STUDIES ON THE SOLUBILISATION OF IRON IN SUBMERGED SOILS AND METHODS TO MINIMISE ITS SOLUBILITY AND TOXIC CONCENTRATION TO PADDY

BY

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DECLARATION

I hereby declare that this thesis entitled "Studies on the solubilisation of iron in submerged soils and methods to minimise its solubility and toxic concentration to paddy" is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title of any other University or Society.

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Vellayani,
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CERTIFICATE

Certified that this thesis entitled "Studies on the solubilisation of iron in submerged soils and methods to minimise its solubility and toxic concentration to paddy" is a record of research work done independently by Sri. P.R. Ramasubramonian under my guidance and supervision and that it has not previously formed the basis for the award of any degree, fellowship or associateship to him.

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INTRODUCTION

INTRODUCTION

Rice, which is the staple cereal food of the people of Kerala, is cultivated over more than 6.7 lakh hectares of land distributed under the various agro-climatic situations in the state. Based on the traditional systems and local nomenclature, the acid rice soils of Kerala are variously described as kari, kayal and karapadom in the Kuttanad region in Alleppey and Kottayam districts, Pokkali in Ernakulam and Trichur districts, Kaipad in Cannanore district, sandy in the Onattukara area occupying portions of Alleppey and Quilon districts, kole in Trichur and Malappuram districts and brown hydromorphic in the mid and mid-upland regions. In all these soils, rice is grown under submerged conditions subject to the availability of water either through rain or by irrigation.

Rice cultivated under submerged conditions has definite advantages in view of the favourable soil conditions created by continuous waterlogging. These include a rise in P^H in acid soils, an increase in the availability of the macro and micro nutrients, a decrease of aluminium toxicity, suppression of weed growth, elimination of pathogenic organisms etc. However, the more undesirable consequences of submergence of soils include, among others, the imbalance of nutrients and the production of toxic factors under the anaerobic conditions resulting from restricted drainage which can adversely affect the normal growth of rice. Soil submergence results in the excessive release of ferrous iron in the soil solution which often creates problems of iron toxicity to the rice plant at different stages of its growth.

The rice soils of Kerala are derived from parent materials rich in iron and many of these soils have a total iron content varying from 3 to 15 per cent. Iron is present in the form of various oxides and hydrated oxides which are reduced under the influence of submergence and anaerobicity.

The problem of iron toxicity has received the attention of soil scientists in India, Sri Lanka, Philippines, Thailand, Malaysia, Indonesia, Liberia, Nigeria, Sierra Leone etc. The problem has been handled in relation to cultivated rice by several investigators (Ponnamperuma, 1955; Mandal, 1962; Sahu, 1968; Tanaka and Yoshida, 1970; Gunawardena, 1974; Virmani, 1976; Breemen van, 1978 and many others). Iron toxicity has also been studied in connection with aqua culture and the reclamation of unproductive coastal acid sulphate soils in the Philippines by Brinkman and Singh (1981) and Singh (1981, a; 1981, b). The problems encountered in iron toxicity and its amelioration in fish pond systems were found to be much more severe in view of the excavations carried out in acid sulphate soils and the bringing up of the sulphidic soils to the surface, their oxidation and consequent liberation of mineral sulphuric acid leading to the leaching of iron and aluminium which along with the soil acidity ultimately results in toxicity to fish fingerlings and to planktons.

Iron toxicity was first reported in Kuttanad rice soils in 1961 (Money, 1961; Subramoney and Kurup, 1961) and some fundamental studies were later made by the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani and at the Rice Research Station, Monkompu.

Kuttanad region has nearly 52,000 hectares of rice land situated mostly at 0.5 to 2 metres below MSL which remain submerged for the greater part of the year. Cropped to rice twice in an year in certain areas and to a single crop in most of the cultivable area, the entire Kuttanad has to be considered as a reclaimed area of the esturies of four major rivers emptying into the adjoining Vembanad lake. Three kinds of rice soils are recognised in this region viz., the kayal, kari and karapadom soils. The kayal lands are the rice fields reclaimed from the bed of the Vembanad lake, with deposits of alluvium and lacustrine shells. Kari lands with the least amount of alluviation and with high water table are characterised by exposed peat soils of low pH which are acid sulphate in nature. The Karapadom fields occupying a much larger area as compared to kayal and kari lands, are situated around the banks of rivers and a net work of channels, canals and waterways and are annually silted up by alluvial materials brought down by rivers and floods.

All waterlogged rice soils of Kerala, in view of their acidic to highly acidic reaction, show varying degrees of iron toxicity during different parts of the year.

Sporadic reports of iron toxicity have been made from various parts of Kerala, particularly the Kuttanad soils and the brown hydromorphic soils derived from lateritic alluvium and the sandy soils of Onattukara. The expression of iron toxicity is highly related to the extent and duration of the drought period preceding soil submergence, ingress of saline water, differential aeration and anaecorobicity caused by the removal and letting in of water during cultivation or during ebb tide and low tide, agricultural practices such as the use of liming materials and by the addition of organic materials, acid forming fertilisers etc. during rice cultivation.

No systematic work to study the problem of iron toxicity, particularly in relation to the factors influencing iron solubilisation and methods of amelioration of iron toxicity, has been attempted in Kerala. In view of this the present work was undertaken to obtain a better understanding of the dynamic aspects of iron in these soils by attempting,

1. to quantity the major forms of iron in soils having relevance to rice nutrition in Kuttanad
2. to find out the interrelationships between soil chemical properties and forms of iron
3. to study the variations in the form of iron in soil profiles
4. to investigate the extent of solubilisation of iron under submerged conditions with time as influenced by levels of salinity, organic matter and ammonium sulphate under laboratory conditions and
5. to test the amelioratory effect of lime in relation to the alleviation of iron toxicity.

REVIEW OF LITERATURE

REVIEW OF LITERATURE

The submerged conditions under which rice is cultivated brings about a series of physico-chemical, biochemical and microbiological changes that provide a completely different set of soil-plant relationships from those observed in the crops of upland soils. Submergence results in undesirable soil conditions leading to the development of toxic reduction products and nutrient imbalances which are reported to have caused physiological disorders in lowland rice, particularly when drainage is impeded. Many scientists have attempted to relate these nutritional disorders of the rice plant to the chemistry of submerged soils (Tanaka and Yoshida (1970).

Considerable research efforts are reported in literature in relation to the study of the chemistry of submerged soils with particular reference to the pre-disposing factors which lead to soil conditions favourable for iron solubilisation, toxic hazards to paddy as influenced by excess soluble iron and methods tried to minimise iron solubilisation, all aiming for a better understanding of the various facets of this major problem. Some of the items of earlier work on these aspects carried out in India and elsewhere, which have relevence to the present study are reviewed below.

1. Forms of iron in submerged soils

The sources of iron in soils are the primary minerals, silicate clays and hydrated oxides with their organic and inorganic derivatives. The iron oxides may occur in rice soils as very fine amorphous to crystalline polymorphic particles of varying solubilities found mainly in the clay fraction, coatings on external and/or internal surfaces of the clay minerals or concretions.

According to Bao et al. (1964) the pH of the medium plays a dominant role in determining the relative proportions among the various forms of iron.

On the basis of available information, Russel (1973) suggested that plants may take up their iron in both the divalent ferrous and trivalent ferric forms.

In Kerala high amounts of available iron were reported by Aiyer et al. (1975) particularly in the kari (Peat) soils of Kuttanad suggesting possibility of iron toxicity to rice.

Bao and Yu (1978) classified the water soluble iron under free ionic and chelated forms and characterised the latter as those carrying a positive charge and those with a negative charge which vary with the soil.

Yu Tian-ren (1980) referring to the water soluble, exchangeable, complexed with organic matter of the solid phase and precipitated forms of iron, reported that water soluble iron increases with decrease in pH at the expense of the precipitated iron. He further reported that exchangeable and organic complexed forms of iron also increase with fall in pH and decrease again at pH values below 4.0 due to competition of H^+ and Al^{3+} ions with Fe^{2+} for exchange sites.

Patel and Dangarwala (1983) estimated the exchangeable ($N.NH_4Ac$, pH 7), available ($N.NH_4Ac$, pH 4.8), reducible ($N.NH_4Ac$, pH 3.0), complexed (EDTA 0.5 M), dilute acid extractable (0.1 N HCl) and free or active iron ($Na_2S_2O_4$) in the rice soils of South Gujarat and studied their relative influences in improving their predictability regarding available iron content.

Ottow et al. (1983) reported that a low CEC implicated both a restricted buffering capacity, as well as limited potential supply of available nutrients. Significant correlations between iron in the rice leaves and CEC or exchangeable Ca and low P and exchangeable K values were noted as the characteristics, indicating the importance of soil nutrient status as a pre-requisite for iron toxicity.

According to Panda (1987), DTPA extractable iron was not a good indicator of available iron in reduced soils, where high organic matter might show higher DTPA extractable iron without showing iron toxicity symptoms, probably due to non involvement of chelated iron in iron toxicity.

Most soils contain different free iron oxides ranging from completely amorphous to highly crystalline forms. Schwertmann (1966) noticed that organic matter could inhibit crystallisation of iron hydroxide. Mckeague et al. (1971) differentiated between organic complexed and amorphous inorganic forms of iron and noted that the difference between oxalate and pyrophosphate extractable iron would give a measure of the amorphous inorganic iron and the dithionite minus oxalate extractable iron would provide an estimate of more or less crystalline iron compounds of the soil.

He Qun and Xu Zu-yi (1980) concluded that the ratio of amorphous iron to free oxide ($\frac{Fe_o}{Fe_d}$), an index of activity of iron oxides, was markedly influenced by submergence.

Munch and Ottow (1980) observed that the crystalline Fe (III) oxides were more stable and more resistant to extraction and decreased in content more slowly when compared to their non-crystalline counter parts and consequently the ratio ($\frac{Fe_o}{Fe_d}$) would diminish with time of submergence due to preferential reduction of amorphous iron (III) compounds.

2. Factors related to iron solubilisation

(i) Submergence

Of the several factors controlling the solubilisation of iron in soils, submergence which results in anaerobic conditions is probably the most important. Islam and Elahi (1954), Ponnamperuma (1955), Mandal (1961), Yu and Liu (1964), Mahapatra (1968), Sahu (1968) and Olomu et al. (1973) have all highlighted the solubilisation of iron in the ferrous state under waterlogged, reducing conditions.

According to Iri et al. (1958) in rice fields under flooded conditions ferrous iron was lowest in the surface layer, but it increased downwards and was highest in the lowest horizons. Oades (1963) noted that in poorly drained black soils the micronutrients were concentrated in the lower horizons. Kubota (1963) found that while the total amounts of iron might be concentrated in the lower horizons, the exchangeable or acid soluble forms might occur principally on the surface. Kawaguchi and Kyuma (1969) reported that water soluble iron moves down and is precipitated below the plough sole giving an Fe (III) oxide horizon in old paddy soils. Gangwar et al. (1971) observed that available iron decreased with increasing coarseness of soil texture in the soil profiles of Nainital foot hills.

Mandal (1962) has recorded increase in iron concentration in soil percolates with increasing period of submergence.

Bao et al. (1964) and Yu Tian-ren (1980) reported that the amount of exchangeable iron was influenced by the CEC of the soil, the amount of sulphur present and soil pH.

Ponnamperuma (1965) studied the ionic equilibria in submerged soils and based on the values of the expressions PE-P Fe^{2+}+3pH, PE-1.5 P Fe^{2+}+4pH and PE+pH obtained, he reported three main iron systems, viz., $Fe(OH)_3$-Fe^{2+},$Fe_3(OH)_8$-Fe^{2+} and $Fe_3(OH)_8$-$Fe(OH)_3$ operating in flooded soils, of which $Fe(OH)_3$-Fe^{2+} equilibrium alone would operate throughout the period of submergence. Singh and Pasricha (1978) and Thind and Chahal (1983) also arrived at similar conclusions. Mahapatra (1968) found that concentrations of the active ions including that of ferrous iron increased as a result of flooding. Further, the distribution of iron between the solid and solution phase was found controlled by the duration of submergence.

Takkar (1969) in laboratory incubation trials obtained marked release of iron from an acid soil at 60 per cent WHC and under submerged conditions with time.

Jose and Raj (1970) stated that submergence resulted in the reduction of Fe^{3+} and production of more soluble compounds of Fe^{2+}. Mukherjee and Basu (1971) found that Fe^{2+} increased upto 20 days of submergence but decreased thereafter.

Investigations by Ponnamperuma (1972, 1977 b) revealed that during submergence soil reduction proceeds in the sequence predicted by the thermodynamics of the involved redox systems. He noticed a peak in the concentration of exchangeable iron or soil solution iron within the first month after flooding followed by a graded decline.

Based on E^o values calculated from measured Eh, pH and Mn concentration Olomu et al. (1973) found that almost all the iron in the soil was complexed with organic matter while manganese was only weakly complexed. Sukla et al. (1975) obtained an apparant negative relationship between available iron and pH. Kabeerathumma (1975) noticed that during submergence the exchangeable iron increased to a peak and then decreased.

The effect of submergence and drying of a waterlogged soil on iron release has been studied by many workers. Savant and Kibe (1969) reported that in acid soils of pH 4.7 - 5.4 submergence and air drying caused an increase in soluble iron. Banerjee and Das (1978) studied the ferrous-ferric transformations under wet and dry conditions and reported trace levels of exchangeable or available Fe^{2+} on wetting followed by drying eventhough the soils examined had high HCl (N) soluble iron and free iron (III) oxides. Toxicity was particularly severe when the soil was completely dried before submergence. Sahrawat (1979) suggested that drying and reflooding an acid sulphate soil aggravated soil acidity and kept high amounts of iron in soil solution to be toxic to rice.

Singh and Patiram (1979) found an increase in soluble Fe^{2+} with time of submergence in the soils of UttarPradesh, the Fe^{3+} first changing to insoluble Fe^{2+} due to microbial activity and then appearing in the soil solution as well as in the exchange complex.

Quesada and Bolomou (1981) concluded from pot experiments that flooding increased ferrous iron content after 12 days which decreased to a minimum on the 33rd day.

In Kerala, Subramoney and Kurup (1961) showed that appreciable amounts of iron were brought into solution by submergence in the acid paddy soils of Kuttanad. Pisharody (1965) reported higher contents of total, water soluble and exchangeable forms of iron in the sub soils than in surface soils under waterlogged conditions in several paddy soil profiles of Kerala. Water soluble iron accumulated in the sub soil under dry conditions, but no regularity could be found in its distribution under submerged conditions. Higher levels of exchangeable iron were observed in heavy soils as compared to coarser soils.

Iu et al. (1981) found that waterlogging of an acid soil for a period of 16 weeks released both iron and manganese from the organic and oxide bound reservoirs.

