Soil and Water Quality of an Acid Sulfate Soil Area in Kelantan Plains, Malaysia and its Effect on the Growth of Rice

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ABSTRACT---*A study was conducted to determine land quality in an acid sulfate soil area in Semerak, Malaysia by studying the soil/water characteristics and their effects on rice growth. Various physico-chemical indicators were selected to assess the quality of the land. A glasshouse experiment was later conducted to alleviate the infertility of the soil for rice cultivation. The treatments were ground magnesium limestone (GML) at the rates of 0, 2 and 4 t/ha, with or without organic fertilizer. Water quality in the paddy fields of the studied area was assessed in terms of its pH, EC, cations (Ca, Mg and K), anions (F, Cl, Br, NO_2, NO_3, PO_4, and SO_4) and heavy metal concentration (As, Cd, Cr, Cu, Mn, Pb, Zn, and Fe). Results showed that applying GML in combination with organic fertilizer at the rate of 4 t/ha had far reaching ameliorative effects on: 1) soil pH which increased from 3.75 to 5.45; and 2) exchangeable Ca which increased from 0.39 to 1.45 $cmol_c$/kg. This in the end had increased rice yield significantly. The original field water pH was very low, with values mostly about 4, which was far below the critical pH for rice production of 6. Ca and Mg in the water ranged from 26.22 to48.71 and 13.75to17.82 mg/l, respectively. The concentration of Al in the water of the rice fields was 203.07-465.76 µM, while that of Fe was 77.46 to 163.90 µM. The concentrations of these two metals were far above the critical level of 15-20 µM. Sulfate concentration in the water was high, ranging from 283.80 to 629.80 mg/l. Heavy metals detected in the water of the rice fields were Mn (0.198-0.906 mg/l), Zn (0.018-0.191 mg/l), As (0.001-0.077 mg/l) and Cu (0.020-0.087 mg/l). This study clearly showed that the quality of the land in the area under study was low; hence, required special agronomic intervention to sustain rice production. GML applied in combination with organic fertilizer at the appropriate rate as proposed in this study is probably the best agronomic practice to alleviate the infertility of the acid sulfate soils for sustainable rice production.*

Keywords---Acid sulfate soil, Al toxicity, heavy metal, land quality, organic fertilizer, rice.

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1. INTRODUCTION

Throughout the history of mankind, various soil management practices have been adopted to increase food for human consumption, but some were without due regard to environmental degradation. Soil degradation is one of the most important indicators for assessing environmental quality. Poor land management practices, including unreasonable land use, has caused deterioration of soil quality, resulting in soil structure degradation and organic matter loss which affect water, air and nutrient fluxes as well as plant growth [1, 2]. In addition, changes in soil quality are not only associated with soil management, but also related to changes in temperature and precipitation [3].

Soil quality is defined as the continued capacity of soil to function as a vital living system within an ecosystem and land use boundaries, sustain biological productivity, promote the quality of air and water environment and to maintain plant, animal and human health [4]. Soil quality cannot be assessed directly; however, soil properties that are sensitive to changes in management can be used as indicators [5]. By choosing some soil physical and chemical indicators, soil quality can be addressed. According [6]soil quality is a function of various factors, such as parent materials, physical properties, chemical properties and topography. Soil physical properties strongly influence soil function that determines potential land uses [7, 8]. Total quality of agro-ecosystems significantly affects soil physical and chemical properties as well as biological soil processes [9]. According to [10], soil with good physical quality also has fluid transmission and storage characteristics that permit correct proportions of water, dissolved nutrients and air for both maximum crop performance and minimum environmental degradation.

For cultivating rice on acid sulfate soils, chemical soil indicators take more attention than physical soil indicators because of the problems resulting from nutrients imbalance and high acidity. A high quality soil not only produces sufficient food and fiber, but also plays an important role in stabilizing natural ecosystem that enhances water and air quality [11]. Good soil quality is characterized by its high productivity without significant soil or environmental degradation [12].A better knowledge of soil quality is essential for designing farming systems, which can maintain or improve soil quality and/or crop production [13, 14]. Soil fertility loss directly affects rice yield because of reduction in soil quality [15].On the other hand, adding organic matter, careful management of fertilizers, pesticides and tillage will protect the soils and eventually improve their quality.

One of the main problem for the acid sulfate soils is drainage discharged containing pyrite (FeS_2) are a serious environmental concern in many regions of the world, with pH often less than 4 and concentrations of iron and aluminum that are high enough to cause serious downstream impacts on flora and fauna [16, 17]. The oxidation of pyrite and other iron-bearing sulfide minerals and the subsequent release of sulfuric acid dissolve iron those are available for crop uptake [18, 19]. Furthermore, pyrite oxidation produces sulfuric acid, which then attacks clay minerals, resulting in the release of aluminum and other acid-soluble metals. Drainage from acid sulfate soils has been associated with its effects on plant growth [20], acidification of water bodies [21, 22, 23, 24,25] and mortality of fish [26].Many environmental problems are associated with discharging of these acidic products into river or lakes having fish and marine creatures or plants that are not tolerant to acidity. Hence, the decline in soil and water quality can have a risk on aquatic ecosystem, industrial, agricultural and human health.

Acid sulfate soils occur naturally in the coastal regions of the world. As reported by [27], these soils are sporadically distributed in the coastal plains of the west and east coast of Peninsular Malaysia (Malaysia), Bangkok Plains (Thailand,), Mekong Delta (Vietnam) and Kalimantan (Indonesia). They are mainly cropped to rice with the yield far below their national average. Pyrite in the soils is formed by bacterial sulfate-reduction, a process requiring anaerobic conditions, sulfate and degradable organic matter [25]. Sulfur will be stored safely in these soils if it is not exposed to the air and oxidized. If it is exposed to the air, pyrite reacts with oxygen and water, producing sulfuric acid and heavy metals that affect both soil and water quality. Sulfuric acid will lower pH that decreases the availability of nutrients. In addition, the high acidity will dissolve toxic aluminum and iron, making them more available to plants and aquatic in the vicinity of acid sulfate soils.

Crop yield is strongly affected by the quality of the land on which it grows [28]. Therefore, the quality of land in acid sulfate areas has a close relation with rice cultivation. Rice is by nature known to have a slight tolerance towards acidity [27]. However, if the pH is too low, rice growth is adversely affected. Another property of soil that affects rice growth is high Al concentration in the water. [27] stated that Al concentration in the water of rice fields cropped to rice in Peninsular Malaysia was > 800 µM, higher than the critical level of 15 µM [29, 30].

The chemical properties of the land that are adversely affecting rice growth should be modified accordingly to sustain rice production. Some agronomic practices that use in ameliorating acid sulphate soil are application of GML or basalt on the soils [30, 27]. Hence, the main purpose of this study were: 1) to determine the quality of soil in Malaysia covered by acid sulfate soils cropped to rice; and 2) to alleviate the infertility of the soils in the area to sustain rice production using ground magnesium with or without organic fertilizer.

2. MATERIALS AND METHODS

2.1. The study area

The study area was located at Semerak, Kelantan, Malaysia (N52.208, E102 28.501) (Figure 1, 2). The state of Kelantan is located in the east coast of Peninsular Malaysia. The area under investigation has tropical wet climate, with average temperature of 32 °C and the annual rainfall of 2290-2540 mm [31]. The climate of this region is influenced by the South China Sea. Kelantan Plainsare portrayed by the presence of a blend of riverine and marine alluvial soils, framed as a result of the ascent and descent in ocean level during the Quaternary [32].

