

A Review

DOI : 10.15740/HAS/AJSS/12.1/221-227

Acid sulfate soils – Its characteristics and nutrient dynamics

■ K. R. DHANYA AND R. GLADIS

Received : 25.03.2017; Accepted : 28.05.2017

MEMBERS OF RESEARCH FORUM:

Corresponding author :

K.R. DHANYA, Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani, Trivandrum, THIRUVANANTHAPURAM (KERALA) INDIA
Email: dhanyamadurai@gmail.com

Co-authors :

R. GLADIS, Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani, Trivandrum, THIRUVANANTHAPURAM (KERALA) INDIA

Summary

Soil is a heterogeneous, dynamic, living system that supports life on earth. Soil health and soil quality are of great relevance in the present day agriculture due to the continuous degradation of soil. Soil acidity is an important parameter that affects the crop yield and quality. Among the acid soils, acid sulfate soils are of great importance because they occupy a considerable area and are potentially productive soils. The objective of this paper is to present a review about the constraints of acid sulfate soils like acidity parameters and nutrient dynamics that hampers crop production.

Key words : Acid sulfate, Pyrite, Sulfuric acid, Acidity, Aluminium, Iron

How to cite this article : Dhanya, K.R. and Gladis, R. (2017). Acid sulfate soils – Its characteristics and nutrient dynamics. *Asian J. Soil Sci.*, 12 (1) : 221-227 : DOI : 10.15740/HAS/AJSS/12.1/221-227.

Introduction

Acid sulfate soils are ubiquitous in nature. They are dynamic systems with a continuous chemical degradation processes due to severe acidification. In India, the distribution of acid sulfate soils are concentrated particularly in two states viz., West Bengal and Kerala. In Kerala, Kuttanad is known to be the “rice bowl of the state”. It includes 50,000 ha of rice fields, out of which 14,227 ha belongs to acid sulfate soils (Typic Sulfaquent) (Beena and Thampatti, 2013).

An outline of acid sulfate soils :

The world pattern of the origin of acid sulfate soils has been steered mainly by post glacial sea level change, but each regional pattern is determined by its unique sedimentary and geomorphological history (Dent and Pons, 1995). The acid sulfate soils were derived from

the formation of Mesozoic, Tertiary, Pleistocene and Holocene which contained oxidizable sulfur compounds (Vuai *et al.*, 2003). Around 24 Mha of land are under acid sulfate soils throughout the world. They are widely distributed in the volcanic and coastal areas of the world. The intrinsic property of these soils is the existence of either sulfuric horizon or sulfidic materials (Anda *et al.*, 2009). These are soils with a pH below 4 that is directly or indirectly caused by sulfuric acid formed by the oxidation of pyrites. The acid reacts with soil minerals and dissolve Al and other acid soluble metals (Vuai *et al.*, 2003). The extreme acidity is caused by the drainage of sulphitic mud that accumulates, in the first place under severely reducing conditions mostly in tidal swamps but also in the bottom sediments of brackish lakes. Problems arise whenever the rate of acid production from oxidation of sulphides exceeds the buffering capacity of soil (Dent

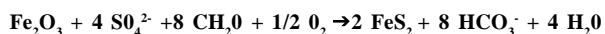
and Pons, 1995).

Anerobic conditions, labile organic carbon and dissolved sulfate provide an perfect environment for sulfate reducing bacteria. These elements along with the dissolved iron from the ferruginous parent material leads to the development of pyrite (FeS_2). Pyrite oxidation is enhanced by microbes especially *Acidithiobacillus ferrooxidans* in pH conditions less than 4 can generate sulfuric acid and mobile Fe^{2+} .

