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Review

Problems, Management, and Prospects of Acid Sulphate Soils in the Ganges Delta

Sukanta Kumar Sarangi [1,*], Mohammed Mainuddin [2,*] and Buddheswar Maji [1]

1 ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning Town 743 329, West Bengal, India
2 Commonwealth Scientific and Industrial Research Organization (CSIRO), Land and Water, Black Mountain Science and Innovation Park, GPO Box 1700, Canberra, ACT 2601, Australia
* Correspondence: sksarangicanning@gmail.com (S.K.S.); mohammed.mainuddin@csiro.au (M.M.)

Abstract: Soil is a finite natural resource and is indispensable for human civilization because it is the medium for food production for the biosphere. Continued soil degradation is a forerunner of catastrophe for the living world. The protection of healthy soils and the restoration of problem soils are strongly needed in the current agricultural scenario as competition for urbanization and other human needs for land resources limits the scope for the further availability of land for agriculture. Naturally occurring degraded soils, such as acid sulphate soils, can be restored with scientific interventions and advanced management strategies. The Ganges Delta is a densely populated region, where the inhabitants' major livelihood is agriculture. Soil acidity and salinity restrict crop performance in this coastal region, particularly the acid sulphate soils (ASSs) posing a risk to agriculture. ASSs are developed from land-use changes from mangrove forest to agricultural land in this region. There is no systematic study on these soil types covering Bangladesh and India. This paper unfolds several aspects related to the characteristics, problems, and detailed management strategies of ASSs relevant to the Gangetic Delta region where these soils continue to be used for intensive agriculture to meet the livelihood needs. Crop yields are very poor in the unmanaged ASSs due to a very low soil pH (<3.5), hampering the growth and development of crops due to nutrient deficiencies and/or toxicities, coupled with soil salinity. There is toxicity of water-soluble Fe, Al, and Mn. The phosphorus nutrition of crops in these soils is affected owing to a high soil P fixation capacity. A deficiency of micronutrients, such as Zn and Cu, was also observed; however, K availability is variable in the soil. The soil acidity is a general problem throughout the soil profile; however, extreme acidity (pH < 3.5) in particular soil horizons is a typical soil characteristic, which creates problems for its efficient management. Specific operations, such as the selective use of soil layers with good properties for crop root growth, major and minor nutrient applications, and soil amendments, including green manuring, application of biofertilizers, and soil microbes, are gradually improving the properties of these soils and bringing back the potential for good crop production. Scientific water/drainage management is needed to gain an agronomic advantage. Evidence of increased crop yields in these soils observed from green manuring, lime, basic slag, and rock phosphate application are presented.

Keywords: acidity; ecosystem; green manures; jarosites; mottles; lime; rice; rock phosphate; toxicity

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1. Introduction

Current demographic trends and the projected growth in the global population (to exceed 9 billion by 2050) are estimated to result in a 60 percent increase in demand for food, feed, and fibre by 2050 [1]. Cropland growth and intensification are the main strategies to boost agricultural production but are also major drivers of biodiversity loss [2]. Therefore, to achieve the sustainable goal of increased food production, it is necessary to identify the areas or soil types for potential food production that are not achieved and are underutilized. Recent studies [3–6] show that soil resources are to be used judiciously to keep their production potential high in the long run [7]. Soils suffer from abiotic stresses, such as acidity, alkalinity, salinity, erosion, sodicity, and waterlogging. Worldwide, 3950 million hectares (Mha) of arable land harbour soil acidity (ultisols or oxisols, pH of 5.5 or lower), affecting about 1043 Mha of farmland in Asia (Near East 5 Mha, Far East 212 Mha, Southeast and Pacific 314 Mha, and North and Central 512 Mha), 659 Mha in Africa, 239 Mha in Australia and New Zealand, 391 Mha in Europe, and 1614 Mha in America [8–10]. Acid soils are distributed in tropical and subtropical regions, constituting approximately 30% of the ice-free land in the world [11], which is 50% of the world's arable land [12,13]. In China and India, 212 Mha or 12% of the agricultural land is classified as acidic [14]. In India, about 28% of the total geographical area is affected by acidity of different degrees [15].

Acid sulphate soils (ASSs) are a group of these soils having high soil acidity and other soil function limitations. These soils were termed as *Kattecleigrondon* or *Kattakali* by the Dutch farmers in the seventeenth century meaning 'Cat Clays' in English for soils of some reclaimed areas that became gradually highly acidic and developed prominent yellowish mottles and crusts composed of jarosite and related sulphates; in northern Germany, similar clays were called *Maibolt* [16]. Acid sulphate soils (ASSs) have been defined by Dent et al. [17] as soils with a pH (1:2.5 in 0.01 M $CaCl_2$) < 4.0, having jarosite mottles or a soluble SO_4-S content > 0.05% within 0.60 m of the soil depth. ASS is characterized by a low pH (<3.5) and the presence of sulphidic materials and/or a sulphuric horizon [18]. Sulphidic materials are defined as those that contain oxidizable sulphur compounds, such as pyrite (FeS_2). They occur in minerals or organic soil materials that have a pH value of <3.5 and that, if incubated as a 1 cm layer under moist aerobic conditions at room temperature, can result in a drop of pH (1:1 by weight in water) within 16 weeks [19,20]. The sulphuric horizon is 15 cm thick or thicker and is composed of either mineral or organic soil materials that have a pH value of 3.5 or less (1:1 by weight in water) and show evidence of the presence of jarosite, directly overlying sulphidic materials and/or 0.05% water-soluble sulphate, that the low pH value is caused by sulphuric acid [19,20].

Acid sulphate soils are also found in the Gangetic Delta of Bangladesh and West Bengal, India (Figure 1). The purpose of this work is to unravel the multi-characteristics of ASS of this region with objectives to efficiently manage the ASS resources, to protect them from further degradation, and to find out prospects of effective planned land use. ASS covers 0.7 Mha area in different pockets of inundated coastal areas in Bangladesh [21]. In the West Bengal part of the Ganges Delta, about 0.5 Mha of coastal soils of Sundarbans are saline and acidic, which represents a serious problem and poses imminent threats to crop production [22]. A recently available estimate [23] shows that in the West Bengal part of the Ganges Delta, soils with a very low pH (<4.5) cover 0.04 Mha, and soils with a pH of 4.5–6.0 cover 0.1 Mha. For centuries, these areas were occupied by dense mangrove forest, which has been cleared for agricultural use due to the increasing population. As a result, the potential ASS is becoming converted to actual/active ASS with a very low soil pH (<4.0) owing to oxidation and the generation of sulphuric acid (H_2SO_4) in the soil [24]. The relevance of these soils is very significant in this region as the 31 million people of Bangladesh and the 23 million people from West Bengal [25] depend on agriculture because alternative land for subsistence food production is not available. The management of these soils is of paramount importance to sustain food production to provide a livelihood as well as protect biodiversity in the poverty-stricken, densely populated coastal region of the Ganges Delta [26].

The total amount of annual rainfall is 1500–2000 mm, of which >80% is received during the monsoon (June–October) period [27] when high rainfall along with tropical cyclones and tidal events cause severe flooding and wind damage [28]. The seasonal mean minimum and maximum air temperatures range from 12–24 °C to 25–35 °C, respectively [27]. In this ecosystem, mangrove vegetation is formed from the influence of tidal flows from the tributaries and distributaries of these river systems. The coastal area of West Bengal spans over an area of about 1.3 Mha, of which about 0.9 Mha are under cultivation/habitation, and about 0.4 Mha are mangrove forest. Mangrove forest soils are found in this swampy habitat along the seacoast of the Delta region of the South 24 Parganas and North 24 Parganas districts of West Bengal. Mangrove tress are adapted to the saline habitats and grow with high saline river water. The production potential of these soils has not been achieved, and most of these soils are underutilized due to a lack of proper scientific management strategies. The geomorphic origin of the soils in this region results in various soil types, such as saline soils and soils with a very low pH underneath. When these soils where exposed for cultivation, the pH further decreased, severely hampering crop production endeavours.