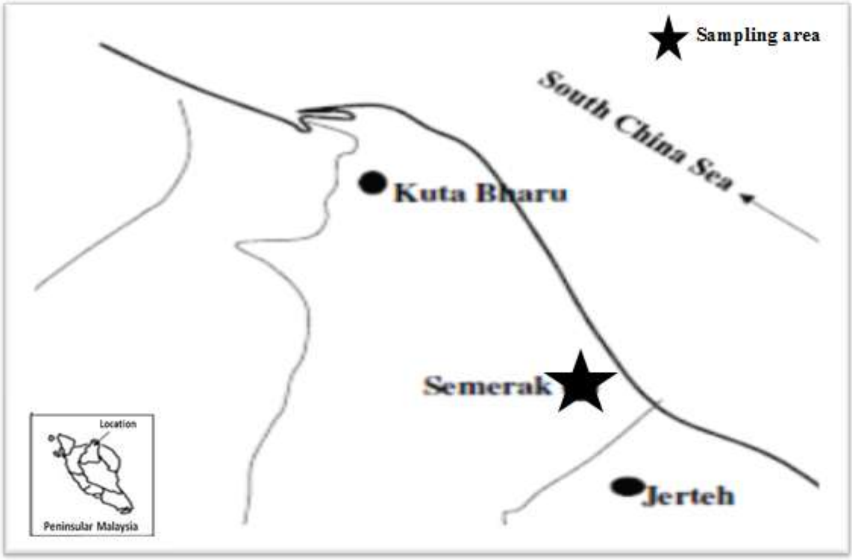

Figure 1: A map of Semerak, Kelantan showing the sampling area

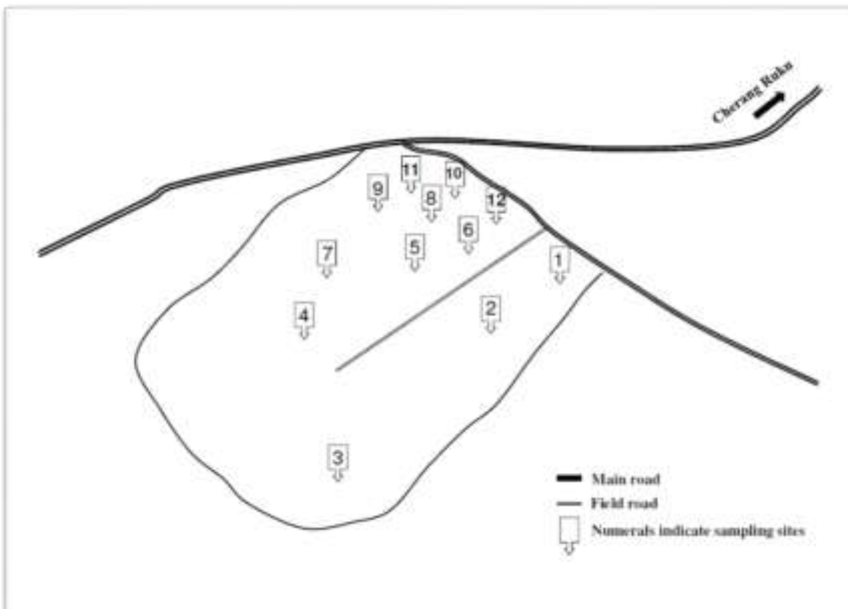

Figure 2: The sampling sites (marked by numbers) in Semerak, Kelantan, Malaysia

2.2. Sampling of Soil and Water

Soil samples were collected at the depth of 0-15 and 15-30 cm from twelve sites in the study area (*Figure 2*). The soils were classified as acid sulfate soils due to their low pH of < 3.5 in the subsoil (tested in the field) as well as the presence of yellowish jarosite mottles at depth (observed during the sampling time). All soil samples were transferred to the laboratory at Universiti Putra Malaysia, Serdang, air-dried in the laboratory, sieved through 2 mm mesh and kept for physico-chemical analyses.

Water samples, collected from the twelve sites in the study area, were kept in polythene containers (500 mL). In the laboratory, 2 mL of concentrated HNO_3 were added to the samples to avoid any changes happening to the metals in the water, like precipitation. Water samples were appropriately processed in the laboratory and kept in suitable containers before being analyzed for various chemical parameters.

2.3. Determination of the physical indicators

Soil texture was determined by the pipette method as described by [33].Bulk density was determined by cylindrical core method [34]. Using bulk density values determined in this study, soil porosity and soil water contents were estimated. Aggregate stability was determined by the wet sieving method of [35], while particle density was determined by the method of [36].

2.4. Determination of the chemical indicators

Soil pH (water 1:2.5) and EC were determined using the method of [37]. The determination of cation exchange capacity (CEC) was carried out by leaching with ammonium acetate 1M NH_4OAc buffered at pH 7 [38]. The Ca, Mg and K in the extracts (exchangeable values) were measured by atomic absorption spectrometry (AAS). Exchangeable Al was determined by the method of [39] using 1 M KCl to extract the Al, which was later determined by AAS. The available P in the soil was determined by the [40] method using auto analyzer (AA). The extractable Fe was measured by double acid method. In this method, Fe was extracted using 0.05 M HCl in 0.0125 M H_2SO_4. Five g of air-dried soil was mixed with 25 mL extracting solution, shaken for 15 minutes and centrifuged at 180 rpm. The supernatant was then filtered through filter paper (Whatman no 42) and the Fe was determined by Perkin Elmer Analyst 400 atomic absorption spectrometry (AAS). Total C, S and N were determined by using CNS TruMac Analyzer.

2.5. Analysis of water from rice fields

Water samples from the rice fields were kept in clean polyethylene bottles based on the advice of [41].Water samples were analyzed for some chemical parameters, such as pH, electrical conductivity (EC), which were measured by pH meter and EC meter, respectively. The pH probe was calibrated using a standard buffer solution of pH 4, 7 and 10, while the EC meter was calibrated with 0.001M KCl to give a value of 14.7 µS/m at 25°C. Perkin Elmer Analyst 400 atomic absorption spectrometry (AAS) was used to determine the cations (Ca, Mg, K and Na). Inorganic anions (F, Cl, $SO_{4,}$ $PO_{4,}$ NO_2, NO_3, and Br) were analysed by ion chromatography APHA 4110B Metrohm 882 compact IC plus. Heavy metals (Fe, Zn, As, Cd, Cr, Cu, Mn and Pb) were measured using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), Perkin Elmer Optima ICP.

2.6. Pot experiment in glasshouse

A glasshouse experiment was conducted using soil from acid sulphate soil and the rice variety MR 219 was used to test the effects of GML and/or organic fertilizer application on its growth. Organic fertilizer used was JITU^{TM}, a sugar cane-based organic fertilizer, at the rate 0.25 t/ha. This organic fertilizer was composed of complete and balanced nutrients needed by rice; such as N (5.03%), P (0.25%) and K (0.35%): hence, was expected to enhance the growth of rice. In addition, it contained beneficial microbes that helped stimulate the growth of root hairs for maximal nutrients adsorption (as claimed by the manufacturer). Factorial Completely Randomized Design (CRD) experiment with three replications and one factor was conducted; ground magnesium limestone (GML) and organic fertilizer were used. The treatments are shown in the Table 1. Soils were analyzed before and 40 days after sowing (DAS) to see the effects of treatments on soil indicators. Rice yield was recorded at harvest, which was after 120 days.

Table 1: Experimental treatments in the glasshouse.