Ottow and Munch (1988) ascribed the reductive dissolution of Fe (III) in hydromorphic paddy soils to direct specific and biochemical processes in which Fe^{3+} act as electron acceptor during energy conversions involving microorganisms. They also concluded that in an anaerobic condition iron reducing bacteria would prefer amorphous form of iron to crystalline form during biological oxidation.

Bandyopadhyay and Bandyopadhyay (1984) observed an increase in water soluble and exchangeable forms of iron with decrease in Eh in the beginning followed by a reversal of these processes after about 20 days of submergence of a coastal saline soil of West Bengal, with and without addition of organic matter.

Eusof (1985) examined the status of iron with reference to crystalline, amorphous and organo-complexed forms and their usefulness in characterising the morphogenesis of the soils in Malaysia. Sah and Mikkelsen (1986) noticed that anaerobic decomposition of drained upland rice soils amended with levels of organic matter added as cellulose and flooded for 85 days significantly increased amorphous iron fractions indicating increased transformation from crystalline form. Savant and McClellan (1987) have illustrated the possible pathways of major transformation of iron oxides occurring in rice soils under wet land rice based cropping system.

Hazra and Mandal (1988) reported that submergence increased the DTPA extractable Fe and Mn and that the soils having higher initial pH values with less clay and organic carbon would record comparatively higher increase in DTPA extractable iron during submergence.

Sharma and Yadav (1988) observed that in sodic soils increasing ESP levels increased Fe and Mn concentrations but reduced their uptake and that drastic rice yield reduction was noticed when ESP was beyond 60 per cent.

(ii) Soil reaction (pH)

Solubilisation of iron by submergence generally takes place in acid soils. But it is also found that the pH of acid soils increased and that of sodic soils decreased as a result of submergence. As pointed out by Jeffery (1961) the Fe^{3+}-Fe^{2+} system is largely responsible for the pH and Eh changes in submerged soils. Takai et al. (1963) and IRRI (1964) have supported this view.

Mukhopadhyay et al. (1967) noted that on submergence there is an initial decline in the pH of soils which they attributed to a possible exchange between the ferrous iron and the adsorbed iron from the soil clay.

Takkar (1969) from laboratory incubation trials obtained an increase in pH followed by high concentration of ferrous iron in acid soil under waterlogged conditions.

According to Ponnamperuma (1972) the initial decrease in the pH of soils may be due to the CO_2 produced by the respiration of aerobic bacteria. However, there is a subsequent increase in the pH of acid soils which is brought about by the reduction of ferric iron to ferrous state and the formation of ferrous hydroxide.

As aluminium is closely related to soil acidity and as iron is electrochemically similar to aluminium, it is expected that iron may also have a role in producing soil acidity. The studies by Takkar et al. (1973) have indicated that the contribution of iron towards soil acidity is less than 35 per cent of that of aluminium, probably due to the precipitation of iron at much lower pH than aluminium. Raman and Thakur (1973) have pointed out that acidity in soils and clays can arise, among others, by the mechanism of the protons associated with the exchange sites also and this is controlled mainly by the aluminium and iron existing in monomeric and polymeric forms in the natural soil system.

Kabeerathumma (1975) noticed that flooding resulted in an increase in soil pH followed by reduction of Fe^{3+} in soil, the extent of pH increase being guided by certain inherent soil characters.

Kumar et al. (1981) observed that the pH of slightly acidic soils of Uttar Pradesh increased on submergence and approached near neutrality after three weeks. Electrical conductivity increased five to ten fold in three weeks and Eh fell markedly. Ion activities of Fe and Zn and the activity ratio $\frac{Fe^{3+}}{Zn^{2+}}$ increased during submergence.

In an acid soil limed to two pH values of 4.0 and 6.0 respectively, Verma and Neue (1988) noticed that an increase in the duration of submergence resulted in more rapid increase in solution pH of low initial pH soil than of high initial pH soil. At the end of 10 weeks both soils had the same pH.

(iii) Redox potential

Redox potential is an index of the intensity factor of the oxidation - reduction status of a soil. As pointed out by Patrick (1964), during submergence of a soil for paddy cultivation, reducing conditions set in, which is manifested through a drop in redox potential (Eh). He observed that an increase in pH is always accompanied by a decrease in Eh and that at low Eh, ferric hydroxide is reduced to ferrous hydroxide according to the equation $Fe(OH)_3 + e \rightarrow Fe(OH)_2 + OH^-$. Low redox potentials in waterlogged soils have also been reported by Pearsall and Mortimer (1939), Urquhart and Gore (1973) and Gotoh and Patrick Jr. (1974).

The influence of soil factors on Eh changes have been studied in detail by Ponnamperuma and Castro (1964), Ponnamperuma et al. (1967), Ponnamperuma (1965, 1972) and many others. When an aerobic soil is submerged its Eh decreases during the first few days, reaches a minimum and then increases and attains a maximum value. It decreases again gradually to a value characteristic of the soil after 8-12 weeks of submergence. The course, rate and magnitude of decrease in Eh depend on the kind and content of electron acceptors, temperature, the duration of submergence and the base status of the soil.

The role of ferrous-ferric (OH) as the principal redox system in submerged soil has been illustrated with thermodynamic evidence by Ponnamperuma and Castro (1964) and Ponnamperuma (1972).

According to Mukherjee and Basu (1971) the Eh and pH values of submerged soils decreased with increasing depth of soil irrespective of the number of days of submergence. The reduction process as evidenced by a sharp decrease in Eh was found to be most active within 10 days of submergence.

Haavisto (1974) noticed that the oxidation-reduction potentials of the upper 50 cm of a waterlogged floating sphagnum peat mat were reduced by an average of 47 mV by heavy rainfall. Even such small changes in Eh are sufficient to alter the valence states of some ions resulting in concentrations of reduced forms which would affect the normal development of plants.

Mandal (1984) suggested that if the redox potential is allowed to fall to very low value, substances toxic to rice plants may be produced.

Bandyopadhyay and Bandyopadhyay (1984) noted a fall in redox potential from 555 mV to 210 mV within four days of submergence and to 110 mV in 20 days. It increased again and reached the value of 150 mV in 40 days. The addition of organic matter in the form of farm yard manure and straw resulted in very sharp reduction in Eh during the course of

20 days. Decreases in soil Eh after flooding in the presence of sesbania straw has been reported by Khind et al. (1987).

(iv) Salinity

Soluble salts in irrigation water may influence the dynamics of iron under submerged situations.

Gerei (1959) noted an increase in easily soluble Fe^{2+} in the upper horizon of irrigated solonets soils in the presence of sulphate ions. According to Ponnamperuma (1977 b) when the soil was submerged, the specific conductance increased in the early phase of submergence, reached a maximum and decreased to a fairly stable value which varied with the soil. The increase in conductance during the first few weeks after flooding was partly due to the release of Fe^{2+} by the reduction of the insoluble ferric iron and the displacement of the cations from soil colloids by Fe^{2+}.

According to IRRI (1965) low pH and high salinity due to sodium chloride or magnesium chloride increased iron uptake and aggravated iron toxicity.

Ponnamperuma (1972, 1977b) noticed that the kinetics of water soluble Fe^{2+} is paralleled by the changes in specific conductivity and the kinetics of $Ca^{2+}+Mg^{2+}+NH_4^{+}+Na^{+}+K^{+}$ suggesting ion exchange reactions between Fe^{2+} and these cations.

Sanchez (1976) reported that Fe^{2+} and Mn^{2+} become the dominant exchangeable cations in flooded soils and displace Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} ions in soil solution by mass action.

Pasricha and Ponnamperuma (1976) reported that high salinity favoured the production of Fe^{2+}, probably by slightly depressing the soil pH and lowering the activity coefficient of Fe^{2+} causing higher equilibrium concentrations after a peak level in water soluble iron.

Tadano (1976) and Tadano and Yoshida (1978) observed that the presence of 1,000 ppm NaCl reduced by two thirds the ability of excised roots and of root extracts to oxidise Fe^{2+} to Fe^{3+} form.

Bandyooadhyay and Bandyopadhyay (1984) noticed that submergence of coastal saline soil (EC 13.6 mmhos/cm^2) resulted in a sharp fall in Eh and caused considerable increase in soluble and exchangeable Fe^{2+} and Mn^{2+} fractions. The effect was more intense in the presence of undecomposed organic matter added in the form of powdered straw.

In a pot experiment to find out the effect of different concentrations of salt, alkali and zinc on iron equilibrium in a submerged sandy loam (typic ustifluent) Sadana and Takkar (1985) found that as the EC increased the pH and the

PE of the soil solution decreased, whereas the concentration of Fe^{2+} increased. ESP had the opposite effect.

(v) Organic matter

The presence of easily decomposable organic matter in the soil enhances the solubilisation of iron.

Islam and Elahi (1954) have reported that the addition of oxidisable materials, especially organic matter promoted the reduction of iron during submergence.

Gopal Rao (1956) noticed that release of iron was greatly favoured by the application of green manures within a period of 30 days and that the Fe^{2+} concentration increased from 1 ppm in control soil to 1000 ppm in green manure treatment.

Mandal (1961) has furnished evidence to show that in the presence of organic matter, the reduction of iron from the ferric to ferrous form was more intense under waterlogged conditions. Applications of green manure and straw released appreciable quantities of Fe^{2+} from the soil upto 21 and 38 days respectively, the straw eluting more Fe^{2+}.

Pisharody (1965) found that organic matter influenced the amount and distribution of water soluble, exchangeable reducible and active forms of iron under submerged condition. The reduction of iron and increase in its solubility was a consequence of anaerobic metabolism of bacteria and appeared to be due to the chemical reduction of Fe^{3+} by bacterial metabolites.

Patnaik and Bhadrachalam (1965) have indicated that the addition of organic manures or green manure may aggravate soil reduction and lead to accumulation of toxic decomposition products.

In a flooded silty clay calcareous soil, Meek et al. (1968) found that flooding without organic matter increased Fe^{2+} concentration in soil solution to a maximum of 2.1 ppm while combination of flooding, organic matter and high temperature increased iron level to 30 ppm.

Takkar (1969) compared the effect of different levels of organic matter and different incubation times under laboratory conditions on the extractable iron using acid, neutral, calcareous and saline alkali soils at 60 per cent WHC and under waterlogged conditions and found marked increase in iron in acid soils at 60 per cent WHC. Under waterlogged conditions, in presence of 8 per cent organic matter added to acid soil, the extractable iron increased from 210 ppm on the 7th day to 1999 ppm on the 90th day. Of the four soils studied the acid soil released maximum iron at all stages.

The influence of intensity of soil reduction on the availability of iron was studied by Mandal and Nandi (1971) by creating different intensities with starch added at the rates of 0, 0.25 and 0.50 per cent to an acid soil of pH 4.85. Available Fe was highest in 0.5 per cent starch treatment. At this level the dry matter yield was also increased significantly in rice.

Misra and Pande (1975) showed that the different forms of iron correlated significantly and negatively with pH and $CaCO_3$ while organic carbon generally showed positive significant correlations.

The periodic release of iron and manganese under anaerobic incubation of red and black soils of Tungabhadra Project Region was studied by Jayaram and Nayar (1972) with and without addition of organic matter. They found that the added organic matter enhanced release of iron and manganese. Release of iron persisted even upto 128 days in black soils while in red soils reduction in iron concentration was noticed by 128 days.

Pal et al. (1979) found that benomyl inhibited the reduction of Fe and Mn in a flooded soil by affecting dehydrogenase activity. Pal and Sethunathan (1980) have reported that hexachlorocyclohexane even at 5 ppm level led to a remarkable decrease in the formation of Fe^{2+} and prevented a drop in the redox potentials in soils.

He Qun and Xu Zu-yi (1980) obtained increased complexed iron under the combined effect of submergence and organic matter addition as powdered milk-vetch. Sharma and Banerjee (1983) reported release of 36 ppm Fe^{2+} during 30 days of submergence of an acid soil containing more organic matter resulting from chelation and reduction. Bandyopadhyay and Bandyopadhyay (1984) noted that the addition of farm yard manure enhanced the intial decrease of redox potential and increased the levels of soluble and exchangeable Fe^{2+} and Mn^{2+} in soils.

In their study of the effect of anaerobic decomposition of organic matter on the amorphous iron content of soils used for rice cultivation under flooded conditions, Sah and Mikkelson (1986) observed significant increase in the transformation of crystalline iron into amorphous form.

Khind et al. (1987) found that the decrease in soil Eh followed by increase in soluble iron after flooding was more pronounced with the addition of sesbania straw.

(vi) Fertilisers

Fertilisers especially the acid forming ones, may enhance the solubilisation of iron in soils.

Wander (1954) has reported that the continued application of ammonium sulphate to soils had strong acidifying effects to depths upto as much as six feet even if the reaction at the top was maintained at a pH of 5.6 - 5.8 by regular liming.

Motomura (1962) noted enhanced mobilisation of iron in soils incubated with ammonium sulphate.

Yamada (1959) and Inada (1965) found increased bronzing after applying ammonium sulphate and concluded that dissolved sulphide after sulphate reduction pre-disposed the plant to iron toxicity.

Subramoney and Kurup (1961) observed that addition of ammonium sulphate and ammonium phosphate favoured scum formation due to iron solubilisation in the submerged acid soils of Kuttanad.

In the waterlogged latosols of Orissa, Sahu (1968) noticed that the application of ammonium sulphate resulted in the aggravation of the bronzing symptoms in rice and in the maximum solubilisation of iron and accumulation in the plant tissue.

Tanaka and Yoshida (1970) in their exhaustive review of the nutritional disorders of the rice plant in Asia, have referred to the 'Mainsha' disorder in Orissa similar to bronzing as due to iron toxicity. This disease was reported to be aggravated by the application of ammonium sulphate.

Sharma and Banerjee (1983) compared the effects of ammonium sulphate and ammonium nitrate at 100 ppm N applied to four soils in West Bengal under two water regimes. They found that ammonium sulphate favoured the formation of Fe^{2+} upto 15 days at 50 per cent WHC while under waterlogged conditions the level of Fe^{2+} went up at a very high rate, probably due to chemical reduction with enhanced microbial activity.

3. Iron as a toxic factor

The importance of iron as an essential micronutrient for crops was recognised as early as in 1915. Its nutritional importance for the rice plant suggests one of the beneficial effects of submergence in the increased supply of available iron. Available information on the requirement and toxic levels of iron to rice are summarised below.