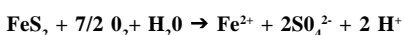
Acid sulfate soils are not harmful to the environment, until they are drained and which is due to the presence of sulfidic materials. But once they are exposed to oxygen, various physical and chemical processes get initiated and the pyrites gets oxidised resulting in the production of sulfuric acid, that leaks into the drainage or flood waters. The runoffs from acid sulfate soils were very acidic with a pH range of 2.87 to 4.29, which is very close to the pH values of the soils. The dominant ionic species in the runoff were Fe^{2+} , Al^{3+} and SO_4^{2-} . The acidity of the runoffs caused the dissolution of metals in the following order $\text{Mn} > \text{Zn} > \text{Cu} = \text{Cd}$ (Vuai *et al.*, 2003). The sulfuric acid lowers pH which makes nutrients less available to plants. The acid dissolves iron and aluminium from the soil so that they become available to plants in toxic quantities in soil water (Rattanapichai *et al.*, 2013).

Genesis of acid sulfate soils :

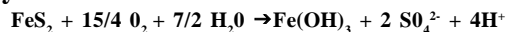
The formation of acid sulfate soils consists of two main processes: formation and oxidation of pyrite. Also, ferrous iron (Fe^{2+}) must be available and it is usually derived from the reduction of insoluble ferric compounds that result from the weathering of clay. Thus, the presence of sulfate from sea water and organic matter from plant growth, anaerobic conditions caused by exclusion of atmospheric oxygen by the excess water, and the presence of Fe^{2+} result in the formation and accumulation of pyrite in tropical coastal wetlands.



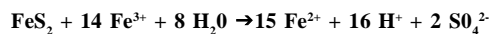
This overall reactions includes reduction of all sulfate to sulfide, followed by oxidation of sulfide (with Fe (III) and O_2 as oxidants) to disulfide (S_2^{2-}). The fine-grained pyrite typical of tidal sediments is readily oxidized upon exposure to air, giving Fe (II) sulfate and sulfuric acid:



Complete oxidation and hydrolysis of iron to Fe (III) oxide yields 2 moles of sulfuric acid per mole of pyrite:



Pyrite is oxidized more rapidly by dissolved Fe (III) than by oxygen :



(Dent and Pons, 1995)

Categories of acid sulfate soils :

Raw acid sulfate soils produced by drainage becomes severely acidic within weeks or months recognized by straw yellow mottles of jarosites around pores and ped faces and acid red drainage water. As long as the oxidation of pyrite continues, acid production occurs and hence rooting is inhibited, thus soil remaining physically unripe (Dent and Pons, 1995).

Ripe acid sulfate soils have profiles at depth, near the bed rock the soil remains waterlogged and reduced, a grey layer still containing pyrite, above this a physically ripe layer with goethite and jarosite mottles, then a ripe horizon with conspicuous red haematite and goethite mottles, still very acidic with pH about 4 and with high exchangeable Al, finally a dark coloured top soil. Also the land is no longer subject to regular tidal flooding and the water table now drops below the level at which pyrite originally accumulated under severely reducing conditions (Dent and Pons, 1995).

Potential acid sulfate soils support the same kind of vegetation as the normal soils. But once they get drained through either anthropogenic activities, natural change of hydrology or through the course of cultivation they pose an enormous threat to the crops, water bodies and soil through the generation of colossal acidity and other ionic species in lethal magnitude. As a result of sulfide oxidation, a substantial amount of Fe and H^+ ions are supplied to the soil profile. Moreover, minerals such as jarosite, schwertmannite, goethite, ferrihydrite, haematite and oxyhydroxides represent a momentous store house of acidity in actual acid sulfate soil (Macdonald *et al.*, 2004).

The actual acid sulfate soils contrast with the potential acid sulfate soils through its peculiar colour, strong acidity, bad odour and sparse vegetation, supplemented with huge amount of sulfuric acid, oxides and hydroxides of iron and aluminium along with stored acidity (Macdonald *et al.*, 2004). Reclaimed acid sulfate

soils revealed a decrease in the soil pH values, increase in the Al^{3+} and Al saturation and extensive cation leaching. Pyrite concentration in reduced layers of the profiles decreased from 2.6 - 5.2 per cent before reclamation to 0.3 – 1.9 per cent after reclamation (Anda *et al.*, 2009).