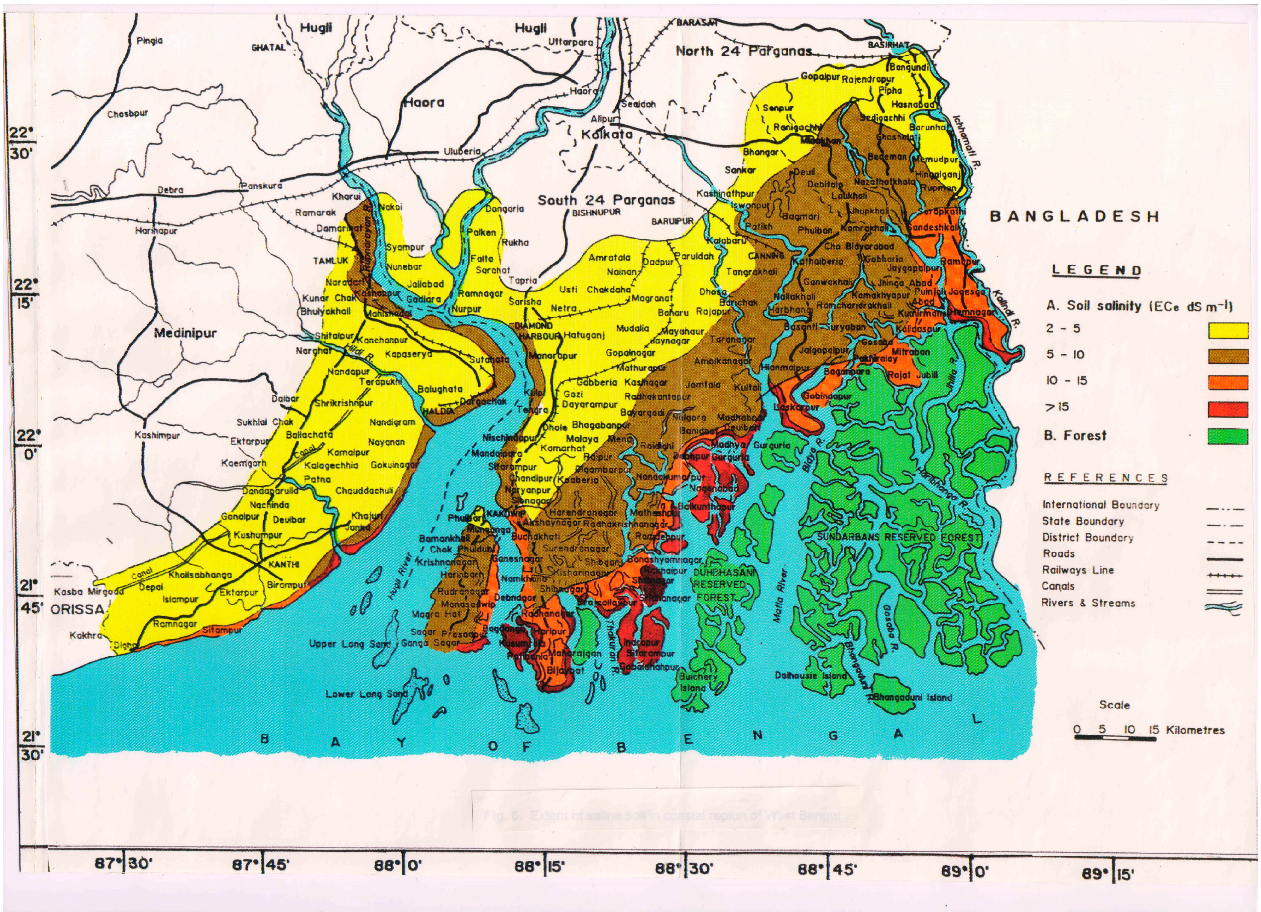


Figure 1. The Ganges Delta covering coastal areas of Bangladesh and West Bengal, India. Source [23].

Brackish and saline mangrove swamps are found near the tidal creeks. In these swamps, pyrite formation is favoured as the deposition and build-up of sediments are slow. Apart from high salinity, the productivity of acid sulphate soils is restricted due to the toxicities of iron, manganese, and aluminium and the deficiencies of phosphorus and calcium [29]. Soil acidification is caused both by the abiotic and microbial oxidation of pyrites (FeS_2). There are several plants species, which can tolerate comparatively higher concentrations of H^+; however, studies with solution cultures show evidence of root damage at a low pH. It is also probable that Al and Mn toxicities are more significant than H^+ concentrations in these soils [30].

The understanding of ASSs in the tropical regions is incomplete due to the limited contributions from the South Asian region [31]. However, the conditions for ASS development in these Delta regions are favourable given that the sulphate required for pyrite formation is derived from salt water intrusion [31] and abundant elements, such as Si, Fe, Mn, and Al, in the lateritic- and basaltic-trapped rocks in the soil [32,33]. These soils remain as potential ASSs until the submerged/swampy conditions are maintained in this mangrove forest ecosystem. There is a gradual deterioration of soil quality in this region due to land excavations/land-use changes, contamination due to trace metals, coastal urbanization, infrastructure development, constructions, seawater ingress, etc. [32,34]. The economy of this region is vastly dependent on agriculture, farming, and fishery, and if the medium used to make a living is degraded, the quality and quantity of the harvest and produce would be impaired; thus, the fiscal balance of the community would be disrupted [35].

Past and current agricultural research strategies in this region mostly focused on salinity- and submergence-related issues, and little attention has been paid to the issue of soil acidity (particularly potential and actual acid sulphate soils). To the best of our knowledge, information on this potentially detrimental issue is scant for the entire Ganges Delta on the extent of the problem, location-wise acidity distribution in the soil profiles; acidity pools; toxicity effects of Fe, Mn, and Al; consequences of drainage/exposure; degrees of crop loss; and possible management options. Obviously, there is no systematic documentation on ASS of this region as the area covered is not as large as compared to an international scale, although the issue is pertinent to millions of people. The problem is confounded with salinity and inundation, and therefore it has not attracted the deserved research attention. In addition, the patchy occurrence of ASS in this region might not have attracted the research attention and complicated the detection of potential and/or active ASS [36]. In this paper, we tried to provide a comprehensive recent view of the problems caused by ASS in the Ganges Delta, case studies of occurrence and observed management strategies, and similar international observations applicable to this region. This study will further invigorate the genuine need for research and development of ASS in the Ganges Delta covering Bangladesh and West Bengal, India.

2. General Characteristics of the Acid Sulphate Soils of the Ganges Delta

2.1. Formation and Distribution of Acid Sulphate Soils in the Ganges Delta

The acidity developed is due neither to the organic acids nor to the leaching of cations but originates from the oxidation of pyrites (FeS_2) and other oxidizable sulphidic materials accumulated in the soils in the past [37]. The tidal marshes and forest vegetation in the Ganges Delta favour a build-up of pyrites through a microbial reduction of sulphate salts in the soil, and this phenomenon may be represented by the equation given by van Breemen [38].

$$\underset{\text{(Soil)}}{Fe_2O_3} + \underset{\text{(Sea water)}}{4SO_4{}^{2-}} + \underset{\text{(SOM)}}{8CH_2O} + \underset{\text{(Dissol. } O_2\text{)}}{0.5O_2} \longrightarrow \underset{\text{(Pyrites)}}{2FeS_2\downarrow} + 8HCO_3{}^{-} + 4H_2O$$

ASS is active (or actual) if sulphide oxidation has been initiated and potentially active, if sulphide oxidation has yet to start. The critical step for the formation of ASS is the generation of sulphuric acid due to sulphide mineral oxidation [39,40]. Pyrite oxidation in ASS may be a natural process (isostatic land rise and drought) or due to anthropogenic activities (groundwater pumping, drainage, and land excavation), resulting in the formation of sulphuric acid and subsequent soil acidification [41–43]. The microbial oxidation of soil organic matter (SOM) using $SO_4{}^{2-}$ ions as an electron sink produce H_2S gas, which in turn may produce FeS_2 in the soil.

$$SO_4{}^{2-} + 2CH_2O \longrightarrow H_2S\uparrow + 2HCO_3{}^{-}$$

$$2Fe(OH)_3 + 4H_2S + 0.5O_2 \longrightarrow 2FeS_2 + 7H_2O$$

When these soils are exposed for cultivation with the provision of drainage, aerobic environments develop in these soils; therefore, there is oxidation of the pyrites or other oxidizable sulphidic materials resulting in free sulphuric acid (H_2SO_4), thus creating severe soil acidity.

$$FeS_2 + 15/4\ O_2 + 7H_2O \longrightarrow Fe(OH)_3 + 2\ SO_4{}^{2-} + 4H^+\ \text{(acid)}$$

The pyrites (FeS_2) under strong oxidizing and acidic conditions in the presence of metallic cations form jarosite mottles and free acid.

$$FeS_2 + 15/4\ O_2 + 5H_2O + 1/3\ K^+ \longrightarrow 1/3\ KFe_3\ (SO_4)_2(OH)_6 + 4/3\ SO_4{}^{2-} + 3H^+$$
(Jarosite)

This yellow-coloured jarosite mottle is one of the most important recognizing characteristics of acid soils developed due to sulphate oxidation. The K^+ may be replaced by Na^+ or H_3O^+ forming natrojarosite or hydronium jarosite. The low level of P and high concentrations of Al and Fe in the acid sulphate soils are primarily responsible for low productivity. All the soils of the Ganges Delta may not fulfill the exact criteria for ASS as laid down by [17,19,20]; however, due to the presence of soil acidity of varying degrees and at varying soil depths and jarosite mottles coupled with extreme soil salinity, these soils are sometimes termed Acid Saline Soils [22], and these soils may be categorized as potential Acid Sulphate Soils [43]. The generic term Acid Sulphate Soils (ASSs) generally refers to both actual (soils or sediments containing highly acidic soil horizons or layers affected by the oxidation of pyrite—iron sulphides) and potential ASSs (containing iron sulphides or other sulphidic materials that have not been exposed to air and oxidized). These soils have been described as the "*nastiest soils on earth*" because of their strong acidity, increased mobility of potentially toxic elements, and limited bioavailability of nutrients [43].

The extensive occurrence of ASS in various parts of the Ganges Delta covering both Bangladesh and West Bengal, India have been reported [22,44–52]. In the Bangladeshi part of the Ganges Delta, ASS exists in the Cox's Bazar, Khulna, Bagerhat, and Satkhira districts, whereas in West Bengal, ASS existence has been reported in the Basanti, Canning I, and Gosaba blocks of the South 24 Parganas district (Table 1).

Table 1. Distribution and degree of soil acidity of acid sulphate soils in the Ganges Delta.