Kapp (1936) observed that the iron requirement of rice under submerged conditions is greater than that of upland soils. He found that the green colour and root growth improved in rice in culture solutions as the concentration of Fe^{2+} reached 1-25 ppm. However, on reaching 50 ppm there was decline in growth and number of tillers. Aiyer (1946) reported that the best results were obtained with an iron concentration of 32 ppm. According to Baba (1958) 45 ppm Fe^{2+} was the critical concentration in soil solution for rice. According to Mandal (1984), 1680 ppm Fe^{2+} was the critical concentration in soil solution. Izhizuka et al. (1961) noticed that iron or manganese at 0.1 ppm level was optimum for rice and above 10 ppm level they were toxic for japonica rice. Ponnamperuma (1955), Takagi (1958) and IRRI (1964) found that water soluble iron at about 500 ppm was toxic to rice. Mulleriyawa (1966) concluded from pot experiments in soils from Sri Lanka that bronzing symptoms appear genorally at iron concentrations of 30-80 ppm. However, Tanaka et al. (1966) observed that rice leaves containing $>$300 ppm iron showed toxicity symptoms of bronzing. In culture solutions Okuda and Takahashi (1965) observed 100-500 ppm iron as toxic while IRRI (1972) recorded 300-400 ppm in soils well supplied with nutrients. Patnaik and Bhadrachalam (1965) from nutrient solution studies maintained that the luxury range of iron for rice was 5-40 ppm (yield remained constant) and toxic range was above 40 ppm. Tanaka and Navasero (1966 b) reported that the critical concentration of iron in culture solution for bronzing to occur was 100 ppm at pH 3.7, but it was frequently over 500 ppm. They also noted that rice leaves containing 300 ppm iron often exhibited bronzing symptoms. They further reported that the iron contents of leachates in flooded condition reached values upto 1700 ppm. The toxic concentrations of iron were given as about 500 ppm by Nhung and Ponnamperuma (1966). Thus, the reported toxic levels of Fe^{2+} in culture solutions vary from 10-20 ppm to more than 500 ppm. There seems to be no simple relationship between iron concentration in the soil solution and the occurrence of iron toxicity.

Information on the critical contents of iron in the rice plant is available from the investigations of Tanaka and Yoshida (1970) leading to the conclusion that the leaf blade of the rice plant containing less than 70 ppm of iron at tillering stage would indicate possible deficiency of this element and leaf blade content of more than 300 ppm at active tillering stage would indicate suspected iron toxicity. They found that young plants are more susceptible to iron toxicity. The above figures were reported as tentative and subject to modification according to the criteria by which the disorders are defined, status of other elements or substances in the soil, growth stages of the plant varieties, climatic conditions etc. They have further reported that even in water culture, it is difficult to determine the critical iron content at which typical bronzing would appear. According to Ota (1968) and Tanaka and Yoshida (1970), apparantly healthy plants may contain more than 1000-1500 ppm iron. Jayawardena et al. (1977) held that the iron contents in the rice plants of different varieties which are moderately affected by bronzing may vary from 110-1100 ppm. Van Breemen and Moorman (1978) suggested that rice plants showed bronzing when dissolved iron in the rooting medium was in the 300-500 ppm range and at low nutrient levels of P and K or with root respiration inhibitors like H_2S, the iron concentration as low as 30 ppm may be toxic to rice. They even suggested that it is probably impossible to define a generally applicable critical iron content in plant tissue and held the view that to confirm iron toxicity, a comparison of the iron contents in leaf blades of affected and healthy plants from the same field would be more useful.

Though rice grown under submerged conditions may be associated with the increase in the availability of iron, certain physiological disorders of rice described in the literature appear to be related to an excess of reduced substances in the soil. Ponnamperuma (1955) reported that iron toxicity is a nutritional disorder of wetland rice associated with excess ferrous iron. The disorder known popularly as 'bronzing' is widespread in the humid tropics and sub tropics. Bronzing is reported in different local names to represent the diseases resulting from Fe, Mn or H_2S toxicity. In India the first report by Woodhouse (1913) was under the name 'Dakhina', in Champaran 'Bhabani' in Darbhanga, 'Ufra' in Mussafarpur and 'Chatra' in Sahabad districts of Bihar and 'Bhangiphutti', in Sambalpur district of Orissa. In India, Gupta (1954) used the term 'yellowing' and Sahu (1959) designated the disorder as 'bronzing'. In Java, Kuilman (1935) named the disorder as 'Mentek', in Hungary it was called 'Brusone'. In Japan, Baba and Harada (1954) named it 'Akagare' and in Malaya, Lockard (1956) used the term 'Penyakit Mera'. In Sri Lanka Ponnamperuma (1958) called it 'bronzing' while in Taiwan, Chang (1961) named it 'Saffocating disease'. The symptoms reported were more or less similar.

Tanaka and Yoshida (1970) characterised bronzing by the appearance of many small brown spots in dark green leaves starting on tips of lower leaves and spreading to basal parts. In severe cases, the brown discolouration would appear even on top leaves. The tints of affected leaves varied with variety, they might be purplish, orange, yellowish brown, brown or purplish brown. The roots were coarse, sparce dark brown and damaged. The bronzed plants analysed to toxic amounts of iron and were associated with low potassium level in the soil. Takijima and Kanaganayagom (1970) presented the supposed mechanism of bronzing and remedies for the disease. They collected rice samoles at milk ripe stage showing retarded growth from many locations in Ceylon. Analysis revealed that bronzed plants contained high iron contents in straw ranging from 720-3580 ppm.

Yoshida (1971) also reported that bronzing in Ceylon differed from bronzing seen in India. In Ceylon bronzing occurred in sandy soils contiguous to lateritic type soils and boggy or peaty soils while in India the trouble occurs mainly on acid and poorly drained soils. Measures for the improvement of iron toxicity in rice were also reported. Solution culture experiments revealed that excess Fe caused intraveinal yellowing which led to browning of old leaves commencing from the tips, followed by retarded plant growth and development with reduced olant height and tillering.

Islam and Choudhury (1960) reoorted that during waterlogging, algal growth and thick depositions of rusty colours resulted. Fe^{3+} was reduced to Fe^{2+} but at the surface the Fe^{2+} was oxidised to insoluble Fe^{3+} due to the presence of oxygen and light.

Subramoney and Kurup (1960) indicated possible relation of the reddish brown scum seen in Kuttanad acidic paddy fields to excess soluble iron. Absence of scum under sterile conditions indicated the involvement of bacterial reduction of Fe^{3+}. Similar findings have been reported by Alexander (1965). Bhargava and Abrol (1984) ascribed the variety of mottle colours observed in different pedons in acid sulphate soils of Kerala to the presence of iron in reduced form under submerged conditions and decaying roots in root channels.

Koshy and Brito Mutunayagom (1961) noted that soluble phosphates in the acid soils of Kerala were converted into insoluble iron and aluminium compounds and these had a bearing on reduced iron and aluminium toxicity.

Ota and Yamada (1962) ascribed bronzing to the combined effect of high aluminium and low calcium in the soil. They had also recognised two types of bronzing, one appearing one to two weeks after transplantation and was associated with sandy soil adjacent to laterite highland and the other associated with peaty or boggy soils appearing when ammonium sulphate was top dressed at 1-2 months after transplanting.

Inada (1966) reported the 'bronzing' symptoms as due to direct iron toxicity resulting from excessive absorption and accumulation of iron in the plant, while 'oranging' symptoms would result from nutrient deficiency (mainly P and K) in the plant induced by relatively high iron levels in soil solution, while Howeler (1985) distinguished between bronzing symptoms caused by excess iron and oranging which occurred at low Fe concentrations in the leaf and reported that the severity of bronzing appeared to be related to low concentrations of P, Ca, Zn, Mg and K in the plant.

Plant mechanisms of tolerance to iron toxicity have been related to the evolution of oxygen from roots, precipitating the free oxides and lessening the transpiration rate. Yoshida (1967) reported the root oxiding power of the rice plant to be 15-30 mg/g dry root, based on naphthyl amine oxidised in 48 hours which was higher than that for many other common crops. He, however, observed substantial difference among the varieties. The oxidising power was greater at the earlier growth stages of rice and it increased with solar radiation and decreased when the plant was deficient in N, P or K. Rice roots often become coated with yellowish red precipitates of unknown composition, presumably ferric-manganic oxides and hydroxides, which are however, not formed around the active root tips which remain white. Tanaka et al. (1968) considered that hydrogen sulphide could aggravate iron toxicity by damaging the oxidising power of the rice roots under certain circumstances. Rorizon (1972) reviewed information on the plant mechanisms of tolerance to iron toxicity in waterlogged soils, which have been related to evolution of oxygen from roots, precipitating the free oxides around their roots and lessening the transpiration rate. Green and Etherington (1977) have studied in detail the root oxidation mechanism with the aid of transmission electron microscope, analysing the iron deposits within the roots with the aid of electron microscope and electron probe analysis and suggested that gaseous oxygen diffusing through cortical air spaces from the aerial part of the plant was responsible for oxidation and precipitation of iron before it reached the conducting tissues, thereby preventing excessive iron uptake. Ottow et al. (1982) have explained the breakdown of iron excluding mechanism of the rice root.

Park and Tanaka (1968) concluded that the cause for brown spotting in rice was iron toxicity which was due to high uptake of iron. Drainage of the soil improved the growth of plants and alleviated the brown spotting symptoms.

Serayonakul (1968) conducted solution culture experiments containing 20, 50, 200, 300, 400, 500 and 600 ppm Fe^{2+}.

He observed that plants grown in 200 ppm Fe and above showed toxicity symptoms with excessive uptake of iron. Plants grown in solutions less than 200 ppm showed no toxicity symptoms but the yields were low.

Sahu (1968) identified three kinds of disorders in rice in the name of bronzing in India, of which the symptoms which occurred in waterlogged latosol alone would qualify for iron toxicity disorder. He attributed the disease among others to an excess of iron concentration in the plant tissue combined with low K.

Juste (1970) observed that accidents attributable to excesses of trace elements were more usually seen in acid soils which have been insufficiently improved.

Howeler (1973) noticed that iron induced oranging disease of rice was associated with K deficiency.

In culture solution Tadano (1974) obtained characteristic brown spotting of rice leaves commencing with older leaves when the Fe content was 550 ppm. The iron content of the shoots was less during the mid stages of rice growth than at early stages. With increase in the iron concentration in the solution the Fe content in the plant increased.

Ottow et al. (1981) while describing the incidence and symptoms of Fe toxicity in lowland rice, found that soils which were toxic in Fe were deficient in P and K and low in bases (Ca) and Zn.

Benckiser et al. (1982) collected rice leaves showing symptoms of iron toxicity from plants of many cultivars growing at various sites in Philippines, Sri Lanka, Brunei, Indonesia, China and Liberia and compared their mineral contents with those of IRRI Cv. grown in greenhouse. The affected leaves were much higher in iron content than the accepted critical level of 300 ppm. Leaf iron content negatively correlated with soil CEC, clay and exchangeable Ca and K, but no corrolation existed between pH and leaf iron content. The higher the amount of available Ca, the lower was the uptake of Fe by plants.

Benckiser et al. (1983, 1984) reported that K and Ca+Mg reduced the uptake of iron significantly and this was ascribed to a decrease in root exudation caused by decreased permeability of root membranes. He observed that fertilisation, in general, enhanced plant growth and decreased iron uptake.

Verma and Tripathi (1984) noticed wide occurrence of bronzing disease of rice grown under submerged condition without lime in acid alfisols of Himachal Pradesh, Uttar Pradesh and J & K, three weeks after planting and ascribed it to excessive iron concentration in plants and submergence was mainly responsible for this disorder.

The mechanism of iron toxicity occurring in the coastal areas of acid sulphate soils with sea water intrusion and acid sandy soils was explained by Mensvoort et al. (1985) as due to the plants' excessive uptake of Fe^{2+} associated with Cl^- and SO_4^{2-} which causes acidification inside the plant.

Cochrane and Sousa (1986) reported that 0.1 M solution of $BaCl_2$ containing 1:10 phenanthrolene indicator served as a satisfactory field test for exchangeable and water soluble iron in Cerrado soils.

From a series of screening trials Virmani (1976) concluded that the rate of development of toxicity symptoms to rice grown in iron toxic swamps and the extent of yield reduction depended upon the level of tolerance of the cultivars. He also reported the possibility of pigmented lines being more tolerant to iron toxicity since some iron is used for anthocyanin production.

Based on dry matter yield reduction of shoots at higher iron concentrations compared to optimum or control treatment, Fageria and Rabelo (1987) classified rice cultivars as tolerant, semi tolerant, moderately susceptible and susceptible. Tolerance of rice cultivars to iron toxicity has been tested by several investigators.

4. Influence of iron toxicity on the uptake of nutrients

(i) Uptake of major nutrients (N, P and K)

Baba and Tajima (1960) observed that rice leaf discolouration due to excessive uptake of iron inhibited the absorption of phosphorus to a greater extent than other nutrients.

Ota and Yamada (1962) compared the nitrogen and potassium contents of bronzed rice plants with those of healthy plants and reported that bronzed plants had higher N and low K contents than healthy plants. Inada (1965) and IRRI (1966) also came across similar observations.

Results of field experiments in loamy sand latosol and swampy low land soils in Orissa conducted by Sahu (1968) revealed higher nitrogen and iron and low potassium contents in bronzed plants. Such plants responded to K application. He also reported suppressed P uptake in bronzed plants and application of P and K and urea spray at AT stage reduced bronzing.

Park and Tanaka (1968) concluded that brown spotting or bronzing in rice due to iron toxicity was associated with high Fe and low K and such plants responded favourably to K applications.

Ota (1968) observed a location where severe bronzing occurred during every season. Chemical analysis of plant samples revealed high N content with higher contents at higher grades of bronzing.

Takijima and Gunawardena (1969) obtained high N and low K during straw analysis from bronzed rice plants in a variety of soils in Ceylon. Phosphorus content clearly decreased with increased incidence of bronzing.

Takijima and Kanaganayagom (1970) from pot and field experiments in iron toxic soil noticed that nutrient composition of straw had high N and Fe and low K contents. They also reported that bronzing was associated with low P contents and appeared to be an exoression of symptoms due to P deficiency and that enhanced P application could prevent bronzing.

Tadano and Tanaka (1970) noticed that the K absorbing power of the roots was low when the roots were suffering from high level of iron. Application of K resulted in growth improvement in these soils and they stressed the need to maintain favourable K status when Fe level was high in growth media.

Tanaka and Yoshida (1970) observed that rice plants low in K often developed bronzing symptoms.

Yoshida (1971) suggested that the roots of K deficient rice plant were unable to oxidise Fe^{2+} and excess Fe^{2+} would enter the plant and produce toxicity symptoms.

Tanaka and Tadano (1972) from studies on rice plants grown in culture solution concluded that when the iron level was higher in culture solution, P uptake was low. The effects of K^+ on Fe^{2+} toxicity of rice were also evaluated in a pot experiment. Roots of plants with K^+ deficiency reduced Fe^{2+} excluding power, thus Fe^{2+} toxicity increased.K application decreased the iron content along with bronzing. Solution culture experiments also revealed that low levels of K with high levels of iron could cause K deficiency to become more serious thereby plants becoming more susceptible to iron toxicity.

Tadano (1975) reported that rice plants deficient in P were more susceptible to iron toxicity than the normal plants.

Tadano (1976) observed that the high Fe^{2+} concentration which occurred in soil solution with rapid decomposition of large applications of fresh organic manure reduced K^+ uptake, increased K deficiency which further decreased the rice roots' ability to exclude Fe^{2+}.

