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REVIEW

Acid sulfate soils: formation, identification, environmental impacts, and sustainable remediation practices

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Abstract Acid sulfate soils (ASS) are prevalent and provide significant environmental hazards due to their capacity to produce high acidity when exposed to oxygen. This study offers a thorough summary of the development, identification, environmental effects, and sustainable remediation techniques for ASS. These soils generally form under anaerobic circumstances in coastal, estuary, and low-lying inland areas, where sulfide minerals build over time. Upon disturbance, ASS emits sulfuric acid, resulting in acidification, mobilization of heavy metals, deterioration of water quality, loss of biodiversity, and disruption of ecosystem services. Identifying ASS by chemical, mineralogical, and geographical methodologies is crucial for alleviating their effects. Sustainable remediation solutions encompass regulated drainage, groundwater management, and organic amendments to improve soil-buffering capacity and facilitate sulfate reduction. Moreover, new advancements in bioremediation, including microbial-assisted sulfate reduction, demonstrate potential for enduring soil stability. Notwithstanding continuous advancements, efficient ASS administration necessitates a cohesive strategy that amalgamates scientific inquiry with pragmatic field implementation. This review emphasizes the necessity for multidisciplinary collaboration to create adaptable, site-specific solutions that mitigate environmental concerns while promoting sustainable land use. This study enhances the management of ASS in fragile ecosystems by addressing critical information deficiencies and investigating new remediation strategies.

Keywords Acid sulfate soils (ASS) · Amelioration · Distribution · Occurrence · Properties · Formation · Identification

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Introduction

Acid sulfate soils (ASS) are characterized by the presence of iron sulfide minerals, primarily pyrite (FeS_2), which form under anaerobic conditions in wet environments. These soils are prevalent in coastal, estuarine, and low-lying inland areas, where sulfate-rich water interacts with iron and organic matter. While stable under waterlogged conditions, ASS pose severe environmental risks when exposed to oxygen, triggering a cascade of acidification reactions that release sulfuric acid and mobilize toxic metals. The degradation caused by ASS affects biodiversity, agricultural productivity, infrastructure, and water quality,

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making their management a significant environmental challenge.

The oxidation of pyrite is a primary driver of soil acidification. When sulfide minerals are exposed to oxygen and water, pyrite undergoes oxidation, leading to the formation of sulfuric acid and the release of dissolved iron. This process is further accelerated by acidophilic bacteria, such as *Acidithiobacillus ferrooxidans*, which catalyze the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) (Iqbal et al., 2024). The resulting ferric iron reacts with additional pyrite, sustaining a cycle of acid production and driving soil pH below 4. Such highly acidic conditions pose serious risks to natural ecosystems and human activities, including agriculture, infrastructure development, and water resource management (Trueman et al., 2020). ASS is widely distributed across the globe, particularly in regions where geological and environmental conditions favor their formation. These include parts of China, the Netherlands, Australia, and the USA, where extensive coastal plains and estuarine ecosystems provide ideal conditions for pyrite accumulation (Hobohm et al., 2021; Mazhar et al., 2022). In these regions, improper land-use practices, such as mining, agriculture, and urbanization, have significantly contributed to ASS disturbance, leading to widespread soil acidification and associated environmental degradation.

Soil acidity is a rising concern in many parts of the USA, particularly in the western and northeastern regions. In the western USA, declining pH levels have been recorded in agricultural lands, with some areas experiencing drops below 5.0, threatening crop productivity. Key drivers of soil acidification in these regions include excessive nitrogen fertilizer use, acid deposition from industrial emissions, and the lack of natural lime sources to buffer soil acidity (Charles & Christie, 2013). In the northeastern USA, high rainfall and acid deposition have exacerbated soil and water acidification. Acid rain, resulting from sulfur and nitrogen oxide emissions, has contributed to the acidification of lakes, rivers, and forest soils, leading to ecosystem imbalances.

A primary contributor is acid rain, which occurs when sulfur dioxide (SO_2) and nitrogen oxides (NOx) are emitted into the atmosphere by industrial discharges and fossil fuel combustion. These pollutants interact with atmospheric moisture to generate sulfuric acid (H_2SO_4) and nitric acid (HNO_3), which are subsequently deposited into the soil by precipitation. This mechanism causes soil pH to drop over time, therefore compromising soil fertility and microbial activity (Nilsson, 2024). In addition to acid rain, agricultural practices significantly contribute to soil acidification. The extensive use of ammonium-based fertilizers, such as ammonium sulfate and urea, results in the release of hydrogen ions during the nitrification process, leading to lower soil pH (Guo et al., 2010). Moreover, continuous crop harvesting depletes essential base cations (e.g., calcium, magnesium, potassium), which are crucial for maintaining soil pH balance (Kartini et al., 2024).

The increased acidity has disrupted nutrient cycles, weakened tree resilience, and affected aquatic biodiversity, highlighting the need for region-specific soil and water management strategies. Studies have shown that humid climates, like those in the northeastern USA, tend to exhibit more acidic soils compared to arid environments, reinforcing the role of climatic factors in soil pH dynamics.

The formation of ASS is controlled by a combination of geological, environmental, and microbiological factors. Under anaerobic conditions, sulfate-reducing bacteria facilitate the reduction of sulfate to sulfide, which then reacts with iron to form pyrite (Rate 2022). The formation of ASS is governed by geological, environmental, and microbiological factors. Under anaerobic circumstances characteristic of wetlands and coastal sediments, sulfate-reducing bacteria catalyze the reduction of sulfate to sulfide, which then reacts with iron to produce pyrite.

This process, albeit natural, produces soils that are extremely reactive upon exposure to oxygen. The disruption of pyrite oxidation generates sulfuric acid and emits hazardous elements, including aluminum, arsenic, and manganese, into the environment (Chowdhury & Singer, 2023). Acidification from ASS poses long-term environmental risks. Once initiated, the acidification process can persist for decades or even centuries, making remediation difficult. Highly acidic runoff contaminates groundwater, rivers, and estuaries, harming aquatic ecosystems. In coastal areas, acidification can lead to fish kills, the destruction of mangrove forests, and the loss of breeding habitats for marine organisms (Yadav et al., 2020). Additionally, the mobilization of toxic metals in these soils further exacerbates ecological damage, as these contaminants accumulate in food chains and disrupt ecosystem balance (Shahabi-Ghahfarokhi et al., 2022).

Microbial communities play a crucial role in the geochemical processes governing ASS. While pH is a major determinant of microbial distribution in acid mine drainage (AMD) environments, other factors such as iron speciation, sulfate concentrations, dissolved oxygen levels, and organic carbon availability significantly influence microbial activity (Rowe et al., 2007). Acidophilic iron-oxidizing bacteria, including *Acidithiobacillus* spp., *Leptospirillum* spp., and *Ferrovum myxofaciens*, drive low-pH Fe(II) oxidation, promoting the formation of secondary iron minerals such as schwertmannite and goethite. These transformations affect the mobility of iron and other metals in ASS, impacting soil chemistry and ecosystem health (Sheng et al., 2017). Understanding microbial interactions in ASS environments is essential for developing bioremediation strategies. Targeting specific microbial processes, such as sulfate reduction and iron immobilization, could offer sustainable approaches to mitigating soil acidification and metal contamination.

The environmental degradation caused by ASS has significant socio-economic consequences. In agricultural regions, declining soil fertility and heavy metal accumulation reduce crop yields and compromise food security. In the Ganges Delta, for example, ASS-induced acidification has lowered soil pH to below 3.5 at significant depths, rendering water sources unsuitable for irrigation and limiting aquaculture potential (Åström, 2022). This loss of productive land exacerbates poverty and economic disparities, particularly in resource-limited communities (Afonso et al., 2021). The economic burden of ASS extends beyond agriculture. Infrastructure development in acidified soils is often costly, as the corrosive effects of sulfuric acid degrade concrete, steel, and other construction materials. Additionally, the treatment of acidified water bodies requires significant financial investment, placing pressure on local governments and communities.

ASS also contribute to global climate change by releasing carbon dioxide (CO_2) through the oxidation of sulfides and acid-mediated carbonate dissolution (Zhang et al., 2020). When sulfuric acid interacts with carbonate minerals such as calcite, CO_2 is released into the atmosphere, adding to greenhouse gas emissions. Microbial activity further accelerates these processes, influencing global carbon cycles. The extent of ASS-related CO_2 emissions remains underexplored, but their potential impact on climate dynamics underscores the need for integrated soil management strategies. Addressing ASS requires not only localized remediation efforts but also broader climate-smart approaches to mitigate their contribution to global warming.

Traditional remediation methods, such as lime application, have been widely used to neutralize soil acidity. However, these methods are often unsustainable due to high costs and the need for repeated applications (Gonzalez Bujedo, 2023). Sustainable practices include using organic amendments like biochar, compost, and manure to improve soil structure, enhance pH buffering, and reduce heavy metal mobility. Controlled drainage systems help regulate water levels, minimizing oxygen exposure and preventing pyrite oxidation. Planting salt-tolerant crops supports agriculture in acidified and saline conditions. Additional research is required to evaluate these strategies' effectiveness in various ecological and socio-economic contexts.

This study aims to develop innovative, site-specific management techniques that integrate environmental sustainability with socio-economic feasibility. By exploring the links between ASS and greenhouse gas emissions, this research contributes to climate-resilient soil management strategies that align with global carbon neutrality goals. Combining theoretical insights with practical applications, this study seeks to establish comprehensive solutions for ASS management, ensuring long-term environmental and socio-economic stability in affected regions.

Comprehending ASS: definition, categories, and principal characteristics

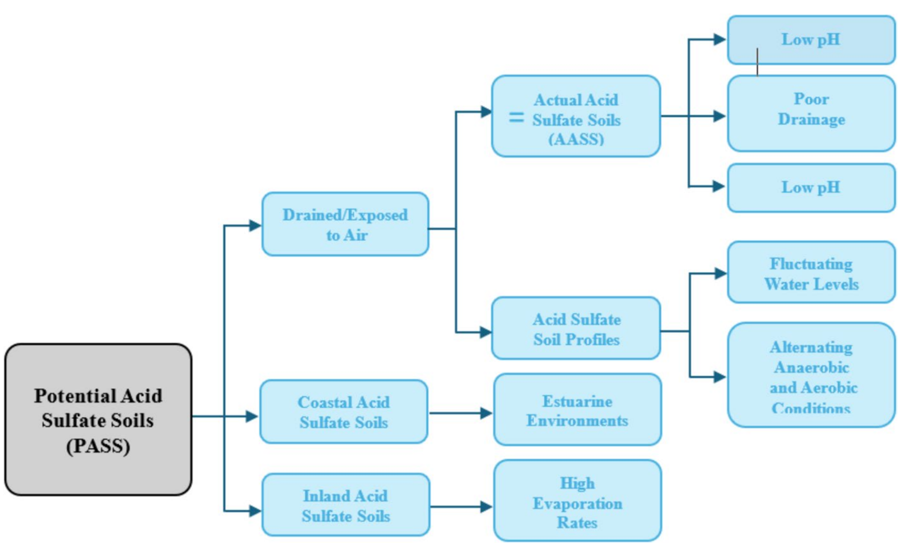
ASS are characterized by the presence of iron sulfides, mostly pyrite, which oxidize upon exposure to air, generating sulfuric acid and creating a highly acidic environment when the soil's neutralizing capability is exceeded (Asare, 2024). ASS are defined as desiccated soils that frequently include free and adsorbed sulfate, exhibit light yellow mottles of jarosite, and generally possess a pH below 4 (Fitzpatrick et al., 2017). These definitions emphasize the distinctive chemical characteristics of ASS and its capacity to generate very acidic conditions when disrupted.

