

The redox potential regulates the occurrence of different toxicities in acid-sulfate soils. Iron has issues with significant reduction, while aluminum can be oxidized, acidified and solubilized. Regulating water is essential to regulating soil in these circumstances (Dent, 1986). A lot of freshwater permeates the soil. Nevertheless, getting enough water can be tricky (Sadao *et al.*, 2009). For fields with a distinct plow layer, Hanhart and Ni (1993) recommended improving the field's overall drainage situation or removing surface water before flowering to avoid a significant decline. It is required to control the water flow, but this has yet to prove easy. The depth of the appearance of the pyrite or jarosite horizons determines how deep the acid sulfate ditches are. The major ditches are connected to the acid-sulfate ditches for acid water drainage (Fig 5). The acid sulfate washing process is more substantial the closer the two acid sulfate ditches are to one another. However, economic efficiency should be considered due to the loss of arable soils. It should be emphasized that washing decreases toxicity and leaches vital nutrients; also, washing loses its effectiveness if the field is frequently dry (Dent, 1986).

The time-consuming and complex soil cleansing procedure depends on various variables. However, Dent (1986) says it works well to ease acid-sulfate soils. Flushing requires a large amount of superior freshwater and treats acid-sulfate soils. Harrowing increases flushing efficiency; without enough water to lower the dangerous concentration, only a tiny portion of the process is harrowing (Minh, 1996). Additionally, in the Central Section of the Mekong Delta, researchers Hanhart and Ni (1993) and Husson *et al.* (2000) found that the optimal time to start cultivating is immediately following the flooding season. There aren't many toxic substances and irrigation keeps crops in good shape during the dry season. However, the Plain of Reeds' insufficient water management means that the window of opportunity for sustaining perfect cultivation conditions is relatively short (2-3 months) and it may not even be long enough to allow for an entire plant cycle.

The start and duration of the best season for cultivation, as well as other agronomic difficulties, are all impacted by the mean-field elevation. Husson *et al.* (2000) claim that soils at high altitudes quickly dry out following a flood. Because extensive flooding results in a prolonged, high reduction and abrupt, strong oxidation, the ideal time to cultivate is relatively brief. Topsoil drains more slowly at medium elevations because tidal movements contribute water to the soil. Longer stretches of ideal weather are experienced.

On the other hand, oxidation close to the cycle's end may present issues. To maximize the time that rice may be grown, farmers on the Plain of Reeds sow the grain relatively early-before the floodwaters have entirely subsided. In a layer of water 20 to 40 cm thick, they dispersed pregerminated rice seeds at the end of December or the beginning of January (Husson *et al.*, 2000). At the end of March or the start of April, short-duration cultivars (90–100 days) are harvested. This technique produces fewer crop stands, which reduces yields since extended submersion reduces tillering and raises plant mortality.

Working in the Mekong Delta, Hanhart and Ni (1993) and Husson *et al.* (2000) found that the ideal farming period was immediately following the flooding season. There aren't many toxic substances and irrigation keeps crops in good shape during the dry season. The window of time when ideal circumstances for agriculture may be maintained in the Plain of Reeds is limited (between two and three months) and it is typically not long enough to allow an entire plant cycle. It is because of the inadequate water management in the area. Mean-field elevation also influences the start and length of the cultivation-friendly season and agronomic issues. Through their actual rice production, farmers in the Mekong Delta demonstrate how much fresh water a dependable irrigation system and the necessary technical washing and sulfate-avoidance measures can supply. Rice may produce 5 to 6 tons/ha of rice even in highly contaminated areas, according to Husson *et al.* (2000), since a plow pan is established and harmful ions are flushed with repeated soil preparation and cultivation cycles. Soil quality and water management on farms at high and moderate altitudes are continuously improving. Delaying sowing in these fields until the end of the plant cycle is conceivable with three or four irrigations, maintaining moist conditions and a favorable redox potential. It can generate up to 5 t/ha in 3 years. Instead, cropping conditions and yield increase exceptionally slowly due to inadequate soil drainage and a massive concentration of organic matter.

The rice yield on acid-sulfate soils is only about 2 tha^{-1}, much less than the national average of 3.8 t ha^{-1}, as Elisa *et al.* (2012) noted. If we increase the output above 5 t ha^{-1}, rice farmers in the affected areas can sustain a reasonable standard of living.