Trolldenier (1981) reported that the root oxidising power was highest with complete nutrition and lowest when K was deficient.

Ottow et al. (1981) found that soils where Fe toxicity occured were P deficient. Low and unbalanced supply of P was reported as one reason for the development of iron toxicity.

Yamanouchi and Yoshida (1981) studied the relationship between leaf tissue tolerance and whole plant tolerance for iron toxicity and observed that P deficiency among other nutrients decreased leaf tissue tolerance.

Ottow et al. (1982) based on plant and soil analysed from various sites affected by bronzing noticed that low K supplying capacity by the iron toxic soil was reflected in the plant tissue analysing to lower K contents.

Benckiser et al. (1982) analysed rice leaf samples collected from many Cv. from various sites in the Philippines, Sri Lanka, Indonesia, China and Liberia and reported high N and Fe contents in the bronzed leaves.

Benckiser et al. (1984) reported that iron toxicity was associated with P deficiency and P fertilisation would improve iron excluding mechanism of the root efficiently. Association of bronzing with K deficiency was also noticed and they suggested that K fertilisation gave positive response.

Yoshida and Yamamuro (1986) ascribed the 'akagare' symptoms on rice in Brunei to iron toxicity. The disorder was remedied by improving drainage and correcting the low pH and low P status.

(ii) Uptake of Calcium, Magnesium and Manganese

Anatagonistic relationship between iron and manganese was reported by several workers. McHargue (1945) noticed that if Mn was deficient in tho plant, there would be an excess of active iron and if Mn concentration was high, chlorosis due to iron shortage would result from low concentrations of iron in the plant. Inada (1965) reported that with excessive iron uptake by rice plant Mn uptake was inhibited.

Baba and Tajima (1960) reported association of bronzing with excessive supply of iron which inhibited nutrient absorbtion of Calcium.

Ota and Yamada (1962), Ota (1968), Takijima and Kanaganayagom (1970) and Tadano (1975) found that bronzed plants had very low contents of calcium, magnesium and manganese as compared to healthy plants.

In solution culture trials, Tadano (1970) observed that higher levels of iron had a depressing effect on the uotake of Ca and Mg by rice plants. The translocation of iron from roots to shoots was accelerated significantly in Mg and Mn deficient plants.

Ottow et al. (1983) analysed soil and plant samples of several geographical iron toxic sites and obtained low Ca, Mg and Mn contents and concluded that those soils were uniformly deficient in Ca, Mg and Mn.

Benckiser et al. (1984) reported that iron toxicity in rice was associated with calcium deficiency and calcium fertilisation to plants grown in iron toxic environment minimised iron toxicity.

5. Amelioration of toxic levels of iron in soil solution

A relatively higher concentration of soluble Fe^{2+} in the soil combined with relatively low pH are considered as major constraints in iron toxic soils. According to Ottow et al. (1982) curing or preventing iron toxicity is not a simple procedure since none of the amelioratory measures suggested would completely eliminate this problem.

(i) Flooding and washing the soil

Most of the wet land rice soils are generally located on relatively imperfectly drained land which is often subject to varying periods of flooding ranging from a few days to a few months in an year.

Hart et al. (1963) and Jordan (1963) suggested that reclamation measures in saline mangrove soils in Sierra Leone included leaching with fresh water or sea water and liming and appeared to be based on divergent experiences rather than on an understanding of the chemical changes in flooded, acid sulphate soils.

IRRI (1971) and Mohanty and Patnaik (1973) recommended flooding of the soil for considerable length of time preferably with addition of organic matter to hasten reduction before puddling and transplanting rice, to overcome iron toxicity. This resulted in the reprecipitation of the released iron. Sahu (1968), on the other hand, suggested provision of drainage, soil application of lime, phosphate and potassium and foliar urea to overcome the bronzing disease of rice. (Mandal and Sinha, 1964; Graven et al. 1965; Wang, 1971). The effect of flooding on the increased P availability and Fe-P relationship was studied by Mahapatra (1968).

According to Ponnamperuma (1977, b) flooding a soil induces a series of chemical and biochemical changes that profoundly affect the availability and loss of nutrients and the generation of substances that can interfere with nutrient uptake or that poison the plant directly.

Ponnamperuma (1965, 1972) was of the view that large amounts of Fe^{2+} and Mn^{2+} brought into solution at low PE values, along with $HCO3^-$ increase the specific conductivity of the soil solution and displace large amounts of Ca^{2+}, Mg^{2+} and K^+ by cation exchange reactions.

To ward off the toxic effects of excess Fe^{2+}, CO_2, organic acids and H_2S, Ponnamperuma (1977, b) suggested that soils should be kept submerged for at least two weeks immediately before planting in tropical lowlands.

Sahrawat (1979) compared the effects of waterlogging and flooding with soil drying on iron toxicity to rice in an acid sulphate soil in Philippines and proposed the management practice of keeping the soil flooded for 10-12 weeks before planting, so that soluble iron would drop below toxic level.

Abu et al. (1989) observed that rice yields varied significantly between varieties and planting dates and suggested that the optimal time of planting to escape serious iron toxicity in the inland valley swamp at Mogbolontor was during the first two weeks of July, when the amount of water would be too high to wash off iron rapidly.

2. Liming

The usefulness of lime as a soil ameliorant for reclaiming the acid and acid sulphate soils and for correcting the toxic effects of Fe^{2+} has been reported by Ponnamperuma (1955, 1958, 1960), Allaway (1957), Abichandani and Patnaik (1961), Subramoney and Kurup (1961), Vaculik (1963), Nhung and Ponnamperuma (1966), Inada (1966), Takijima and Kanaganayagom (1970), Tanaka and Tadano (1972), Koshy (1973) and many others.

Mandal and Sinha (1964), Graven et al. (1965), Sahu (1968) and many others have found that lime could reduce Fe^{2+} and Mn^{2+} toxicities by reducing their solubility under waterlogged conditions or by precipitation as their hydroxides.

Ponnamperuma (1972) reported that with each unit increase in soil pH, there was several fold decrease in the availability of Fe^{2+} and Mn^{2+} and suggested that the building up of high concentrations of water soluble Fe^{2+} could be prevented by liming.

In laboratory incubation and pot experiments conducted by Kuruvilla and Patnaik (1973) to study the effect of lime on the amelioration of acid sulphate soils of Kerala it was indicated that these soils could be reclaimed by leaching of salts followed by application of lime and continuous flooding.

Sukumaran and Money (1973) assessed the effect of liming materials applied at fractional levels of LR on the toxic factors in the kari soil, Kuttanad and indicated that application of lime materials in quantities equivalent to 1/10 and 1/5 of LR reduced the exchangeable H^+ and Al^{3+} and water soluble Fe^{2+}. Burnt lime was found more effective than dolomite.

Singh and Dahiya (1975) noticed that the addition of increasing levels of $CaCO_3$ to soil resulted in a decrease in all the forms of iron.

Brady (1980) suggested that iron toxicity could be ameliorated by liming but quantities required are often prohibitive.

The effects of MnO_2 and $CaCO_3$ (5 t/ha) on iron toxicity symptoms and rice yield were studied by Ponnamperuma and Solivas (1981) in a flooded acid sulphate soil at Philippines. Based on symptoms at 4 and 8 weeks of transplanting, the best treatment was IR 43 (moderately tolerant variety) in the presence of $CaCO_3$ and MnO_2 and the worst was IR-26 (moderately susceptible variety) in the absence of $CaCO_3$ and MnO_2.

Verma and Tripathi (1984) reported that although liming could not alleviate bronzing, it delayed the appearance of symptoms (about 25 days) till flowering after which bronzing started.

Lopes and Machado (1985) while studying the effect of fertilisers and lime application in reducing iron toxicity symptoms in the field with and without organic matter found that oranging symptoms were most intense in the untreated control.

Bishnoi et al. (1988) found that liming on an average increased significantly DM yield of soyabean and also uptake of N, P, K, Ca and Mg. Base saturation, lime potential and effective CEC were increased while exchangeable acidity and toxic metals Al^{3+}, Fe^{2+} and Mn^{2+} were decreased to 66.4, 43.3 and 100 per cent respectively.

3. Silicate

Experimental application of calcium silicate to sugarcane in Hawaii on soils by McGeorge in 1924 resulted in beneficial growth response which was ascribed to improved utilisation of soil phosphorus by the plant.

Yoshii (1941) and Yoshida (1958) found that silicate increased the resistance by rice to blast diseases and that the resistance was proportional to the concentration of silica in the culture medium.

The beneficial influence of silica on rice growth has been emphasised by Demolon (1950) and particularly by Japanese workers ([illegible]; Ishibashi and Akiyama, 1960; Comhaire, 1966).

Jackson and Sherman, 1953 and Sawhney and Jackson, 1958 had noted that irrigation with siliceous waters increased in CEC of soils and modified some other properties due to high silica potential favourable for the formation of montmorillonite.

Okuda and Takahashi (1962) demonstrated that silica decreased the excessive uptake of Fe and Mn by rice and decreased Fe and Mn toxicity in rice plants. They explained this by the action of silica on the oxidising power of the rice roots.

Dutta et al. (1962) reported that increased uptake by the plant (cereals) of the P contained in the soil was possible when silica was applied.

Subramoney (1965) suggested the use of magnesium silicate in acid sulphate soils of Kuttanad to inhibit the production of H_2S and other toxic factors.

Clements et al. (1965) and Clements (1968) obtained considerable response in sugarcane to the application of calcium meta silicate upto 8 t/acre to an aluminous-ferruginous latosol believed to contain toxic amounts of Fe^{2+} and Al^{3+} and attributed this to the elimination of soil toxicities.

Sherman (1969) reported that application of silicate decreased the available Mn^{2+}, Fe^{2+} and active Al concentration in soils.

Park et al. (1972) found that for the liming of strongly acidic top soils (pH 3.6 to 4.2), slower acting Wollastonite (Calcium silicate) was more suitable than $CaCO_3$, at the rate of 3 to 6 tons/ha.

Ponnamporuma (1972) noticed increased availability of silicon ~~noticed~~ in soils when submerged, due to release of silicon sorbed on hydrous oxides of iron (III) following reduction of iron (III) to iron (II).

Kuruvilla (1974) found that though ameliorative measures such as lime application and repeated flushing with fresh water could improve acid sulphate soils and produce better grain yield during the subsequent season, very often problems of low pH and Fe and Al toxicity reappeared on drying the soil after harvest. For such situations, he proposed magnesium carbonate or magnesium silicate where the resultant sulphates formed by interaction were more soluble than $CaSO_4$ formed when lime alone was added.

Karunakara Panicker (1980) obtained increased yields of grain and straw in paddy in Kuttanad, by field application of magnesium silicate.

The beneficial effect of magnesium silicate (steatite) in reducing Al toxicity to rice in acid soils of Kerala, has been indicated by Abraham (1984).

MATERIALS AND METHODS

MATERIALS AND METHODS

The experiments included in this work were carried out in the submerged rice soils of Kerala, where iron toxicity is likely to be a serious problem during rice cultivation. The kayal (reclaimed lake beds), kari (acid sulphate) and karapadom (lateritic hydromorphic with deposited alluvium) soils of Kuttanad (Fig.1), the brown hydromorphic soils of the midland lateritic zone and the sandy soils of Onattukara region were thus included in the study.

In the first experiment the distribution of water soluble, exchangeable and active forms of iron was studied in 27 surface soil samples collected from the waterlogged paddy fields of Kuttanad. The samples were collected from a depth of 0-20 cm from six locations in the kayal, nine locations in the kari and 12 locations in the karapadom areas.

The second experiment was a study of the downward variation in the distribution of different forms of iron in eight profiles. Two profiles each from the kayal, kari and karapadom areas and one profile each representing the Onattukara and the midland brown hydromorphic soil were used in the study.

The third experiment consisted of a series of incubation studies in which the effect of salinity, organic matter and ammonium sulphate on the release of iron was traced in typical submerged rice soil from the kayal, kari, karapadom and brown hydromorphic sites.

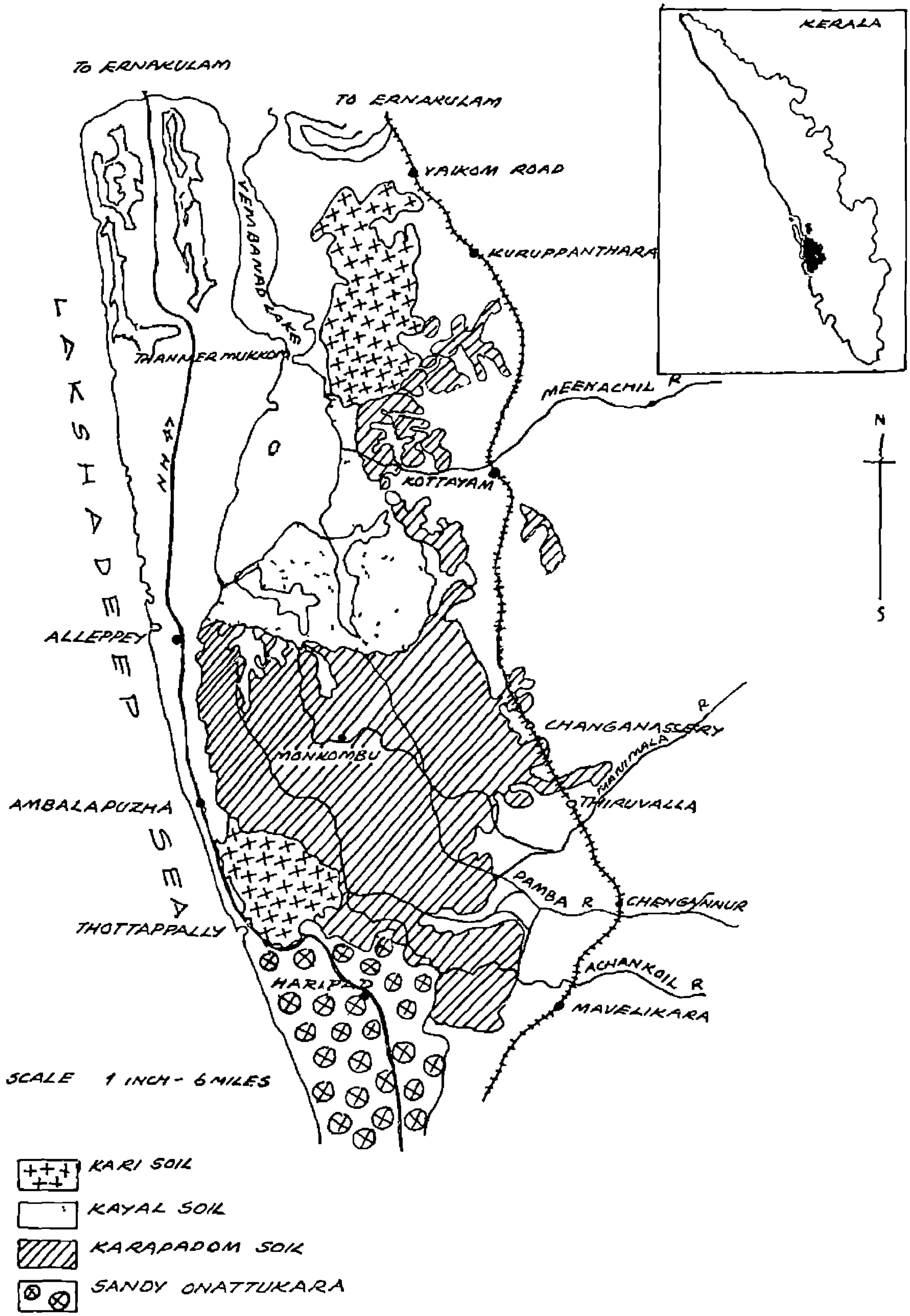

FIG. 1 SITE PLAN KUTTANAD

The fourth experiment also involved incubation studies in which the influence of lime on the amelioration of iron toxicity was examined.