ASS are of worldwide importance, with an estimated 17 to 24 million hectares recognized as worrisome owing to their potential for considerable acidification as showed in Fig. 1. They are often categorized into three primary types: potential ASS, actual ASS, and post-active ASS (Boman et al., 2024). These soils often have inadequate drainage, a dark gray to gray, and textures varying from silty clay loam to clay, with pH values frequently under 4.

Potential ASS may remain unoxidized and may include unoxidized iron sulfides, sustaining a virtually neutral pH range of 6.5 to 7.5. When disturbed and exposed to air, these soils may swiftly oxidize, producing sulfuric acid and converting into actual ASS. This process often leads to the development of jarosite, a yellow mottled mineral generated as a by-product of sulfide oxidation. Actual ASS, with a pH below 4, generally exhibits the whole environmental consequences of acidification, including the leaching of hazardous metals and the degradation of soil quality (Nyman et al., 2023a, b). Potential ASS denotes soils that have experienced acidity, resulting in enduring alterations in chemical composition, often necessitating comprehensive treatment to alleviate detrimental impacts. When weathering and soil formation processes in active ASS progress to a point when sulfide minerals are absent near the surface and the pH exceeds 4, often as a result of liming and drainage, the soils are classified as post-active ASS (Fanning et al., 2017). ASS is often used for rice cultivation, shrimp farming, and salt production, contingent upon local topography, flooding frequency, irrigation infrastructure, soil acidity, and drainage salinity. The possibility of acidity during oxidation presents significant threats to these operations and requires meticulous control to avert environmental harm.

The distinctive characteristics of ASS differentiate it from other soil types. These soils contain reduced inorganic sulfides (RIS), the oxidation of which induces acidification, possibly decreasing pH values below 3 (Jayalath et al., 2021). The oxidation process emits several hazardous metals, nutrients, and rare earth elements, including iron (Fe), aluminum (Al), copper (Cu), cobalt (Co), zinc (Zn), cadmium (Cd), arsenic (As), phosphate (HPO_4^{2-}), yttrium (Y), and lanthanum (La), into the environment. Moreover, soil and drainage water acidity deplete oxygen in aquatic habitats, produce detrimental gasses such as hydrogen sulfide (H_2S), and devastate landscapes, hence exacerbating deforestation. The high acidity and ensuing environmental processes pose considerable risks, requiring an interdisciplinary strategy for successful management and assessment of ASS (Rizwan et al., 2024). Comprehending the difference between sulfidic and sulfuric soil elements is essential. Sulfidic soils possess unoxidized RIS and may experience significant acidification upon disturbance, while sulfuric soils are inherently acidic owing to the oxidation of reduced sulfur molecules. Sulfidic materials generally

Fig. 1 Flowchart illustrating the types of ASS with key characteristics



originate from coastal and estuary sediments, brackish lakes and lagoons, or salinity-affected wetlands. The formation of these materials depends on four critical factors: an iron supply, organic matter, sulfate from tidal or saline waters (where bacteria convert sulfate to sulfide), and a consistent anaerobic environment to promote sulfate reduction (Mayakaduwage et al., 2023). In summary, ASS have unique traits influenced by pronounced acidity resulting from RIS oxidation. This process results in environmental issues including soil and water acidification, mobilization of hazardous metals, aquatic deoxygenation, emission of deleterious gasses, and landscape deterioration. Effective identification and control of ASS are essential to reduce their environmental effect, considering their intricate chemistry and behavior under varying situations.

Formation, identification, and distribution of ASS

ASS are naturally occurring soils formed when sulfide minerals, particularly iron sulfides, are exposed to oxygen through natural processes. This exposure triggers chemical reactions that produce sulfuric acid, which can lead to soil acidification and environmental challenges. These soils, often located in coastal and estuary regions, were initially buried, maintaining sulfides in an anaerobic, stable condition. Upon drainage or exposure to air, sulfides undergo oxidation, resulting in the formation of sulfuric acid. A summary of the principal processes involved in ASS formation is showed in Fig. 2.

Formation

Formation of pyrite

Pyrite accumulation occurs due to a specific set of conditions commonly present in tropical coastal areas. The sulfur in pyrite derives from sulfate found in seawater, which is converted into sulfide via biological activities in anoxic sediment. The bacterial reduction of sulfate necessitates an energy supply, and these coastal regions typically possess abundant organic matter resulting from robust plant growth. The presence of ferrous iron (Fe^{2+}) is crucial, often acquired via reducing insoluble ferric compounds formed during clay weathering. The development and accumulation of pyrite in tropical coastal wetlands result from a confluence of sulfate from saltwater, organic matter from plant growth, anaerobic conditions due to excessive water restricting air oxygen, and the presence of Fe^{2+}.

$$Fe_2O_3(s) + 4SO_4^{2-}(aq) + 8CH_2O + {}^1/_2\,O_2(g) = 2FeS_2(s) + 8HCO_3^-(aq) + 4H_2O(l) \tag{1}$$

The entire reaction entails the transformation of all sulfate into sulfide, which is subsequently oxidized to disulfide (S^{2-}) utilizing Fe(III) and O_2 as oxidizing agents. The conversion of FeS to FeS_2 via a solid–solid reaction is a gradual process, occasionally requiring several months or even years to produce measurable

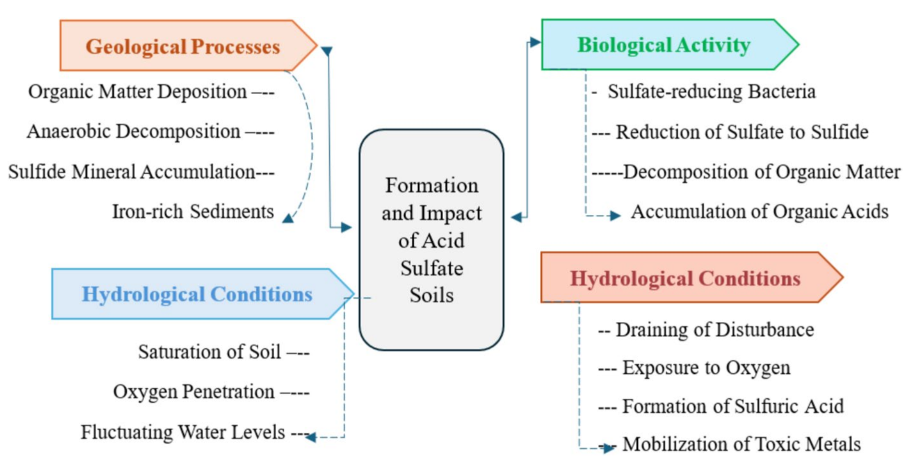


Fig. 2 Formation of ASS based on geological process, biological activity, hydrological conditions, and oxidation process in soils

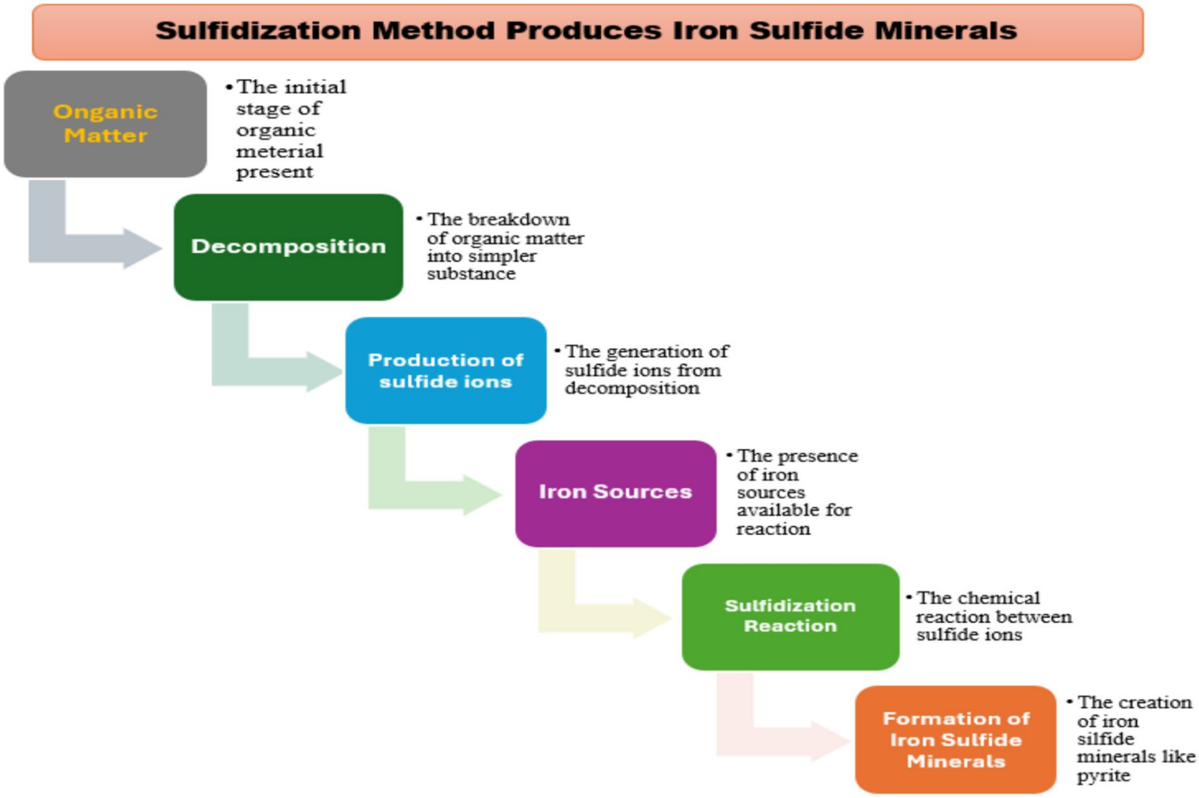


Fig. 3 Schematic diagram illustrating the generalized process of sulfidization which leads to the formation of iron sulfide minerals and potential ASS (Rabenhorst et al., 2020)

quantities of pyrite which discussed in Fig. 3. Under optimal conditions, the direct precipitation of Fe^{2+} and S^{2-} might facilitate the fast formation of pyrite within days, as recorded by Van Mensvoort and Dent (2020).