Groundwater level management

Tuong (1993) asserts that Beye (1973) and Yin and Chin (1982) have already commented on the adverse effects of the decline in groundwater levels. It resulted in the general advice that prospective acid sulfate soils should be managed by maintaining a high groundwater level away from the pyrite layer to prevent oxidizing pyrite. The impact of groundwater depth on the capillary of acid sulfate and toxins in the surface layer during the dry season is something to be concerned about, according to Tuong (1993), who emphasizes the function of water level in controlling chemical processes in acid-sulfate soil. When sulfidic acid sulfate is close to the ground surface, high groundwater levels prevent the drainage of deposited salts on the soil surface and restrict aeration (Fig 6). Indraratna *et al.* (1995) also claim that the rise in groundwater levels successfully prevents aluminum and pH levels that are too high.

Surface water management

Establishing a proper acid-sulfate drainage system is another commonly and successfully employed technique (Xuan, 1986). In the early rainy season, this canal system may facilitate the drainage of acid sulfate salts from the topsoil. However, the economic effectiveness of this approach could be better. Additionally, they can wash acid sulfate in salty water, a valuable method for reducing the quantity of Al^{3+} exchanged in soil colloids (Mensvoort *et al.*, 1993). This approach can be used if enough fresh water is nearby to wash the salt off immediately. Ni (1987) claimed that washing acid sulfate with fresh water after leaching it with saline water lowers the amount of dissolved salt and aluminum exchange in soil colloids. Al^{3+} exchange is more crucial and salt content has less impact on decreasing aluminum toxicity.

Liming and rational use of fertilizers

Liming can lessen or stop Al^{3+} toxicity in moderately active acid sulfate soils when the low topsoil pH is 3.6 and 4.2 (Fig 7). According to Breemen and Pons (1978), 3-6 tons/ha is the optimum amount. However, liming alone was less successful on the Mekong Delta's acidic soils. High efficiency

Fig 6: Leaching of acid sulfate soil toxicity.

Fig 7: Lime application for acid sulfate soil.

is obtained when lime application is paired with phosphate fertilizer, mainly when applied alone (Ba, 1980; Nghia, 2014). Lime and P fertilizer applications marginally increase the availability of phosphorus in the soil. This soil type's available P concentration is increased by using phosphate rock. Therefore, keeping them within a reasonable range will help manage excess Fe and Al. In the first crop, Tri (1998) found that restricting the dose to 10 tons/ha had little impact on pH increase.

Nevertheless, the Al^{3+} concentration dramatically dropped while the pH increased by around 1 unit due to the reduction process during flooding. Thu and Minh (2022) say that using urea humate, controlled slow-release NPK and balanced conventional fertilizers helped raise the number of valuable nutrients and the number of microorganisms in acid-sulfate soils. It illustrates the apparent effects of washing on the soil surface after a single crop and the reduction process after the submersion phase. The findings were consistent with those of Karthik and Maheswari (2020); humic acid sprayed in a field converts into easily obtainable humic chemicals that directly or indirectly influence plant development. In addition, Abubakar *et al.* (2023) were also notified that using biochar alone or combined with other soil amendments raises pH levels. Applying biochar, silicon and phosphorus is intimately related to maize (*Zea mays* L.) and the soil's acidity. Although biochar can lessen exchangeable soil acidity, its effects on lowering soil Al toxicity can be more significant when paired with phosphate and silicon.

In the past, steel slag, a by-product of the steel industry, was a better soil amendment to enhance acid sulfate soils in the Mekong Delta because it had a very high pH and included a lot of Ca, Mg and SiO_2 (Tan *et al.*, 2014; Thanh *et al.*, 2014).

Suitable crops and land use

The full potential of acid-sulfate soil can be realized by adding the right plant structures. Suitable land use types can be identified based on the nature and properties of the soil. To determine whether the Mekong Delta's soil was appropriate for growing rice (using double or triple rice cropping seasons or traditional rice), Tuong *et al*. (1991) employed hydrological variables as land features. The chosen hydrological land characteristics are typical for coastal acid sulfate land and include tidal influence, the amount and distribution of rainfall with a focus on the occurrence of dry spells in the early rainy season, the times when salt surface water is present during the dry season, the depth and duration of freshwater floods during the wet season and the suitability of canals for irrigation. The impact of these traits on rice farming was looked into and evaluated. A land evaluation study examined the extent of acid-sulfate soil in the Mekong Delta (Mensvoort, 1996). Other land use categories, such as rice, sugar cane, pineapple, tolerant annual crops, sensitive annual crops and *Melaleuca leucadendron*, were documented in addition to the soil qualities and hydrology. Factor ratings were developed for each land usage type (LUT) for acidity, future acidity, flood hazard, freshwater availability and salt intrusion tolerance based on farmers' experiences in the delta.