Symbol	Treatment
T1	Control
T2	2 t GML/ha
T3	4 t GML/ha
T4	2 t GML/ha + organic fertilizer
T5	4 t GML/ha + organic fertilizer

2.7. Statistical analysis

Data available from this study were analyzed by ANOVA for analysis of variances and Tukey test for mean comparison using SAS version 9.3 (SAS Institute, Inc., Cary, N.C., USA).

3. RESULTS AND DISCUSSION

3.1. Soil Quality

Good soil quality means that the particular soil is able to supply enough essential nutrients needed for the healthy growth of crops. For such a good soil, nutrients are sufficiently available and ready to be used by the plants, and at the same time they are not expected to be leached into the groundwater or have toxic materials that affect living creatures in the soil.

3.1.1 Physical indicators

The physical state of a soil has a direct influence on the quality of the environment and on crop production [42]. Further, the balance of air and water required to enhance soil quality is maintained by a well-aggregated soil (existing in good physical condition) [43]. Physical soil quality indicators include soil temperature, water holding capacity, soil texture, topsoil depth, porosity, bulk density and aggregate stability. Results from this study showed that the texture of the soil ranged from silty clay loam to clay loam (Table 2), which was considered a good texture for rice growth as it has the capacity to retain water. Rice is usually grown on soils of widely varying particle-size classes, mostly of medium (fine loamy) to fine (fine clayey) particle-size distribution in their surface horizon.

Table 2: Topsoil particle-size distribution of the acid sulfate soils in Semerak, Malaysia.

Samples	% Clay	% Silt	% Sand	Texture
1	25.96	47.42	17.93	Loam
2	23.35	57.57	19.01	Loam
3	36.72	58.97	4.27	Silty clay loam
4	30.25	63.57	6.16	Silty clay loam
5	29.30	65.97	4.70	Silty clay loam
6	34.39	59.35	6.22	Silty clay loam
7	37.18	50.29	12.46	Silty clay loam
8	25.11	45.19	28.16	Loam
9	29.39	49.60	20.96	Silty clay loam
10	31.51	56.86	8.59	Silty clay loam
11	29.72	63.91	6.48	Silty clay loam
12	29.41	64.24	6.31	Silty clay loam

The bulk density of the soils under investigation was found to be at the good level, which means they could provide structural support for water and solute movement as well as aeration (Table 3).

Table 3: Selected physical properties of the topsoil of the acid sulfate soils Kg. Golok, Kemasin-Semerak, Kelantan, Peninsular Malaysia.

Sites	Bulk density (g/cm^3)	article density (g/cm^3)	Porosity
1	1.20	2.35	0.50
2	1.20	2.45	0.52
3	1.10	2.36	0.54
4	1.10	2.44	0.55
5	1.30	2.64	0.51
6	1.10	2.55	0.57
7	1.00	2.56	0.58
8	1.40	2.40	0.42
9	1.30	2.50	0.48
10	1.40	2.30	0.40
11	1.00	2.45	0.60
12	1.20	2.60	0.54

3.1.2. Chemical indicators

3.1.2.1. Soil pH

Soil pH in the current study was mostly ≤ 4 (Table 4), indicating the presence of high amount of acidity. This pH level was far below the critical pH for rice production of 6 as determined by [29, 30] When pH is less than 5, Al in the water will be hydrolyzed to produce more acidity, causing stress to the growing rice plants in the field [27]. Adjusting soil pH to the appropriate level for sustainable crop cultivation is a very important step in soil management. One of the concepts of soil quality is achieving a desired purpose; thus, maintaining soil pH at an acceptable level for healthy rice growth is a key aspect of soil quality. Removing excess hydrogen ions in the soil should be done to manage soil quality issue relating to soil acidity.

Table 4: Changes in the chemical properties of the soils with depth (0-15) cm and (15-30) cm.

Sites	Depth(cm)	pH	EC(dS/m)	Exchangeable cations (cmol$_c$/kg)				CEC (cmol$_c$/kg)	Extractable Fe (mg/kg)	Total N (%)	Total S (%)
				Ca	Mg	K	Al				
1	0-15	5.53	0.39	2.20	1.41	0.18	3.06	13.14	183	0.19	0.12
	15-30	4.14	0.12	0.86	1.09	0.28	3.28	10.71	190	0.07	0.07
2	0-15	4.71	0.20	1.19	1.09	0.16	3.55	7.03	200	0.15	0.08
	15-30	3.54	0.11	0.49	0.57	0.10	3.81	10.07	208	0.11	0.09
3	0-15	3.72	0.09	0.60	0.56	0.20	4.15	11.42	212	0.27	0.12
	15-30	3.62	0.10	0.28	0.29	0.17	4.77	12.85	240	0.19	0.13
4	0-15	3.61	0.10	0.34	0.35	0.15	3.68	11.57	172	0.22	0.15
	15-30	3.55	0.10	0.10	0.36	0.16	4.10	13.71	189	0.08	0.07
5	0-15	4.24	0.10	1.33	1.22	0.22	2.94	11.35	170	0.07	0.09
	15-30	5.99	0.11	2.95	1.67	0.12	2.50	10.42	183	0.12	0.08
6	0-15	4.23	0.13	1.32	1.34	0.11	3.87	13.14	264	0.17	0.18
	15-30	3.74	0.12	0.94	1.01	0.16	4.33	12.21	301	0.06	0.11
7	0-15	4.36	0.10	1.09	1.06	0.20	3.28	9.21	283	0.20	0.12
	15-30	3.85	0.10	0.62	0.61	0.06	3.38	8.57	314	0.09	0.08
8	0-15	4.14	010	0.89	0.96	0.16	3.78	9.35	158	0.18	0.12
	15-30	3.54	0.10	0.63	0.69	0.16	4.14	8.57	172	0.10	0.09
9	0-15	4.58	0.10	1.13	1.21	0.12	3.98	8.78	203	0.42	0.08
	15-30	4.00	0.10	0.73	1.00	0.14	4.26	7.57	232	0.47	0.11
10	0-15	3.53	0.10	0.75	0.74	0.19	2.04	9.71	302	0.57	0.13
	15-30	3.41	0.10	0.20	0.44	0.21	2.32	9.42	335	0.40	0.07
11	0-15	5.95	0.15	0.85	0.91	0.22	2.45	13.92	208	0.57	0.22
	15-30	4.07	0.13	0.12	0.46	0.07	3.11	9.92	240	0.40	0.11
12	0-15	3.89	0.14	2.84	1.58	0.15	3.45	9.21	134	0.51	0.10
	15-30	3.53	0.10	1.16	0.43	0.07	3.87	9.71	153	0.39	0.05

Soil chemical, biological and physical properties are affected by pH. Nutrients availability, elemental toxicity and microbial activities have a very close relationship with soil pH which, in turn, affects rice growth**.** Soil pH regulates the solubility of nutrients and elements. Therefore, it controls the availability of nutrients for plant uptake. At low pH level, the solubility of some elements, like Al and Fe, increases and change to toxic level [27]. On the other hand, the availability of some essential nutrients, like Ca, Mg and K, will decrease, creating unfavorable conditions for plant to habitat as shown in Table 4. In addition, at low pH level commonly seen in the study area, phosphorous is expected to be precipitated as insoluble Al-Fe-phosphate that reduces the availability of P for rice growth [44]. This phenomenon occurs frequently in acid sulfate soils which naturally contain high concentration of Al and/or Fe.

Biological properties are also affected by low pH, by regulating the biochemical transformations of minerals and organic materials in the soils. At very low pH, because of low microbial activity, the process of organic matter mineralization is de-accelerated. Nitrification and nitrogen fixation are also inhibited bylow pH. Physically, as soil pH affects cations availability, the aggregate stability will be affected because cations like Ca are used as bridges between organic colloids and clays.