Oxidation of pyrite

The fine-grained pyrite commonly found in tidal sediments undergoes rapid oxidation upon exposure to air. The oxidation of pyrite is profoundly affected by microbial activity, especially by iron- and sulfur-oxidizing bacteria, including *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans*. These microorganisms expedite the oxidation process by accelerating the transformation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), hence facilitating pyrite breakdown (Schippers et al., 2014). Moreover, they facilitate the synthesis of sulfuric acid, hence decreasing pH and encouraging prolonged oxidation. This microbial mediation is especially pertinent in acid mine drainage (AMD) conditions, where biological activity results in swift and significant pyrite weathering. This process results in the formation of Fe (II) sulfate and sulfuric acid:

$$FeS_2 + 7/2O_2 + H_2O = Fe^{2+} + 2SO_4{}^{2-} + 2H^+ \tag{2}$$

Complete oxidation and hydrolysis of iron from pyrite lead to the creation of Fe (III) oxide, along with 2 mol of sulfuric acid for each mole of pyrite:

$$FeS_2 + 15/4O_2 + 7/2H_2O = Fe(OH)_3 + 2SO_4{}^{2-} + 4H^+ \tag{3}$$

The oxidation of pyrite can occur more quickly in the presence of dissolved Fe (III) than with oxygen, according to

$$FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 16H^+ + 2SO_4{}^{2-} \tag{4}$$

This reaction yields iron (II) ions, hydrogen ions, and sulfate ions, which further react within the soil, resulting in the formation of diverse oxidation products. One such product is jarosite, a distinct pale-yellow mineral represented by the chemical formula $KFe_3(SO_4)_2(OH)_6$. Jarosite forms exclusively in environments with acidity levels ranging from pH 2 to 4 and high oxidation potential exceeding 400 mV. This mineral is a common feature of many ASSs and is easily identified by its sharp X-ray diffraction pattern. Jarosite, while metastable in ASS, eventually hydrolyzes to become goethite. The presence of pale yellow jarosite mottles, along with pH levels, is used as a diagnostic criterion for classifying ASS (Grigg et al., 2024). However, certain ASS, particularly those rich in organic matter, may lack jarosite. Jarosite formation can occur rapidly from the oxidation of dissolved Fe (II) sulfate released during pyrite oxidation. Alternatively, it may form more slowly through the hydrolysis of existing jarosite described as Fig. (5.

$$Fe^{2+} + SO_4{}^{2-} + 1/4O_2 + 3/2H_2O = FeOOH + 2H^+ + SO_4{}^{2-} \tag{5}$$

$$Jarosite = 3FeOOH + 2SO_4{}^{2-} + K^+ + 3H^+ \tag{6}$$

In well-drained and deeply developed ASS, the B horizon may contain some Fe (III) oxides that manifest as hematite, resulting in distinctive red mottles.

Formation of gypsum

If the soil contains a notable quantity of a substance that can neutralize acidity, like $CaCO_3$, a precipitation reaction could occur:

$$2CaCO_3 + KFe_3(SO_4)_2(OH)_6 + 5H_2O + H^+ = 2CaSO_4 \cdot 2H_2O + 3Fe(OH)_3 + K + +2CO_2 \tag{7}$$

The presence of gypsum formation in ASS suggests that the soils are comparatively suitable for agricultural purposes.

Identification

ASS regions are often defined by wetland conditions, restricted access, and thick flora, notably resilient tall grasses (McFarland et al., 2024). Detecting the existence of Actual ASS is a very simple endeavor, as there are numerous indications to observe. It was observed that a visual sign of developing acid sulfate conditions in drained fishponds is the emergence of a reddish tint on the pond's bottom (Indraratna et al., 2020). Recent research have identified many dependable field markers (Johnson et al., 2024; VanZomeren et al., 2020), which are further substantiated by our observations. The details of discussion of ASS identification are mentioned in Table 1.

Distribution of ASS

ASS is located in various climatic zones globally, ranging from frigid and temperate regions to humid tropical places. Nevertheless, they appear to be predominantly prevalent in tropical deltas (Sarangi et al., 2022). The map (Fig. 4) illustrates the global distribution of acid soils, which are further classified by pH levels into two soil strata: topsoil (0–30 cm) and subsoil (30–100 cm). The topsoil (0–30 cm) is illustrated in Fig. 4a: Soils that are highly acidic (pH $\leq$ 4.5) are frequently encountered (red): primarily situated in tropical regions, such as the Amazon basin in South America and specific regions of Central Africa. Primarily situated in tropical regions, such as the Amazon basin in South America and specific regions of Central Africa and also prevalent in northern regions, including Siberia and numerous regions of northern Europe. Moderately acidic soils (pH 4.6–5.5) (shown in orange) predominate throughout extensive regions of Southeast Asia, Sub-Saharan Africa, and Central and Eastern Europe. Extensive coverage throughout North America and South America especially in coastal wetlands, estuary habitats, and low-lying floodplains, where sulfate-rich marine or estuarine sediments have undergone oxidation, resulting in the development of ASS.

In Fig. 4b, the subsoil (30–100 cm) is depicted: Soils that are highly acidic (pH $\leq$ 4.5) continue to be the most prevalent: It is prevalent in regions that are analogous to the topsoil, such as the Amazon basin, central Africa, and northern Eurasia. Particularly in tropical climates, there are specific expansions in relation to the topsoil stratum. Moderately acidic soils (pH 4.6–5.5) exhibit extensive distribution: located in various regions of Southeast Asia, southern Africa, and certain areas of North and South America.

Tropical locations display elevated levels of highly acidic soils, indicative of climate influences and

Table 1 ASS identification methods with features

Category	Indicators/methods	Details
Signs of ASS	Low soil pH	Indicates acidic conditions
	Yellow jarosite spots	Appears on soil surface when disturbed
	Iron-rich deposits in drainage channels	Sign of oxidation and acidity
	Lack of plant growth	Especially visible on dikes
	Distinctive odor	Sulfurous scent due to hydrogen sulfide
	Reddish tint in fishponds	Reddish-orange crust on pond bottoms indicates acid sulfate development
Field identification	Acidity after drying	Acidic reaction in dried soil samples
	Soft, organic-rich sediments	Presence of halophytic plant remnants signals potential ASS
	Mangrove vegetation	Especially Rhizophora species, associated with sulfidic sediments
	Soil coloration	Dark gray to black hues may suggest sulfidic material
	Sulfurous odor	Detected when soil is disturbed
	Visible sulfur compounds	Jarosite and sulfur mottles on soil surfaces
	Odor from combusted organic matter	Sulfurous smell from burning driftwood or roots
	Landscape position	Often found inland, on lower slopes with poor drainage
	Ecological impact	Fish deaths after rainfall may indicate acidic, metal-laden water from nearby soils
Analysis of Pyrite	Pyrite identification methods	Includes chemical, microscopic, and X-ray diffraction methods
	Rapid oxidation method	Using H_2O_2 to oxidize dried soil, followed by titration (Butterly et al., 2022)
	Slow oxidation methods	Shade-drying with moistening over 2 months or storing moist soil in polyethylene bags (Bloomfleld & Coulter, 1974)
	Recommendations	Rapid oxidation method is suitable for large-scale sample processing (Medawela et al., 2022)
Challenges	Environmental and logistical obstacles	Wetland conditions, poor access, thick vegetation make ASS identification difficult
	Need for comprehensive evaluations	Singular signs may be inconclusive; soil testing and environmental context awareness are essential

organic matter decomposition processes. Temperate and boreal regions exhibit acidic environments, especially in Europe and North America. Acidification is typically more pronounced in regions with substantial precipitation and inadequate buffering capability.

Table 2 illustrates the distribution of ASS in several Asian countries, including their locations, areas, soil types, and data reliability. These regions are defined by the presence of Sulfaquents, Sulfaquents, and Sulfic Tropaquepts, typically associated with wetland ecosystems and mangrove habitats. The trustworthiness of data fluctuates with location.

Ecological impacts of ASS

Due to the prevalence of ASS in densely populated regions of developing nations, those most adversely affected by their detrimental effects on ecosystem services, such as diminished agricultural and aquacultural productivity, are often the least capable of addressing these challenges. Although ASS represent a minor fraction of globally problematic soils, the problems associated with their cultivation and the resulting environmental impacts can significantly influence well-being, especially at local and individual levels. The Millennium Ecosystem Assessment (MA) acknowledges agriculture's significance not only in food provision but also as a source of employment and economic benefits, providing sustenance and a social safety net for rural families, hence improving health (DRENNING 2021). Research indicates that ASS substantially influence the diversity and composition of fish, benthic invertebrates, and macrophytes and also the total impacts on ecology that are described in Fig. 5. This diagram depicts the environmental impact of ASS, emphasizing six primary

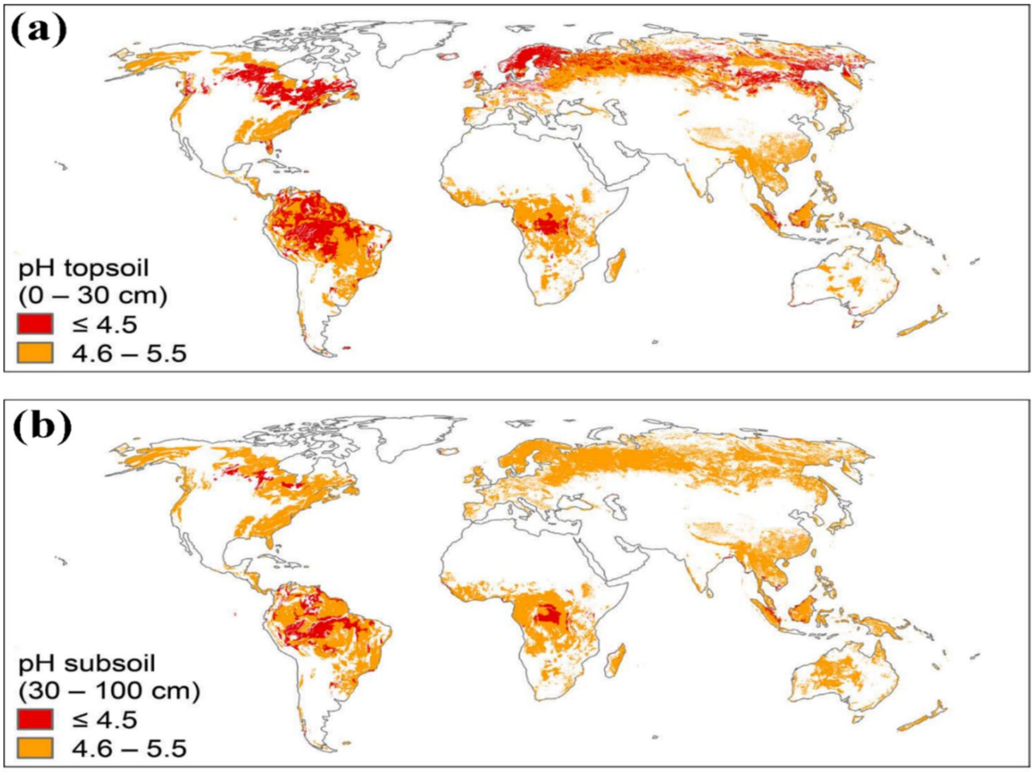


Fig. 4 The distribution of acid soils worldwide in topsoil (0–30 cm) (**a**) and subsoils (**b**). Soil pH is presented in two classes: pH ≤ 4.5 (strongly acid soils) and pH 4.6–5.5 (moderately acid soils) (Brunner & Sperisen, 2013)

effects: increased acidity due to sulfuric acid release, heavy metal mobilization, decreased oxygen levels from organic matter breakdown, reduced biodiversity, altered community structures, and habitat degradation, making wetlands less suitable for organisms.