Location	Soil pH	Block/District	Country	Reference
Cheringa	3.4	Cox's Bazar	Bangladesh	[51]
Dulahazara	3.3	Cox's Bazar	Bangladesh	[52]
Shamnagar	3.2–4.0	Satkhira	Bangladesh	[46]
Chakaria, Teknaf, Maheshkhali	<4.0	Cox's Bazar	Bangladesh	[45]
Dacope, Shamagar	<4.0	Khulna	Bangladesh	[45]
Morrelgonj	<4.0	Bagerhat	Bangladesh	[45]
Bashkhali, Kutubdia, Ramu, Ukhiya, Sadar	<4.0	Cox's Bazar	Bangladesh	[45]
Debhatta, Kaliganj, Satkhira, Tale	<4.0	Khulna	Bangladesh	[45]
Bagerhat Sadar, Rampal, Kauche	<4.0	Bagerhat	Bangladesh	[45]
Kheria	4.2	Basanti, South 24 Parganas	West Bengal, India	[49]
Nirdeshkhali, Simultala, Sarberia	<4.0	Basanti, South 24 Parganas	West Bengal, India	[47]
Fulmalancha, Simultala	3.0–4.9	Basanti, South 24 Parganas	West Bengal, India	[44]
Bara Dumki	3.4–6.6	Canning I, South 24 Parganas	West Bengal, India	[44]
Bhupendrapur	3.2–6.9	Gosaba, South 24 Parganas	West Bengal, India	[50]
Nirdeshkhali, Simultala	3.8–4.5	Basanti, South 24 Parganas	West Bengal, India	[22]
Malancha, Nirdeshkhali, Simultala	3.3–5.9	Basanti, South 24 Parganas	West Bengal, India	[48]
Amjhara, Rajbari, Canning	3.6–4.8	South 24 Parganas	West Bengal, India	[48]

The entire Ganges Delta receives unimodal monsoonal rain, which causes waterlogging, and subsequent to the withdrawal of the monsoon, there is a drying of the soil causing annual alternating wetting and drying cycles [27]. These seasonal and alternating wet–dry conditions create reducing and oxidizing environments, which in turn facilitates the dissolution of oxides, hydroxides, carbonates, and adsorption/desorption processes in the soil resulting in higher concentrations of trace metals (Ba, Rb, V, Cr, Ni, As, Pb, Ga, Co, Cs, Nb, and W) and major oxides (Al_2O_3, Fe_2O_3, K_2O, and MgO) in the upper soil layers [53]. Thus, the geographic situation of the coastal region, rainfall pattern, and congenial parent material favour the formation of acidic soils in the Ganges Delta.

2.2. Distinguishing Characteristics of Acid Sulphate Soils of the Ganges Delta

The soil pH of ASS in the West Bengal part of the Ganges Delta has been reported within 3.3–5.9 and an electrical conductivity of soil saturation extract (ECe) of 0.95–6.25 dS m^{-1}, and the exchangeable acidities of these soils have been contributed to both exchangeable H^+ and Al^{3+} ions [47]. However, a higher soil salinity (11.2 dS m^{-1}) in the surface soil layer (0–15 cm) is also reported [22,54]. In some locations, subsurface (>100 cm soil depth) salinity (8.5–12.5 dS m^{-1}) was observed in these soils [55]. These soils have a pH usually below 4 caused by the formation of sulphuric acid from the oxidation of pyrites (FeS_2) or other sulphidic parent materials. In the presence of metallic cations, there is the formation of jarosite [$KFe_3(SO_4)_2(OH)_6$] and free acids. Jarosite is a basic iron potassium sulphate produced by the action of sulphuric acid on aluminosilicate minerals and is found in an acidic horizon having a pH of 3.65–3.5 or less [56]. Studies on ASS characteristics representing the Kamalkathi series situated in the Shamnagar thana of the Satkhira district of Bangladesh revealed the presence of jarosite mottles in the B22 (45–65 cm) horizon of the profile with a very low soil pH (3.4–4.0), confirming the classification as actual ASS [46]. The jarosite mottles are the most important recognizing feature of these soils along with a very low pH. The presence of jarosites near the surface or root zone soil hampers the crop root growth as it makes the soil acidic with the rising water table. These are broadly categorised as actual acid sulphate soils when the pH is <4.0 and the sulphate (water soluble sulphate) content is about 5 g kg^{-1} [57]. Potential acid sulphate soils are the soils under hydromorphic conditions due to poor drainage with high amounts of pyrites, and under these conditions, the pH may not be very low, but when these soils are drained or exposed to air, the oxidation results in the formation of acids, and, as a result, the pH goes down drastically. When brought under cultivation, these soils pose serious constraints to crop growth and development. In these soils, there is toxicity of iron, manganese, and aluminium and a deficiency of available phosphorus. In the Ganges Delta, these soils are locally called "*KOIMURO MATI*" or "*KOSH MATI*". The exposed soils are dark grey in colour and silty clay loam to clay in texture with a very low pH (<4).

The ASS in the Indian part of the Ganges Delta region contains comparatively higher organic carbon (OC) in the Ap and BA horizons (0–70 cm), and because of depositions of organic matter [23], the OC content decreases at the lower depths (Table 2). However, in some areas, the presence of high OC at lower depths is observed due to the early deposition of organic matter in the soil [44]. There is a wide variation of the Cation Exchange Capacity (CEC) of these soils, ranging from 19 to 27 cmol(p^+) kg^{-1} or more due to variations in organic matter and clay content [23]. Among the cations are $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, and the anions are $SO_4^{2-} > Cl^- > HCO_3^-$ [23]. There is toxicity of water-soluble Fe, Al, and Mn. The phosphorus nutrition of crops in these soils is affected owing to a high soil P fixation capacity. A deficiency of micronutrients, such as Zn and Cu, is also observed; however, there is plenty of K in the soil due to K-containing salts, such as KCl and K_2SO_4, and a high S content due to the presence of sulphuric horizon. In the Bangladeshi part of the Ganges Delta, the characteristics of ASS (Table 3) resemble to a great extent those in the West Bengal part, except the higher clay content and less soil salinity in the soil profile in the Bangladeshi part and a higher sodium content in the West Bengal part. However, soil salinity is a seasonal phenomenon in the coastal region, and it may vary with the time of soil sampling.

2.3. Recent Case Study on Soil Profiles of Acid Sulphate Soils in the Ganges Delta

A recent soil profile study (Table 4) by ICAR-CSSRI, RRS, Canning Town under a cropping system intensification project (2016–2022) on Bali and Gosaba islands [25,58–60] reveals that soil acidity and salinity are critical constraints to crop production in the Sundarbans region; however, the surface soils are relatively less acidic compared to the subsurface soils. Subsurface soil acidity is more severe in the Bijoynagar area of Bali Island where the acid sulphate layer occurs beyond the 80 cm soil layer with severe soil acidity (pH below 3.5). Jarosite mottles are found in the subsurface layers, and when soil tillage brings these soil clods with mottles to the surface, constraints to crop production are further aggravated (Figure 2a,b). Soils on Sonagaon are deficient in nitrogen and phosphorus, whereas on Bali, soils have moderate levels of N and P. Salinity stress affects crop production at both sites, and there are Al and Fe toxicities. Management strategies for these soils involving green manuring, rice cultivation, and application of lime/rock phosphate before sowing of the dry season crops at these sites are described later in this paper.

Table 2. Characteristics of acid sulphate soils of Indian part of the Ganges Delta.

Physicochemical Characteristics					**Ionic Composition of Saturation Extract (mel^{-1})**				
Horizon	**Ap**	**BA**	**Bwg1**	**Bwg2**	**Horizon**	**Ap**	**BA**	**Bwg1**	**Bwg2**
Depth (cm)	0–20	20–71	71–125	125–240	Na^+	50.1	25.1	46.7	33.4
Colour (moist) Matrix	5Y 5/1	5Y 4/1	5Y 4/1	5Y 4/1	K^+	1.3	0.5	1.2	1.2
Colour–Mottles	7.5YR 5/6, mlp	2.5YR 3/6, mlp	2.5YR 3/6, mlp	2.5YR 3/6, flp	Ca^{2+}	6.2	1.7	2.0	2.0
Texture	sic	sicl	sic	sic	Mg^{2+}	13.9	2.2	2.5	2.8
Clay (%)	46	38	46	46	Cl^-	20.0	6.7	11.7	10.0
pH (1:2)	4.1	4.4	4.3	6.1	$SO_4{}^{2-}$	35.1	13.4	6.7	8.4
ECe (dSm^{-1})	14.5	7.7	7.0	7.5	$HCO_3{}^-$	1.0	1.0	0.5	1.0
SAR	3.9	4.4	5.4	5.2	CEC (cmol(p$^+$) kg^{-1})	26.6	23.4	22.1	19.4
ESP	11.6	13.2	15.8	20.6	Base sat. (%)	63.9	64.9	70.1	88.1
OC (%)	1.25	1.28	0.55	0.34					

Source: [23].

Table 3. Characteristics of acid sulphate soils of Bangladeshi part of the Ganges Delta.

Physicochemical Characteristics						**Ionic Composition (cmol kg^{-1})**					
Horizon	**Ap**	**B21**	**B22**	**B23**	**C1**	**Horizon**	**Ap**	**B21**	**B22**	**B23**	**C1**
Depth (cm)	0–10	10–45	45–65	65–100	100–125	Na^+	4.88	4.88	4.43	4.37	4.55
Colour (moist) Matrix	5Y 6/1 (dry)	5Y 3/1 (m)	5Y 3/1 (m)	5Y 3/1 (m)	3 N (w)	K^+	1.82	1.56	1.29	1.23	1.07
Colour–Mottles	C1Pdb	C1Pdb	C1Pdb	C1Pdb	C1Pdb	Ca^{2+}	3.68	3.48	2.42	2.06	3.26
Texture	Sic	C	C	C	Sic	Mg^{2+}	6.00	6.00	4.37	4.39	3.57
Clay (%)	55	63	59	60	34	H^+	4.18	4.62	5.28	6.16	5.00
pH (1:1)	3.4	4.0	3.6	3.5	3.4	CEC (cmol(p$^+$) kg^{-1})	26.71	26.94	27.18	18.62	19.13
ECe (dSm^{-1})	1.30	0.61	0.68	0.83	0.19	Base sat. (%)	61.32	59.09	46.03	64.71	65.08
OM (%)	3.05	1.59	1.40	2.44	1.88						

Source: [46].