3.1.2.2. Exchangeable Aluminum

Exchangeable Al in the soils was high, ranging from 2.33 to 4.89 $cmol_c$/kg (Table 4). The surface of rice root is negatively-charged, so the positively-charged Al ion is naturally attracted to it [29, 27]. At low pH of <5, Al dissolves readily, causing toxicity to rice plants [45]. Hence, the presence of high Al concentration in the soils under study could severely affects the morphology of rice roots that resulted in the decrease of root surface area, which in the end caused Ca and Mg deficiencies [46].

The release of Al in various forms from clay minerals in the soils of our study was largely pH dependent, of which the dominant forms were Al^{3+} and $AlOH^{2+}$ [47]. Hence, we believed that growing rice in the acid sulfate soils of the current study would strongly be affected by aluminum toxicity. If the roots of rice had absorbed the toxic Al, it would accumulate in them and eventually damaged their normal function. If this happened, water could not be taken up sufficiently, resulting in less nutrient uptake to support normal rice growth. As Figure 3 shows, Al in soil was negatively correlated with soil pH, meaning that when soil pH was lowered, Al concentration was linearly increased and the R was 0.77.

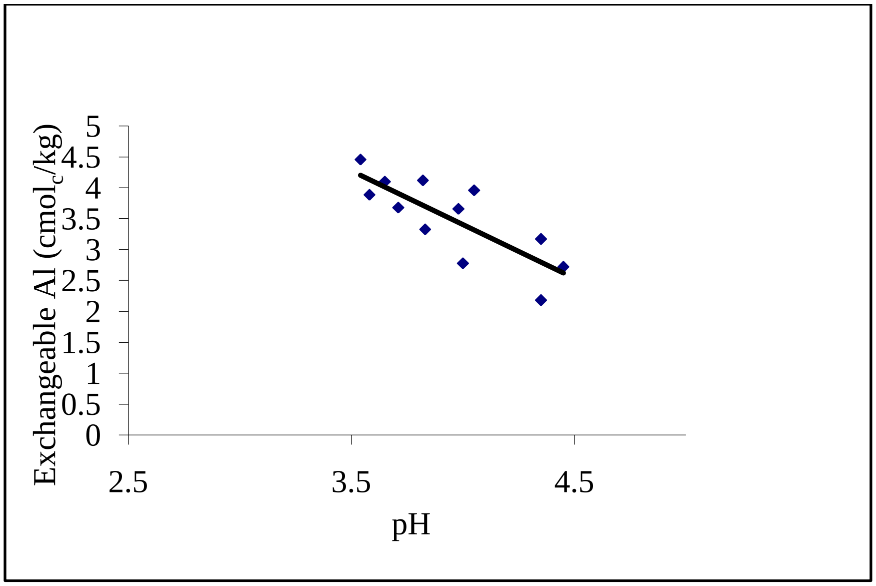

Figure 3: Relationship between exchangeable Al and soil pH

3.1.2.3. Extractable Iron

Iron toxicity is a complex nutrient disorder. There are many reasons for the incident of Fe toxicity in rice; one of them is deficiency of Ca, Mg, K, P and Zn [44].Various studies conducted in Asia and Africa indicated that iron deficiency had a direct effect on rice grown in acid sulfate soils. [48] made an analysis of soil data in relation to Fe toxicity in Asian soils and suggested that Fe toxicity was common in the young acid sulfate soils (Sulfaquepts), but was rare in the older, more deeply developed acid sulfate soils (SulficTropaquepts) which do not produce high levels of Fe^{2+} upon submergence.

For the soils under study, Fe concentration ranged from 168 to 310 mg/kg (Table 4). According to Nhung et al.[49] Fe concentration above 500 mg/kg was considered toxic to rice growing in the soils. The red color of the water in the paddy fields of the Kelantan Plains is indicative of the presence of excessive amounts of Fe [50]. Iron is commonly associated with acid sulfate soil conditions [25]. Soil-leaching studies had shown that Fe was leached in order of magnitude higher than other metals present within the soil, except Al [51]. The concentration of Fe was closely related with pH as in Figure 4, the R was 0.71.

3.1.2.4. Nutrients Deficiency

The adverse effects of soil health and soil quality arise from nutrient imbalance in soil, excessive fertilization, soil pollution and soil loss processes [52, 53]. Managing soil quality through nutrient management is an important function of chemical soil quality to supply sufficient nutrients for crop growth. Calcium is important in soil conditioning and plant nutrition. In the soil, it has an important role in determining soil physical and chemical characteristics, which is soil pH and structures. Soils having sufficient Ca have good structures, good drainage and are friable. Therefore, by adding lime as ground magnesium limestone (GML) to acid sulfate soil, Ca concentration will be increased [50].
For the current study, the untreated topsoil exchangeable Ca was less than 2 $cmol_c$/kg soil (Table 4), which is the required level for the healthy rice growth [54].In general, Mg acts like Ca in the soils; both stay in soil solution and exchange complexes. Mg is closely related with soil pH, as soil pH increases Mg also increases. Exchangeable Mg in the soil was about 1 $cmol_c$/k g (Table 4), which is the required level for rice production as found by [55].. We believed that GML application at the appropriate rate would be able to alleviate Ca and Mg deficiency in the soils. The presence of extra Ca and Mg in the soils can partly contribute to the alleviation of Al toxicity as had been shown by [56].

3.2. Water Quality

3.2.1. Cations

It is no doubt that the quality of the water used for agriculture is very important for the healthy growth of crops. Features such as salts, pH and alkalinity determine the suitability of the water for crop production. Quality and quantity of water has very close relation to plants as each plant has a specific need for water. This is because water is used to transport dissolved sugar and other nutrients through the plant. Therefore, without proper balance of water, the plant not only is undernourished, but also is physically weak and cannot support its normal growth. Furthermore, water quality determines the stability of soil structures; clay particles will be separated by the presence of moisture and exchangeable sodium, and this will reduce water movement and aeration in the soil.

For the soils under study, due to high acidity and the presence of high amounts of Al and/or Fe, discharge from them to the water bodies nearby would undergo many changes that deteriorated its quality. Based on the data available from this study, many water properties were strongly affected as shown in Table 5. It was observed that water pH ranged from 3.14 to 4.14, which was a common phenomenon for areas occupied by acid sulfate soils in Malaysia [27]. According to Department of Environment [57], this range is classified under class V for Malaysian rivers. This low pH might have environmental problems, for example, metals and structures made of cement will slowly be dissolved.

Table 5: Chemical properties of water in the rice fields.