When the actual acid sulfate soils are again inundated, the minerals get dissolved and the ions are released into the soil solution. The dissolved metal ions in turn under goes oxidation, hydrolysis and precipitation reactions generating acidity (Macdonald *et al.*, 2004). The clay textured acid sulfate soils have an enormous potential mineral acidity pool than sandy textured acid sulfate soils (Macdonald *et al.*, 2004). Sterk (1991) calculated that a shower of 36.3 mm in 30 minutes could leach 143.6 mmol(+) m^{-1} of acidity from the topsoil of a new (three months) raised bed of acid sulfate soil.

Variation in the depth of the groundwater table is a controlling factor of pH and redox potential in acid sulfate soils. Strong acidic condition by pyrite oxidation due to deepening of groundwater deteriorates agricultural productivity during dry season. On the other hand, toxicity due to reduced Fe under reductive conditions are caused by the high groundwater table during the wet season (Kawahigashi *et al.*, 2012).

Nutrient dynamics :

Soil pH is an important factor which determines the availability and toxicity of nutrients in acid sulfate

soil. These soil contain low total micro-organisms and their amount vary considerably according to vegetation type and soil management practices (Panhwar *et al.*, 2015). As soil pH decreased, the availability and mobility of metal cations increased due to the chemical form in which these metal cations are present in the soil solutions (Reddy *et al.*, 1995). Soil pH and organic carbon content were positively and significantly correlated with exchangeable K^+ , Ca^{2+} and Mg^{2+} content (Behera and Shukla, 2015). The main problems of acid sulfate soils are limited availability of plant nutrients and toxicities caused by Fe, Al and Mn (Cho *et al.*, 2002).

Al toxicity is considered as the most important limiting factor for plants growing in acid sulfate soils. Plants can detoxify Al in the rhizosphere by producing organic acids which can chelate Al, rendering it unavailable to the growing crops. Citrate and malate are mostly present in the root tips. Under Al stress, rice root exuded organic acids that reduce the effects of Al toxicity by forming Al-citrate or Al-malate (Panhwar *et al.*, 2015).

The amount of extractable Al in the soil and its uptake by the soyabean plants increased as the soil pH decreased and the relationship is non- linear when the soil pH falls below 4.4. Minh *et al.* (1997) reported that harrowing the land three times followed by flushing is an appropriate way to remove the Al from the top soil during the rainy season, because of the large volume of fresh water.

Soil series	Potential acidity	Exchangeable acidity	Exchangeable Al	Exchangeable H+
Ambalapuzha	35.78	2.06	1.41	0.65
Purakkad	89.34	4.96	2.9	2.05
Thottapally	38.57	3.09	2.03	1.02
Thuravur	78.23	6.15	3.91	2.43
Kallara	88.56	5.08	3.15	1.93
Thakazhi	40.74	4.06	2.32	1.82

Sample No.	Soil pH	DOC (mg l ⁻¹)	Cu ²⁺ activity (-log) ^a		Zn ²⁺ activity(-log) ^a	
			With DOC	without DOC	With DOC	Without DOC
1	6.6	56.9	7.74	6.38	7.32	6.18
2	5.6	26.2	7.67	7.20	5.91	5.61
3	5.4	37.2	7.73	6.83	6.64	5.96
4	5.1	12.7	7.87	7.41	6.30	6.01
5	2.5	11.4	6.09	5.93	5.13	5.04
6	2.4	14.4	6.12	5.92	5.02	4.91

Inhibition of the absorption of exchangeable bases, which is mainly due to the presence of excess Al, which affect the productivity of acid sulfate soils and limit nutrient availability to plants. Detrimental effects of soil acidity on plant growth includes stunted root growth due to the presence of Al, increased availability of Fe, Mn, Cu and Zn with decrease in soil pH (Behera and Shukla, 2015). The solubility of Al is relatively higher at low pH. Besides, its toxicity, it also limits the availability of other essential nutrient elements such as P, Ca and Mg (Foy, 1992). Minh *et al.* (1997) reported that harrowing the land three times followed by flushing is an appropriate way to remove the Al from the top soil during the rainy season, because of the large volume of fresh water.