A significantly greater variety of indigenous land use systems than first believed is possible on acid-sulfate soils. Vietnamese farmers demonstrated that they could grow rice, yams, sweet potatoes, cassava, pineapples, sugar cane, fruit trees and shrimp ponds on this soil in the Mekong Delta. Land users must possess advanced knowledge of soil and water management (Mensvoort, 1996). For instance, Tri, (1998) offered various land use options for the Mekong Delta's acid sulfate soils based on evaluating the soil's flexibility. The models cassava (a), rice-shrimp (b), sugarcane (c) and pineapple (d) (Fig 8) have also been

Fig 8: Cultivation models on acid sulfate soil: cassava (a), rice-shrimp (b), sugarcane (c) and pineapple (d).

presented, according to Xuan (1993). These have also been applied successfully to acid-sulfate soils that may be contaminated with salt water.

Technical cultivation management

According to Monre (2016), the amount of acidic and saline soil in the Mekong Delta varies across locations. In addition to natural reasons, human factors such as excessive groundwater consumption for local life, production and development also play a crucial role in saltwater intrusions. Additionally, the aims of land use also have a distinct impact on saline intrusion. As a result, it is necessary to balance the protection of soil resources with the economic development strategy to increase the effective use of land resources (Hien and Than, 2022). As a result, it's essential to create agricultural techniques that are highly economical for saline and acid-sulfate soils.

Before anything else, fields and tillage methods need to be designed. Canals and trenches in the fields are required to release acid sulfate if wet rice is to be grown (Minh, 1996). Acid sulfate levels are decreased through upland farming. It is recommended to use soil-adapted crops and cultivars and to choose varieties resistant to or tolerant of acid sulfate. Upland crops produced in acidic soils include sugarcane, yams, bananas, corn, sesame, melaleuca and eucalyptus. Selecting acid-tolerant cultivars can quickly and economically remove toxicity in acid-sulfate soils. Choose types that can withstand acidity and determine the best farming model by integrating various farming techniques (APDA, 2006; Cho *et al.*, 2002; Minh *et al.*, 2020).

Effective farming techniques, including aquaculture (extensive), shrimp, rice and fish, as well as mangrove tree systems, are reportedly gradually improving their effectiveness on salty soils, according to Danh (2015), Nga and Tinh (2018) and Tin *et al.* (2022).

CONCLUSION AND RECOMMENDATIONS

In the Mekong Delta, there are wide variations in the volume of sulfidic or acid sulfate-producing material, the depth at which potential and active sulfate soils are found and the topsoil thickness of acid sulfate soils. The Mekong Delta, Vietnam's central rice-producing region, stands out for its intense cultivation, rice planting and inconsistent fertilizer application. Soils that contain acid sulfate are especially susceptible to the consequences of climate change. Therefore, regarding soil quality and the existence of hazardous substances, it is imperative to ascertain and forecast how various acidic soil biological zones will react to drought, water scarcity, rainstorms, floods, saltwater intrusion and rising sea levels.

Choosing cultivars that can survive salt or acid sulfate is simple and affordable. In the interim, designing suitable farming models is required. Additionally, one must know the distribution, physicochemical composition and biological characteristics of acid sulfate soils to manage and use the soil effectively in the current context.

Conflict of interest

All authors declared that there is no conflict of interest.

REFERENCES

Abubakar, W., Uddin, M., Kasim, S., Zaibon, S., Shamsuzzaman, S.M., Haque, A.N.A. and Reza, A. (2023). Biochar and silicon for sustainable agriculture in acid soil-nutrient dynamics and maize production: A review. Agricultural Reviews. https://doi.org/10.18805/ag.RF-260.