2.4. Problems of Acid Sulphate Soils of the Ganges Delta

The crop yield in the highly acidic saline soils (pH < 4.0) occasionally found in several places in this region is extremely poor [23]. Many a time, crops on such soils show the visual toxicity and deficiency symptoms for several elements [59]. Crop and animal husbandry are enterprises that depend on soil quality [61] and encounter hinderances when there are acid saline soils. In an undisturbed state below the groundwater table, ASS are benign [62], however, anthropogenic activities such as drainage for agriculture; aquaculture ponds; construction of canals/houses/industrial estates; and roads can disturb ASS and lead to the oxidation of the sulphides they contain. The consequence is the generation of sulphuric acid and the associated toxic metal ions (iron, manganese, and aluminium) coupled with a deficiency of nutrients, especially available phosphorus, due to high acidity; this causes a very poor yield of agricultural crops. The germination of seeds is affected resulting in a patchy population, stunted and deformed leaves, and poor root growth [63]. Restricted root growth in the subsurface as a result of toxic levels of aluminium and a reduced uptake of other essential nutrients from the subsurface soils layers [64] also contribute to salinity development. Poor root growth of trees in these soils makes them prone to uprooting/lodging under high winds during cyclones and storms [65]. The major soil-related problems are described below.

Table 4. Physicochemical properties of acid saline soils of Bijoynager, Bali, Sonagaon, and Gosaba Islands, Sundarbans.

Soil Depth (cm)	Texture	OC (%)	CEC	pH (1:2 Soil:Water)	EC dSm^{-1} (1:5 Soil:Water)	N	P	K	Al^{3+} [cmol(p^+)kg^{-1}]	Fe (mg kg^{-1})
						(kg ha^{-1})				
Bijoynagar (Bali Island)										
0–15	Sicl	0.57	14.7	6.1	1.73	257	17.3	455	0.11	73.2
15–30	Sil	0.89	13.3	5.5	1.01	337	15.5	503	0.25	193.3
30–50	Sil	0.87	13.5	5.3	1.57	299	12.7	509	0.31	225.8
50–80	Sicl	0.75	13.7	4.5	1.21	285	11.3	523	1.37	271.1
80–120	Sicl	1.55	14.1	3.5	1.35	375	37.9	475	4.88	301.1
120–150	Sil	0.97	11.3	3.3	1.52	355	41.5	411	4.06	343.3
Sonagaon (Gosaba Island)										
0–15	Sic	0.49	14.5	5.0	1.79	189	10.4	372	0.27	195.5
15–30	Sicl	0.62	14.1	4.7	1.65	263	10.1	427	1.11	235.7
30–50	Sil	0.57	13.9	4.6	1.58	254	11.5	455	1.03	244.1
50–80	Sicl	0.48	13.7	4.9	1.81	185	10.7	489	0.49	203.8
80–120	Sicl	0.52	14.3	4.8	1.75	195	12.5	466	0.67	199.9
120–150	c	0.53	12.5	4.5	1.66	203	15.6	433	1.21	256.5

Source: [60].

(a)

(b)

Figure 2. Yellow jarosite mottles found in the plough layers of acid sulphate soils on Sonagaon and Gosaba islands, Sundarbans: (**a**) Soil clods containing mottles; (**b**) Surface-tilled soil layer with abundance of jarosite mottles. Source: Authors' own collection from Sonagaon village on Gosaba island in the Indian part of the Ganges Delta.

2.4.1. Poor Physical Properties

Due to high acidity, in the pH range of 4.0–4.5, there is leaching of dissolved organic carbon [66]. Since soil organic carbon (SOC) is positively related to soil macroaggregate formation [67], a decrease in SOC has a negative impact on soil structure. The main source of dissolved organic carbon in soil usually originates from root exudates [68]; therefore, the suppression of root growth in these soils hampers soil aggregation. Undisturbed soils have a steely blue-grey colour, and oxidised soils are quite dry with a burning appearance of a dark to pale brown colour [69]. Yellow and orange mottles are also visible, yellow due to jarosites and orange due to other iron oxide minerals [70]. Sparse vegetation in such soil is due to stunted root growth and low soil microbial activity [71].

2.4.2. Nutrient Deficiencies and Toxicities

Nutrient deficiency and/or toxicity issues in this region are very location-specific. However, in general, most acid saline soils in the Ganges Delta show a deficiency of phosphorus, calcium, and sometimes potassium, whereas levels of exchangeable magnesium may be high [30]. In the Bangladeshi part of this region, there are reports of phosphorus, calcium, and magnesium deficiencies [72]. There is also toxicity of aluminium, manganese, and iron observed due to an increase in the solubility and in the soil solution concentration of these ions. A toxic concentration of Al to the extent of 0.059 g kg^{-1} in the soil is reported from the Dinajpur and Rangpur areas of Bangladesh [73]. Al toxicity causes root deformity as it interferes with cell division in plant roots, decreases root respiration, increases cell wall rigidity, and interferes with the uptake and transport of Ca, Mg, K, P, and water to the plants [74]. The soil solution Fe^{2+} concentrations that significantly affect lowland rice yields vary from 10 to >2000 mg L^{-1} [75]. The acidic solution dissolves aluminium and toxic heavy metals, such as arsenic, contained in the soil [76] and poses problems to crop growth. The sequence of trace metal concentrations in the soils of Sundarbans was found to be in the order of Fe > Mn > Ni > Zn > Cr > Cu > Pb > Cd, while the toxicity sequence was Pb > Ni > Cd > Fe > Mn > Zn > Cu [77]. Plant root development also suffers due to the toxic effect of gases (H_2S and CO_2) and organic acids [78]. Phytotoxic organic acids, such as acetic acid, n-butyric acid, and propionic acid, accumulate in these soils [79]. A substantial quantity of H_2S gas is often released from paddy fields in the coastal acid saline soil as a result of a reduction in the sulphate salts to sulphides [80]. A part of the sulphides formed in the soil evolve as H_2S gas to the air causing environmental contamination [81]. The H_2S gas emission from coastal marshes is observed over the whole year; however, the emission is higher in the plant-growing season than in the nongrowing season [82]. The remaining part of the generated gas combines with the soluble metallic cations in the soil resulting in mostly insoluble metallic sulphides [83] of which iron sulphide is the major one. These insoluble metallic sulphides coat the surface of rice roots and interfere in the process of nutrient uptake by the roots [84]. Free hydrogen sulphide is highly toxic to flora and fauna and affects their growth [78]. The deposited sulphides produce a dark shade to the paddy soil, which is commonly observed in most of the rice-growing areas in the coastal zone [85]. The formation of sulphide (H_2S) gas due to a sulphate reduction, affects the root respiratory activity of the rice crop resulting in '*Akiochi*' disease [86]. Plants become deficient in N, K, Si, and bases, and the iron content in plant tissues increases to toxic levels [87]. Plants become prone to other diseases, such as brown spot and blast, caused by *Helminthosporium oryzae* and *Pyricularia oryzae*, respectively [87].

2.4.3. Soil Salinity

Soil salinity is an inherent problem of the soils of the Ganges Delta due to the capillary rise of salts from the brackish groundwater present in shallow depths and the deposition of salts on the soil surface [88]. The hydrology of polders in the Ganges Delta is complex, with water (and usually salt) exchanged amongst the atmosphere, the soil–water–plant system in the polder, the underlying groundwater, and the surrounding rivers [89]. The severity of salinity is location-specific and variable by soil depth. The electrical conductivity of the saturation extract (ECe) ranges from 1.1 to 10.2 dSm^{-1} on the surface and 1.0–13.3 dSm^{-1} in the subsoils, which show an irregular distribution with different depths [50]. However, the salt concentrations in the soil solution increase as the soil dries, and the resulting increase in the soil solution's salt concentration (i.e., decrease in solute potential) limits crop water uptake even at higher levels of soil water [58]. The ingress of saline river water during high tides due to breach of embankments caused by cyclones and other natural calamities also increases the soil salinity in the 0–80 cm soil depth range to 12.6–16.8 dSm^{-1} [60]. Hinderances in drainage also accentuate the salinity issue in the Ganges Delta.

In ASSs of the coastal areas, some of the problems result from salinity as well as from acidity, particularly in dry seasons when acid-forming salts, such as rozenite ($FeSO_4{\cdot}4H_2O$), form in crusts at the soil surface; this salinity is different from that which develops from the seawater source [90]. In these soils, salts produced upon the oxidation of the sulphides may be more important than the direct addition from seawater [91]. This high salinity due to high soluble chloride (Cl^-) concentrations ($\leq$17 mg g^{-1} soil) and high soluble sulphate ($SO_4{}^{2-}$) concentrations ($\leq$17 mg g^{-1} soil), in addition to the extremely low pH of the surface soils contributes to land denudation, instigation or perpetuation of pyrite oxidation, and ASS-related land scalding [92]. Another notable feature in these soils is that the highest salinity usually coincides with the lowest pH, which is unusual in normal saline soils [91,92]. The sulphate salts of Fe and Al referred to as acid salts [93] cause both low pH (acidity) as well as osmotic stress similar to neutral salts, as well as toxicity effects on seed germination and plant growth due to excess Al and Fe [92]. Therefore, if the salinity of coastal soils is only thought to originate from seawater, and reclamation practices are oriented towards blocking out seawater from these soils, a cycle of sulphide oxidation may be set off with disastrous acidity as well as salinity consequences for the soils and associated ecosystems [91].