Impacts on agriculture

Agricultural production is crucial for supporting societies reliant on agricultural products to fulfill their daily food requirements. This is particularly crucial in developing countries because population concentrations frequently exceed the available cultivable land. The situation deteriorates due to the continuous conversion of vital wetlands, such as ASS (peatlands), into agricultural land (Huang et al., 2021; Minh et al., 2020; Zak et al., 2021). As a result, the degradation of essential wetland ecosystems has been occurred, which are crucial for sustaining agriculture and biodiversity. Figure 6 outlines the negative effects of soil acidity on agriculture and the environment. Soil acidity disrupts microbial activity, poses management challenges, reduces crop yields, and releases toxic elements, all of which collectively degrade soil health, diminish agricultural productivity, and necessitate intervention for soil restoration.

Moreover, the development of infrastructure and the continued reliance on conventional agricultural practices, as observed in Finland during the past century (Estévez Nuño, 2020; Kronberg et al., 2024), have exacerbated the difficulties encountered by these communities.

Agricultural soil contamination has resulted from variables such as sulfuric acid production, accumulation of mineral contaminants, and deficits in essential minerals such as phosphorus, as noted by the soil quality assessment of coastal salt-affected acid soils of India (Mahajan et al., 2020). Furthermore, noxious odors originating from hydrogen sulfide (H_2S) or organic sulfur compounds have exacerbated this issue (Long et al., 2024). Consequently, numerous

Table 2 The distribution of actual and potential ASS in Southeast and East Asia. (Karananidi et al., 2022)

Country	Area name	Area (thousand ha)	Reliability[a]	Soil classification
Bangladesh	Chittagong	200[b]	–	Sulfaquents, Sulfaquents
	Khulna Sundarban	200[b]	–	Sulfaquents
Burma		180[b]	–	Sulfaquents
	Coastal Areas			
China	South of Fukien	67	+	Sulfaquents, Sulfic Haplaquepts
India	Kerala	110	+	Highly organic Sulfaquents, partly (26,000 ha) affected by salinity
	W. Bengal	280[b]	–	Sulfaquents
Indonesia	Kalimantan and Sumatra	2,000	–	Mainly highly organic Sulfaquents and Sulfaquents and Sulfihemists
Cambodia	Khmer	200	+	Mainly Sulfaquepts
Japan		4	+ +	Sulfaquepts, Sulfic Haplaquepts
		17	+ +	Potentially acid shallow sea bottom
Malaysia	W. Malaysia	150	+	Highly organic Sulfaquepts and Sulfaquepts, perhaps also Sulfihemists
	Sarawak	10	–	Mangrove marshes acidified due to lobster mounds
Philippines	Luzon, Mindanao	7	–	Sulfic Tropaquepts, Sulfaquepts, Highly organic Sulfaquepts
South Korea		3	+	Sulfic Haplaquepts, Sulfaquepts
Thailand	Bangkok Plain	600	+ +	Sulfic Tropaquepts (550,000 ha), Sulfaquepts (−10,000 ha), Sulfaquepts (50,000 ha)
	Southeast Coast	20	+	Sulfaquepts, Sulfaquents
	Peninsula	50	+	Sulfaquepts, partly highly organic
Vietnam	Mekong Delta	1000	–	Mainly Sulfaquepts (partly highly organic), smaller areas of Sulfic Tropaquepts and highly organic Sulfaquents

[a]Reliability of hectarage estimate: – = poor, + = fair, + + = good

[b]These figures are probably gross overestimates

agricultural soils have become unfit for regular agriculture due to the presence of diverse pollutants (Fernández-Landero et al., 2023; Khuong et al., 2023). The identified principal factors contributing to soil issues in these regions, including diminished soil fertility and productivity resulting from the oxidation of iron compounds owing to reclamation and drainage operations (Panhwar et al., 2020). These activities result in a decrease in soil organic matter, prompting the release and buildup of iron and other metals from soil minerals. This accumulation leads to soil acidity, nutrient deficiency, and an incapacity to sustain agricultural growth.

Alterations in climatic conditions or a reduction in soil pH might result in changes to adjacent soil systems (Azman et al., 2023; Bautista et al., 2023). Thus, there exists a significant risk of mobilizing potentially deleterious elements within these soil systems (Hulisz et al., 2022; Mattbäck et al., 2022; Nadłonek et al., 2024; Nyman et al., 2023a, b; Ponting et al., 2021; Toivonen & Boman, 2024). Investigations aimed at monitoring changes in metal distributions resulting from leakage from ASS have identified elevated concentrations of Al, Co, Cd, Cu, Mn, Ni, and Zn in both surface and subsurface layers of bottom sediments (Dalhem et al., 2019; Seidl et al., 2022; Wallin, 2018). The alterations in soil nitrogen distribution due to these events can substantially affect crop production and yields. Comparable results were documented in several regions (Maftu'ah et al., 2023). Prolonged drought periods or poor soil management, when combined with reduced soil pH, might hinder biological processes in the soil (Mathew, 2023; Ratmini & Suprihatin, 2023), exacerbating negative impacts on crop development and output. The elevated acidity levels within the pH range of 4.0 to 4.5 lead to the breakdown of organic carbon in the environment (Yu et al., 2023).

Soil organic carbon (SOC) content is positively related to the presence of soil macro-aggregates (Yu et al., 2022; Zhang et al., 2023); this means that a drop in SOC may hurt the integrity of the soil. Root exudates, predominantly emitted by plant roots, substantially enhance the dissolved organic carbon content in the soil (Jumar et al., 2022). Thus, the inhibited development of roots in these acidic soils can obstruct the process of soil aggregation. In their natural condition, soils have a steely blue-gray hue, whereas oxidized soils present a charred look and demonstrate significant aridity. The yellow and orange mottling in soils is due to the presence of jarosites and other iron oxide minerals, respectively. The absence of vigorous root development and reduced soil microbial activity result in limited vegetation under these soil conditions (Hartmann & Six, 2023).

Impacts on aquatic ecosystem

Water is an essential resource utilized for several purposes, including agriculture, urban and industrial applications, recreational activities, and sports (Mishra, 2023; Nourredine et al., 2023). Unfortunately, disrupted ASS considerably contributes to acidity problems in both freshwater and coastal water systems (Makomere, 2023; Simate, 2021). There was an investigation of the acidity levels in drainage water from disturbed ASS in East Trinity, Queensland, Australia (Xu, 2022). Their findings indicated increased acidity in the water, highlighting the significant impact of disturbed ASS on water quality and availability.

The presence of ASS poses a considerable public issue due to the massive discharge of heavy metals into aquatic systems. This has been noted to adversely affect aquatic creatures, as demonstrated by the extensive fish mortality events in New South Wales, Australia, during the 1980s (Tarunamulia et al., 2024a). Moreover, the existence of ASS can inflict significant harm on aquatic ecosystems (Li et al., 2022). This phenomenon adversely affects marine and terrestrial habitats, perhaps causing a reduction in biodiversity and the mortality of mangroves (Chau et al., 2021; Michael, 2021; Sarangi et al., 2022). The ramifications of ASS in Australia are eliciting considerable apprehension. Aquatic life is adversely affected (Alongi, 2021), and there is an observation accompanied by a decline in biodiversity and mangrove mortality (Dittmann et al., 2022; McLuckie, 2020). In the Swan Coastal Plain of Western Australia, analyses have indicated elevated concentrations of heavy metals in both ground and surface water in regions impacted by ASS. This presents hazards to water quality and public health (Beavis et al., 2023). The concentration of elements in a well has surpassed the established standards for drinking, recreation, and occasionally irrigation, highlighting the gravity of the situation (Laskar, 2023; Priyadharshini & Babu, 2023). Similarly, research conducted among employees in South Australia has

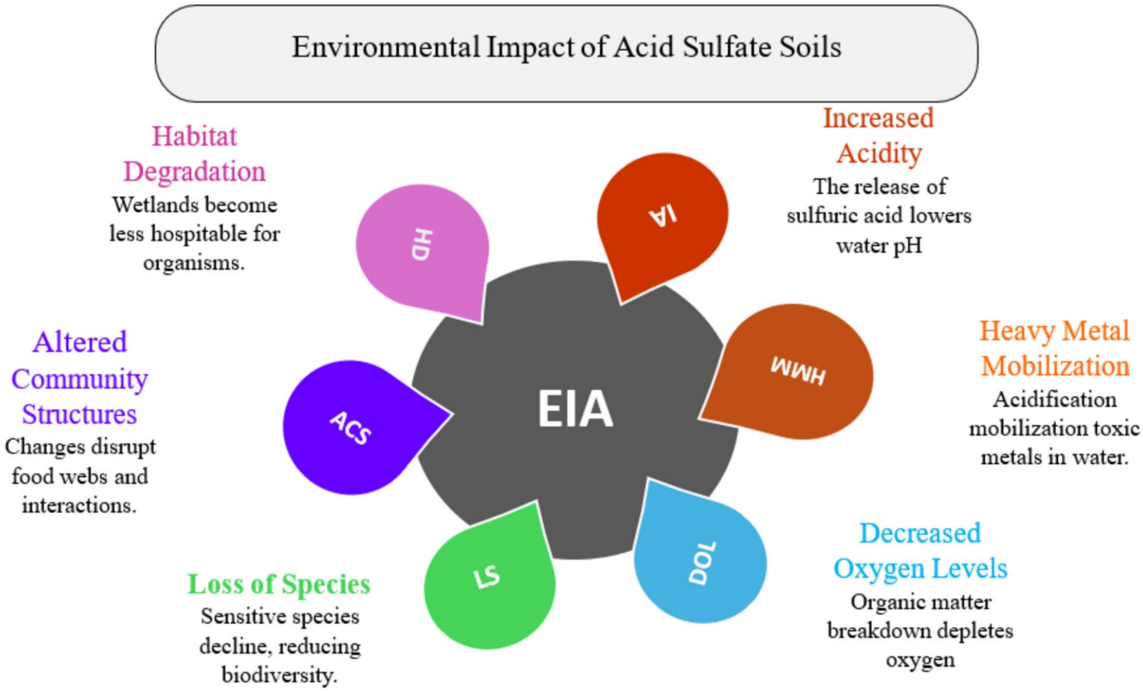


Fig. 5 Ecological Impacts of ASS

highlighted comparable outcomes. Figure 7 illustrates the environmental impacts of water pollution, particularly in aquatic ecosystems. The key effects include loss of biodiversity, acidification, dissolved toxic metals affecting water quality, nutrient cycling disruption, ecosystem service degradation, and altered habitats. These impacts collectively threaten aquatic life, ecosystem stability, and water quality.