Samples	pH	EC (dS/m)	Cations (mg/l)				Al (µM)	Fe (µM)
			Ca	Mg	K	Na		
1	3.53	0.54	30.62	13.92	1.50	13.06	203.07	104.00
2	3.14	0.57	33.35	14.51	2.52	13.45	398.46	98.64
3	4.01	0.58	33.69	16.27	2.50	13.35	433.46	130,00
4	3.54	0.65	28.35	14.44	9.10	13.86	383.07	85.43
5	4.12	0.85	43.21	17.69	4.05	15.18	448.07	137.65
6	3.92	1.28	48.71	14.67	8.67	15.65	443.84	99.43
7	3.81	0.59	39.49	15.95	3.31	13.64	420.00	87.10
8	3.95	0.61	26.22	13.75	5.14	12.97	465.76	81.97
9	4.14	0.56	27.87	13.98	4.10	13.28	324.61	163.90
10	3.59	0.76	41.67	17.82	3.00	14.21	206.92	77.46

The EC of the water was low; hence, it was not expected to be harmful to crops growing in the soils under investigation. The EC of these samples were found to be within the recommended level found by [57]. Calcium concentration in the water ranged from 26.22 to 48.71 mg/l, which was high. This was probably because some of it might have come from lime application when the farmer owning the land grew rice. Acid sulfate soils need to be adequately limed at regular interval so as to increase soil pH with concomitant precipitation of Al and/or Fe [27].Likewise, magnesium concentration was high, ranging from 13.75 to 17.82 mg/l. This is consistent with the belief that the paddy fields were limed before the water for the study was sampled. The lime used in Malaysia is ground magnesium limestone which contains high amount of Ca and Mg. In this water, potassium concentration ranged from 1.50 to 9.10 mg/l, while that of Na was from 13.06-15.65 mg/l. These values were normal for water of the paddy fields in acid sulfate soils of the Kelantan Plains [50].
The concentration of aluminum in the water varied, ranging from 203.07 to 465.76 µM. This level is considered very high by any standard, way above the critical level for rice growth of 15 µM [29, 30], which was consistent with the finding of[58]. Iron concentration ranged from 77.46 to 163.90 µM, which was also far too high for the healthy growth of rice [59].

3.2.2. Major Anions

The discussion on water quality with regard to anion concentrations was based on the level proposed by [57]. As shown in Table 6, fluoride concentration in the water ranged from 0.31 to 0.83 mg/l, which would not pose harmful effect on both soils and crops in the area under study. This level of F was considered acceptable for water in the country. Chloride concentration was 20.10-47.42 mg/l, which was regarded as low. According to [57], 80 mg/l is usable for agriculture. High quantity of chloride will restrict plant growth. In the soils under study, its concentration was also low.
Usually, nitrite concentration in water is very low (0.05-0.13 mg/l) compared to that of nitrate (1.01-3.90 mg/l) because in oxygenated water it is easily converted to nitrate. According to [57], the acceptable level was 1 and 7 mg /l for nitrite and nitrate, respectively. Phosphate concentration was about 0.1 mg/l, indicating the maximum acceptable level to avoid accelerated eutrophication; above 0.2 mg/l is not normal for Malaysians rivers according to [57]; this range would lead to accelerated growth and many consequent problems. Bromide concentration was very low, ranging from 0.04 to 0.15 mg/l. As expected, the concentration of sulfate was very high, ranging from 283.80 to 629.69 mg/l. [60] stated that the concentration of SO_4 would be double as a result of pyrite (FeS_2) oxidation as shown by the following reaction:

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

Table 6: Important anions in the water from the rice fields.

Samples	F	Cl	NO_2	Br	NO_3	PO_4	SO_4
	(mg/L)						
1	0.56	20.10	ND	ND	1.17	0.19	283.80
2	0.54	23.33	ND	ND	1.01	0.10	353.42
3	0.35	22.60	0.12	0.04	3.84	0.12	432.30
4	0.42	30.77	0.11	0.15	2.47	ND	420.88
5	0.31	47.42	0.11	ND	2.47	0.11	625.80
6	0.83	35.33	ND	ND	1.09	0.27	629.69
7	0.52	22.89	0.11	0.11	2.39	0.09	420.45
8	0.43	20.60	0.13	0.13	1.21	ND	326.69
9	0.40	21.47	0.13	0.13	2.88	0.15	335.59
10	0.36	25.62	0.05	0.05	3.90	ND	583.08

ND = Not detected

3.2.3. Heavy Metals

It is believed that metals leached from sulfidic soils can greatly contribute to metal accumulation in the water bodies in the surrounding area [61]. These metals may subsequently have negative effects on the ecosystem by causing adverse impacts on organisms [62]. Heavy metals are natural trace components of the aquatic environment, but their levels can be increased by industrial wastes, geochemical structure, agricultural and mining activities [63].

In the current study, the concentration of heavy metals in the water of the rice fields was, in most cases, not in the range that affects soil quality or plant growth (Table 7). It was found that the arsenic concentration ranged from 0.012 to 0.077 mg/l; this range was not too high that pose a threat to marine organisms. Arsenic has been observed to become more mobile in acid sulfate soils during rewetting phase [64] with its mobility increased by high carbonate concentrations/alkalinity [65]. We found that cadmium concentration ranged from 0.001 to 0.003 mg/l, which was lower than the accepted concentration of 0.01 mg/l according to [57].Chromium concentration in the water ranged from 0.001 to 0.005 mg/l; it is only toxic to organisms if the concentration is 2000 to 105,000 mg/l. Mercury is lethal to human life. Fortunately, its concentration in the water of this study (0.020 - 0.087 mg/l) was below the critical level of 0.1 - 2.0 mg/l according to [57].

Table 7: Heavy metals in the surface water of the rice field

Samples	As	Cd	Cr	Cu	Mn	Pb	Zn
		---------------------------------- (mg/l) ----------------------------------					
1	0.012	0.002	0.001	0.081	0.495	0.012	0.128
2	0.019	ND	0.003	0.059	0.528	0.020	0.139
3	0.015	ND	0.003	0.039	0.577	0.028	0.051
4	0.013	0.001	0.003	0.087	0.541	0.021	0.191
5	0.028	ND	0.003	0.045	0.906	0.030	0.050
6	0.012	0.003	0.004	0.049	0.643	0.010	0.119
7	0.016	0.001	0.002	0.041	0.568	0.017	0.063
8	0.077	0.001	0.003	0.051	0.515	0.020	0.105
9	0.015	0.002	0.002	0.053	0.460	0.031	0.146
10	0.020	0.002	0.005	0.020	0.198	0.022	0.018

ND = Not detected

Manganese concentration ranged from 0.198 to 0.906 mg/l, which was a little higher than the recommended level for crop growth. In the absence of dissolved ferrous iron or through the action of oxidizing bacteria, Mn may be precipitated at a lower pH [66]. Lead concentration ranged from 0.010 to 0.031 mg/l; the recommended field water is 0.1 mg/l according to [57] Zinc concentration was found to be0.018-0.146 mg/l, which was considered not harmful to the organisms living in the water.

3.3. Effects of Soil Amendments on soil properties and plant growth

3.3.1.Changes in soil chemical properties

GML application gave ameliorative effects on soil properties as shown in Table 8. It was shown that applying GML improved soil quality via alleviating soil acidity, eliminating Al and/or Fe toxicity, enhancing nutrients availability, which was consistent with the study of [67]. Applying GML alone or in combination with organic fertilizer significantly increased soil pH that precipitated Al as Al-hydroxides [27]. In the treatment where GML was applied at 4 t ha^{-1} in combination with organic fertilizer, soil acidity was almost neutralized. Applying GML together with organic fertilizer would speed up the reduction of Fe^{3+} to Fe^{2+} [68], and the latter was precipitated as inert Fe-hydroxides when pH increased [69]. It means that the exposure of the rice roots to the toxic Fe^{2+} was shorter than it otherwise was. This finding is in agreement with the study of Tran and Vo (2004) who found that adding organic fertilizer in flooded acid sulfate soils reduced Fe toxicity significantly. Figure 4 shows that extractable Fe decreased as soil pH increased, shown by the equation