Andriesse, W. (Ed.). (1993). Acid Sulphate Soils: Diagnosing the Ills. In: Selected papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. [Dent, D., L., van Mensvoort, MEF (Eds.)], ILRI. https://library.wur.nl/WebQuery/wurpubs/fulltext/199709#page=11

APDA, (2006). Base Study on Impact of Population- Vietnam, Issue on Agriculture and Rural Development. The Asian Population and Development Association.

Astrom, M. (2001). The effect of acid soil leaching on trace element abundance in a medium-sized stream, W. Finland. Applied Geochemistry. 16(3): 387-396. https://doi.org/10.1016/S0883-2927(00)00034-2.

Astrom, M. and Astrom, J. (1997). Geochemistry of stream water in a catchment in Finland affected by sulphidic fine sediments. Applied Geochemistry. 12(5): 593-605. https://doi.org/10.1016/S0883-2927(97)00016-4.

Ba, L.H. (1980). The Difficult Problems of the Study on Acid Sulfate Soil in This Present Time. Paper Presented at Second Conference on the Acid Sulfate Soil. 30-42.

Beye, G. (1973). Etude comparative de différents engrais phosphatés pour la fumure phosphatée du riz en sols de rizière très acides de Basse Casamance. L'Agronomie Tropicale. Série 1, Riz et Riziculture et Cultures Vivrières Tropicales. https://agritrop.cirad.fr/421045/.

Brady, (1981). Soil factors that influence rice production. In: Institute of Soil Science, Academia Sinica (ed.). Proceedings of Symposium on Paddy Soil. Science Press. Beijing, 1-16.

Breemen, N., Burrough, P.A., Velthorst, E.J., van Dobben, H.F., de Wit, T., Ridder, T.B. and Reijnders, H.F.R. (1982). Soil acidification from atmospheric ammonium sulphate in forest canopy throughfall. Nature. 299: 548-550. https://doi.org/10.1038/299548a0.

Breemen, N.V. (1980). Acid Sulphate Soils. In: Land Reclamation and Water Management. Developments, Problems and Challenges. A Collection of Articles Published at the Occasion of ILRI's Silver Jubilee (1955-1980). In ILRI Publication International Institute for Land Reclamation and Improvement. 27: 53-57.

Breemen, N. van. (1976). Genesis and Solution Chemistry of Acid Sulfate Soils in Thailand (p.) [Phd, Pudoc]. https://library.wur.nl/WebQuery/wurpubs/70246.

Breemen, N. van and Pons, L.J. (1978). Acid Sulfate Soils and Rice. In Soils and Rice; Proc. Symp. Int. Rice Research Institute, Los Banos, (pp. 739-761). https://research.wur.nl/en/publications/acid-sulfate-soils-and-rice

Callinant, R., Sammut, J. and Fraser, G. (1996). Epizootic Ulcerative Syndrome (red spot disease) in Estuarine Fish-Confirmation that Exposure to Acid Sulfate Soil Runoff and an Invasive Aquatic Fungus, Aphanomyces sp., are Causative Factors. 146-151.

Cho, K.M., Ranamukhaarachchi, S. and Zoebisch, M.A. (2002). Cropping systems on acid sulfate soils in the central plain of Thailand: Constraints and remedies. At: Bangkok, Thailand Volume: Symposium No. 63, Paper No. 812. pp 1-10.

Cook, F., Hicks, W., Gardner, E., Carlin, G. and Froggatt, D.W. (2000). Export of Acidity in Drainage Water from Acid Sulphate Soils. Marine Pollution Bulletin. 41: 319-326. https://doi.org/10.1016/S0025-326X(00)00138-7.

Danh, V.T. (2015). Assessment of adaptive capacity to saline intrusion in agricultural production in coastal areas of Tra Vinh province. Scientific Journal of Can Tho University, Part D: Political Science. 36: 64-71.

Dent, D. (1986). Acid Sulphate Soils: A Baseline for Research and Development. International Institute for Land Reclamation and Improvement/ILRI.

Dent, D.L. and Pons, L.J. (1995). A World Perspective on Acid Sulphate Soils. [Geoderma 67 (1995) 263-276]. Geoderma. 68(3): 225. https://doi.org/10.1016/0016-7061(95)00064-U.

Elisa, A.A., Shamshuddin, J., Fauziah, C. and Fauziah (2012). Utilization of an Acid Sulfate Soil in Malaysia Rice Cultivation. Proceeding 7th International Acid Sulfate Soil Conference, Towards Harmony between Land Use and the Environment.