Panhwar *et al.* (2015) reported that Al toxicity was reduced by PGPB of the genus *Bacillus*, *Stenotrophomonas* and *Burkholderia* via production of organic acids that were able to chelate the Al and the production of polysaccharides that increased solution pH. The release of phytohormones further enhanced rice growth that resulted in yield increase. In addition, PGPB was able to increase the soil pH from 4 to 6. They were able to produce polysaccharides that might adsorb H⁺ ions from the solution and thus, increasing the rhizosphere pH. Application of ground magnesium limestone GML, biofertilizer and ground basalt positively influenced rice growth due to reduction in Al toxicity. GML in addition supplied Ca and Mg required for the plant growth.

Beena and Thampatti (2013) studied the acidity characteristics of acid sulfate soils of Kuttanad and revealed that the potential acidity of surface soils varied from 32.87 to 110.5 cmol (+) kg⁻¹. The potential acidity is chiefly comprised of hydrolytic acidity and exchangeable acidity, the dominant being hydrolytic acidity contributing 70.22 to 97.20 per cent of potential acidity. The exchangeable acidity of soils ranged from 1.23 to 8.1 cmol (+) kg⁻¹. The contribution of exchangeable H⁺ and exchangeable Al to exchangeable acidity do not show a defined pattern exhibiting wide variation (Table 1).

Incorporation of organic matter into the sulfuric soil increased the soil pH and the extent of increase depend upon the moisture level. The pH increase is due to the fact that the aerobic decomposition of organic matter leads to the depletion of oxygen and this favors metabolic conversion of sulfates to sulfides by anaerobes (Michael *et al.*, 2015). Soil gases like CO₂ accumulate during the initial period of submergence. The partial pressure of

CO₂ (p CO₂) is higher in soils rich in organic matter, but p CO₂ decreases within 1-4 weeks of submergence due to many factors such as conversion to insoluble carbonates, reduction to methane, decreased microbial activity etc. Davidson and Janssens (2006) revealed that the wetlands, peatlands and permafrost soils generally contain higher carbon densities than upland mineral soils, and together they make up enormous stocks of carbon globally. Potential for CO₂ production and global warming of various soils was in accordance with C mineralization and this explains the role and capacity of various land use under consideration to store and release carbon (Chacko *et al.*, 2014).

The carbon sequestration rate of undisturbed wetlands was lower (15% for mangrove and 55% for saltmarsh) than disturbed wetlands, but the carbon store was higher for undisturbed wetlands (65% for mangrove and 60% for saltmarsh) (Howe *et al.*, 2009). Prabha *et al.* (2013) found that in wetland rice soils, application of biochar in appropriate proportion has a significant influence over the soil carbon dynamics by increasing the major soil carbon sequestration parameters like soil organic carbon (SOC), particulate organic carbon (POM) and microbial biomass carbon (MBC) and has the ability to combat global warming without affecting the rice productivity.

The availability of P, B and N is restricted to pH intervals because of different processes (Behera and Shukla, 2015). P is one of the limiting nutrients in acid soils which often have high P fixing capacity due to their high Al and Fe oxide concentrations. Most of the P added through mineral fertilizers to these soils gradually reacts with Fe and Al compounds and is transformed into relatively insoluble P compounds (Verma *et al.*, 2005). Acid sulfate soils have a high capacity to fix phosphate, symptoms of phosphate deficiency are commonly observed in many crops (Sanyal *et al.*, 1993). Higo *et al.* (2010) reported that the inoculation with the arbuscular mycorrhizal fungi or crop rotation with mycorrhizal plants improved the growth of maize in limed acid sulphate soils.