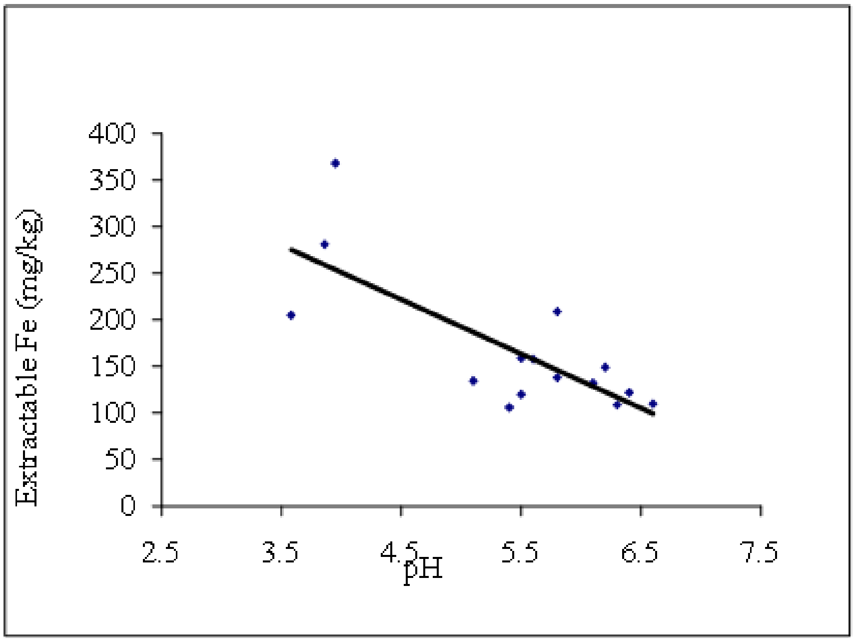

Figure 4: Relationship between extractable Fe and soil pH

The application of GML was not only able to increase pH that removed Al from the solution, but also supplied adequate amounts of Ca, Mg (Table 8), which were very important for the healthy growth of rice [50, 70]. There was positive relationship between soil pH and exchangeable Ca(*Figure 5*). The Ca, to some extent, had the ability to reduce the toxic effect of Al [71, 56]. In addition, it was shown by [56] that the presence of extra Mg could also contribute to the alleviation of Al toxicity.

The available P in the soil increased as the rate of GML combined with organic fertilizer increased. According to [55] rice needed between 7 and 20 mg kg^{-1} of P for its healthy growth (Table 8). Lime application can stimulate microbial activity that release P into soils [72].Therefore, by combining GML with organic fertilizer containing beneficial microbes as had been done in this study, soil quality had improved somewhat that was translated into improved rice growth and eventually its yield.

Table 8: Chemical properties of the soil at harvest.

Treatments	pH	Exchangeable cations ($cmol_c$/kg)				Fe (mg/kg)	P (mg/kg)
		Ca	Mg	K	Al		
T1	3.79 ^{c}	0.97 ^{a}	0.71 ^{a}	0.14 ^{b}	2.22 ^{ab}	284.85 ^{a}	3.18 ^{a}
T2	5.33 ^{b}	1.15 ^{a}	0.56 ^{a}	0.19 ^{ab}	2.49 ^{a}	120.17 ^{b}	2.85 ^{a}
T3	5.86 ^{ab}	1.93 ^{a}	0.74 ^{a}	0.15 ^{b}	1.83 ^{b}	159.00 ^{b}	2.64 ^{a}
T4	5.86 ^{ab}	1.65 ^{a}	0.61 ^{a}	0.21 ^{ab}	2.07 ^{ab}	148.33 ^{b}	2.20 ^{a}
T5	6.36 ^{a}	1.53 ^{a}	0.50 ^{a}	0.50 ^{a}	1.87 ^{b}	121.33 ^{b}	3.36 ^{a}

Means followed by the same letter within a column are not significantly different at $P<0.05$

3.3.2. Effects of amendments on rice yield

In Malaysia, applying GML into acid sulfate soils is a standard practice for rice production [50,27]. Usually one month after application, GML reacts with the soil and subsequently improves its quality. Increase in pH by liming improves nutrients solubility which become more available to rice. It was found that the yield of rice was low in the control treatment due to soil acidity, where soil pH was less than 4 (Table 9). This study showed that rice yield was positively correlated with soil pH (Figure 5) with R value 0.922.

Table 9: Effects of amendments on rice growth and yield

Treatments	Panicle number	Panicle length (cm)	Yield (g grain weight/pot)
T1	4^{a}	14.00^{d}	10.37^{c}
T2	5^{a}	16.50^{c}	13.20^{b}
T3	5^{a}	18.50^{b}	14.13^{b}
T4	5^{a}	19.10^{b}	13.75^{b}
T5	5^{a}	21.10^{a}	16.20^{a}

Means with the same letter are not significantly different at $P < 0.05$

One of the biggest benefits of adding lime is to optimize soil and crop productivity and growth. The roots of rice plants usually grow healthier if the soil is supplied with adequate lime because they are exposed to less amount of toxic aluminum; hence, the growths of their roots are enhanced. At the rate of 4 t/ha of GML in combination with organic fertilizer, plant height, filled panicles and the grain yield were significantly higher than that of the control treatment (Table 9), which was similar with the finding of [73].

The highest panicle numbers (5), panicle length (21 cm) and weight of 1000 grains were found in the GML combined with organic fertilizer treatment. [74] stated that rice yield increased from 2 to 4.5 t/ha/season after annual GML application of 2 t/ha. The increase in yield using this agronomic practice was confirmed by the study of [75].

4. CONCLUSIONS

This study had shown the effects of soil and water quality on rice grown on an acid sulfate soils in Malaysia. It was found that without applying lime and organic fertilizer, rice grew poorly, producing low yield. This was because soil pH was low and the concentration of Al and/or Fe in the water was way above the critical level for rice production. The infertility of the soils can be alleviated satisfactorily by applying GML at the appropriate rate in combination with organic fertilizer. Under natural conditions, it was found the concentration of heavy metals and toxic anions in the water of the acid sulfate soils under investigation were below the level considered harmful to either human being or plants in its vicinity. This study found that acid sulfate soils in Malaysia can sustain rice production if the agronomic practiced proposed in this study is adopted.

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CONFLICTS OF INTEREST---The authors declare no conflict of interest.

6. REFERENCES

[1]Golchin, A., Oades, J. M., Skjemstad, J.O. and Clarke, P. (1995). Structural and dynamic properties of soil organic matter as reflected by 13C natural abundance, pyrolis is mass spectrometry and solid state 13C NMR spectroscopy in density fractions of an oxisolunder forest and pasture. Australian Journal of Soil Research, 33, 59-76.

[2] Tejada, M., Garcia, C. and Gonzalez, J.L. (2006). Hernandez. Use of organic amendment as a strategy for saline soil remediation: influence on the physical, chemical and biological properties of soil. Soil Biology Biochemistry, 38, 1413–1421.

[3] Andrews, S. S., Karlen, D. L. and Cambardella, C. A. (2004). The soil management assessment framework: Aquantitative soil quality evaluation method. Soil Science Society of America Journal, 68,1945-1962.

[4] Doran, J. W. andSafley, M. (1997). Defining and assessing soil healthand sustainable productivity. In: Pankhurst, C., Doube, B.M.,Gupta, V.V.S.R. (Eds.), Biological Indicators of Soil Health.CAB International, Wallingford, Oxon, UK, pp. 1–28.

[5] Andrews, S. S., Karlen, D. L. and Cambardella, C. A. (2004). The soil management assessment framework: Aquantitative soil quality evaluation method. Soil Science Society of America Journal, 68, 1945-1962.

[6] Zhang, Y. C.,Rossow, W. B., Lacis, A. A., Oinas, V. andMishchenko, M. I. (2004). Calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP and other global data sets: Refinements of the radiative transfer model and the input data. Journal of Geophysics Research, 109, D19105.