FAO, (1998). The State of Food and Agriculture, 1998: Rural Non-farm Income in Developing Countries. Rome, Italy. https://www.fao.org/documents/card/en/c/e6259450-e20e-5d8e-a776-969bd28761cb.

Hanhart, K. and Ni, D.V. (1993). Water Management on Rice Fields at Hoa An, Mekong Delta, Vietnam. In: Selected Papers Ho Chi Minh City Symp. Acid Sulphate Soils, Vietnam 1992. ILRI Public. 53, D.L. Dent, M.E.F. van Mensvoort (eds.) (pp. 161-175). https://research.wur.nl/en/publications/water-management-on-rice-fields-at-hoa-an-mekong-delta-vietnam.

Hien, P.T. and Than, C.H. (2022). Renovating land Law Policies to Promote Agricultural Economic Development in the Mekong Delta. Can Tho University Scientific Journal, 58(SDMD), Article SDMD. https://doi.org/10.22144/ctu.jvn.2022.203.

Hung, N.N., Dang, L.V. and Phuong, L.N. (2019). The amount of nutrients N, P and K absorbed by rice plants on acid sulfate soil in the Mekong Delta. Vietnam Journal of Agricultural Science. 17(3): 187-195.

Husson, O., Hanhart, K., Phung, M. T. and Bouma, J. (2000). Water management for rice cultivation on acid sulphate soils in the Plain of Reeds, Vietnam. Agricultural Water Management. 46(1): 91-109. https://doi.org/10.1016/S0378-3774(99)00108-0.

Indraratna, B., Sullivan, J. and Nethery, A. (1995). Effect of groundwater table on the formation of acid sulphate soils. Mine Water and the Environment. 14: 71-83. https://doi.org/10.1007/BF02914854.

Karthik, A. and Maheswari, M. U. (2020). Smart Fertilizer Strategy for Better Crop Production. Agricultural Reviews. https://arccjournals.com/journal/agricultural-reviews/R-1877.

Kyuma, K. (1976). Paddy soils in the Mekong Delta of Vietnam. Center for Southeast Asian Studies, Kyoto University.

Mensvoort, M.E.F. (1996). Soil Knowledge for Farmers, Farmer Knowledge for Soil Scientists: The Case of Acid Sulphate Soils in the Mekong Delta, Vietnam.

Mensvoort, M. van, Nhan, N., Tran, K.T. and Tri, L.Q. (1993). Coarse Land Evaluation of the Acid Sulphate Soil Areas in the Mekong Delta Based on Farmers' Experience. Selected Papers Ho Chi Minh City Symp. Acid Sulphate Soils, Vietnam 1992. ILRI Public. 53, D.L. Dent, M.E.F. van Mensvoort (Eds.). pp 321-329.

Minh, L.Q. (1996). Integrated Soil and Water Management in Acid Sulfate Soils: Balance Agricultural Production and Environmental Requirements in the Mekong Delta, Vietnam. Wageningen University. https://lrcopac.ctu.edu.vn/pages/opac/wpid-detailbib-id-16337.html.

Minh, V.Q. and Vu, P.T. (2015). Effective Use of Acid And Saline Soils in the Mekong Delta. National Workshop on Land Use in Vietnam and Challenges. 167-174.

Minh, V.Q., Vi, P.T., Khoa, L.V., Du, T.T., Tri, L.Q. and Dung, T.V. (2020). Major Land Uses on Acid Sulfate Soils of Hau Giang province, Vietnam. International Journal of Environment, Agriculture and Biotechnology. 5(1): Article 1. https://ijeab.com/detail/major-land-uses-on-acid-sulfate-soils-of-hau-giang-province-vietnam/

Monre, (2016). Saline Intrusion in the Mekong Delta-Effective Solutions to Climate Change. Science and Technology. https://www.most.gov.vn/vn/Pages/Thongbaoloi.aspx?requestUrl=http://www.most.gov.vn/vn/tin-tuc/7039/xam-nhap-man-tai-dong-bang-song-cuu-long-nhung-giai-phap-ung-pho)%20-hieu-qua-trong-dieu-kien-bien-doi-khi-hau.aspx.