The details of soils collected and the methods adopted for the four experiments are given below

1. Studies on surface soils

The surface samples were collected immediately after a harvest when the soils were sufficiently moist, but not waterlogged. The stumps of the rice plants were pulled out, the organic debris removed and the soil collected up to a depth of 20 cm with the help of a spade, packed in polythene bags and brought to the laboratory. About half of each soil was air dried, powdered with a wooden pestle, passed through a 2 mm sieve and stored in labelled polythene bags for the determination of the general physico-chemical characteristics. The other half was kept in the moist condition in polythene bags and used for the determination of water soluble, exchangeable and active forms of iron. The following methods were used for the various determination.

(i) Texture The texture of the surface samples was determined by feeling the moist soil between the thumb and the forefinger.

(ii) Moisture 10 g of the soil was dried in an air oven at 100-105°C to constant weight and the loss in weight was expressed as per cent on oven dry basis. The moisture percentage was determined for computing the various components on moisture free basis.

(iii) Soil reaction (pH) The pH was determined in a 1:2.5 soil water suspension using a Perkin-Elmer pH meter and glass electrode.

(iv) Electrical conductivity (EC) The electrical conductivity was determined in the 1:2 water extract using a 'Solubridge'.

(v) Organic carbon Organic carbon was estimated by the Walkley and Black's rapid titration method as given by Jackson (1973).

(vi) Cation Exchange Capacity The cation exchange capacity was determined by the neutral N Ammonium acetate method as described by Jackson (1973).

(vii) Iron Total iron, as well as the water soluble, exchangeable and active forms of iron in the moist samples were determined as follows

(a) Total iron

Total iron was determined in the hydrochloric acid extract of 10 g of the air dried soil. 20 ml of the extract was transferred to a 250 ml Erlenmeyer flask reduced with zinc and dilute sulphuric acid, filtered through glass wool and the filtrate titrated with standard 0.1 N potassium dichromate using potassium thiocyanate as the external indicator. From the quantity of dichromate consumed, the percentage of iron (Fe) in the soil was calculated and expressed on moisture free basis.

(b) Water soluble iron

To 10 g of the soil taken in an Erlenmeyer flask 100 ml of distilled water was added and the suspension shaken in a shaker for two minutes. It was then filtered through a Whatman No. 42 filter paper and the clear filtrate collected. To an aliquot of the filtrate 2 ml of 10 per cent hydroxylamine hydrochloride (in water) was added followed by 1 ml of a 1.5 percent solution of orthophenanthrolene in 95 per cent alcohol. The pH was adjusted to 2.8 - 3.2 with a few drops of a 25 per cent aqueous solution of sodium citrate. The mixture was kept in a water bath at 70°C for 10 minutes and then allowed to stand outside for 30 minutes till the development of the colour was complete. The colour was then read in Klett-Summerson Photoelectric Colorimeter using a green filter (480-520 μ) .

(c) Exchangeable iron

To the soil left after the extraction of the water soluble iron was added 200 ml of neutral N ammonium acetate solution. The suspension was shaken vigorously for 20 seconds and filtered quickly through a Whatman No.5 filter paper fitted to a Buchner funnel under suction. The filtrate was evaporated to dryness over a sand bath until all the ammonium acetate was eliminated. The last traces of organic matter were removed by treatment with a few drops of aqua regia and then evaporated to dryness. The evaporation was repeated with aqua regia till dark colour completely disappeared and the residue became white. The residue was taken up with a few drops of NHCl, made upto a convenient volume and the iron determined in a suitable aliquot colorimetrically as in the case of water soluble iron, after reduction with hydroxylamine hydrochloride and the development of the colour with orthophenanthrolene reagent.

(d) Active iron

Active iron was estimated by the method suggested by Asami and Kumada (1959). One gram soil was weighed into a 250 ml Erlenmeyer flask and treated with 3 g sodium dithionite and 100 ml of 0.02 M EDTA. The reaction mixture was placed in a water bath maintained at 75°C for 15 minutes with occasional shaking. The supernatant liquid was filtered into a 250 ml volumetric flask and the residue washed down with 10 per cent sodium chloride solution and made upto volume. Iron was determined in an aliquot after reduction with hydroxylamine hydrochloride by the orthophenanthrolone colorimetric method and expressed as active iron.

Statistical analysis

The analytical data obtained as above were subjected to statistical analysis to make a comparative study of the chemical properties of the kayal, kari and karapadom soils of Kuttanad and to bring about the interrelationships between pH and the water soluble, exchangeable and active forms of iron in the soils as well as with other soil chemical characteristics.

2. Profile studies

The studies were undertaken on the soil profiles representing Kuttanad as well as the sandy Onattukara and brown hydromorphic soils which are the major acid soils where iron toxicity to rice is encountered occasionally. Two profiles each from the kayal, kari and karapadom areas and one profile each of the Onattukara and brown hydromorphic groups were used in this study. Profile pits were cut to a depth of 100 cm and soils were collected from depths of 0-25, 25-50, 50-75 and 75-100 cm immediately after harvest. The moist soils were packed in polythene bags and transferred to the laboratory. Half of each sample was air dried, powdered sieved and stored in labelled polythene bags for mechanical analysis and the determination of the general physico-chemical characteristics. The other half was kept in the polythene bags in the moist condition and used for the determination of the different forms of iron.

The mechanical analysis of the soils was carried out by the International Pipette method as given by Piper (1966). Moisture, pH, organic carbon and cation exchange capacity as well as total, water soluble, exchangeable and active forms of iron were determined by the methods used for the studies on the surface soils as described above.

Statistical analysis

The analytical data obtained as above were subjected to statistical analysis to study the profile-wise and depth-wise variations in the chemical properties of the soil types and also the forms of iron.

3. Incubation studies

The effect of salinity, organic matter (farm yard manure) and ammonium sulphate on the release of iron in the soluble form was studied in the soils representing the typical submerged rice fields viz., the kayal, kari and karapadom soils as well as a brown hydromorphic soil in a series of incubation experiments. The major physico-chemical characteristics of the surface soils used for the incubation studies are presented in Table 1 (a).

(a) Salinity

Glazed, cylindrical porcelain pots of capacity 2.5 l were used in this study. The pots were fitted with a delivery tube and pinch clip at the bottom and placed on table in such a way that the leachate could be collected from the delivery tube. A half inch layer of coarse sand was placed at the bottom of each pot and over it were placed small broken granite pieces to facilitate easy drainage and to avoid clogging of the outlet. Two kilograms each of the air dried soils were

Table 1a Physico-chemical characteristics of soils used for incubation studies

Sl. No.	Soil type	Mechanical analysis				N (per cent)	P (per cent)	K (per cent)	CEC (cmol(+)kg^{-1})	pH (H_2O)	Electr. cond (dSm^{-1})	Organic carbon (per cent)	Iron			
		Coarse sand (per cent)	Fine sand (per cent)	Silt (per cent)	Clay (per cent)								Total iron (per cent)	Water soluble (ppm)	Exchangeable (ppm)	Active (ppm)
1.	Kayal	1.2	72.0	2.6	16.6	0.21	0.03	0.08	7.5	5.2	3.2	3.96	9.1	45	198	1010
2.	Kari	1.5	5.0	19.1	63.4	0.31	0.12	0.08	23.9	3.8	3.0	6.12	12.5	65	168	1818
3.	Karapadom	7.5	47.2	19.1	18.0	0.24	0.04	0.13	7.2	4.4	2.6	2.90	17.6	56	220	1222
4.	Brown hydromorphic	9.0	10.2	20.2	54.3	0.15	0.03	0.09	7.0	5.1	1.1	1.30	12.5	25	160	858

transferred into the pots and treated with water of different salinity levels. The salinity levels used were the following

1. No salinity	100 per cent water
2. 25 per cent salinity	25 per cent sea water + 75 per cent water
3. 50 per cent salinity	50 per cent sea water + 50 per cent water
4. 75 per cent salinity	75 per cent sea water + 25 per cent water
5. 100 per cent salinity	Sea water

The sea water used in this study was collected from the sea at the Kovalom beach. The data on the analysis of sea water used in the study are presented in Table 1 (b). The water of different salinity levels was added to the soil in each pot and allowed to stand to a height of 5 cm. A layer of paraffin oil was also added to prevent oxidation of the iron going into solution by contact with atmospheric oxygen. The level of water in the pots was maintained at the same height by the periodical addition of water of the respective salinity level.

Samples of drainage water were collected from each pot at intervals of 0, 5, 10, 25, 40, 50, 75 and 90 days. While collecting the drainage water the initial few ml were dis-

Table 1 b Analytical data on sea water

1.	pH	8.0
2.	Salinity	32 ‰
3.	Specific conductivity	57000 micromhos/cm
4.	Total salts	1253 me/l
5.	Dissolved oxygen	4.2 ml/l

carded and it was collected in beaker under a layer of liquid paraffin. The iron was estimated in the leachate colorimetrically by the orthophenanthrolene method.

(b) Organic matter

The procedure was similar to the one adopted for studying the effect of salinity. Two kilograms of each air dried soil were mixed with dried farm yard manure at the rates of 0, 1, 2, 4 and 8 g per pot. The soil treated in this manner was taken in the pots and then water was added to a level of 5 cm above the soil surface. A layer of liquid paraffin was added above the water to prevent the oxidation of iron going into solution. Leachates were collected after 0, 5, 10, 25, 40, 50, 75 and 90 days and the iron estimated.

(c) Ammonium sulphate

Two kilograms each of the soils were treated with ammonium sulphate at the rate of 0, 50, 100, 150 and 200 kgN/ha and the experiment conducted as in the case of the organic matter treatment. Leachates were collected at the same intervals and the iron going into solution estimated.

Statistical analysis

The following analysis of variance was performed to study the changes in iron release from soils on flooding with water alone and in the presence of different ameliorants for various periods.

ANOVA

Source	df
Between soils (S)	3
Between treatment levels (T)	4
Between periods (P)	7
Between soils and treatment levels (ST)	12
Between treatment levels and period (TP)	28
Between soils and period (SP)	22
Between soils, treatment levels and period (STP)	84
Total	159

4. Amelioration of iron toxicity in submerged rice soils by the use of lime

The restraining effect of lime on iron solubilisation was studied in another set of incubation trial using the same air dry soils as detailed under experiment 3. The ordinary builder's lime containing 98 per cent CaO was used in this experiment. Three levels of lime were used viz., 0, 600 and 1000 kg/ha and the experiment was carried out as indicated under experiment (3). Leachates were collected at the same intervals and the iron estimated in the leachates as in the earlier treatments.

Statistical analysis

The analysis of variance performed to study the changes in iron release from soils on flooding in water alone and in the presence of lime used as an ameliorant, for various periods was as follows.

ANOVA

Source	df
Between soils (S)	3
Between treatment levels (T)	2
Between periods (P)	7
Between soil and treatment level (ST)	6
Between treatment level and period (TP)	14
Between soils and period (SP)	21
Between soils, treatment level and period (STP)	42
Total	95

Since the experiment was singly replicated, SxTxP interaction was treated as error and the treatment levels were tested against this interaction for the significance of their effects.

RESULTS

RESULTS

I Forms of iron in surface soils in relation to their physico-chemical properties

Kayal soil

The results in relation to the physico-chemical properties of six surface soils from the kayal lands of Kuttanad along with the contents of different forms of iron are presented in Table 2 and mean values are given in Table 5.

Active iron represented the major form of iron in the kayal soils of Kuttanad. Its content varied from 1642 to 3595 ppm in different locations, with a mean value of 2506 ppm. The least content of active iron was found in the soils from Kavalam while Sreemoolam kayal soil registered the maximum. Exchangeable iron content varied between 144 ppm at Kavalam and 208 ppm at Marthandom kayal with a mean content 175 ppm. Wator soluble iron which constituted a comparatively lower proportion was found to have the lowest value of 94 ppm at Chathurthiakari and highest value of 130 ppm at Kavalam and Marthandom kayals with an average content of 114 ppm. Textural analysis indicated that the kayal soils were predominantly clayey with fairly high values for cation exchange capacity which ranged between 12.4 cmol(+)kg^{-1} at Chathurthiakari and 19.5 at Kavalam. The organic carbon status was also fairly high and ranged from 4.0 to 8.8 per cent with a mean of 6.4 per cent. The soils

Table 2. Forms of iron in the surface layers of kayal soils in relation to their physico-chemical properties

Sl. No.	Location	Soil group	Texture	pH	Organic carbon (per cent)	Electrical conductivity (dSm^{-1})	CEC ($cmol(+)kg^{-1}$)	Forms of iron (ppm)		
								Water soluble	Exchangeable	Active
1.	Kavalam	Kayal	Clay	3.9	4.0	2.2	19.5	130	144	1642
2.	Pulinkunnu	,,	Clay loam	4.5	6.1	1.2	14.5	101	167	2414
3.	Chathurthiyakari	,,	Clay loam	4.9	7.0	0.8	12.4	94	175	2555
4.	Marthandam kayal	,,	Clay	4.0	6.6	3.0	15.5	130	208	2460
5.	Sreemoolam kayal	,,	Clay loam	4.5	8.8	5.0	16.0	120	172	3595
6.	Neelamperoor	,,	Clay loam	5.0	6.0	2.5	18.5	110	185	2367
	Mean			4.5	6.4	2.5	16.1	114	175	2506

were acidic with pH values ranging from 3.9 at Kavalam to 5.0 at Neelamperoor and averaging 4.5. The electrical conductivity recorded the highest value of 5 dSm^{-1} in the Sreemoolam kayal soil and minimum of 0.8 dSm^{-1} at Chathurthiakari.

Table 6 provides results of intercorrelation between physico-chemical properties and forms of iron. The results reveal that the water soluble iron in the soil was negatively and significantly correlated ($r = -0.8136$) with the pH of the soil. Positive and significant correlation was found between the active iron and the organic carbon contents ($r = 0.9798$) of the soil. The CEC was found to be correlated negatively with exchangeable iron and active iron and positively with water soluble iron contents but none of these was significant even at 10 per cent level.