[7]Fernández-UgaldeO,Virto I.,Bescansa, P., Imaz, M.J., Enrique, A. andKarlen, D.L. (2009). No-tillage improvement of soil physical quality in calcareous, degradation-prone, semiarid soils.Soil and Tillage Research, 106, 29-35.

[8] Griffiths B.S., Ball, B.C., Daniell, T.J., Hallett, P.D., Neilson, R., Wheatley, R.E., Osler, G. andBohanec, M. (2010). Integrating soil quality changes to arable agricultural systems following organic matter addition, or adoption of a ley-arable rotation. Applied Soil Ecology, 46, 43–53.

[9] Flores-Delgadillo L., Fedick, S.,Solleiro-Rebolledo, E., Palacios-Mayorga, S., Ortega-Larrocea, P., Sedov, S. andOsuna-Ceja, E. (2011). A sustainable system of a traditional precision agriculture in a Maya homegarden: Soil quality aspects. Soil and Tillage Research, 113, 112–120.

[10]Topp, G.C., Reynolds, W.D., Cook, F.J., Kirby, J.M. and Carter, M.R. (1997). Physical attributes of soil quality. Soil Quality for Crop Production and Ecosystem Health,25, 21–58.

[11] Griffiths, T. L. (2010). Probabilistic models of cognition: exploring representations and inductive biases. Trends in Cognitive Science, 14, 357–364.

[12]Govaerts, B., Sayre, K. andDeckers, J. (2006). Minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. Soil Tillage Research, 87, 163–174.

[13] Qi, H., Yao, C., Cai, W., Girton, J., Johansen, K.M. and Johansen, J. (2009). Asator, a tau-tubulin kinase homolog in Drosophila localizes to the mitotic spindle. Dev. Development Dynamics, 238, 3248--3256.

[14]Bonanomi, G., D'Ascoli, R., Antignani, V. andZoina, A. (2011). Assessing soil quality under intensive cultivation and tree orchards in Southern Italy.Applied Soil Ecology, 47, 184-194.

[15]Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security.Science, 304, 1623-1627.

[16]Callinan, R.B., Fraser, G.C. andVirgona, J.L. (1993). Seasonally recurrent fish mortalities and ulcerative disease outbreaks associated with acid sulphate soils in Australian estuaries. Paper presented at the Fourth International Symposium on Acid Sulphate Soils, Ho Chi Minh City, Vietnam. The Working Group on Acid Sulphate Soils of the International Society of Soil Science.

[17]WendelaarBonga, S.E. andDederen.L.H.T. (1986).Effects of acidified water on fish.Endeavour 10, 198-202.

[18]Evangelou, V. P. (1995). Pyrite Oxidation and its Control, *CRC Press*, New York, USA.

[19]Appelo, C. A. J. and Postma, D. (1999). Variable dispersivity in a column experiment containing MnO_2 and FeOOH coated sand. Journal Contam Hydrology, 40, 95 -106.

[20] Moore, P. A. and Patrick, W. H. (1991). Aluminum, boron and molybdenum availability and uptake by rice in acid sulphate soils.Plant and Soil, 136, 171–181.

[21]Sammut, J., White, I. and Melville, M.D. (1996). Acidification of an estuarine tributary in eastern Australia due to drainage of acid sulfate soils.Marine and Freshwater Research, 47, 669-684.

[22]Nguyen, T.T. andWilander, A. (1995). Chemical conditions in acidic waters in the plain of reeds,Vietnam.Water Resources, 29, 1401–1408.

[23]Astrom, M. andBjorklund, A. (1995). Impact of acid sulfate soils on stream water geochemistry in western Finland.Journal ofGeochemistry Exploration, 55, 163–170.

[24] Wilson, W.A. (1999). Substrate targeting of the yeast cyclin-dependent kinase Pho85p by the cyclin Pcl10p. Molecular Cell Biology, 19, 7020-70230.

[25] Cook, F. J., Hicks, W., Gardner, E. A., Carlin, G. D. andFroggatt, D. W. (2000). Export of acidity in drainage water from acid sulphate soils, Marine Pollution Bulletin, 4, 319-326.

[26]Sammut, J. and Melville, M. (1995). Impacts of poor water quality on fish. In: Brierly, G.J. and Nagel, F. (editors), Geomorphology and river health in New South Wales. Proceedings of a conference held at Macquarie University. October 7, 1994. Graduate School of the Environment, Macquarie University, Working Paper 9501.

[27]Shamshuddin, J., Elisa, A.A., Shazana, M. A. R. S., Fauziah, C. I., Panhwar, Q.A. andNaher, U.A. (2014). Properties and management of acid sulfate soils in Southeast Asia for sustainable cultivation of rice, oil palm, and cocoa. Advances in Agronomy, 124, 91-142.

[28] FAO. (1985). The ICS: The Interlinked Computerized Storage and Processing System of Food and Agricultural Commodity Data Users' Manual. FAO/ESS, Rome.

[29] Elisa, A. A., Shamshuddin, J. andFauziah, C.I. (2011). Root elongation, root surface area and organic acid exudation by rice seedling under Al^{+3} and/or H^{+} stress. American Journal of Agricultural Biology Science, 6, 324-331.

[30]Shamshuddin, J., Elisa, A.A., Ali, M., Siti, R. andFauziah, C.I. (2013). Rice defense mechanisms against the presence of excess amount of Al^{+3} and Fe^{+2} in the water. Australian Journal of Crop Science, 7, 314-320.

[31]Ooi, J.B. (1963). Land, people and economy of Malaya.London: Longmans. Green& Co.

[32]Tjia, H.D. (1973). Geomorphology. In: De Sitter, L.U., Ed., Geology of the Malay Peninsula, John Wiley & Sons, Inc., Hoboken. pp. 13-24.

[33] Gee, G.W. andBauder, J.W. (1986). Particle-size analysis.p.383–411.InA.Klute (ed.) Methods of soil analysis.Part 1.2nd ed. Agron.Monogr. 9. ASA and SSSA, Madison, WI.

[34]Wilke, M.B. (2005). Determination of Chemical and Physical Soil Properties. In: Margesin, R. and Schinner, F., Eds., Manual for Soil Analysis, Monitoring and Assessing, Soil Bioremediation, Springer-Verlag Berlin Heidelberg, Germany. pp. 47-95

[35] Kemper, W.D. andRosenau, R.C. (1986). Aggregate Stability and Size Distribution. In: Klute A, editor. Methods of soil analysis.Part 1.Physical and mineralogical methods. Madison, WI.

[36] Blake, G. R. and Hartge, K. H. (1986). Bulk Density, in A. Klute, ed., Methods of Soil Analysis, Part I. Physical and Mineralogical Methods: Agronomy Monograp.h. pp. 363-375

[37] Rowell, D.L. (1994). Soil Science: Methods and Applications; Longman: Harlow, UK.

[38]Benton, Jr. J. (2001). Laboratory Guide for Conducting Soil Tests and Plant Analysis. New York, USA:CRC Press LLC.Soil science: Methods and applications D. L. Rowell, Longman Scientific and Technical, Longman Group UK Ltd, Harlow, Essex, UK (co-published in the USA with John Wiley and Sons Inc. New York.

[39]Barnhisel, R. andBertsch, P.M. (1982). Methods of soil analysis.Part 2.Chemical and microbiological properties.American Society of Agronomy Inc. and *Soil Science Society of America*, Inc. Madison, Wisconsin USA. pp. 275-300.

[40]Bray, R. H. and Kurtz, L.T. (1945). Determination of total, organic and available forms of phosphorus in soils.Soil Science, 59, 39-45.