2.4.4. Variable Acidity in Variable Depths

The soil acidity (pH) measured with different methodology varied in the pH value in a 2:1 soil:water suspension > pH—KCl > pH—H_2O_2 [22]. The pH measured in the soil:water suspension showed the value of $\leq$4.0 at variable depths of 45–90 cm [22], 25–130 cm, 0–140 cm, 136–196 cm [44], and 67–150 cm [50]. The pH of surface soils of the Indian part of the Ganges Delta categorized as <4.5, 4.5–6.0, 6.0–8.0, and >8.0 covered an approximate area of 0.04, 0.10, 0.70, and 0.02 Mha, respectively [23].

2.4.5. Adverse Impact on Ecosystem and Biodiversity

The high acidic discharges upon the drainage of acid sulphate soils kill fish species and severely affects the biodiversity of wetlands with substantial death of mangroves [87]. At Bijoynagar (Bali Island in the Ganges Delta) where the soil pH is <3.5 in the soil layers below a depth of 80 cm, the dried ponds in these areas had layers exposed and severe acidity, and nutrient toxicities were observed (Figure 3a). Acid saline soils of the Ganges Delta are generally used for monocropping of rice during the *Kharif* season. Following heavy rainfall, the acid and metal ions, including the arsenic present in the sediments forming the soils or those that exist as the chemical components of pyrite, drain into adjacent waterbodies. This water is not suitable to be used as irrigation water for cultivation in the area and degrades cultivated soils, aquatic ecosystems, infrastructure, and human health (Figure 3b). Problems are faced when new land configuration is created, such as in order to establish new fish ponds or water harvesting structures. In such soils, there is insufficient growth of algae and plankton due to the poor condition of the pond water. Fish also grow more slowly and die suddenly, or they are prone to diseases and parasites [56]. ASS is also a source of CO_2 emission due to microbial respiration (8.7–41.1%) as well as abiotic pathways of acidic dissolution and hydroxyl (OH) radical oxidation (14.6–27.6%) to CO_2 production [94].

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

Figure 3. Adverse impact of acid sulphate soils on ecosystem: (**a**) Affected pond in the Bijoynagar village of Bali Island; (**b**) Cultivated soil with toxic effects of elements in Canning Block of South 24 Parganas. Source: Authors' own collection from the farmers' fields in the Indian Sundarbans region of the Ganges Delta.

3. Management of Acid Sulphate Soils of the Ganges Delta

The application of lime, rock phosphate, and single superphosphate is found to be beneficial in improving soil properties and crop yields in the acid sulphate soils of Sundarbans [49,95]. Furthermore, the addition of locally available Ca-rich oyster shell in powdered form along with green manures/leaf manures has proven to be an effective ameliorative agent [96]. Management measures for the potential and active acid sulphate soils comprise the following broad strategies.

3.1. Chemical and Engineering Measures

Soil amendments of various types depending upon availability and effectiveness could increase the soil pH and later favour crop growth and development [29]. Chemical soil amendments, such as lime, dolomite, rock phosphate, basalt, slag, etc., are commonly used [97]. The toxic effects of Al, Fe, and Mn can be overcome by the application of calcitic limestone (calcium carbonate), dolomitic limestone (calcium and magnesium carbonate), burnt/quick lime (calcium oxide), hydrated/slaked lime (calcium hydroxide), magnesium carbonate, basic slag ($CaSiO_3$), or other alkaline/liming materials to increase the soil pH and precipitate the toxic metals and thus increase plant growth [98]. The concentration of H_2S in the soil solution can be significantly reduced by using ferrous sulphate in the soil as it is precipitated as FeS [23]. The neutralizing value of a liming material is compared by the Calcium Carbonate Equivalent (CCE). The CCE of calcium carbonate is 100%, and for basic slag, dolomite, hydrated lime, and quick lime, it is 86, 109, 136, and 179, respectively [99].

3.1.1. Liming of Acid Sulphate Soils

The health of coastal acid sulphate soils of India can be improved, and the rice yield could be increased by the application of lime, super phosphate, and rock phosphate [100]. Available phosphorus in the soil increases slightly due to liming and the application of P fertilizers. The application of rock phosphate to this soil also increases the available P content of the soil. The excess availability of Fe and Al could be controlled by proper levels of liming. The lime dose determined by the KCl extraction method with a lime factor of 4.0 (or lime dose determined by Shoemaker's method with a lime factor of 0.5) was found to be most suitable for coastal acid soils of the Ganges Delta [101]. The powdered form of locally available oyster shell rich in Ca, is also a cost-effective amendment for ASS [49]. The $CaCO_3$ content of the oyster shell is 90–95%, which is as effective as natural limestone [102]. For acid sulphate soils in Andaman, the use of amendments, such as limestone and MnO_2, resulted in a higher yield of lowland rice; however, when the soil salinity is high, the leaching of excess salts is essential before the application of the amendments [103]. The toxic effects of Al and Fe are also well managed by liming. The depression of toxic soluble Al may be due to the formation of trivalent A1 and $A1(OH)_3$ by reacting with OH^- ions. The use of MnO_2 decreased the concentration of Fe^{2+}, and the effect was more pronounced in the soil with a pH of 3.4 compared to the soil with a pH of 4.6. The application of liming materials in small quantities at short intervals may be more useful as the influence of liming on potential acidity is negligible, and it lasts for a short period [104].

Basic slag, a byproduct from the steel industry, can be collected almost free of charge in Bangladesh [51], and it has a very high pH (9.6) containing 20.8% Ca, 9.8% Mg, and 12.8% SiO_2, and it is a better soil amendment for ASS reclamation in the Ganges Delta [105]. Basic slag at 20 t ha^{-1} when used under the ridge–ditch technique with a 0.6 m height of the ridge with top soil at the top, a pyrite layer in the middle, and a jarosite layer on the bottom of the ridge resulted in a higher yield (4.0–4.4 t ha^{-1}) of rice in ASS of the Bangladeshi part of the Ganges Delta [21]. The reclamation of ASS occurring in the Cox's Bazar area of Bangladesh by the application of basic slag at 30 t ha^{-1} under soil saturated conditions before a couple of months of crop cultivation, significantly increased the soil's pH and improved the ionic balance between Ca and Mg, one of the vital problems in the ASS of the Ganges Delta [106].

The pond bottom soil with acid sulphate content may be reclaimed economically by the application of hydrated lime ($Ca(OH)_2$) at 2300 kg ha^{-1} or burnt lime (CaO) at 260 kg ha^{-1} to a desirable pH (7.4–8.6); however, the dolomite ($CaMg(CO_3)_2$) requirement is very high (50 t ha^{-1}) and hence expensive in the reclamation process [107].

3.1.2. Integrated Nutrient Management

Integrated nutrient management (INM) in acidic soils (pH < 5.5) involves the use of organic manures, biofertilizers, and lime in conjunction with chemical fertilizers for better soil health and higher crop production instead of chemical fertilizers alone [108]. Proper nutrient management is another important component of crop management, especially for high-yielding, dry-season rice crops. The target is to maintain or even improve soil fertility, limit the costs of fertilizer, and obtain high yields. This can be achieved by the optimum use of chemical fertilizers in integration with the locally available organic sources of plant nutrients. Because most of the farmers in the Ganges Delta possess cattle as an integral component of their farming system, FYM as a cheap and easily available source of organic nutrients can be one of the important components of INM [101]. *Azolla*, another possible component of INM, is a free-floating water fern that in symbiotic association with cyanobacterium *Anabaena azollae* fixes the atmospheric nitrogen [109]. Its incorporation improves soil nutrients primarily due to the nitrogen fixed by the *Anabaena* species of blue-green algae (BGA) present in the lobes of the *Azolla* leaves. Farmers can produce their own *Azolla* inoculums in ponds and ditches that are common in coastal areas. The mean temperature during the *Boro* season in most of the areas falls within the range (20–30 °C) required for *Azolla* cultivation, making climatic conditions mostly congenial for its good growth [88].

In Indonesia, the use of composted oyster mushroom baglog waste at 15 tha^{-1} integrated with chemical fertilizers (urea, super phosphate, and potassium chloride) in ASS supplied N, P, and K in available forms and reduced the amount of soluble Al and Fe [68]. In Bangladesh, INM involving poultry manure biochar (PMB) and dolomite increased the system productivity of Mustard-*Boro*-transplanted *Aman* and Maize-Jute-transplanted *Aman* cropping systems from 55.4 to 82.8% in acidic soil [110]. The composition and chemical properties of PMB used in the above study were organic carbon (337.6 g kg^{-1}), total nitrogen (30.8 g kg^{-1}), pH (8.5), CEC (35.68 cmolc kg^{-1}), available P (1437 mg kg^{-1}), available K (22.61 cmolc kg^{-1}), and available S (2094 mg kg^{-1}).

INM strategies have several advantages to minimize the antagonistic effects resulting from hidden deficiencies and the nutrient imbalance; improve and sustain the physical, chemical, and biological functioning of the soil; and protect the ecosystem by the promotion of C sequestration, reducing nutrient losses to water bodies and the atmosphere [111]. Sustainable crop and soil productivity achievement in problem soils lies with the integrated use of organic sources of nutrients from crop residues, animal/bird manures, green manures, green leaf manures, oilcakes, biofertilizers, and industrial by-products in conjunction with soil amendments and inorganic fertilizers [112].

3.1.3. Engineering Measures

Powell and Martens [76] reported on the hydraulic suppression of the acid export from the soil and the buffering of existing acidic water with neutralizing materials. Regular tidal inundation of the low-lying areas keeps soils wet and hence prevents the oxidation of pyrite and the generation of additional acid. The treatment of acid drainage water with hydrated lime $Ca(OH)_2$ increases buffering and precipitates iron and aluminium compounds within the site. Hydraulic separation is suitable for coarse-textured soils containing iron sulphides, and sluicing or hydrocycloning are used to hydraulically separate the sulphides from the sandy materials [10]. This technique is quite effective in areas where the sediments contain <10–20% clay and silt and have a low organic matter content. The separated sulphidic material extracted via the process requires special management involving either neutralization or strategic reburial [113]. Subsurface chemical (fine-grained $CaCO_3$ median grain size 2.5 μm) treatments (injection through subsurface irrigation) increased pH and decreased acidity and concentrations of aluminium in acid sulphate soils [114].