Kari soil

Table 3 presents data on some of the physico-chemical properties of typical kari soils collected from nine different locations in Kuttanad. As in the case of kayal soils, active iron represented the major form of iron in these soils also. The active iron content was higher than in kayal soils and ranged from 2410 to 5200 ppm with a mean content of 3862 ppm. Karumadi III recorded the lowest content of active iron while appreciably high values were recorded by Thottapally I soil

Table 3. Forms of iron in the surface layers of kari soils in relation to their physico-chemical properties

Sl. No.	Location	Soil group	Texture	pH	Organic carbon (per cent)	Electrical conductivity (dSm^{-1})	CEC ($cmol(+)kg^{-1}$)	Forms of iron (ppm)		
								Water soluble	Exchangeable	Active
1.	Karumadi I	Kari	Sandy clay loam	3.8	9.6	4.5	13.8	148	172	4850
2.	Karumadi II	,,	,,	3.9	7.8	3.8	14.5	138	170	3316
3.	Karumadi III	,,	Clay loam	4.0	6.3	3.7	16.8	121	145	2410
4.	Purakad I	,,	Clay	3.8	10.5	3.5	16.5	122	213	5178
5.	Purakad II	,,	Clay loam	4.0	7.9	3.0	17.5	138	164	3830
6.	Thottappally I	,,	Clay	3.2	10.2	4.1	14.9	148	216	5200
7.	Thottappally II	,,	Clay	4.0	8.5	3.0	18.5	136	210	3482
8.	Mundar	,,	Clay	3.7	9.0	5.2	18.8	148	223	3585
9.	Vadayar	,,	Clay	3.5	8.5	4.9	18.6	165	230	3410
	Mean			3.8	8.7	4.0	16.7	140	194	3862

followed by Purakad I. Exchangeable iron varied from 145 ppm at Karumadi III to 230 ppm at Vadayar and averaged 194 ppm. In all the soils the exchangeable iron content was more than the water soluble iron. Water soluble iron ranged from 121 ppm at Karumadi III to 165 ppm at Vadayar with a mean of 140 ppm. All the soils were predominantly clayey in texture. However, the soils from Karumadi I and II were found to belong to the textural class of sandy clay loam. The cation exchange capacity of kari soil was found to be the highest among the Kuttanad soils and ranged from 13.8 cmol(+)kg^{-1} at Karumadi I to 18.8 at Mundar with a mean of 16.7. Kari soils registered appreciably high contents of organic carbon ranging from 6.3 per cent at Karumadi III to 10.5 per cent at Purakad I followed by 10.2 per cent at Thottappally I and averaging 8.7 per cent. All the samples were highly acidic with pH values ranging from 3.2 at Thottapally I to 4.0 at three sites-Karumadi III, Purakkad II and Thottapally II. Mean pH of the kari soils was found to be 3.8. Similarly, all the samples recorded high electrical conductivity values ranging between 3.0 and 5.2 dSm^{-1} with a mean of 4.0 dSm^{-1}. Mundar soil recorded the highest conductivity while Purakkad II and Thottapally II soils the lowest.

Table 6 provides the results of intercorrelations between some of the physico-chemical properties of the kari soil and forms of iron contained in them. It was noticed that significant negative correlation existed between the pH of the soil and water soluble iron (r = -0.6110). Exchangeable iron was also significantly and negatively correlated (r = -0.6327) with pH. Water soluble iron and electrical conductivity of kari soil were positively and significantly correlated (r = 0.6740). Active iron content of the kari soil was significantly and positively correlated (r = 0.9554) with organic carbon.

Karapadom soil

Table 4 presents the data on some of the physico-chemical characters of typical karapadom soils of Kuttanad collected from 12 different locations.

As with kayal and kari soils, the karapadom soil also contained appreciable amounts of active iron ranging from 1460 ppm at Monkompu I to a maximum of 3980 ppm at Edathwa I with a mean of 2683 ppm. Exchangeable iron varied from 150 to 310 ppm with a mean of 197 ppm. Thakazhi II soils had the minimum exchangeable iron while Kidangara had the highest content. In all the soils studied the exchangeable iron content recorded higher values than water soluble iron. The water soluble iron content varied from 79 to 121 ppm with a mean of 101 ppm. Moncompu I soil recorded the lowest water soluble iron and Monkompu II recorded highest content. All the soils were

Table 4. Forms of iron in the surface layers of karapadom soils in relation to their physico-chemical properties

Sl. No.	Location	Soil group	Texture	pH	Organic carbon (per cent)	Electrical conductivity (dSm^{-1})	CEC ($cmol(+)kg^{-1}$)	Forms of iron (ppm)		
								Water soluble	Exchangeable	Active
1.	Ambalapuzha	Karapadom	Clay	4.2	4.2	2.4	12.0	110	203	1816
2.	Vezhapra	,,	Clay loam	4.4	4.9	1.5	11.5	94	190	1925
3.	Monkompu I	,,	Clay loam	4.9	3.9	1.3	15.8	79	161	1460
4.	Monkompu II	,,	Clay loam	4.3	6.3	2.4	14.2	121	170	2364
5.	Thalavady I	,,	Clay loam	5.0	5.8	0.9	9.8	110	248	3010
6.	Thalavady II	,,	Clay loam	4.5	9.9	1.8	15.2	98	165	3905
7.	Edathwa I	,,	Clay	4.8	10.1	2.0	15.5	97	220	3980
8.	Edathwa II	,,	Clay loam	4.5	6.0	2.5	12.0	120	155	2034
9.	Thakazhi I	,,	Clay loam	4.9	10.0	2.8	16.2	84	154	3920
10.	Thakazhi II	,,	Clay loam	5.1	6.1	1.1	17.0	89	150	2284
11.	Neerettupuram	,,	Clay loam	5.5	5.7	0.8	10.5	89	243	2190
12.	Kidangara	,,	Clay loam	5.0	8.0	0.8	8.0	115	310	3308
	Mean			4.8	6.7	1.7	13.1	101	197	2683

either clayey or clay loam with pH values varying between 4.2 and 5.5 with a mean of 4.8. Ambalapuzha soil recorded the lowest pH while the soil from Neerettupuram had the highest pH. The cation exchange capacity of Karapadom soil varied between 8.0 and 17.0 cmol(+)kg^{-1} with a mean of 13.1 cmol(+)kg^{-1} of the soil. The soil from Kidangara recorded the lowest CEC and Thakazhi II soil the highest. The contents of organic carbon ranged from 3.9 per cent in Monkompu I soil to 10.1 per cent in the soils from Edathwa I with a mean of 6.7 per cent. The electrical conductivity values were found to be comparatively lower than those of kayal and kari soil , with a minimum of 0.8 dSm^{-1} recorded by the soils from Neerettupuram and Kidangara and maximum of 2.8 dSm^{-1} recorded by the soil from Thakazhi I.

Table 6 provides results of intercorrelation between physico-chemical properties of the karapadom soil and forms of iron. It was found that pH and water soluble iron were negatively correlated but was not significant. Significant positive correlations, however, existed between active iron and the organic carbon content (r = 0.9600) of the soil. The exchangeable iron was significantly and negatively correlated with the cation exchange capacity of the soil (r=-0.8052). Water soluble iron was negatively correlated with cation exchange capacity but was significant at 10 per cent level only (r = -0.5316). Exchangeable iron and electrical conductivity were also negatively correlated (r = -0.5886).

A comparison of these three soil types with respect to their physico-chemical properties and forms of iron and their contents (Table 5) indicates that the pH of kari soil was significantly less than that of the kayal and karapadom soils. Kayal and karapadom soils had the same pH status. It was also found that the organic carbon content of kari soil was significantly higher when compared to karapadom and kayal soils which did not significantly differ. Electrical conductivity was also significantly higher for the kari soil followed by kayal and karapadom soils which were on par. The cation exchange capacity of karapadom soil was significantly low compared to kari and kayal soils which were on par. Among the three soils kari soil had the highest CEC. Kari soil recorded significantly higher contents of water soluble iron while no significant difference could be seen between the kayal and karapadom soils. Among the three soils the karapadom soil had the least content of water soluble iron while the kayal soil had the least content of exchangeable iron and active iron. Exchangeable iron did not differ significantly among the three soils. Similar to water soluble iron, the active iron content of kari soil was also significantly high compared to kayal and karapadom soils which did not differ significantly.

Table 5. Comparison of Kuttanad surface soils with respect to physico-chemical properties and forms of iron: Mean values

Soil type	pH	Organic carbon (per cent)	Electrical conductivity (dSm^{-1})	CEC (cmol(+)kg^{-1})	Iron (ppm)		
					Water-soluble	Exchangeable	Active
Kayal	4.47	6.42	2.45	16.07	114.17	175.17	2605.50
Kari	3.77	8.70	3.97	16.66	140.44	193.67	3862.33
Karapadom	4.76	6.73	1.69	13.14	100.50	197.42	2683.00
$F_{2, 24}$	19.26**	3.90*	14.78**	5.66**	20.20**	0.67ns	6.04**
CD kayal vs kari	0.40	1.99	1.04	2.76	15.56	42.59	955.81
CD kayal vs karapadom	0.38	1.89	0.98	2.62	14.76	40.41	906.76
CD kari vs karapadom	0.33	1.67	0.87	2.31	13.02	35.63	799.68

* Significant at 5 per cent level

** Significant at 1 per cent level

ns Not significant

Table 6. Correlation between the physico-chemical properties of Kuttanad surface soils with forms of iron

Chemical properties	Kayal (n=6)			Kari (n=9)			Karapadom (n=12)			Kuttanad soil (n=27)		
	Iron (ppm)			Iron (pom)			Iron (ppm)			Iron (ppm)		
	Water soluble	Exchangeable	Active	Water soluble	Exchangeable	Active	Water soluble	Exchangeable	Active	Water soluble	Exchangeable	Active
pH	-0.8136**	0.1503	0.3483	-0.6110*	-0.6327*	-0.5553	-0.4810	0.3749	0.1418	-0.8464***	0.0870	-0.4314**
Organic carbon	-0.2327	0.4389	0.9798***	0.2355	0.6480*	0.9554***	-0.0610	0.0480	0.9600***	0.3443*	0.2030	0.9429***
Electrical conductivity	0.6151	0.1826	0.6397	0.6740**	0.4274	0.1128	0.2079	-0.5886**	0.1425	0.7770***	-0.1046	0.5215***
CEC	0.6602	-0.3207	-0.4148	0.1162	0.4353	-0.4780	-0 5316*	-0.8052***	0.1463	0.3528*	-0.4574**	0.1328

*	Significant at 10% level
**	Significant at 5% level
***	Significant at 1% level
n	Sample size

Table 6 contains the results on the intercorrelation between the physico-chemical properties and iron content of the 27 Kuttanad surface soils considered together. Both water soluble and active forms of iron contents showed significant negative correlation with pH, the former at 1 per cent level (r = -0.8464) and the latter at 5 per cent level (r = -0.4314). The active iron content was significantly and positively correlated with organic carbon at 1 per cent level in all the three soils of Kuttanad (r = 0.9429). Positive correlation also existed between the electrical conductivity and the water soluble iron (r = 0.7770) and active iron (r = 0.5215). The cation exchange capacity was found to be significantly and negatively correlated at 5 per cent level (r = -0.4574) with the exchangeable iron content of the soil.

II Distribution of forms of iron in the soil profiles in relation to the physico-chemical properties

a) Physico-chemical features of the soil profiles

Data relating to the physico-chemical characteristics of the profiles of the kayal, kari and karapadom soils of Kuttanad, sandy soils of Onattukara and midland brown hydromorphic soil from Kottarakkara, and depth-wise distribution of forms of iron in these soil profiles are presented in Tables 7(a) and 7(b) and Fig . 2 to 5. Table 8 provides data on the

Table - 7 a   Physico-chemical characteristics of the soil (Profile)

Sl. No.	Soil type (location)	No.	Depth (cm)	Coarse sand (Per cent)	Fine sand (Per cent)	Silt (per cent)	Clay (per cent)	p^H (H_2O)	Organic CARBON (Per cent)	Electrical conductivity ($d\ S\ m^{-1}$)
1	Kayal I (SreeMoolam Kayal)	1	0-25	0.62	43.75	35.25	12.45	4.4	3.9	4.5
		2	25-50	0.60	43.62	33.60	15.00	4.2	4.5	4.0
		3	50-75	0.80	47.40	21.00	22.50	4.0	4.5	4.0
		4	75-100	0.80	48.50	18.50	23.50	4.0	4.5	4.0
2	Kayal II (Chithira Kayal)	5	0-25	1.20	51.38	32.52	7.28	5·4	4.1	2.6
		6	25-50	0.30	56.09	26.22	7.03	5.6	4.1	2.5
		7	50-75	0.92	57.00	30.00	5.02	4.5	4.0	2.3
		8	75-100	1.10	55.00	31.80	4.74	4.4	4.1	2.5
3	Kari I (Purakad)	9	0-25	1.80	7.20	18.20	59.03	3.8	8.3	3.0
		10	25-50	2.00	7.20	18.10	59.00	3.9	8.5	3.0
		11	50-75	2.30	5.94	16.10	58.30	4.0	9.7	2.9
		12	75-100	42.50	1.32	15.90	20.70	3.4	10.4	3.5

Sl. No.	Soil type (location)	No.	Depth (cm)	Coarse sand (Per cent)	Fine sand (Per cent)	Silt (Per cent)	Clay (Per cent)	pH (H_2O)	Organic carbon (Per cent)	Electrical conductivity (d S m $^{-1}$)
4	Kari II (Mundar)	13	0-25	6.20	8.60	10.60	51.50	3.5	12.6	4.1
		14	25-50	10.50	8.90	10.60	48.50	3.5	12.5	4.2
		15	50-75	50.40	10.20	10.98	21.85	3.5	10.5	4.6
		16	75-100	59.50	9.25	10.50	17.90	3.1	2.1	4.8
5	Karapadom I (Thakazhi)	17	0-25	2.00	31.60	45.20	10.30	4.9	5.8	3.5
		18	25-50	1.80	33.40	22.50	36.50	3.7	2.4	4.3
		19	50-75	1.90	39.20	11.10	39.40	3.8	4.1	4.8
		20	75-100	2.00	38.40	9.20	42.10	3.9	4.0	4.7
6	Karapadom II (Edathwa)	21	0-25	30.50	15.50	4.60	38.90	5.3	5.1	3.1
		22	25-50	58.20	23.60	8.00	5.00	5.1	2.4	3.4
		23	50-75	59.20	22.20	6.00	7.00	5.7	2.3	2.7
		24	75-100	59.50	20.10	7.00	8.50	5.6	2.4	3.0