Vegetables tested for metal concentrations in produce irrigated with water contaminated by ASS showed variety across different plant sections (Ashie et al., 2024). The composition of water significantly influences metal absorption by plants (Gavrilescu, 2021; Singh & Steinnes, 2020). A separate experiment has investigated changes in metal distribution throughout Finland's Vora River (Nordmyr et al., 2008). Their findings revealed considerable downstream movement and deposition of large amounts of Al, Cd, Co, Cu, Mn, Ni, and Zn in estuarine silt. Notably, metals such as Fe, Cr, and V, which can be readily trapped in ASS, did not show concentration in sediment cores, indicating increased mobility of these elements. This phenomenon has caused significant damage to aquaculture (Fitrani et al., 2020). A separate investigation in Australia, the Richmond River of oxidized sulfidic soils, performed a metal mobilization test, demonstrating rapid metal release. Dissolved concentrations often above the Australian water quality standards for maintaining ecosystem health (Tsatsaros et al., 2020).

In addition to acidification and metal release, another critical ecological threat associated with the oxidation of sulfide-containing sediment is the depletion of oxygen levels in aquatic ecosystems (Bjerregaard et al., 2022). This process results from the conversion of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), leading to a reduction in water oxygen levels (Lu et al., 2022). This mechanism is considered a significant contribution to the pollution of aquatic and estuarine ecosystems (Bashir et al., 2020). An acidic aquatic environment, characterized by low oxygen levels and elevated quantities of toxic metals, is damaging to the majority of aquatic creatures (Okereafor et al., 2020). The deficiency of oxygen and the discharge of acidic runoff can result in significant adverse effects on many aquatic species, coastal fisheries, and the breeding grounds of marine organisms. Incidents of this nature have been observed and documented in diverse aquatic

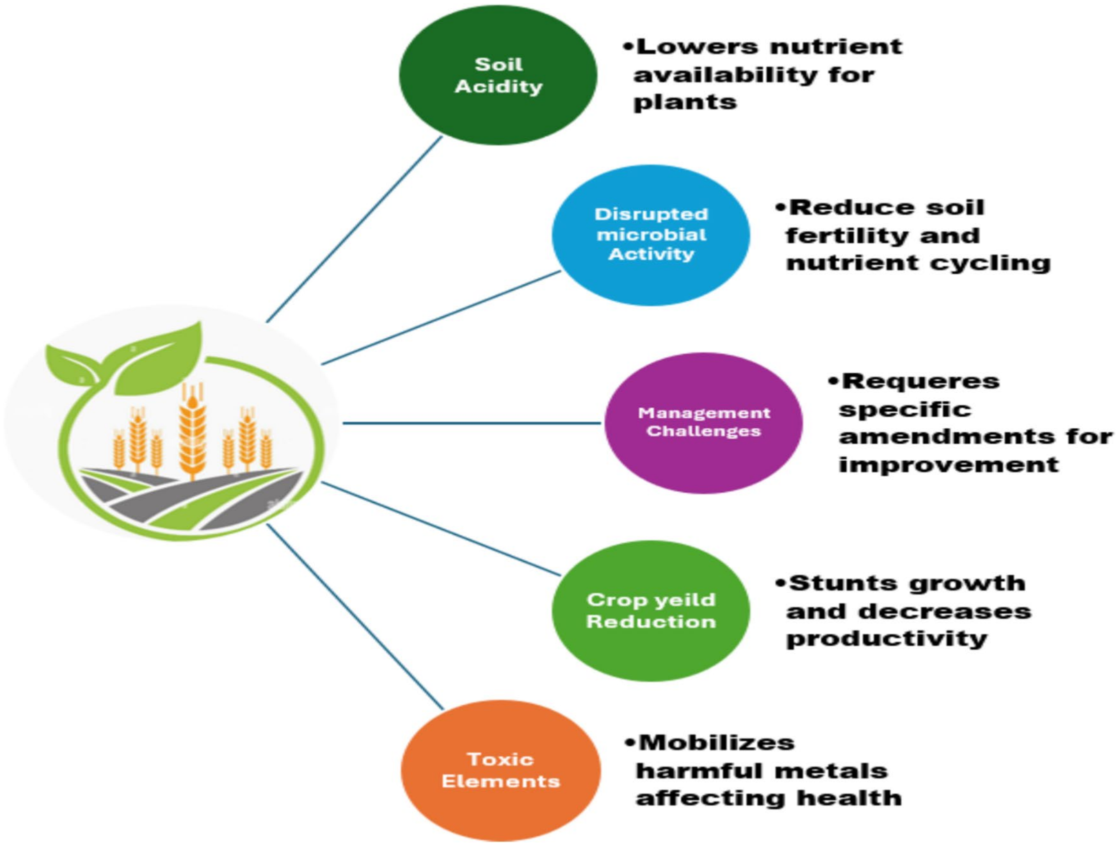


Fig. 6 Effects of AAS on agriculture

environments, such as lagoons, rivers, aquaculture ponds, natural lakes, and water channels, resulting in the extinction of fish and other aquatic organisms (Kader et al., 2023; Kasper et al., 2022; Nashath et al., 2024; Petranich et al., 2021; Rajts & Shelley, 2020; Ren et al., 2021). Furthermore, alterations to breeding and rearing habitats (Yang et al., 2024) are expected to affect reef fish populations. The oxidation of hazardous heavy metals and metalloids in water can interact with other elements, releasing oxidized minerals into aquatic systems that may be ingested by aquatic flora and animals, ultimately resulting in their demise (Das et al., 2023; Kolawole & Iyiola, 2023).

Impacts on living things

The adverse consequences of low soil pH on plant root growth and development are a major concern, particularly when this stressor affects more than half of the world's arable land (Jing et al., 2023). Nonetheless, considerable exploration remains regarding the impact of soil acidity on plant health. Farmers reliant on food crops are at considerable risk due to the buildup of harmful elements and the progression of soil acidification (Ghani et al., 2024; Liu et al., 2022). Studies on wheat (*Triticum aestivum*) and cucumber (*Cucumis sativus*) have shown that metals impede seed germination, root elongation, and the growth of coleoptiles and hypocotyls (Abou Seeda et al., 2024). In Malaysia, diminished cocoa (*Theobroma cacao*) yields have been associated with ASS (Rojas et al., 2022). Pasture species such as cocksfoot (*Dactylis glomerata*), phalaris (*Phalaris aquatica*), and weeping grass (*Microlaena stipoides*), in addition to crop species like Triticum spp. and barley (*Hordeum vulgare*), are adversely impacted by low soil pH (Bedaso et al., 2022). A comparable study revealed that certain plant roots exhibit sensitivity to acidity, with lateral roots being more vulnerable than seminal roots (Haling et al., 2010). Aluminum toxicity from

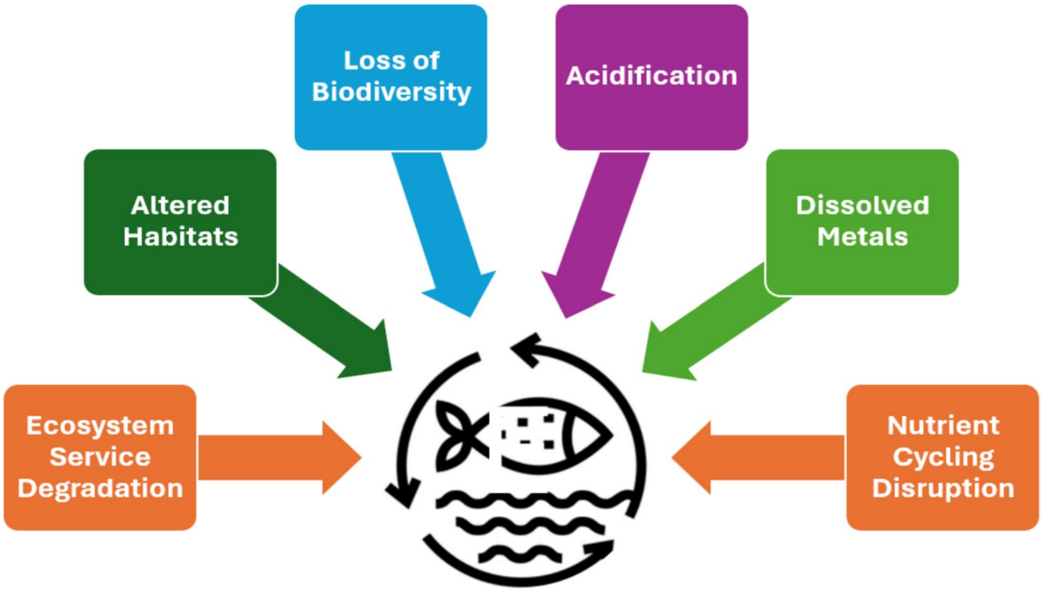


Fig. 7 Impact of AAS on aquatic ecosystem

ASS has been documented to inhibit the growth of rice plants in Thailand and Vietnam (Khuong et al., 2022; Ray, 2023). However, there is a dearth of research offering insights into uptake and accumulation, particularly regarding the study of mineral pollutants in plant biomass (Rashid et al., 2023). Currently, only restricted information exists concerning the chemical composition of agricultural food crops grown on ASS (Fältmarsch et al., 2009, 2010). An investigation was conducted to observe the influence of soil geochemistry on the concentrations of certain elements in cabbage (Brassica oleracea L. var. capitata) (Fältmarsch et al., 2009). Their studies indicated that important elements such as Ca, P, Ni, Mn, Cu, and Fe did not demonstrate substantial increases. Conversely, a comparable study conducted in Finland revealed elevated concentrations of Mn, Co, and Ni in oat grains (Kaur et al., 2023). The buildup of metals in consumable plant parts poses a direct threat to the human food chain. The problem of insufficient data regarding crops cultivated in regions with ASS (Ding et al., 2022; Fältmarsch et al., 2010). Furthermore, there is insufficient research on the development of food crops such as lucerne, along with staple crops like wheat, rice, and maize, under ASS conditions. It is noteworthy that no research has been undertaken to investigate the impact of ASS-contaminated water on agriculture, cattle, and aquaculture (Buschmann et al., 2008; Hinwood et al., 2006).