[41]Rayment, G.E. and Higginson, F.R. (1992). Australian Laboratory Handbook of Soil and Water Chemical Methods.Inkata Press, Port Melbourne.

[42]Arshad, M.A., Lowery, B. and Grossman, B. (1996). Physical tests for monitoring soil quality.pp.123- 142.

[43] Lowery, B., Arshad, M.A., Lal, R. and Hickey, W.J. (1996). Soil water parameters and soil quality.pp.143-157.

[44] Dent, D. L. (1986). Acid Sulfate Soils: A Baseline for Research and Development. International Institute for Land Reclamation and Improvement.Wageningen, the Netherlands.*ILRI* Publ.

[45] Yang, P. L., Baum, Bi. B.A., Liou, K. N., Kattawar, G.W.,Mishchenko, M.I. and Cole, B. (2013).Spectrally consistent scattering, absorption, and polarization properties of atmospheric ice crystals at wavelengths from 0.2 to 100 µm. Journal of Atmosphere Science, 70, 330-347.

[46]Ridolfi, L.,D'Odorico, P., Porporato, A. and Rodriguez-Iturbe, I. (2000). Impact of climate variability on the vegetation water stress.Journal Geophysics Research, 105, 18013–18025.

[47]Bache, D.H. (1985). Prediction and analysis of spray penetration into plant canopies. In: British Crop Protection Council Monograph No. 28: Application and Biology, E.S.E. Southcombe (Ed); BCPC Publications, Croydon, England. Pp 183-190.

[48]Moormann, F. R. and van. Breemen, N. (1978). Rice: soil, water, land. International Rice. Research Institute, Los Baños, Philippines.

[49]Nhung, M.M. andPonnamperuma, F. N. (1966). Effects of calcium carbonate, manganese dioxide, ferric hydroxide, and prolonged flooding on chemical and electrochemical changes and the growth of rice in flooded acid soil.Soil Science, 102, 29-41.

[50]Shamshuddin, J. (2006). Acid Sulfate Soils in Malaysia.Serdang: UPM Press.

[51] Miller, G.H., Alley, R.B., Brigham-Grette, J., Fitzpatrick, J.J., Polyak, L., Serreze, M. and White, J.W.C. (2010). Arctic Amplification: can the past constrain the future? Quaternary Science Reviews, 29, 1779-1790.

[52] Zhang, L., Rothman, N., Wang, Y., Hayes, R.B., Bechtold, W., Venkatesh, P., Yin, S., Wang, Y., Dosemeci, M., Li, G., Lu, W. and Smith, M.T. (1996). Interphase cytogenetics of workers exposed to benzene. Environ Health Perspectives,6, 1325-9.

[53]Hedlund, A., Witter, E. andAn, B.X. (2003). Assessment of N, P and K management by nutrient balances and flows on peri-urban smallholder farms in southern Vietnam. European Journal of Agronomy,20, 71–87.
[54]Palhares, M. (2000). Recommendation for fertilizer application for soils via qualitative reasoning.Journal of Agricultural Systems, 67, 21-30.
[55]Dobermann, A. and Fairhurst, T. (2000). Rice: Nutrient disorders and nutrient management. IRRI, Los Banos, the Philippines.
[56]Shamshuddin, J., Fauziah, I.C. andSharifuddin, H.A. (1991). Effects of limestone and gypsum application to a Malaysian Ultisol on soil solution composition and yields of maize and groundnut.Plant and Soil, 134, 45-52.
[57] DOE. (2008). National Water Quality Standards.Ministry of Natural Resources and Environment, Kuala Lumpur, Malaysia.86 pp.
[58]Sammut, J., White, I. and Melville, M. D. (1996). Acidification of an estuarine tributary in eastern Australia due to drainage of acid sulphatesoils.Water Research Foundation of Australia, Canberra.
[59]Alia, F.J., Shamshuddin, J., Fauziah, C.I., Husni, M.H.A. andPanhwar, Q.A.(2015).Effects of aluminum, iron and/or low pH on rice seedlings grown in solution culture. International *Journal of Agriculture and Biology*,17, 702-710.
[60]Stumm, W. and Morgan, J.J. (1996). Aquatic Chemistry, Chemical Equilibria and Rates in Natural Waters, 3rd ed. John Wiley and Sons, Inc., New York.
[61]Sundström, R., MÅström, M. andÖsterholm, P. (2002). Compari-son of the metal content in acid sulfate soil runoff and industrial effluents in Finland.Environmental Science and Technology, 36, 4269–4272.
[62] Phillips, D. J. H. and Rainbow, P.S. (1994). Biomonitoring of Trace Aquatic Contaminants, 2nd edn. Chapman and Hall, London. UK.
[63]Kalay, M. andCanli, M. (2000). Elimination of essential (Cu, Zn) and nonessential (Cd, Pb) metals from tissue of a freshwater fishTilapiazilli. Turkish Journal of Zoology, 24, 429–436.
[64] Burton, T.A., Smith, S.J. and Cowley, E.R. (2008). Monitoring streambanks and riparian vegetation – multiple indicators.Version 5.0. U.S. Department of the Interior, Bureau of Land Management. Idaho State Office. Boise, ID.
[65]Appelo, C. A. J., Van der Weide, M. J. J., Tournassat, C. andCharlet, L. (2002). Surface complexation of ferrous iron and carbonate on ferrihydrite, and the mobilisation of arsenic. Environmental Science Technology, 36, 3096-3103.
[66] Hedin, R.S. andWatzlaf, G.R. (1994). The effect of anoxic limestone drains on mine water chemistry. In proc. Of the int. Land reclamation and mine drainage conference and 3rd Int. conference on the abatement of acidic drainage, Pittsburgh, PA.
[67]Fageria, N. K. andBaligar, V. C. (2008). Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production.Advances in Agronomy, 99, 345-431.
[68]Muhrizal, S., Shamshuddin, J., Fauziah, C.I. andHusni, M.H.A. (2006). Changes in iron-poor acid sulfate soil upon submergence. Geoderma, 131, 110-122.
[69]Shamshuddin, J. andAnda, M. (2012). Enhancing the productivity of Ultisols and Oxisols in Malaysia using basalt and/or compost.Pedologist, 55, 382-391.
[70]Panhwar, Q.A., Shamshuddin, J., Naher, U.A., Radziah, O. andMohdRazi, I. (2014). Biochemical and molecular characterization of potential phosphate-solubilizing bacteria in acid sulfate soils and their beneficial effects on rice growth. PLoS One, 9, e97241.
[71] Alva A.K., Asher, C.J. and Edwards, D.G. (1986). The role of calcium in alleviating aluminum toxicity.Australian Journal of Soil Research, 37, 375-383.
[72]Kyuma, K. (2004). Paddy Soil Science, Kyoto University Press.
[73] Lee, J.H. Kim, M.H. and Lee, Y.J. (1993). Information Retrieval Based on Conceptual Distance in IS-A Hierarchies. Journal of Documentation, 49, 188-207.
[74] Ting, C.C., Rohani, S., Diemont, W.S. andAminuddin, B.Y. (1993).The development of an acid sulfate area in former mangroves in Merbok, Kedah, Malaysia. In Selected Papers of the Ho Chi Minh City Symposium on Acid Sulfate Soils, ed. Dent DL, Van MensvoortMEFWageningen, The Netherlands. pp. 95-101.
[75]Suswanto, T., Shamshuddin, J., Syed Omar, P.M. andTeh, C.B.S. (2007). Effects of Lime and Fertiliser Application in Combination with Water Management on Rice (Oryza sativa).Cultivated on an Acid Sulfate Soil.Malaysian Journal of Soil Science,11, 1 – 16.