Sl. No.	Soil type (location)	No.	Depth (cm)	Coarse sand (Per cent)	Fine sand (Per cent)	Slit (Per cent)	Clay (Per cent)	p^H (H_2O)	Organic carbon (Per cent)	Electrical conductivity (d S m^{-1})
7	Sandy Onattukara (Krishnapuram)	25	0-25	14.20	45.80	25.00	11.10	5.9	1.2	0.6
		26	25-50	9.10	46.00	27.00	15.02	5.0	1.4	0.4
		27	50-75	3.20	48.45	26.50	16.50	5.7	2.0	0.4
		28	75-100	2.60	42.10	28.50	20.00	5.7	2.0	0.6
8	Brown hydromorphic (Kottarakkara)	29	0-25	16.20	16.50	25.56	37.00	5.1	3.9	1.3
		30	25-50	14.80	12.60	23.12	44.00	5.3	4.2	1.1
		31	50-75	14.00	12.60	23.00	45.00	5.3	4.0	1.0
		32	75-100	12.60	11.10	22.80	48.50	5.2	3.7	1.2

mean values of each profile of the concerned soil tyoe and Table 9 providos data on the mean values for each soil type.

a. Physico-chemical features of the soil profiles

1) Size fractions in the soil

i. Coarse sand

The coarse sand content differed significantly in profiles sampled from different locations. However, no significant difference was seen between depths. The coarse sand content of the kayal soil profile was the lowest and was not significantly different from that of the kari, karapadom, sandy and the brown hydromorphic soil profiles. However, Profile II of kari and Profile II of karapadom had high coarse sand contents. The highest mean content of 51.85 per cent coarse sand was seen in Profile II of karapadom soil (Table 8)

ii. Fine sand

Both the profiles of kari soil recorded the lowest contents of fine sand and were on par. The kayal and karapadom soil Profiles and the sandy soil profile had high contents of fine sand. Among the profiles, the Profiles I and II of kayal had the highest fine sand content (45.82 per cent and 54.87 per cent respectively), followed by Profile I of karapadom with 35.65 per cent. However, in kayal and karapadom soil profiles. location wise difference was also seen. Depth wise difference was not noticeable.

iii. Silt

Profiles I and II of kayal soil, the sandy soil profile and the brown hydromorphic soil profile were not significantly different. Silt content in these profiles was significantly higher when compared to Profiles I and II of kari and the Profile II of karapadom soils. The Profiles I and II of kari were also similar in their silt content. Highest silt content was found in the Profile II of kayal soil and least in the Profile II of karapadom soil.

iv. Clay

Clay content was not significantly different in the different locations of the kayal, kari and karapadom soils. However, the clay contents in kayal soil, karapadom soil Profile II and the sandy soil profile were significantly low. Highest clay content was seen in the Profile I of the kari soil and least in Profile II of the kayal soil.

2. Chemical properties

i) pH

The lowest pH was recorded by both the profiles of kari soil (3.8 and 3.4) and was on par with Profile I of karapadom soil (3.6). Sandy soils had the highest pH (5.6). Significant difference could be noticed between the profiles of kayal, kari and karapadom soils. However, the sandy soil profile and the Profile II of karapadom soil were on par. Profile II of karapadom soil and brown hydromorphic soil profile, Profile I of kari and Profile I of karapadom soil and Profile II of kari were also on par.

ii) Organic carbon

The organic carbon contents of Profiles I and II of kari soil were significantly high. These two profiles recorded the highest mean organic carbon content (9.2 and 9.4 per cent respectively) and were on par. However, Profiles I and II of karapadom soil were not similar in their organic carbon contents. In Profile II of karapadom soil organic carbon was significantly low. Sandy soil profile had the lowest mean organic carbon content (1.65 per cent) which was significant. Compared to the Profile II of karapadom soil and the profile of sandy soil the organic carbon contents of all the other profiles were higher.

iii) Electrical conductivity

Electrical conductivity value was highest in the Profile II of kari soil and Profile I of karapadom soil and were on par. These were significantly higher compared to others. Profile I of kari and Profile II of karapadom were also on par. Sandy soil profile had the lowest electrical conductivity and was significantly low.

b. Forms of iron in the soil profile

(i) Total iron

From the data presented in the mean Tables 8 and 9 and figures 2 to 5 it could be seen that the total iron content decreased with depth in both the kayal soil profiles, Profile II of kari and Profile I of karapadom soil. In Profile I of kari, Profile II of karapadom and the profiles of sandy and brown hydromorphic soils increases were noted though not appreciable. The total iron content in the kayal soil profiles varied from 4.95 to 10.80 per cent with a mean value of 6.93 per cent. In the kari soil it ranged between 3.57 per cent to 6.84 per cent (with mean of 4.66 per cent) while in karapadom soil it varied between 3.14 per cent and 7.66 per cent with mean content 5.15 per cent. From the mean value Table 8 it was clear that sandy soil had the least content of total iron (1.8 per cent), while kayal soils had the highest content, which however appreciably decreased with depth. The total iron in the brown hydromorphic soil was found to vary between 5.4 and 6.6 per cent, with a mean of 5.35 per cent.

Mean Table 8 indicates that Profiles I and II of kayal soil and Profile II of karapadom soil were on par and recorded the highest content of total iron. Profile II of karapadom soil and the profile of brown hydromorphic soil were on par.

Table - 7 b Depth wise distribution of iron in soil (Profile)

Sl. No.	Soil type (location)	Profile	Samples	Smaple depth (cm)	Total iron (Per cent)	Iron (ppm)		
						Water soluble	Exchangeable	Active
1	Kayal (Sree Moolam kayal)	I	1	0-25	8.52	135	274	2820
			2	25-50	6.06	185	359	3016
			3	50-75	6.88	206	310	3432
			4	75-100	6.32	195	302	3566
2	Kayal (Chithira kayal)	II	5	0-25	10.80	105	336	2920
			6	25-50	6.66	141	322	2810
			7	50-75	5.25	214	348	3434
			8	75-100	4.95	225	354	3584
3	Kari (Purakad)	I	9	0-25	5.77	124	238	4682
			10	25-50	5.30	210	255	4540
			11	50-75	4.42	225	276	3624
			12	75-100	6.84	198	243	4982

Sl. No.	Soil type (location)	Profile	Samples	Sample depth (cm)	Total iron (Per cent)	Iron (ppm)		
						Water soluble	Exchangeable	Active
4	Kari (Mundar)	II	13	0-25	3.70	132	298	4715
			14	25-50	3.67	145	290	4740
			15	50-75	3.63	200	275	4812
			16	75-100	3.57	190	330	5216
5	Karapadom (Thakazhi)	I	17	0-25	4.10	110	278	2820
			18	25-50	5.00	130	396	3432
			19	50-75	3.14	172	354	3616
			20	75-100	3.20	193	398	3750
6	Karapadom (Edathwa)	II	21	0-25	4.26	135	320	2912
			22	25-50	6.95	198	371	3630
			23	50-75	7.66	124	168	2832
			24	75-100	6.85	120	175	2660

Sl. No.	Soil type (location)	Pro-file	Samples	Sample depth (cm)	Total iron (Per cent)	Iron (ppm)		
						Water soluble	Exchangeable	Active
7	Sandy Onattukara (Krishnapuram)	I	25	0-25	0.92	4	22	212
			26	25-50	1.28	12	134	414
			27	50-75	2.02	64	212	672
			28	75-100	2.86	57	210	695
8	Brown hydromorphic (Kottarakkara)	I	29	0-25	5.4	23	146	1640
			30	25-50	5.6	14	119	2080
			31	50-75	5.8	15	121	2104
			32	75-100	6.6	14	135	2122

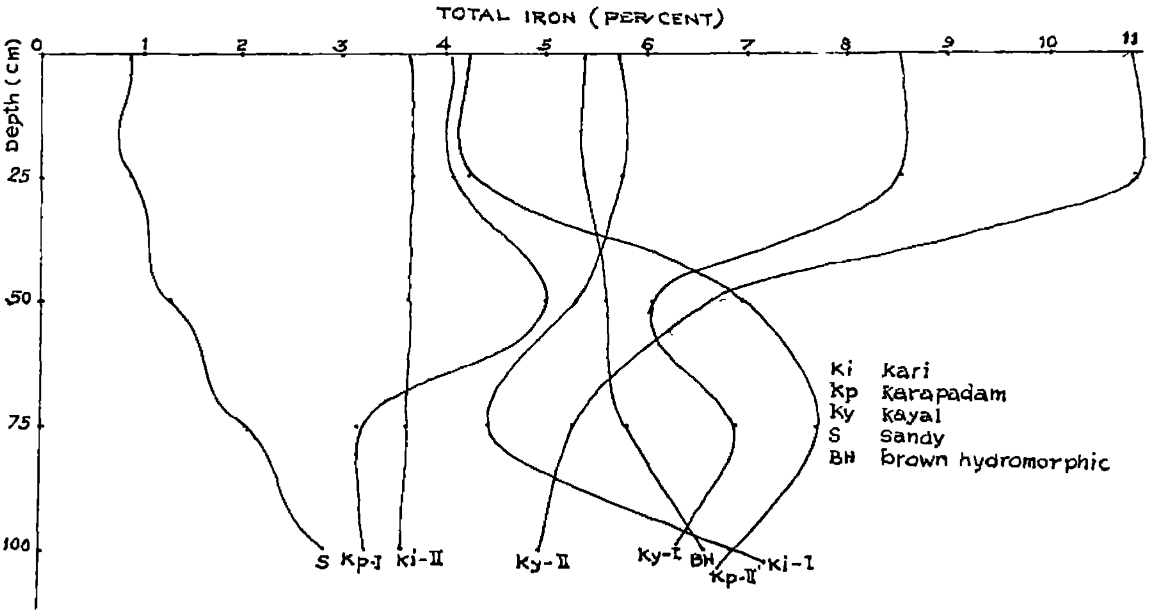

Fig. 2 VARIATION OF TOTAL IRON CONTENT WITH SOIL DEPTH (vide TABLE 7b)

The mean iron content was least in the profile of the sandy soil and was significantly less compared to the others. Profile II of karapadom soil recorded high content of total iron in comparison with Profiles I and II of kari soil, Profile I of karapadom soil and the profile of the sandy soil.

(ii) Water soluble iron

Water soluble iron was found to vary between 105 and 225 ppm in the kayal, 124-225 ppm in kari and 110 to 198 ppm in karapadom soil profiles. This form of iron recorded an increase with depth in all the wet land rice soil profiles of Kuttanad except karapadom soil Profile II. The pattern of increase, however, slightly varied. Among the Kuttanad soils, kayal soil Profile II had the least content of 105 ppm water soluble Fe^{2+} seen on the surface, while kayal soil Profile I and karapadom soil Profile II registered the highest surface contents of 135 ppm, followed by kari soil Profile II with 132 ppm Fe^{2+}. It was noticed in Table 7(b) that the Profile II of karapadom soil alone, however, showed decreases with depth, though not appreciably. It has to be noted from Table 7 a that this profile has registered increased pH with depth and decrease in the organic carbon content from 5.1 at the surface to 2.4 per cent at 75-100 cm depth. The mean content of water soluble iron in the two profiles (Table 9) was,

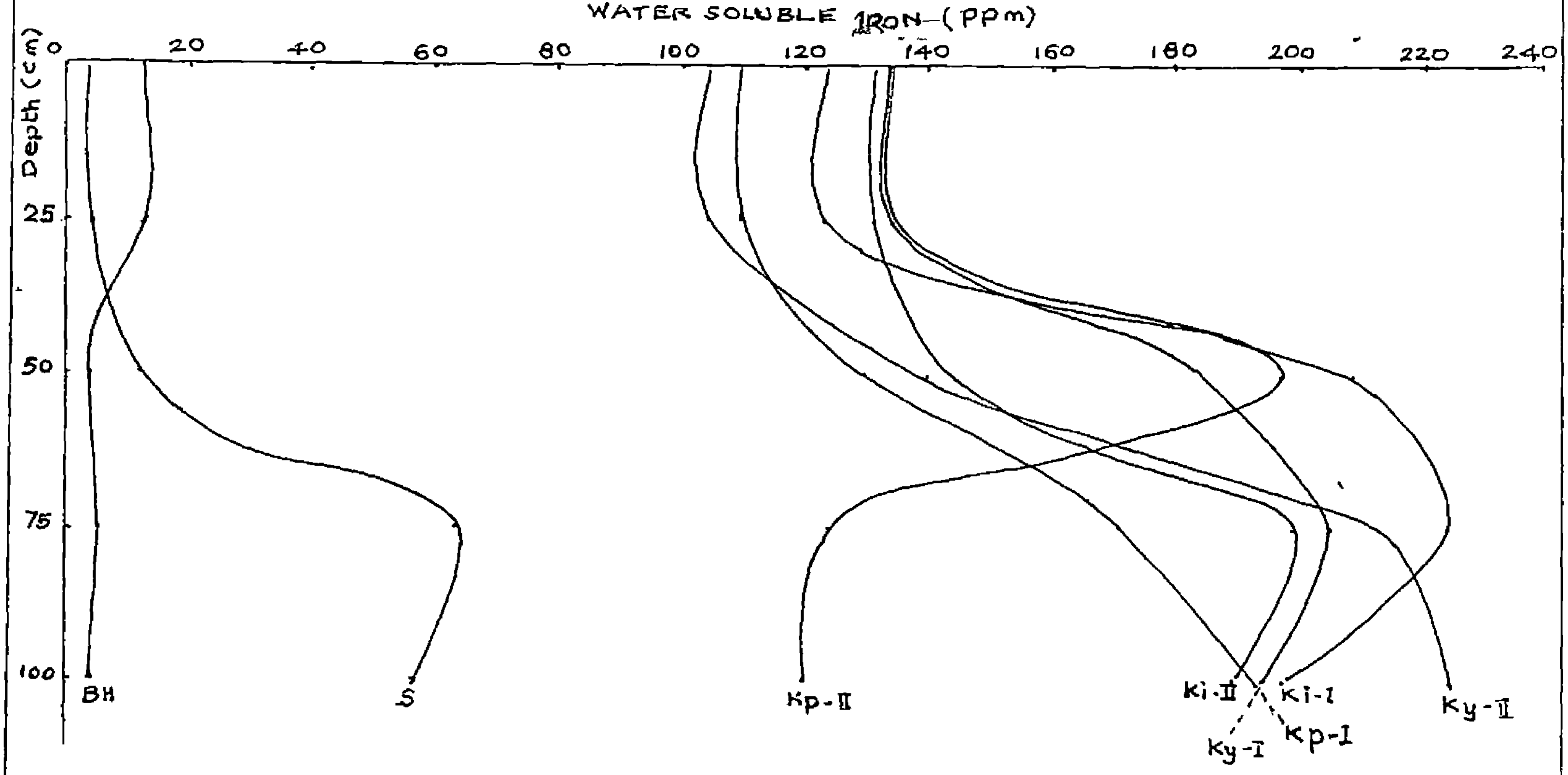

Fig 3. VARIATION OF WATER SOLUBLE IRON WITH SOIL DEPTH (vide TABLE 7b)

however, highest in kari soil amounting to 178 ppm, followed by kayal soil with 176 ppm and karapadom soil with 143 ppm. Among the sandy Onattukara and brown hydromorphic paddy soil profiles, water soluble iron was, in general, low. In the sandy soil profile, the Fe^{2+} content increased from 4 ppm on the surface to 57 ppm at 75-100 cm depth while in the brown hydromorphic soil profile the water soluble iron fell from 23 ppm on the surface to 14 ppm down the profile at 75-100 cm depth.