Keene *et al.* (2004) reported that in acid sulfate soils, surface soils showed less equilibrium K⁺ potential values than subsurface soils. The natural oxidation of sulfide-bearing minerals and sulfuric acid attack on clay minerals during the ripening of acid sulfate soils, result in the changes to the clay mineral structure and depletes K from the clays of the floodplain surface. These

pedogenic changes in clay mineralogy are accompanied by natural hydrological and oxidation processes that cause upward leaching and export of K from acid sulfate soil landscapes. Potassium deficiency is associated with the formation of the sulfide mineral oxidation product jarosite, which acts as an infinite sink for K in the upper sulfuric horizon and reduces the amount of K that is readily available for plant growth. In acid sulfate soils, on submergence Fe (II) and Mn (II) dominate, which can bring exchangeable K into solution form due to cation exchange. Availability of K also decreases due to the formation of sparingly soluble Fe- K complexes.

Soil pH and OC content were positively and significantly correlated with exchangeable K⁺, Ca²⁺ and Mg²⁺ content (Behera and Shukla, 2015). Ahmed and Wilson (1992) reported that the exchangeable Mg²⁺ concentration of the soils was very high in relation to Ca²⁺, which is indicative of old marine deposits in which the Ca is largely leached out, but Mg is maintained at a relatively high level, probably as a result of progressive clay disintegration and release of Mg.

Variations in the depth of the groundwater table is a controlling factor of pH and redox potential in acid sulfate soils. Strongly acidic conditions by pyrite oxidation due to deepening of the water table deteriorates agricultural fields in the dry season. On the other hand, toxicity due to reduced Fe under reductive conditions is caused by the high groundwater table in the wet season (Husson *et al.*, 2000).

In an acid sulfate soil, as the soil pH decreases, the availability and mobility of metal ions increases, which is chiefly attributed by the chemical forms in which these ions are present in soil solution. As the pyrite layer oxidises, the concentration of dissolved sulfate increases which modify the chemical speciation and relative distribution of chemical forms of Cu, Pb and Zn in soils (Reddy *et al.*, 1995).

Reddy *et al.* (1995) reported that the pyrite oxidation leads to the decrease in pH from 6.6 to 2.24 (Table 2), which is also associated with the increase in the dissolved sulfate concentration from 2.59 to 4.388 mg l⁻¹, decrease in the dissolved organic carbon (DOC) concentration from 56.9 to 14.4 mg l⁻¹ and increase in the dissolved Cu, Zn and Pb concentration from 0.06 to 0.42 mg l⁻¹, 0.084 to 4.60 mg l⁻¹ and 0.003 to 0.046, respectively.

Reddy *et al.* (1995) reported that as pH decreased, the dissolved concentrations of Cu and Zn were increased and the dissolved concentration of Pb increased and then

decreased. Chemical speciation suggests that at near neutral pH, metal DOC complexes were predominant in the soil water extracts. At very low pH, metal ionic forms (e. g. Cu²⁺ or Zn²⁺) and metal ion pairs (e.g. CuSO₄⁰ and ZnSO₄⁰) were predominant. The availability and mobility of Cu, Zn and Pb will increase in low pH environments due to the chemical form in which these metals are present in the soil solutions.

Management of acid sulfate soils :

There are both traditional and modern practices for the successful management of acid sulfate soils. One among those practices is the application of liming materials. Lime is the most suitable amendment for the treatment of acid soils due to its high solubility and should be applied at the rate of 6.25 to 12.5 ton/ha. The use of lime material along with chemical fertilizer especially nitrogen and phosphorus can increase productivity (Rattanapichai *et al.*, 2013).