Many research studies have investigated the use of food crops on soils contaminated by ASS (Haling et al., 2010; Kochian et al., 2004). Nevertheless, these studies frequently utilized soil types devoid of ASS contamination or were performed in regulated laboratory settings where synthetic metal contaminants were introduced. The investigation revealed increased levels of Cd, along with significantly raised quantities of Al and Pb. An initial investigation examining human exposure to metals in ASS-disturbed groundwater revealed elevated metal levels in the hair of individuals utilizing bore water for personal cultivation (Hinwood et al., 2006). The heightened use of groundwater and bore water for irrigation during arid seasons has elicited concerns regarding potential exposure dangers. Research undertaken in multiple locales has revealed the possible hazards associated with exposure to heavy metals like cadmium, lead, arsenic, and aluminum (Al-Swadi et al., 2022; Khatun et al., 2022; Nag et al., 2022). The detrimental impact of metals such as aluminum on living beings indicates a deficiency in comprehensive data concerning the prevalence of diseases associated with animal production on ASS (Bjerregaard et al., 2022). Comprehensive evaluations of the effects of ASS on human well-being have established that the presence of metals and acidity may pose a risk to human health (Ljung et al., 2009).

The role of ASS in greenhouse gas emissions

Emissions of greenhouse gases are a serious problem that affects ecosystems and the climate of the planet. Significant volumes of sulfur and carbon-containing gases, such as sulfur dioxide (SO_2), hydrogen sulfide (H_2S), carbon dioxide (CO_2), and methane (CH_4), can be released into the atmosphere by ASS (Bond & Sun, 2021).

Sulfur dioxide emission

Climate change is impacted by the presence of SO_2 in the atmosphere because it alters the solar radiation balance. It accomplishes this by dispersing solar energy and altering the microphysical characteristics of water clouds by serving as cloud condensation nuclei. As described in recent studies, larger sinks of vital disease-causing SO_2 are produced from process-ASS, contributing to the global challenges of acid rains, cloud formation while catalyzing to climate change. In fact, ASS occupy nearly 25 million km^2, leaching approximately 3.0 Tg/S annually (Macdonald et al., 2004). SO_2 synthesis transpires under oxidative conditions owing to its strong water solubility (Kinsela et al., 2007). This process usually takes place when previously oxygen-deprived soil encounter oxygen-rich conditions, such as prolonged dry periods, human-made drainage, or the deposition of dredged material in elevated regions (VanZomeren et al., 2020). It was suggested that the evaporation of sulfite-containing soil water may be the cause of the SO_2 emission (Macdonald et al., 2004). The scientists saw a significant rise in SO_2 emissions from the simulated system in the later phases of evaporation. Additionally, they found a high link between the evaporation process and field emissions of SO_2 from ASS. Thus, the interaction of iron sulfide and nitrate minerals may result in the emission of sulfur and nitrogen gasses. When ASS are exposed to high temperatures (e.g., burning or industrial processes), sulfate compounds can decompose and releasing SO_2 ($CaSO_4 \rightarrow CaO + SO_2 + 0.5O_2$). In anaerobic conditions, microbial reduction of sulfate to gaseous sulfur compounds like SO_2 or hydrogen sulfide (H_2S) can occur ($O_4^{2-} + 4H_2 + 2H^+ \rightarrow H_2S + 4H_2O$); H_2S may further oxidize to form SO_2 under oxidizing conditions. Consequently, the existence of reduced sulfur molecules in the soil suggests a possible reason for SO_2 emissions from ASS (Takemura, 2020). ASS have been identified as sources of sulfur-containing gases. Research has shown that coastal ASS under sugarcane cropping emitted SO_2 and H_2S, highlighting the potential environmental impact of sulfur gas release from ASS.

Hydrogen sulfide emission

The emission of H_2S is a significant concern due to its function as both a greenhouse gas and a harmful air pollutant. Sulfate-reducing bacteria decompose organic materials under anaerobic circumstances, generating H_2S as a byproduct in ASS (Novair et al., 2024). Sulfate-reducing bacteria are generally anaerobic microorganisms that employ sulfate as their final electron acceptor in respiration (Barton & Fauque, 2022). Bacteria and archaea may both do sulfate reduction and are present in settings where sulfate is accessible and circumstances are adequately reducing (O'Sullivan et al., 2005). In anaerobic conditions, sulfate-reducing bacteria (SRB) outcompete methanogens for substrates (e.g., hydrogen and acetate). This reduces methane (CH_4) emissions as sulfate reduction inhibits methanogenesis.

It indicates that H_2S gas exhibits lower solubility in water, resulting in a positive correlation with soil moisture levels at subsurface depths (Kinsela et al., 2011). This indicated the role of anaerobic bacteria in H_2S production in ASS. The findings underscore the intricate relationship between climatic factors and H_2S emissions from ASS (Azad et al., 2005). Elevated H_2S emission rates were observed in warmer seasons, owing to heightened microbial activity during these times. The maximum H_2S emission occurred in July, attaining a rate of 1.167 ± 0.19 mg per square meter per hour, while the minimum emission was recorded in September at 0.077 ± 0.01 mg per square meter per hour.

Carbon dioxide and methane emissions

The oxidation of organic matter in ASS results in CO_2 emissions. A study examining the effects of acidifiers on soil GHG emissions found that the application of elemental sulfur (ES) and sulfuric acid (SA) to calcareous soils led to significant CO_2 emissions.

Specifically, the study reported cumulative CO_2 emissions of up to 12.7 Mg CO_2 ha^{-1} over a 12-month period following the application of 1000 kg ha^{-1} of ES. Common sites for ASS, coastal wetlands are thought to account for around one-third of all continental shelf carbon. The carbon in these wetlands oxidizes and then leaks into the atmosphere when they are drained. For example, the drainage of a tropical mangrove forest resulted in the release of 150 tons of CO_2 per hectare (Macdonald et al., 2010). A significant amount of the equi-molar quantities of generated CO_2 is expected to remain dissolved in the floodwaters. This may explain the increased CO_2 emissions observed when these floodwaters are drained.

The main mechanism is that the high acidity in ASS accelerates the breakdown of organic matter, leading to the release of CO_2 through microbial respiration, aerobic decomposition ($CH_2O + O_2 \rightarrow CO_2 + H_2O$) and anaerobic decomposition ($CH_2O \rightarrow CO_2 + CH_4$). ASS can act as sources or sinks for CH_4, depending on environmental conditions. While specific quantification of CH_4 emissions from ASS is limited, the aforementioned study observed that the application of sulfuric acid increased CH_4 emissions, with cumulative emissions reaching up to 0.15 kg CH_4 ha^{-1} over 12 months. Researches indicated that 94% of total CO_2 and CH_4 emissions during inundation came from floodwater and the marsh surface, which were the primary cause of carbon loss (Gatland et al., 2014). In localized anaerobic pockets within ASS, methanogenesis can still occur if sulfate is depleted or unavailable. Organic matter decomposition by methanogens results in CH_4 emissions (e.g., $CH_3COOH \rightarrow CH_4 + CO_2$) or hydrogenotrophic methanogenesis: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$.

It was found that exposed conditions resulted in higher CO_2 emissions than flooded settings (Jimenez et al., 2012). CO_2 degassing accounted for 88–90% of carbon loss, whereas CH_4 contributed 5.3–0.01% (Cole et al., 2007). CH_4 might have a major effect on global warming because it was responsible for between 50 and 62% of CO_2-equivalent emissions during the flood period (Shindell et al., 2009).

Nitrous oxide emissions

A powerful greenhouse gas, nitrous oxide (N_2O), with a potency 298 times greater than that of carbon dioxide, is released from ASS due to microbial processes, contributing significantly to climate change and environmental degradation (Macdonald et al., 2010). N_2O emissions from ASS are influenced by factors such as soil pH, moisture content, and nitrogen availability. The same study reported that the application of ES and SA led to increased N_2O emissions, with cumulative emissions of up to 4.5 kg N_2O ha^{-1} over 12 months following the highest ES application rate. Due to their capacity to store large amounts of nitrogen, ASS may be a source of both nitrogen release into water bodies and atmospheric N_2O emissions (Yli-Halla et al., 2020). The presence of organic carbon and the redox potential of ferrous and ferric iron in ASS are the causes of this emission. There is a chance of greenhouse gas emissions when the percentage of water surpasses 60%, and it can come from the oxidation of ammonia or the reduction of ferric iron (Clément et al., 2005).

Coastal lowland ASS constitutes approximately 5% of Australia's sugarcane soil but may contribute nearly 25% of the nation's N_2O emissions from sugarcane cultivation (Macdonald et al., 2010). The usual processes of carbon and nitrogen cycling in ASS are anticipated to be improved by the frequent application of mineral nitrogen fertilizers, which amount to about 150 kg N ha^{-1}, as well as by increases in soil temperatures, moisture, and carbon levels. The moisture content in the soil influences N_2O production via nitrification and denitrification processes (Denmead et al., 2010). The acidic conditions in ASS promote the conversion of nitrogen compounds into N_2O, especially in fluctuating aerobic-anaerobic zones.

The effects of greenhouse gas emissions on the environment

Emissions of greenhouse gases (GHGs) have a major effect on the environment, causing extreme weather, increasing sea levels, and global warming. Heat is trapped in the atmosphere by the buildup of gases like CO_2, CH_4, and N_2O, which causes climate change, ecosystem disruptions, and a decline in biodiversity. Ocean acidification further threatens marine life, while poor air quality affects human health, increasing respiratory diseases and food insecurity. Economically, climate-related disasters cause financial losses and social instability, particularly in vulnerable communities. Mitigating these effects requires transitioning to renewable energy, enhancing energy efficiency, and enforcing international climate policies to reduce emissions and protect the planet.

Amelioration of ASS

Million hectares of ASS in South and Southeast Asia are either unproductive or offer minimal outputs due to elevated acidity levels. Nonetheless, employing efficient strategies to enhance these areas for rice or alternative crops could perhaps mitigate the anticipated food shortages in the forthcoming years. These soils are situated in low-lying areas conducive to rice farming. In order to enhance these wetland ASS regions, it is possible to implement a variety of enhancement measures by adhering to the management procedures outlined in Fig. 8.

Leaching

Excessive concentrations of soluble salts and aluminum tend to build in ASS when they are buried underwater. To resolve this issue, it is essential to eliminate these compounds, achievable through a process known as leaching. Nonetheless, entirely neutralizing all possible acidity through the application of limestone can be prohibitively expensive. A more viable strategy for improving the treatment of ASS entails promoting the oxidation of pyrite, facilitating the following leaching of acid, and subsequently mitigating any residual acidity (Mourinha et al., 2022). Managing soils with elevated jarosite concentrations poses significant issues, necessitating extended leaching durations, potentially reaching 90 days, and an increased water volume, almost four times the soil's weight, to raise the pH. Conversely, soils with reduced jarosite content generally require merely 10–30 days of leaching (Sarangi et al., 2022).