Nedeco, (1993). Mekong Delta Master Plan, Thematic Study on Environmental Impacts. United Nations Development Program: Vol. 3: Existing Ecological Conditions and Present Status of Environmental Protection and Guidelines for Environmental Protection and Monitoring. Government of Vietnam, State Planning Committee, World Bank, Mekong Secretariat, United Nations Development Program.

Nga, B.T. and Tinh, H.Q. (2018). Forest Shrimp System in Sustainable Development in the Coastal Area of the Mekong Delta. pp 6-13.

Nghia, N.D. (2014). The Role of Biochar: Efficient Production and Application of Biochar. Science and Technology Information Center. Department of Science and Technology Ho Chi Minh City.

Ni, D.V. (1987). Salt Water Leaching for Improvement of Acid Sulfate Soils. In: Report of a Mission to Vietnam.

Olk, D.C. and Cassman, K.G. (2002). Role of Organic Matter Quality in Nitrogen Cycling and Yield Trends in Intensively Cropped Paddy Soils. 17. World Congress of Soil Science, Bangkok (Thailand), 14-21 Aug 2002. https://scholar.google.com/scholar_lookup?title=Role+of+organic+matter+quality+in+nitrogen+cycling+and+yield+trends+in+intensively+cropped+paddy+soilsandauthor=OLK%2C+D.C.%2C+National+Soil+Tilth+Laboratory%2C+%28USA%29.+USDA%2FARSandpublication_year=2002.

Ponnamperuma, F.N. (1972). The chemistry of Subnmerged Soils. Advances in Agronomy. https://unioncounty-fl.gov/wp-content/uploads/52-The-Chemistry-of-Submerged-Soils.pdf

Pons, L. J. (1973). Outline of the Genesis, Characteristics, Classification and Improvement of Acid Sulphate Soils. Publication.https://scholar.google.com/scholar_ lookup?title=Outline+of+the+genesis%2C+characteristics%2C+classification+and+improvement+of+acid+sulphate+soilsandauthor=Poms%2C+L.J.andpublication_year=1973

Pósfai, M. and Buseck, P.R. (2010). Nature and Climate Effects of Individual Tropospheric Aerosol Particles. Annual Review of Earth and Planetary Sciences. 38(1): 17-43. https://doi.org/10.1146/annurev.earth.031208.100032.

Ren, D.T.T. (1999). Lectures on Soil Fertility and Manure. Can Tho University.

Rorison, I. H. (1972). Acid Sulphate Soils (1-1).

Sadao, N., Eiichi, K., Dong, J.K., Shingo, U., Shigeo, I., Wesley, W., Wallender, W. and Pisoot, V. (2009). Improvement of Leaching Methods for Acid Sulfate Soil. https://doi.org/10.13031/2013.27425.

Sammut, J., White, I. and Melville, M.D. (1996). Acidification of an estuarine tributary in eastern Australia due to drainage of acid sulfate soils. Marine and Freshwater Research. 47(5): 669-684. https://doi.org/10.1071/mf9960669.

Sen, L.N. (1988). Influence of various water management and agronomic packages on the chemical changes and on the growth of rice in acid sulphate soils-WUR. https://www.wur.nl/nl/publicatie-details.htm?publicationId=publication-way-36373930.

Shamshuddin, J., Elisa Azura, A., Shazana, M.A.R.S., Fauziah, C.I., Panhwar, Q.A. and Naher, U.A. (2014). Chapter Three-Properties and Management of Acid Sulfate Soils in Southeast Asia for Sustainable Cultivation of Rice, Oil Palm and Cocoa. In: Advances in Agronomy, [D. L. Sparks (Ed.)], Academic Press. (Vol. 124, pp. 91-142). https://doi.org/10.1016/B978-0-12-800138-7.00003-6.

Stumm, W. and Morgan, J. (1981). Aquatic Chemistry, 2nd edn.

Takai, Y. and Kamura, T. (1966). The mechanism of reduction in waterlogged paddy soil. Folia Microbiologica. 11(4): 304-313. https://doi.org/10.1007/BF02878902.

Tan, H.D., Minh, V.Q., Dung, L.V. and Khoa, L.V. (2014). Efficacy of steel slag fertilizer on rice yields growth on acid sulfate soil (net house conditions). Journal of Soil Science. Vietnam Soil Science Association. 35-38.