The best technique for managing acid sulfate soil is to avoid disturbing or draining the iron pyrite layer. There is no single method for the reclamation and management of acid sulfate soils. The soil acidity can be reduced to a great extent by liming and leaching, which in turn improve soil productivity. The soil conditions can be improved significantly by adequate drainage, frequent application of water and moderate application of lime. Adequate drainage is essential for leaching in order to reduce acidity. The control of water table during dry season so as to curb penetration of oxygen into iron pyrite layer. This could be accomplished by flooding, controlled irrigation, formation of subsoil hard pan etc. (Cho *et al.*, 2002).

A study conducted in the acid sulfate soils of Indonesia indicated that application of biochar decreased soil bulk density, soil strength, exchangeable Al and soluble Fe and increased porosity, available soil water content, C-organic, soil pH, available P, CEC, exchangeable K, and Ca. Out of these improvements, only soil carbon, phosphorus, exchangeable Al, soluble Fe and soil strength significantly influenced rice biomass (Masulili *et al.*, 2010).

Conclusion :

Millions of hectares of acid sulfate soils of South and Southeast Asia lie idle or cultivated with poor results largely because of strong acidity. If these lands can be improved for cultivation especially rice, the food deficits expected in South and Southeast Asia in future may be

reduced. Although acid sulfate soils exhibit considerable limitations to agricultural use. However, with appropriate soil and crop management measures, the productivity of these soils can be improved.