Table 3 demonstrates the beneficial effect of leaching on rice cultivation in two varieties of flooded ASS: one from Vietnam and the other from the Philippines. Leaching resulted in a notable drop in specific conductivity and sulfate concentrations, a slight increase in pH levels, and a decrease in soluble iron concentration and carbonic acid gas pressure. The alterations were more pronounced in the Vietnamese soil than in the Philippine soil. Leaching significantly reduced aluminum concentrations in both soils, decreasing from 69 to 0.6 ppm in the Vietnamese soil and from 106 to 11 ppm in the Philippine soil at the experiment's onset. Leaching alone on Vietnamese soil yielded the highest production of straw and grains. Conversely, in Philippine soil, this method was inadequate due to the consistently elevated levels of Fe^{2+}. Nonetheless, the practical execution of leaching frequently encounters challenges, including soil density and the land's low elevation.

Drainage

We have implemented a shallow drainage system that entails the excavation of a comprehensive network of shallow ditches. The area between two ditches is elevated, and rice is cultivated on these elevated beds. This strategy has demonstrated considerable efficacy, with rice production often doubling in the first year, and in the subsequent year, numerous farmers have reported yield increases ranging from two to four times (Mafra et al., 2022).

Submergence

Flooding of acidic soil typically results in an increase in pH, as evidenced by research (Amrutha et al., 2023; Tang et al., 2022). Prolonged saturation of the soil until the pH attains an optimal level can successfully mitigate aluminum toxicity and diminish iron toxicity. This advantageous state facilitates the regular growth of rice plants, as evidenced by studies (Haider et al., 2022). Researchers conducted a field study in Thailand on ASS and found that a pre-submergence period of 6 weeks before planting led to a noteworthy 7.7% rise in grain yields over three consecutive years (Vo, 2022).

Lime as ameliorant

Numerous research studies have recorded that the use of lime is the most effective method for increasing soil pH. The addition of lime plays a crucial role in the recovery and stabilization of certain sludges, particularly those containing heavy metals or acidic components. The stabilized sludge can be repurposed for beneficial uses, such as soil amendments or construction materials, contributing to sustainable waste management. The amalgamation of leaching and liming produced the most substantial outcomes. The sludge generated from lime treatment consists of metal hydroxides—$Fe(OH)_3$, $Al(OH)_3$, $Mn(OH)_2$, Gypsum ($CaSO_4 \cdot 2H_2O$), unreacted lime ($CaCO_3$ or $Ca(OH)_2$), organic matter, and sediment particles (Mackie, 2010). Instead of disposal, the sludge can be

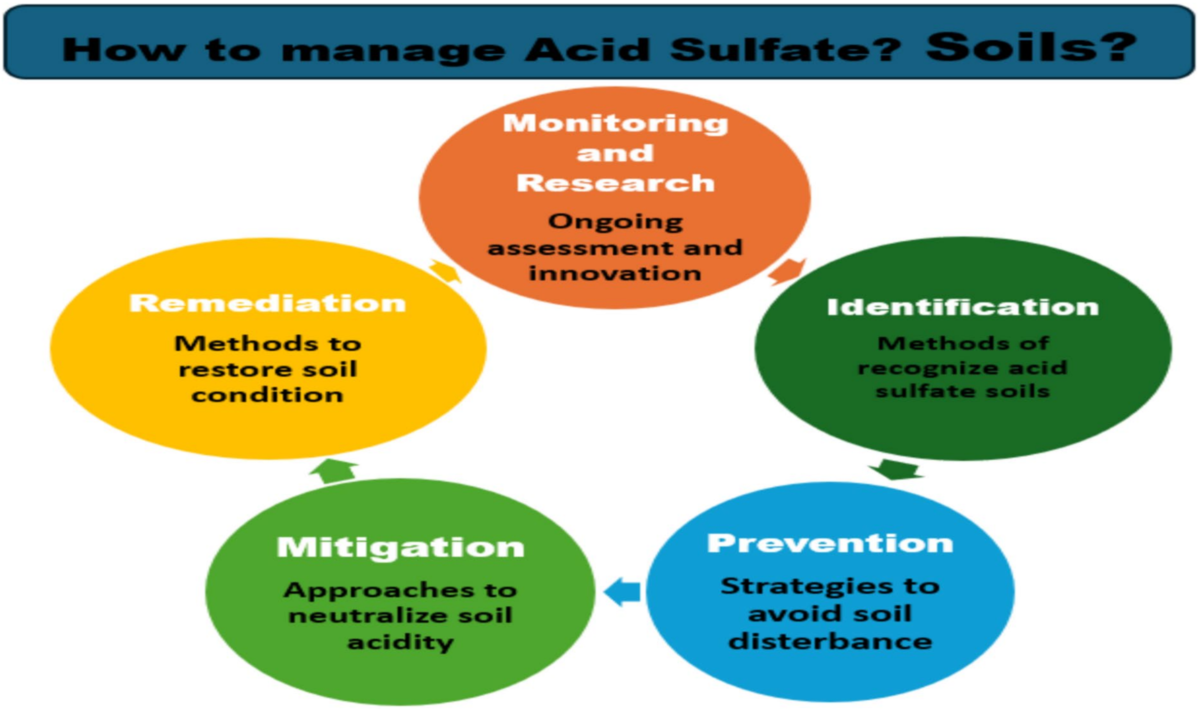


Fig. 8 Management procedure of ASS

Table 3 Influence of leaching and liming on the yield of rice on two flooded ASS (ISHAK, 2022)

Treatment	Soil from Vietnam (g/plot)		Soil from the Philippines (g/plot)	
	Grain	Straw	Grain	Straw
Control	21	24	0	0
Limed to pH 5.5	64	64	79	76
Leached	78	75	11	20
Leached + limed	88	78	83	82

recovered and repurposed for environmental applications. Gypsum-rich sludge can be reintroduced into soil to improve structure and reduce acidity, provides calcium and sulfur as nutrients for plant growth, and also helps in reducing aluminum toxicity, which affects root development.

Table 2 demonstrates the beneficial effects of liming on ASS in Vietnam and the Philippines. Adding lime, superphosphate, and rock phosphate to coastal ASS in India can make it better and lead to more rice being grown (Bhowmick et al., 2020). Adding lime and phosphorus fertilizers to the soil slightly increases the amount of phosphorus that is available, but rock phosphate works especially well.

Appropriate lime levels also function to control the excessive presence of iron and aluminum. The optimal lime dosage for the coastal acidic soils in the Ganges Delta was determined using the KCl extraction method with a lime factor of 4.0, or alternatively, Shoemaker's method with a lime factor of 0.5 (Sarangi et al., 2024). A cost-effective remedy for ASS entails utilizing locally sourced oyster shell powder, abundant in calcium (Yang et al., 2022). Oyster shells consist of 90–95% $CaCO_3$, rendering them similarly effective as real limestone. The incorporation of limestone and MnO_2 into the soil of the Andaman region resulted in a significant increase in lowland rice yield. In instances of elevated soil salinity, it was imperative to initially leach out surplus salts prior to the application of these amendments (Bhowmick et al., 2020). The generation of trivalent Al and $Al(OH)_3$ through interactions with OH^- ions seems to account for the decrease in dangerous soluble aluminum. The incorporation of MnO_2 led to a decrease in Fe^{2+} concentration, especially in soil with a pH of 3.4 compared to 4.6. Liming has a small and temporary effect on potential acidity. Therefore, by following the approach, the rare but regular use of lime materials could result in greater benefits (Conyers et al., 2020).

Manganese oxide (MnO_2) addition

The robust oxidative-reduction potential of the MnO_2^--Mn^{2+} system causes the addition of manganese dioxide to the soil to impede the reduction process. The incorporation of manganese dioxide at a 1.0% weight content into the soil produced many impacts (Panhwar et al., 2023). This involved reducing the concentrations of Al^{3+} and Fe^{2+} in the soil solution, a slight increase in the pH of the soil solution, a significant increase in the Mn concentration in the soil solution, and a noticeable delay in the decrease of SO_4^{2-}. Moreover, the incorporation of MnO_2 at concentrations between 0.4 and 0.8%, in conjunction with $CaCO_3$, significantly alleviated the harmful effects induced by Al and Fe. Furthermore, there was research that indicated the inclusion of MnO_2 enhanced rice grain production (Singh et al., 2023).

Use of resistant varieties

Excessive accumulation of water-soluble iron in wetland rice farming results in a prevalent nutritional ailment termed iron poisoning (Zandi et al., 2021). This problem considerably obstructs development in regions with ASS (Nhung & Ponnamperuma, 1966) and was subsequently validated (Huang et al., 2024). Although techniques such as liming and drainage help alleviate iron toxicity, a more direct and economical approach for small-scale farmers in South and Southeast Asia is to utilize crop varieties that exhibit inherent tolerance to these conditions (Ghosh et al., 2022). Exploiting acidic soils can be beneficial by planting crops or varieties that endure low pH levels and aluminum toxicity. Plants such as pineapple, oil palm, rubber, coconut, and cassava are acknowledged for their considerable endurance to these circumstances. Moreover, the mango tree has exhibited tolerance to acidic soils (Jiao et al., 2024). Certain acid-tolerant plant species can be used to reclaim ASS by pH improvement through root exudates. Some plants release alkaline root exudates, which help buffer soil acidity over time. Leguminous plants such as Acacia and Sesbania improve nitrogen availability and soil health in ASS. Certain plants, known as hyperaccumulators, absorb and store toxic metals in their tissues: Vetiver grass (*Chrysopogon zizanioides*)—absorbs heavy metals in acidic soils, water hyacinth (*Eichhornia crassipes*)—removes metals from acidic waters, *Brassica species* (mustard plants)—known for metal accumulation. Grasses and reeds, such as Phragmites australis, help in stabilizing ASS (Osman, 2018). Algae and certain plant species play a crucial role in the remediation of acidic environments by neutralizing acidity, stabilizing metals, and enhancing ecosystem recovery (Du et al., 2022). Incorporating bioremediation with traditional lime treatments can create a more sustainable and cost-effective solution for ASS remediation.