3.2. Agronomic Measures

3.2.1. Soil Profile Distribution during Land Modification

The economic consideration is one of the bottlenecks for reclamation of vast areas of acid sulphate and highly saline coastal swamps [115]. The ill-advised reclamation strategies of these potential lands in the coastal region by the exclusion of brackish water through dicing and by digging fishponds resulted in the further degradation and subsequently desertion of several hectares of mangrove land in Southeast Asia and Africa [116]. In the absence of a sufficient volume of good quality water and other requisites for water quality management, the potential acid sulphate soils may not be tampered with; alternatively, it may be better to utilize this land for other economic purposes, such as biodiversity conservation, forestry, salt pans, etc. Alternatively, other minimum disturbance reclamation strategies, such as flooded rice cultivation and the use for shallow fish ponds that in some cases may be suitable to produce shrimp (prawns) may be adopted [91]. Before undertaking any interventions for land modifications, a detailed sample profile study is essential to ascertain the existence of highly acidic materials and layers [117]. If any land modification is to be carried out, the soils with a favourable pH range need to be separated and rearranged in the surface layer for cropping and plantation options.

3.2.2. Green/Organic Manuring and Mulching

Green manuring involves in situ ploughing under and the incorporation of undecomposed green plants, particularly legumes, such as *Dhaincha* (*Sesbania* sp.), Sunnhemp (*Crotalaria juncea*), etc., for the purpose of improving soil fertility, productivity, and physical conditions [110]. This increases soil fertility by the addition of organic matter (OM) as well as nitrogen [118]. The addition of OM improves the soil structure, water-holding capacity, and microbial activity [119]. In the Ganges Delta, green manuring is practiced before the wet/*Kharif* rice season. *Dhaincha* (*Sesbania aculeata*) is the preferred species for green manuring in this area with a seed rate of 30–35 kg ha^{-1} sown in May to June using pre-monsoon rain and ploughed under in July during the puddling operations of *Kharif* rice. Green manure crop should be incorporated into soil at the vegetative stage to obtain maximum benefit. It should be turned into soil when the foliage is tender at about 7–8 weeks after sowing. Matured plants become woody in later stages of growth; therefore, it is necessary to bury them before transplanting the paddy for its proper decomposition [120].

To decrease the rate of P fixation during the growing season of crops, silica-rich materials, such as decomposed rice hull and poultry manure, may be applied [121]. Organic materials, such as bunch ash, produced by incineration of the thrashed oil palm fruit bunches have an extremely basic (pH), containing 41% K_2O, 4% P_2O_5, 6% MgO, and 5% CaO, and is a good material to increase the pH of acid sulphate soils [18]. When reclaimed soil is brought under cultivation, mulching with organic materials, such as paddy straw that is readily available in the Ganges Delta, may be practiced. Paddy straw mulching reduces soil salinity, conserves soil moisture, improves bulk density, and increases soil organic carbon content [122].

3.2.3. Selection of Tolerant Crops and Varieties

The Al tolerance of canola (*Brassica napus*), *Arabidopsis thaliana*, tobacco (*Nicotiana tabacum*), and alfalfa (*Medicago sativum*) has been reported to be enhanced by increasing organic acid biosynthesis through the overexpression of citrate synthase or malate dehydrogenase genes derived from plants or bacteria [123]. Rice varieties recommended for acid saline soils (pH 4.0–5.5) of the Ganges Delta are Mahsuri, Canning 7, SR 26B, and K.D. Mali [124]. Differential responses of lowland rice varieties to Fe toxicity and their ability and strategies to adjust plant growth and metabolism to overcome the stress are also reported [125]. Pineapple and sugarcane grow well on acid sulphate soils, and fruit crops, such as mangoes, citrus fruit, bananas, and watermelons, can be grown successfully under a raised-bed system (ridge and ditch system) in such soils [126].

3.2.4. Leaching after Drainage/Aeration

Ameliorative treatments of acid sulphate soils include the leaching of the acid formed during oxidation because the application of limestone to neutralize all the potential acidity will be very expensive, and a more practical solution may be to encourage the oxidation of pyrite and the subsequent leaching of acid and then to counteract the residual acidity [17]. Soils with a very high jarosite content require more periods of leaching (up to 90 days) to increase the pH compared to soils with a lower jarosite content (10–30 days) and by using water four times the weight of the soil [47].

The reclamation of acid sulphate soils for aquaculture pond was suggested by [55]. The pond bottom is ploughed to a depth of 10 cm and then harrowed to small clods (not into a powder) and allowed to dry for 2–3 weeks before the start of aquaculture. Then, brackish or salt water (pH 7–9) is allowed to fill the pond. When the pH of the water drops to 3–4, the pond is drained and refilled with new brackish or saline water with a high pH. This process is repeated until the pH of the pond water remains constant at a value just below 5 (4–6). The pond is then drained, and about 0.5 t ha^{-1} of lime ($CaCO_3$) is applied on the surface (not to be incorporated) soil.

3.2.5. Maintaining a High Water Table

Pyrite oxidation and the development of acute soil acidity may be managed by maintaining a high water table in the soil [127], and the outcome of this strategy is observed very quickly. This process results in a reduced condition as the organic matter is decomposed at a faster rate by the microorganisms, resulting in lowering the soil acidity and increasing the soil's pH [128]. Maintaining a high-water table is practically an ideal option in the paddy fields, where adequate fresh water is used as irrigation [129]. Improved agronomic and irrigation water management strategies play a significant role in ameliorating the comparatively less toxic and older acid sulphate soils, which are seemingly suitable for rice cultivation [130]. Science-based rigorous drainage and irrigation management could significantly increase the crop and water productivity of these soils [131].

The continued submergence of acid saline soils of the Ganges Delta for 52 weeks resulted in an increase in soil pH from 3.5 to 3.9 where no lime was added and to 4.5 where lime (6 tha^{-1}) was applied [54]. An increase in the concentrations of Fe^{2+} and Al^{3+} in the soil was observed due to continuous submergence; however, there was a decrease in the salinity and Mn^{2+} concentration (Table 5).

Table 5. Effect of long-term submergence on acid saline soils of the Ganges Delta with and without lime application.

Treatments	ECe (dSm^{-1})	pH in Water	Fe^{2+} (ppm)	Al^{3+} (ppm)	Mn^{2+} (ppm)
Initial soil (Control)	11.2	3.5	693.0	12.0	21.0
Soil after 52 weeks of submergence without lime	6.7	3.9	2037.5	36.7	17.2
Soil after 52 weeks of submergence with lime	8.0	4.5	2506.3	36.3	17.2

Source: [54].

3.2.6. Microbial Remediation

By re-establishing reducing conditions within the bunded area, pyrite oxidation may be reversed by sulphate-reducing bacteria (SRB), which is a natural process and cost-effective if in situ microbial generation of the acid-neutralising capacity is significant [113]. Remediation via re-establishment of reducing conditions requires submergence and the addition of biodegradable organic carbon (OC) to stimulate the activity of reducing bacteria [132]. The inoculation of SRB at 10% of the compost weight followed by incubation at ± 35 °C for 4–7 days until the SRB grow with the formation of bubbles on the surface of the compost followed by application to the soil resulted in an increase in soil pH and a decrease in soil sulphate levels [133]. The microbial degradation of the added organic matter under water-saturated and anaerobic conditions generates electrons, which are accepted by a sequence of electron acceptors including nitrate, Mn and Fe oxides and sulphate, resulting in the reformation of pyrite with an increase in pH [134]. The inoculation of microbes, such as phosphate-solubilizing bacteria (PSB) and free-living, nitrogen-fixing bacteria, produce low-molecular-weight organic acids and phytohormones, such as indoleacetic acids (IAAs), which chelate the Al^{3+} ions and reduce the Al toxicity [135]. The application of biofertilizers to rice crops cultivated in ASS can enhance plant growth and yield due to the effect of phytohormones, reduction in nutrient toxicity, and better availability of phosphorus due to the solubilization of insoluble native P [104].

The treatment of ASS with PSB (*Caballeronia* sp. EK) increased seed germination of tomato (*Lycopersicon esculentum* L.) by 60%; plants grew with more than three times as many leaves, and there was a 45.2% increase in adenosine triphosphate over the untreated control soil [136]. The synergistic effect of soil amendments with the application of biofertilizers in ASS has been observed for sustainable rice cultivation in Southeast Asia. The application of ground limestone/basalt at 4 t ha^{-1} or biochar at 5 t ha^{-1} in combination with biofertilizer (4 t ha^{-1}) fortified with PSB increased the soil's pH from the initial value of 4.08 to above 5 with a corresponding increase in rice yield from 3.2 t ha^{-1} under the control to >5 t ha^{-1} under the combined application of the soil amendment with the biofertilizer [137]. The application of rice husk biochar produced by pyrolysis at 500 °C for 60 min with a pH of 10.01 and containing C (27.34%), N (0.54%), P (0.13%), K (3.55%), Ca (0.12%), and Mg (0.08%) in combination with N_2-fixing and phosphate-solubilizing bacteria increased the soil's pH to 5.36 from the initial level of 3.89 and increased the rice grain yield from 3.20 tha^{-1} under the control to 5.04 tha^{-1} with treatment [138]. An important aspect of the microbial remediation of ASS is the addition of organic matter as a substrate for microbes. The best remediation success was achieved by the addition of 50% of the native soil OC as wheat straw, resulting in fast pH neutralization, strongly reducing condition and decreased sulphur and iron concentrations in the soil solution [139]. Better mineral nutrition of the pioneer plants, forbs, and legume shrubs in acid sulphate soils is achieved by arbuscular mycorrhizal (AM) colonization [140].