Tan, P.S. (2001). Research on biogeographical zoning of fertilizer effectiveness in Vietnam. State-Level Thesis Report Science and Technology.

Tan, P.S. (2005). Research Results to Improve Fertilizer Efficiency for High-Yielding Rice in the Mekong Delta. In: Agricultural Science and Technology and Rural Development 20 Years of Innovation. National Political Publishing House. 3: 315-327.

Thanh, N.N., Tan, H.D., Dung, L.V., Khoa, L.V. and Minh, V.Q. (2014). Efficacy of Steel Slag as Fertilizer on Rice Yields Growth on Acid Sulfate Soil (Net House Conditions. 3: 38-41.

Thomas, P. and Varley, J.A. (1982). Soil Survey of Tidal Sulphidic Soils in the Tropics: A Case Study. The Bangkok Symposium on Acid Sulphate Soils ISSC. 52–72. http://www2.alterra.wur.nl/Internet/webdocs/ilri-publicaties/publicaties/Pub31/pub31-h3.pdf

Thu, T.A. and Minh, V.Q. (2022). Improving soil properties and rice yield on saline-affected acid sulfate soil by controlled-release fertilizer. Indian Journal of Agricultural Research. doi: 10.18805/IJARe.AF-753.

Tin, N.H., Du, P.A., Thinh, H.C., Duyen, C.M., Long, H.V. and My, N.V. (2022). Financial performance and stability of the Shrimp-Forest model in the Mekong Delta. Scientific Journal of Can Tho University. 58(2). Article 2. https://doi.org/10.22144/ctu.jvn.2022.054.

Tri, L.Q. (1998). An Overview of Soil Constraints and Their Management. In: Soil Constraints and Their Management. Department of Soil Science and Land Management, Faculty of Agriculture, Can Tho University.

Tuong, T., Minh, L.Q. and Khanh, T. (1991). Effect of Water Table Depth on Evaporation and Distribution of Salts and Moisture in a Bare Acid Sulphate Soil. In: Rice Production of Acid Soils of the Tropics. [P. Deturck and F.N. Ponnamperuma (Eds.)] Institute of Fundamental Studies, Kandy.

Tuong, T.P. (1993). An Overview of Water Management on Acid Sulfate Soils. Print: Selected papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. [D. Dent and MEF van Mensvoort (eds)], ILRI Publ. 265-280.

Van, W. and Putu (1992). Simulation Model of Physical and Chemical Processes to Evaluate Water Management Strategies. In: Acid Sulfate Soil in the Humid Tropics: Simulation Model of Physical and Chemical Processes to Evaluate Water Management Strategies. AARD and LAWOO, 11-18.

WRB-FAO, (2007). World Reference Base for Soil Resources 2006 (First update 2007) A Framework for International Classification, Correlation and Communication. World Soil Resources Reports.

Xuan, T.X. (1986). Present Land Use of Potential and Actual Acid Sulphate Soils in the Mekong Delta', Bangkok (Thailand). https://scholar.google.com/scholar_lookup?title=Present+land+use+of+potential+and+actual+acid+sulphate+soils+in+the+Mekong+deltaandauthor=Vo-Tong+ Xuan%0A++++%28Cantho+Univ.+%28Viet+Nam%29%29 and publication_year=1986.

Xuan, V.-T. (1993). Recent Advances in Integrated Landuse on Acid Sulfate Soils. In: Selected papers of the Ho Chi Minh City Symposium on acid sulphate soils. [D. Dent and MEF van Mensvoort (eds)], ILRI Publ. 129-136.

Xuan, V.-T. (1997). Entering the 21st Century, Crop Nutrition and Food Safety. In: Agriculture-Resources and Fertilizer use in Vietnam. Young Publishing House, City, Ho Chi Minh City.

Xuan, V.-T. and Matsui (1998). Development of farming systems in the Mekong Delta: JIRCAS,CTU, CLRRI, Vietnam.

Yin, T.P. and Chin, P.Y. (1982). Effect of water management on field performance of oil palms on acid sulphate soils in Peninsular Malaysia. Publication - International Institute for Land Reclamation and Improvement. https://scholar.google.com/scholar_lookup?title=Effect+of+water+management+on+field+performance+of+oil+palms+ on+acid+sulphate+soils+in+Peninsular+Malaysiaand author=Yin%2C+T.P.andpublication_year=1982.