Microbial remediation

The oxidation of pyrite can be efficiently inhibited through the utilization of sulfate-reducing bacteria (SRB), representing a natural and economical approach. This is especially effective when sufficient acid-neutralizing capability is produced by bacteria in the vicinity (Li et al., 2024). Acidophilic iron–oxidizing bacteria (AIOB), such as species from the genera *Acidithiobacillus*, *Acidithrix*, and *Alicyclobacillus*, contribute in ASS remediation through biomineralization, which immobilizes toxic metals, stimulation of sulfate-reducing bacteria to neutralize acidity, and tidal inundation strategies that enhance microbial-driven restoration of soil and water quality (Larson et al., 2014). To implement this restoration, it is essential to inundate the area to reinstate decreasing conditions. Furthermore, the incorporation of biodegradable organic carbon (OC) is essential to enhance the activity of reducing bacteria (Yang et al., 2021). The optimal method entails incorporating SRB at a concentration of 10% of the compost's weight. The mixture must be incubated at 35 °C for 4 to 7 days to promote growth and the development of bubbles on the compost surface. Thereafter, the mixture may be administered to the soil, leading to elevated soil pH and diminished sulfate concentrations (Zhu et al., 2023).

Under anaerobic and saturated circumstances, microorganisms decompose organic matter, releasing electrons that are utilized by diverse electron acceptors such as nitrate, manganese and iron oxides, and sulfate. This process leads to the development of pyrite and an increase in pH levels (Sarangi et al., 2022). The introduction of particular microorganisms, including nitrogen-fixing bacteria, phosphate-solubilizing bacteria (PSB), and free-living bacteria, can result in the synthesis of tiny organic acids and plant hormones such as indoleacetic acids (IAAs). These compounds facilitate the binding of aluminum ions (Al^{3+}) and mitigate their toxicity (Naher et al., 2018). The application of biofertilizers to rice crops in regions with ASS can significantly improve plant health and yield via many methods. The mechanisms encompass the impact of plant hormones, mitigation of nutrient toxicity, and enhanced availability of phosphorus resulting from the decomposition of insoluble native phosphorus (P), as emphasized in the research (Panhwar et al., 2020). The integration of biofertilizers and soil additives has proven helpful in advancing sustainable rice cultivation in Southeast Asia. Recent studies indicate that the application of PSB (Caballeronia sp.) to ASS soil resulted in a notable 60% increase in the germination of tomato (*Lycopersicon esculentum*) seeds. Moreover, the treated soil demonstrated more than threefold leaf growth and a significant 45.2% enhancement in adenosine triphosphate relative to untreated soils (Kim et al., 2021). Biological systems help in pH neutralization, metal immobilization, and ecosystem restoration in ASS. Certain microalgae and cyanobacteria can thrive in acidic conditions and play a crucial role in pH neutralization and carbonate secretion. Algae perform photosynthesis, absorbing CO_2 from water and producing bicarbonates and carbonates, which help increase pH in acidic water bodies. Some species, such as Chlorella and Scenedesmus, can tolerate acidic conditions and aid in buffering acidity over time. Algae have the ability to absorb and immobilize heavy metals like iron (Fe^{3+}), aluminum (Al^{3+}), and manganese (Mn^{2+}) through biosorption and bioaccumulation. Metal ions bind to the cell walls of algae, reducing their bioavailability and toxicity (Tarunamulia et al., 2024b). Algal ponds have been used in acid mine drainage treatment to raise pH and remove metals. Certain species like Gloeocapsa and Euglena mutabilis can survive in $pH < 3$ and assist in bioremediation.

Application of organic materials

Numerous research studies have demonstrated the critical role of organic matter in influencing soil pH, particularly in mitigating acidification caused by processes like pyrite oxidation. The characteristics of organic matter significantly affect soil pH fluctuations and the rate of pH recovery (Kacem et al., 2024). Recent research further highlights that readily available and relatively inexpensive plant organic matter offers an effective solution for preventing soil acidification caused by sulfuric acid or for mitigating its long-term effects. This approach is particularly appealing in underdeveloped agricultural regions, where resources for costly amendments like agricultural lime or alkaline materials such as sandy loam are limited. However, the use of organic matter must be carefully managed. Excessive incorporation can exacerbate soil acidification and increase the solubility of Fe^{2+}, while minimal additions are often linked to reducing toxic metal availability and improving nutrient accessibility. Organic acids, such as acetic acid derived from decomposing organic matter, can enhance soil acidity (Yadav et al., 2020). To elevate soil pH, incorporating organic materials with low to moderate carbon-to-nitrogen ratios under reducing conditions is recommended, as this method helps maintain optimal pH levels for plant growth and nutrient availability. While these findings underscore the potential of organic matter as a cost-effective strategy for soil pH management, further investigations are needed to evaluate its broader applicability and long-term implications.

In the early stages of organic matter decomposition, several acetic acids are produced. Simultaneously, acetic acid is oxidized while Fe^{3+} is decreased (Sokolova, 2020). Nonetheless, the Fe chelation process by organic acids remains suboptimal during the initial breakdown phase. This results from the presence of high molecular weight organic acids, such as humic and fulvic acids, which demonstrate remarkable iron chelation properties. These acids have significantly elevated overall acidity levels—humic acid measures 500–900 meq/100 g, while fulvic acid measures 1400 meq/100 g, rendering them highly reactive molecules (Nikoosefat et al., 2023). Organic compounds that have seen further humification mostly produce these organic acids.

Improving the characteristics of ASS entails employing rice straw, the principal organic substance obtained from rice cultivation in ASS areas. Nevertheless, it is imperative to compost the straw before application. This method is economically beneficial, as each ton of straw indirectly enhances the soil's nutrient profile, contributing around 5 to 8 kg/ha of nitrogen (N), 0.7 to 1.2 kg/ha of phosphorus (P), and 12 to 17 kg/ha of potassium (K). These essential elements derive from rice straw (Hu et al., 2024).

Technology for optimum fertilization

ASS demonstrates a markedly decreased reproductive rate both prior to and following restoration initiatives. This arises from the effective absorption and retention of supplemental fertilizers, which may impede the supply of vital nutrients for plant growth. Despite the quick release rate of superphosphate fertilizers, a significant proportion of these nutrients is lost by water runoff. To address this issue, it is essential to select the appropriate method and timing for fertilizer application. An efficacious technique entails dividing each fertilizer dose into two applications: the initial application prior to planting and the subsequent application 4–5 weeks after planting. This division aids in reducing the fixation of phosphorus due to soil constituents. Moreover, to reduce nutrient losses due to water movement, rice fields should be planted and fertilized in coordination with the tide cycle. It is reasonable to apply fertilizer immediately after rehydrating rice fields, which increases nutrient uptake by the plants.

Natural phosphate is highly effective in phosphorus fertilization for acidic soils, owing to its slow-release characteristics and the inclusion of beneficial byproducts like calcium and magnesium. Its effectiveness depends on factors such as soil acidity, composition, and application strategy, with residual effects lasting up to three years (Liu et al., 2020). ASS, which are often deficient in nitrogen and phosphorus, benefit significantly from phosphate application. For instance, applying 24.3 kg/ha of P_2O_5 significantly improved rice grain yield at various pH levels, except at pH 4.5, where the difference was not statistically significant.

Table 4 further illustrates the application of phosphate rock in acidic soils in Vietnam, demonstrating both its immediate and long-term effects. In the first season, Lao Cai phosphate alone had minimal impact, but in the second year, it increased rice yields by 62%. Similarly, nitrogen and potassium fertilizers had limited effects when used without phosphate, showing only slight benefits in subsequent seasons. However, combining nitrogen, potassium, and phosphate significantly enhanced both the immediate and enduring benefits of phosphate application. These findings highlight the importance of optimizing phosphate release and integrating it with other fertilizers to maximize agricultural productivity in acidic soils.

Eco-friendly strategies for managing ASS and enhancing sustainability

Researchers have shown that using calcium-rich oyster shells, often found in coastal areas, together with green or leaf manures, may effectively improve acidic soils while supplying vital nutrients (Das, 2014). These techniques signify a potential yet under examined field of research, since they use locally accessible resources that are economically feasible and ecologically sustainable. A burgeoning field of inquiry is water management, whereby regulating the water table may inhibit pyrite oxidation by restricting the soil's exposure to oxygen (Nadakavukaren & Caravanos, 2020). Methods such as maintaining a high-water table via regulated drainage have shown efficacy in mitigating acidification and decreasing

Table 4 Direct and residual effects of high-grade Lao Cai rock phosphate with and without N + K on rice yield in ASS at an Lac experiment station (Montange, 1999)

Treatment	First season		Second season		Combined effect per 100 kg of phosphate rock (kg paddy)
	Paddy yield (t/ha)	Immediate effect (t/ha)	Paddy yield (t/ha)	Immediate effect (t/ha)	
Control	1.57	–	0.87	–	
Phosphate 600 kg/ha	1.60	0.03	1.41	0.54	95
N60K30	1.48	–	1.08	–	
N60K30 + phosphate 600 kg/ha	2.82	1.34	1.91	0.83	361
LSD 0.05	0.12		0.18		

the discharge of heavy metals, therefore safeguarding soil and water resources. The efficacy and practicality of these strategies in various environmental contexts remain largely unexamined, underscoring an additional study gap that needs further inquiry. Technological advancements, like remote sensing for soil mapping and real-time monitoring systems, improve the capacity to predict and manage the repercussions of ASS. Research on bio-remediation with acid-tolerant microorganisms is increasingly gaining prominence. Climate change intensifies ASS issues due to increasing sea levels and severe weather phenomena. Adaptive management measures, such as the implementation of climate-resilient crops and efficient water management systems, are essential.

Conclusions and prospects

ASS pose significant environmental challenges due to their potential to release sulfuric acid upon exposure to oxygen, leading to soil degradation, waterway acidification, and harm to ecosystems. Sustainable remediation strategies, including controlled re-flooding, lime application, and bio-based amendments, offer promising solutions to mitigate their negative effects. A comprehensive approach that integrates scientific understanding, land management practices, and policy regulations is essential to ensure long-term environmental sustainability while minimizing the risks associated with ASS. However, a critical knowledge gap remains in the sustainable management of ASS, as much research focuses on short-term solutions rather than long-term strategies. While advancements have been made in understanding ASS chemistry and biology, more precise reclamation methods and long-term impact studies are needed. Emerging technologies such as GIS, geostatistics, and hydrogeochemical modeling offer new opportunities for mapping and assessing ASS, enabling more effective remediation strategies. Given the socio-economic importance of ASS management in regions like the Sundarbans and Mekong Delta, tailored, region-specific solutions are essential to ensure environmental sustainability and agricultural productivity.

Substantial gaps remain in our knowledge of how to effectively manage and rehabilitate these soils on a large scale. The key to overcoming these challenges lies in developing integrated, region-specific strategies that consider the long-term environmental sustainability of ASS management, alongside economic feasibility. It is essential that future research focuses on filling these gaps by investigating the socio-ecological contexts of ASS in different parts of the world, including the interactions between soil chemistry, microbiology, land use, and socio-economic factors. By advancing both scientific knowledge and practical applications, we can move towards more sustainable, resilient systems for managing ASS that not only address environmental risks but also foster long-term agricultural productivity and socio-economic development.

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