3.2.7. Wetland Rice Cultivation under Submergence

Rice is a semiaquatic crop and grows under waterlogged/flooded conditions, where the pH rises resulting in the elimination of aluminium toxicity and the minimization of iron toxicity. The major adaptive feature of rice to waterlogging is the formation of aerenchyma. This aerenchyma constitutes the gas spaces and becomes interconnected, which becomes the channel for continuous aeration between roots and shoots [141]. Rice plants handle waterlogging stress by forming lysigenous aerenchyma and a barrier to radial O_2 loss in the roots in order to supply O_2 to the root tip [142]. Therefore, a zone of oxidized layers is formed around the roots as a result of ferric hydroxide precipitates as a brown crust, preventing the uptake of ferrous (Fe^{2+}) ion [18]. If the water's pH is greater than 3, the precipitation of Fe occurs as $Fe(OH)_3$; this coats the rice's roots and prevents the uptake of Fe^{2+} [143]. Rice roots can take in Fe only in soluble form, not as Fe hydroxides; therefore, to reduce the toxicity of Fe^{2+}, the water's pH should be increased beyond 5 by applying amendments, such as basalt at 4 t ha^{-1} or higher. Rice seedling roots release organic acids in the presence of high amounts of Al in the water to defend themselves against Al toxicity [18].

Reduced conditions prohibit soil acidity build-up. However, special management measures, including fertilizer application, are needed to harvest optimum rice yields. Continuous flooding is essential in such soils as alternate wetting and drying significantly increase the water-soluble iron to more than ten times (585 ppm) higher than that in the continuously flooded water (50 ppm) treatment [144]. Toxic effects due to H_2S gas can be managed in rice fields by the occasional stirring of the rice soil in between rows to release

H_2S in the air and reduce crop damage [145]. The main criterion used to determine the extent of limitation due to soil acidity is the depth of the jarositic horizon. Acid sulphate soils where jarosites are within 40 cm of the soil layer are poorly suited for paddy cultivation due to severe limitations, and soils with jarosites within 40–100 cm are moderately suitable for paddy cultivation [70]. When the jarositic layer is beyond 100 cm soil depth, these soils are well suited for paddy cultivation [70].

3.3. Integration of Green Manuring with Application of Soil Amendments

The application of soil amendments can help reclaim problem soils and improve their quality. In Sundarbans, the application of lime, rock phosphate (RP), and green manure (GM) were highly beneficial for the amelioration of acid sulphate soils and led to significant improvements in the growth and yield of *Kharif* rice and *Rabi* maize [73]. *Dhaincha* (*Sesbania aculeata*) was used as the GM crop (Figure 4a). It was broadcast with a seed rate of 30–35 kg ha^{-1} in May and ploughed under and incorporated into soil in July at the tender stage, which is about 7–8 weeks after sowing [146]. Green manuring was performed before transplanting the *Kharif* rice. The amendments, such as lime and RP, were applied after the harvest of the *Kharif* crop and one month before the planting of the *Rabi* crops (Figure 4b,c).

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

Figure 4. Acid saline soil management by green manuring and application of soil amendments in the Sundarbans region of the Ganges Delta: (**a**) Green manuring with *Sesbania aculeata*; (**b**) Application of lime before sowing of *Rabi* crops; (**c**) Rock phosphate an alternative soil amendment. Source: Authors' own collection from the farmers' fields under CSI4CZ project in the Ganges Delta.

The combined package of GM + lime + RP resulted in the highest rice grain yields, which was statistically similar with GM + RP (Table 6). During 2017, GM resulted in a grain yield increase from 3.96 t ha^{-1} (under control treatment) to 4.45 t ha^{-1}, and the yield further increased to 5.74 t ha^{-1} when GM was combined with liming [59]. During 2018, a significant jump in rice grain yield was observed from 3.79 t ha^{-1} without GM to 5.27 t ha^{-1} by practicing GM. The application of lime and RP to *Rabi* crops had a significant effect on *Kharif* rice [73]. Therefore, GM and the application of soil amendments can sustain higher yields in these poor-quality soils of Sundarbans.

Table 6. Rice grain yield (t ha^{-1}) in *Kharif* 2017 and 2018 under acid saline soil management.

Treatments	*Kharif* 2017	*Kharif* 2018
Control (no amendment)	3.96 c	3.79 c
Green manuring (GM)	4.45 b	5.27 ab
Lime at 1.5 t ha^{-1}	4.23 c	4.68 b
RP at 0.25 t ha^{-1}	4.17 c	4.91 ab
Lime + RP	4.68 b	5.39 ab
GM + Lime	5.74 ab	5.47 ab
GM + RP	6.04 a	5.38 ab
GM + Lime + RP	6.17 a	5.66 a

Figures with same letter in a column are not significantly different. Source: [60].

There was a significant improvement of soil pH due to GM and the application of rock phosphate (Figure 5). The effect of the soil amendment was studied in a hybrid maize crop in a rice–maize cropping system in these acid saline soils with four treatments viz. control (no amendment), lime, rock phosphate, and lime + rock phosphate. The observations of the soil pH were made during the *Rabi* season. The soil pH increased from about 5 to more than 5.5 due to these treatments [59].

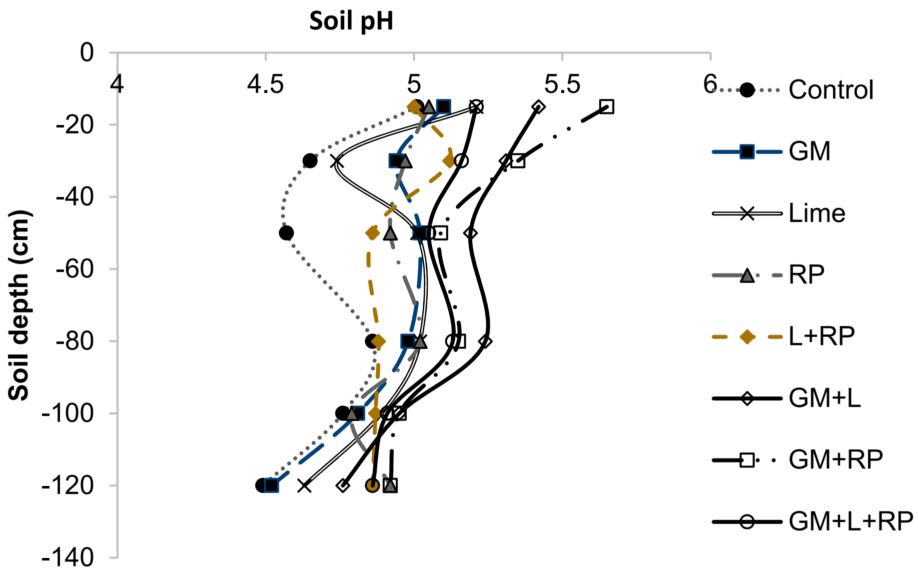


Figure 5. Increase in soil pH of acid sulphate soils by green manuring during pre-*Kharif* and application of soil amendments during the pre-Rabi season in the Ganges Delta. Source: [59].

Beneficial effects of the application of soil amendments on maize crop growth (plant height and root length), yield attribute, and yield were observed in the treatments over the control (Table 7). The maize kernel yield increased to 5.4–6.0 t ha^{-1} in the amended plots, which was significantly higher over the yield recorded in the control plot (2.6 t ha^{-1}); however, among the amendments, the differences in kernel yield were statistically non-significant (Table 7).

Table 7. Performance of maize under different acid sulphate soil management treatments during *Rabi* 2018–2019.

Treatments	**Plant Height (cm)**	**Root Length (cm)**	**1000 Kernel wt (g)**	**Kernel Yield (t ha^{-1})**
Control (no amendment)	148.0 b	21.0 c	261.9 c	2.6 b
Lime at 1.5 t ha^{-1}	199.2 a	34.6 a	320.7 a	5.6 a
Rock phosphate (RP) at 0.25 t ha^{-1}	199.8 a	36.4 a	298.1 b	6.0 a
Lime + RP	203.9 a	27.9 b	286.6 b	5.4 a

Figures with same letter in a column are not significantly different. Source: [60].

In the acid saline soils of Sundarbans, the application of lime along with paddy straw mulching also helped increase the yield of the *Rabi* season crops. Both liming and paddy straw mulching significantly increased the maize kernel yield from 1.93 t ha^{-1} to 3.45 t ha^{-1} (Table 8).

The soils (pH < 4.0) are rich in exchangeable Al and Fe and highly deficient in available P. These soils show very poor crop yields. The soils are very low in available P with a high P fixation capacity. The available phosphorus in the soil increases slightly due to liming and the application of P fertilizers. However, over liming decreases crop yield [147]. The available P content of the soil also increased due to the application of rock phosphate. The beneficial effect of rock phosphate may not be immediately reflected, and its effect may be observed after a few initial cropping seasons [145]. The liming of the soil and the application of high doses of P fertilizer, particularly water-soluble phosphate fertilizers, would improve the crop yield [49]. Reliming may be necessary after a few years. The combination of green manuring, the application of a half dose of lime requirement (1.33 tha^{-1}), and the double dose of the recommended P fertilizer (80 kg ha^{-1}) increased the soil pH and grain yield of *Kharif* rice and *Rabi* sunflower in the Ganges Delta [49]. The grain yield of *Kharif* rice increased from 1.62 tha^{-1} under the control to 4.33 tha^{-1} due to green manuring combined with the application of a half dose of lime and a double dose of P; the yield was at par (4.36 tha^{-1}) with the application of the full (2.66 tha^{-1}) lime requirement (Table 9).