Literature Cited

- Ahmad, N. and Wilson, H.W. (1992).** Acid sulfate soils of the Caribbean region-their occurrence, reclamation and use. *Soil Sci.*, **153** (2): 154-164.
- Anda, M., Siswanto, A.B. and Subandiono, R.E. (2009).** Properties of organic and acid sulfate soils and water of a 'reclaimed' tidal backswamp in Central Kalimantan, Indonesia. *Geoderma*, **149**(1): 54-65.
- Beena, V.I. and Thampatti, K.C.M. (2013).** Characterization of Acidity in acid sulphate soils of kerala. *J. Life Sci.*, **7** (8): 907 – 912.
- Behera, S.K. and Shukla, A.K. (2015).** Spatial distribution of surface soil acidity, electrical conductivity, soil organic carbon content and exchangeable potassium, calcium and magnesium in some cropped acid soils of India. *Land Degradation Dev.*, **26** (1) : 71-79.
- Chacko, F. M., Sreekanth, N.P., Prabha, S.V., Padmakumar, B. and Thomas, A.P. (2014).** Soil carbon dynamics and global warming potential of selected soil series and land use categories. *Oct. J. Env. Res.*, **2** (1): 10-21.
- Cho, K.M., Ranamukhaarachchi, S.L. and Zoebisch, M.A. (2002).** Cropping systems on acid sulphate soils in the central plains of Thailand: constraints and remedies. Technical paper No. 812, 17th WCSS, 14 – 21 August 2002, Thailand.
- Davidson, E.A. and Janssens, I.A. (2006).** Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, **440** (7081) : 165-173.
- Dent, D.L. and Pons, L.J. (1995).** A world perspective on acid sulphate soils. *Geoderma*, **67**: 263-276.
- Foy, C.D. (1992).** Soil chemical factors limiting plant root growth. In: *Limitations to plant root growth*. Springer, New York, U.S.A., pp. 97-149.
- Higo, M., Isobe, K., Kang, D.J., Ujie, K., Drijber, R.A. and Ishii, R. (2010).** Inoculation with arbuscular mycorrhizal fungi or rotation with mycorrhizal plants improves the growth of maize in limed acid sulfate soil. *Plant Prod. Sci.*, **13** (1) : 74-79.
- Howe, A.J., Rodriguez, J.F. and Saco, P.M. (2009).** Surface evolution and carbon sequestration in disturbed and undisturbed wetland soils of the Hunter estuary, southeast Australia. *Estuarine, Coastal Shelf Sci.*, **84** (1): 75-83.
- Husson, O., Phung, M.T. and Van Mensvoort, M.E.F. (2000).** Soil and water indicators for optimal practices when reclaiming acid sulphate soils in the plain of reeds, *Viet Nam. Agric. Water Manag.*, **45**: 127-143.
- Kawahigashi, M., Do, N.M., Nguyen, B.V. and Sumida, H. (2012).** Effective land and water management for controlling solutes from acid sulfate soils in Mekong delta paddy fields. *Pedologist*, **55** : 458-465p.
- Keene, A., Melville, M.D. and Macdonald, B.C.T. (2004).** Using potassium potentials to examine nutrient availability in an acid sulfate soil landscape, Northern Australia. SuperSoil 2004: 3rd Australian New Zealand Soils Conference, 5–9 December 2004, University of Sydney, Australia.
- Macdonald, B.C.T., White, I., Keene, A., Melville, M.D. and Reynolds, J. (2004).** Acidity, metals and acid sulfate soils. Super soil 2004: 3rd Australian New Zealand Soils Conference, 5 – 9 December 2004, University of Sydney, Australia.
- Masulili, A., Utomo, W.H. and Syechfani, M.S. (2010).** Rice husk biochar for rice based cropping system in acid soil 1. The characteristics of rice husk biochar and its influence on the properties of acid sulfate soils and pice growth in West Kalimantan, Indonesia. *J. Agric. Sci.*, **2** (1) : 39-47.
- Michael, P.S., Fitzpatrick, R. and Reid, R. (2015).** The role of organic matter in ameliorating acid sulfate soils with sulfuric horizons. *Geoderma*, **225** : 42-49.
- Minh, L.Q., Tuong, T.P., Van Mensvoort, M.E.F. and Bouma, J. (1997).** Contamination of surface water as affected by land use in acid sulfate soils in the Mekong River Delta, Vietnam. *Agric. Ecosyst. Environ.*, **61**(1) : 19-27.
- Panhwar, Q.A., Naher, U. A., Radziah, O., Shamshuddin, J. and Razi, I.M. (2015).** Eliminating aluminum toxicity in an acid sulfate soil for rice cultivation using plant growth promoting bacteria. *Molecules* [e-journal] **20**. Available : www.mdpi.com/journal/molecules. ISSN 1420-3049 [21 march 2016].
- Prabha, S.V., Renuka, R., Sreekanth, N.P., Padmakumar, B. and Thomas, A.P. (2013).** A study of the fertility and carbon sequestration potential of rice soil with respect to the application of biochar and selected amendments. *Ann. Environ. Sci.*, **7**: 17-30.
- Rattanapichai, W., Kiren, J., Duangpatra, P. and Kanghae, P. (2013).** Effect of soil conditioner on growth and yield of rice grown under acid sulfate soil. *Mendel Net.*, 147-151.
- Reddy, K.J., Wang, L. and Gloss, S.P. (1995).** Solubility and mobility of copper, zinc and lead in acidic environments. In: *Plant-soil interactions at low pH: Principles and management*, Springer Netherlands, pp. 141-146.
- Sanyal, S.K., Dedatta, S.K. and Chan, P.Y. (1993).** Phosphate sorption desorption behaviour of some acidic soils of South and Southeast Asia. *Soil Sci. Soc. Am. J.*, **57**: 937-945.
- Sterk, G. (1991).** Leaching of acidity from the top soil of raised

beds on acid sulphate soils in the Mekong Delta, Vietnam. Technical paper No. 8, EEF Project STD-Vietnam. Department of Soil Science and Geology, Agricultural University, Wageningen.

Verma, S., Subehia, S.K. and Sharma, S.P. (2005). Phosphorus fractions in an acid soil continuously fertilized with mineral

and organic fertilizers. *Biol. Fertil. Soils*, **41**: 295–300.

Vuoi, S.A., Nakamura, K. and Tokuyama, A. (2003). Geochemical characteristics of runoff from acid sulfate soils in the northern area of Okinawa Island, Japan. *Geochemical J.*, **37** (5) : 579-592.

★ ★ ★ ★ ★ of **12th** Year
★ ★ ★ ★ ★ of Excellence ★ ★ ★ ★ ★