Table 8. Maize yield in acid sulphate soils of the Ganges Delta (West Bengal) during *Rabi* 2018–2019.

Treatment	Kernel Yield (t ha^{-1})
Control	1.93 d
Lime at 1.5 t ha^{-1}	2.89 c
Paddy straw mulch at 6.0 t ha^{-1}	3.08 b
Lime + Paddy straw mulch	3.45 a

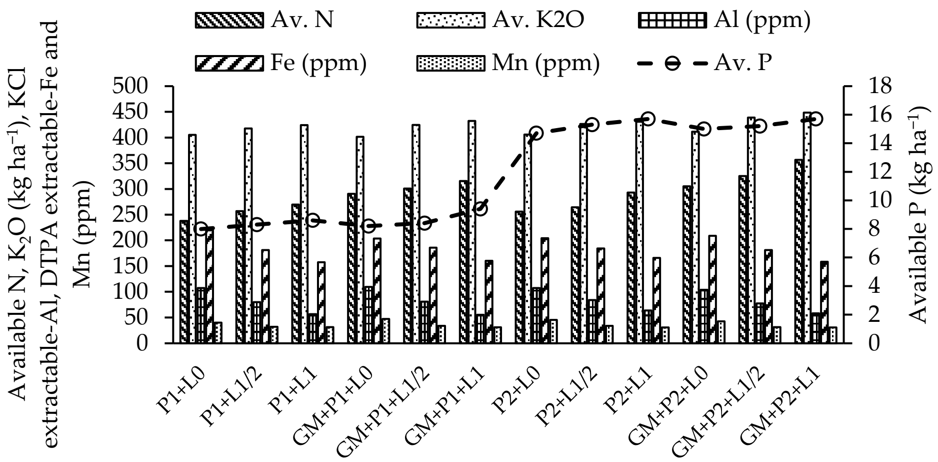
Figures with same letter in a column are not significantly different. Source: [60].

Table 9. Increase in soil pH and yield of crops in acid sulphate soils of the Ganges Delta through integrated management (green manuring, liming, and phosphorus application).

Treatments	Soil pH	Grain Yield (tha^{-1})	
		Kharif Rice	*Rabi* Sunflower
Control	4.2	1.62 a	0.89 a
P1 + L0	4.3	2.8 b	1.23 b
P1 + L1/2	5.2	3.14 c	1.7 e
P1 + L1	5.8	3.15 c	1.75 ef
GM + P1 + L0	4.3	3.21 c	1.35 c
GM + P1 + L1/2	5.4	3.69 d	1.78 e
GM + P1 + L1	6.1	3.8d e	1.84 g
P2 + L0	4.1	3.62 d	1.59 d
P2 + L1/2	5.3	3.97 e	2.05 h
P2 + L1	6.1	3.93 e	2.08 h
GM + P2 + L0	4.6	4.01 e	1.67 e
GM + P2 + L1/2	5.2	4.33 f	2.13 h
GM + P2 + L1	6	4.36 f	2.17 h

GM: Green manuring with Sesbania; P1: 40 kg P_2O_5 ha^{-1}; P2: 80 kg P_2O_5 ha^{-1}; L0: No lime application; L1/2: Half dose of lime requirement (1.33 tha^{-1}); L1: Full dose of lime requirement (2.66 tha^{-1}); Figures with same letter in a column are not significantly different. Source: [49].

The effect of the combination of treatments was also observed on the *Rabi* sunflower crop, with a significant increase in yield from 0.89 tha^{-1} under the control to 2.13–2.17 tha^{-1} under green manuring, liming, and P fertilizer application [49]. Green manure increased the available N status; the application of P_2O_5 improved P nutrition, and lime reduced the toxicity effect by reducing the KCl-extractable Al and the DTPA-extractable Fe and Mn contents of the soil (Figure 6).



GM: Green manuring with Sesbania; P1: 40 kg P_2O_5 ha^{-1}; P2: 80 kg P_2O_5 ha^{-1}; L0: No lime application; L1/2: Half dose of lime requirement (1.33 tha^{-1}); L1: Full dose of lime requirement (2.66 tha^{-1})

Figure 6. Effect of green manuring, liming, and P fertilizer application on soil-available nutrients of acid saline soils of the Ganges Delta. Adapted from [49].

4. Acid Sulphate Soils from the Perspectives of the Ganges Delta

According to a recent report to the United Nations, almost one third of the world's farmable land has disappeared in the last four decades [148]. Soil degradation is the loss of the intrinsic physical, chemical, and/or biological qualities of soil either by natural or anthropic processes, which result in the diminution or annihilation of important ecosystem functions [149]. Degradation reduces the long-term ability of soils to provide the complex multitude of services upon which the very survival of humanity is dependent [150]. Acid sulphate soils are used for agriculture in various parts of world, including in the Ganges Delta, but they are limited due to their present production capacity, with lower and unsustainable yields and are underutilized. Scientific management and restoration and policy interventions are needed to harness their sustainable potential as well as to make these soil systems as productive as highly fertile soils.

4.1. Research Outlook on Acid Sulphate Soils

Present research, development, and scientific inventions are very limited on the productive utilization and conservation of ASS. Though research efforts were made to characterize these soils, research strategies for their large-scale, sustainable use need to be formulated. Mapping of the spatial distribution to obtain the current status of utilization may be performed by using modern geographical information systems, modelling approaches, and other geostatistical and information technology tools. Soil hydrogeochemical models are effective predictive tools to ascertain the best reclamation practice [151]. Machine learning methods can be used following the digital soil mapping approach involving methods, such as Random Forest, Gradient Boosting, and Support Vector Machine [152]. Artificial neural networks demonstrated promising predictive classification abilities for the mapping of potential acid sulphate soils on a large scale [153].

4.2. Awareness vis-à-vis Extension of Developed Management Strategies

The knowledge of the farming community regarding their own soil resources with the hidden constraints of the ASS needs to be strengthened, and awareness generation regarding the safe handling and sustainable/multiple utilization of such land is pertinent. There are technologies to reduce the negative effects of ASS by various measures as described previously in this paper; however, there is a necessity to popularize such measures amongst the user groups and extension personnel. New innovations for the practical applications of the package of practices also boost the spread of the existing knowledge on the management of ASS. Precautions and care during land-use changes as well as during the widening, dredging, and excavation of water-harvesting/irrigation infrastructures, such as canals, ponds, and furrows, are essential, as these activities may increase the source of acidic pollution to the waterways [154]. Under the climate change scenario, there are predictions of the greater vulnerability of the coastal and deltaic regions, resulting in frequent seawater ingress and the inundations of low-lying cultivated fields [28]. The inundation of coastal lowland ASS with seawater or even water with low salt concentration (10–50% seawater concentration) can mobilize high concentrations of Al, Fe, Nis and Zn and increase soil acidity further [155]. Keeping these facts in mind, the brackish water aquaculture practices with intentional flooding of seawater, which is gaining in popularity among the farming community in the Ganges Delta [156], needs precautions, stringent guidelines of use, and modern management options.

4.3. Policy Framework for Sustainable Use of ASS

There is a need for appropriate technical and procedural guidelines to avoid an adverse impact of ASS on the environment and achieve good management practices for its use for agricultural production in areas underlain by ASS in the Ganges Delta. Appropriate guidelines may be developed by using the accumulated knowledge as reported in this paper and elsewhere and as guidelines formulated for other countries, such as in Western Australia [157]. These guidelines may help the state/local governments in decision making while pursuing land-based developmental activities in this region. These may be prohibitive for certain purposes and regulatory for others based on research evidence [52]. In Denmark, legislation prohibits the drainage of areas classified as potential acid sulphate soils without prior permission from environmental authorities [153]. There should be similar restrictions in other regions. Regulations may be for a minimum disturbance and the neutralization of the acidity before its use. Modern technologies and machines may help minimize the disturbance of ASS, while ensuring safe utilization. Neutralization techniques as per the best results, economics, and availability of amendments in the locality are required to be followed. The faulty use of such land has several environmental consequences, including loss of habitat, loss of amenity, sedimentation and erosion, arrested soil ripening, pollution, and other economic and social impacts. Guidelines, precautions, and restrictions need to be formulated particularly for land-use changes and conversions in such soils. Therefore, to formulate the best framework for this region, international-, national-, and local-level expertise and policies may be consulted by the involvement of all concerned including the farming communities, agricultural agencies, policy makers, etc.

5. Conclusions

Acid sulphate soils form by natural process but pose a serious threat to agriculture, ecosystems, and animal kingdom due to unscientific anthropogenic interventions. These soils need a specific management strategy that is different from other problem soils. The potential ASS turns to actual ASS under drainage/oxidation resulting in the formation of sulphuric acid, which reduces the pH significantly. A diagnosis of ASS with respect to the occurrence of sulphidic materials and a sulphuric horizon is essential to formulate prudent management strategies. Integrated nutrient management involving green manuring and the application of organic matters, crop residues, biochar, biofertilizers, microbial formulations, and liming could restore soil fertility and the productivity of these soils. When used for agriculture, the selection of tolerant crops and varieties is essential. Apart from agriculture, other land-use options on such soils, such as pisciculture, animal husbandry, agroforestry, and biodiversity conservation, may be contemplated without disturbing the soil profile. Perspective planning of use of such soils requires guidelines, regulations, and policies for the safe handling and sustainable production without hampering the environmental and ecological balance.

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and editing, S.K.S., M.M. and B.M.; visualization, M.M.; supervision, B.M.; project administration, S.K.S. and B.M.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

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