Mean Table 8 indicates that the water soluble iron was significantly different in the different profiles. Depthwise differences were also noticed. Water soluble iron was found to increase with soil depth upto 50-75 cm and then a slight decrease was noticed at 75-100 cm depth. However, there was no difference in the water soluble iron content at 50-75 and 75-100 cm depths. In sandy soil and brown hydromorphic soil the mean content of water soluble iron was significantly low with the least mean content (17 ppm) in brown hydromorphic soil. No significant difference could be noticed between the two profiles of kayal soil and between the two profiles of karapadom soil, while in the kari soil the water soluble Fe^{++} in Profile II was significantly less compared to that in Profile I. Highest mean water soluble Fe^{2+} was noticed in

Table 8. Physico-chemical properties in relation of forms of iron in soil (Profiles): Mean values

Sl. No.	Soil type	Profile Number	Coarse sand (per cent)	Fine sand (per cent)	Silt (per cent)	Clay (per cent)	pH	Organic carbon (per cent)	Elec. cond. (dSm^{-1})	Total iron (per cent)	Water soluble iron (ppm)	Exchangeable iron (ppm)	Active iron (ppm)
1.	Kayal soil (Sreemoolam kayal)	I	0.705	45.817	27.088	18.362	4.150	4.350	4.125	6.945	180.25	311.25	3208.50
2.	Chithira kayal (Chithira kayal)	II	0.680	54.668	30.135	8.518	4.975	4.075	2.475	6.915	171.25	340.00	3187.00
3.	Kari soil (Purakad)	I	12.150	5.145	17.075	49.258	3.775	9.225	3.100	5.583	189.25	253.00	4457.00
4.	Kari soil (Mundar)	II	31.650	9.238	10.670	34.938	3.400	9.425	4.425	3.643	166.75	298.25	4870.75
5.	Karapadom soil (Thakazhi)	I	1.925	35.650	22.000	32.075	3.575	4.075	4.325	3.660	151.25	356.50	3404.50
6.	Karapadom soil (Edathwa)	II	51.850	20.350	6.400	14.850	5.425	3.050	3.050	6.430	144.25	258.50	3008.50
7.	Sandy soil (Onattukara)	I	7.275	45.588	26.750	15.655	5.575	1.650	0.500	1.770	34.25	144.50	498.25
8.	Brown hydromorphic soil (Kottarakkara)	I	14.400	13.200	23.620	43.625	5.225	3.950	1.150	5.850	16.50	130.25	1986.50
	$F_{7, 21}$		8.200**	214.188**	6.958**	5.275**	16.201**	8.277**	92.008**	7.363**	21.890**	9.256**	64.637**
	CD		18.531	3.530	9.372	19.075	0.646	2.884	0.448	2.008	42.355	81.724	500.568

** Significant at 1% level

Profile I of kari soil (189 ppm) and least (17 ppm) in the brown hydromorphic soil.

(iii) Exchangeable iron

As in the case of water soluble Fe^{2+}, exchangeable iron also recorded an increase with depth in all the wet land rice soil profiles of Kuttanad, except karapadom soil Profile II. The surface content of exchangeable iron was least (238 ppm) in kari soil Profile I, while it was highest (336 ppm) in kayal soil Profile II, followed by karapadom soil Profile II with 320 ppm. In karapadom Profile II, the exchangeable iron dropped from 320 ppm on the surface to 175 ppm at 75-100 cm depth. The exchangeable iron varied from 168-398 ppm in karapadom soil profiles, from 238 to 330 in the kari soil profiles and from 274 to 359 ppm in kayal soil profiles with mean contents of 308, 277 and 326 ppm respectively. Sandy soil profile registered the lowest content of 22 ppm exchangeable iron on the surface layer and this increased upto 212 ppm with depth. In the brown hydromorphic soil profile, however, exchangeable iron showed decreasing trend with depth. From the mean value Table 9 it is clear that kayal soil had the highest content of 326 ppm exchangeable iron, followed by karapadom soil profile with 308 ppm. The brown hydromorphic soil had the least exchangeable iron content of 130 ppm. It

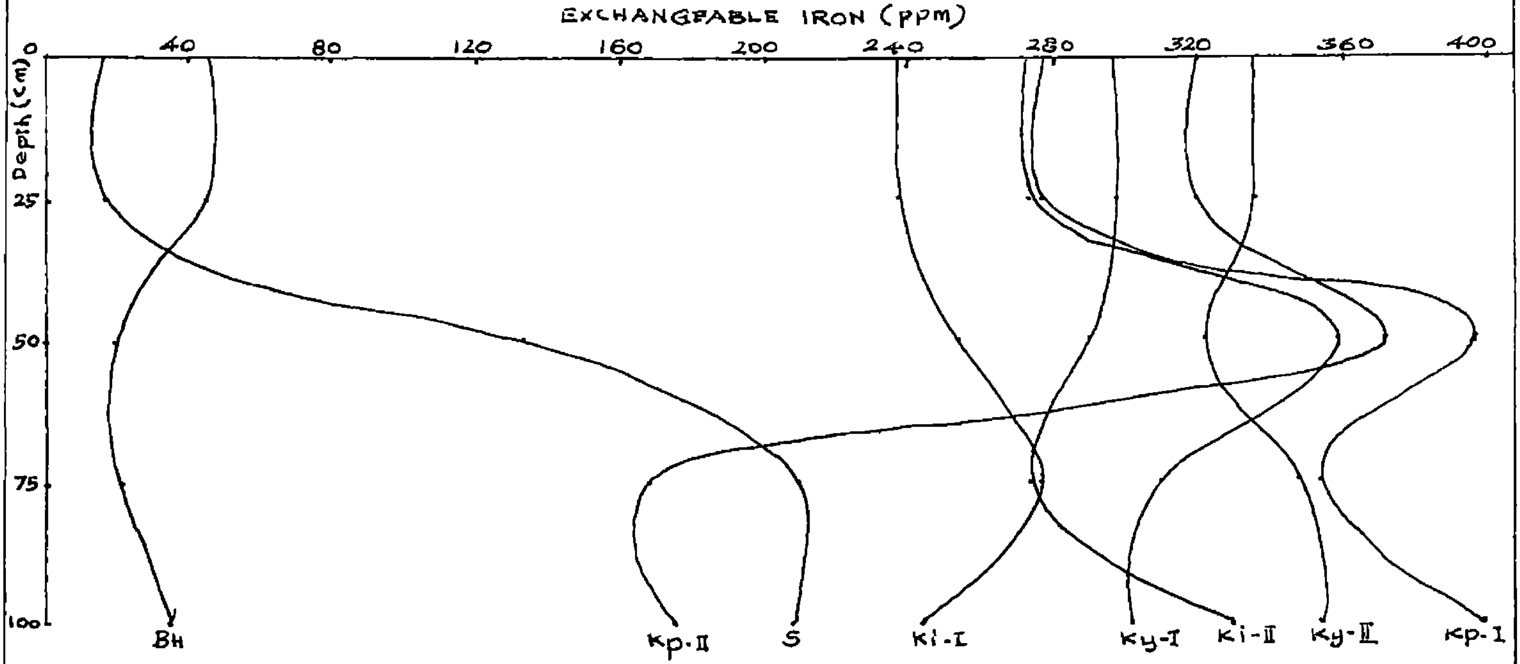

Fig. 4 VARIATION OF EXCHANGEABLE IRON CONTENT WITH SOIL DEPTH
(vide TABLE 7b)

Table 9. Mean content of different forms of iron in soils (Profiles)

Sl. No.	Soil type	Samples	pH (H_2O)	Organic carbon (per cent)	Elec. conductivity (dSm^{-1})	Forms of iron			
						Total (per cent)	Water soluble (ppm)	Exchangeable (ppm)	Active (ppm)
1.	Kayal	8	4.0-5.6 (4.6)	3.9-4.5 (4.2)	2.3-4.5 (3.3)	4.95-10.80 (6.93)	105-225 (176)	274-359 (326)	2810-3584 (3199)
2.	Kari	8	3.1-4.0 (3.6)	2.1-12.6 (9.3)	2.9-4.8 (3.8)	3.57-6.84 (4.66)	124-225 (178)	238-330 (277)	3624-5216 (4672)
3.	Karapadom	8	2.8-5.7 (4.5)	2.3-5.8 (3.6)	2.7-4.8 (3.7)	3.14-7.66 (5.15)	110-198 (143)	168-398 (308)	2660-3750 (3207)
4.	Sandy	4	5.0-5.9 (5.6)	1.2-2.0 (1.65)	0.4-0.6 (0.5)	0.92-2.86 (1.77)	4-57 (34)	22-212 (145)	212-672 (498)
5.	Brown hydromorphic	4	5.1-5.3 (5.2)	1.7-2.2 (2.0)	1.0-1.3 (1.2)	5.40-6.60 (5.85)	14-23 (17)	119-146 (130)	1640-2122 (1987)

Figures within paranthesis indicate average for the soil type was also noticed that the exchangeable Fe^{2+} content was invariably higher than the water soluble Fe^{2+}.

Mean Table 8 indicated that the exchangeable iron content was highest (357 ppm) in Profile I of karapadom soil and least (145 ppm) in sandy soil profile. Profile wise difference was noticed in the kayal and kari soils. Depth wise difference could not, however, be seen.

(iv) Active iron

Active iron content varied from 2810 to 3584 ppm in the kayal soil profiles, from 3624 to 5216 ppm in the kari soil profiles and from 2660 to 3750 ppm in the karapadom soil profiles with mean values of 3198, 4672 and 3207 ppm respectively (Table 9). From the mean value Table it is clear that kari soil has the highest content of active iron, followed by karapadom and kayal soils. The active iron content in sandy (Onattukara) soil ranged from 212 ppm on the surface to 695 ppm at the 75-100 cm depth, while in brown hydromorphic soils it ranged between 1640 on the surface and 2122 ppm at lower depths studied, registering a mean content of 1987 ppm. The least active iron content (498 ppm) was noticed in the sandy soil. The active iron content progressively increased with depth in all the soil profiles, except Profile II of karapadom soil, where a decrease from 2912 to 2660 ppm was noticed.

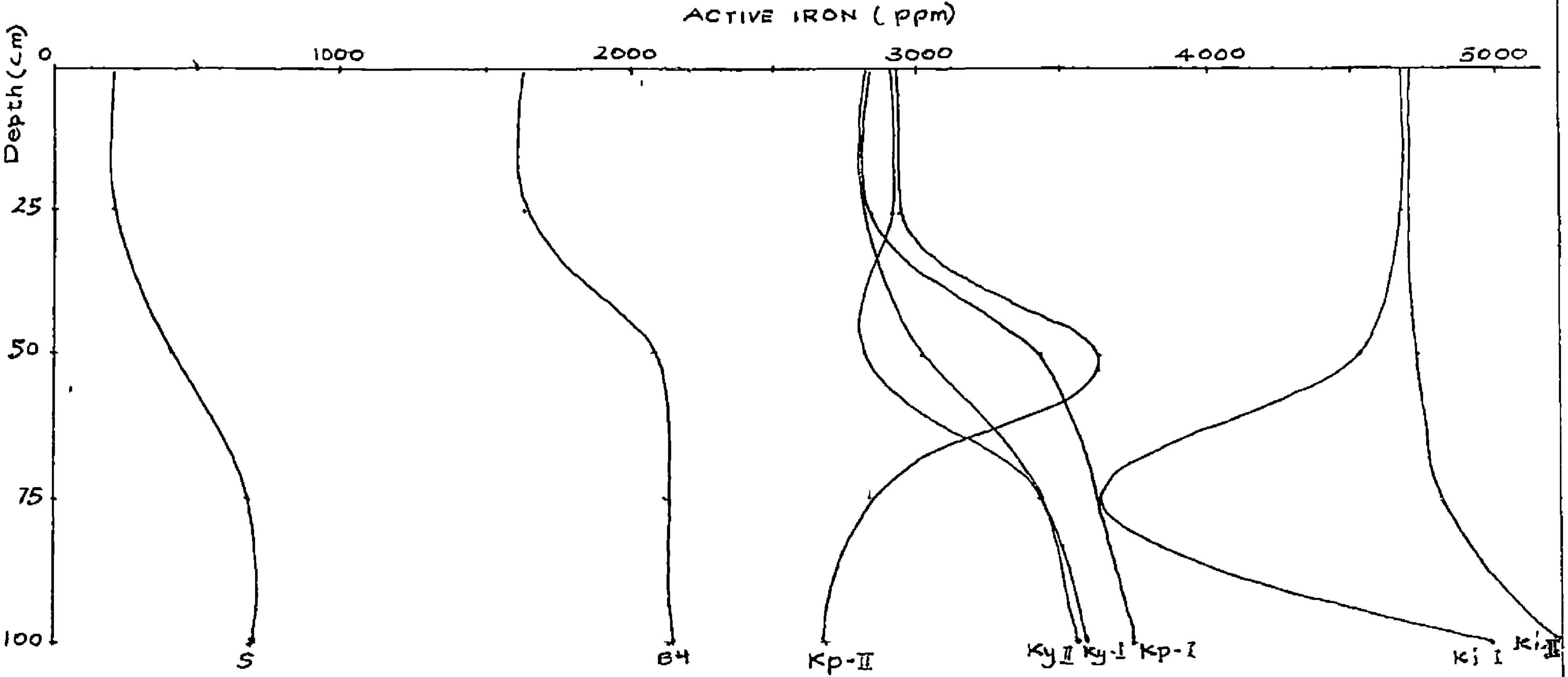

Fig 5 VARIATION OF ACTIVE IRON CONTENT WITH SOIL DEPTH
(vide TABLE 7b)

It was noticed from the mean Table 8 that the highest active iron content was in the kari soil profiles (mean 4457 and 4871 ppm) and minimum in sandy soil (498 ppm). Profile-wise difference could not be seen in kayal soil, while in kari and karapadom soils there was difference. However, no significant difference could be seen in the Profiles I and II of kayal and karapadom soils.

III Incubation of soils under flooded conditions with added amendments and their effect on iron solubilisation

The results of the incubation study of soils carried out under laboratory conditions using kayal, kari and karapadom soils of Kuttanad and brown hydromorphic paddy soil from Kottarakkara for a period of 90 days maintained under the submerged conditions are presented in Tables 10 to 27 and graphically illustrated in Fig. 6 to 12. The major physico-chemical characteristics of the surface soils used for the incubation studies are presented in Table 1(a).

(i) Influence of sea water submergence on the release of Fe^{2+}

Data relating to the influence of sea water submergence on the release of Fe^{2+} from soils are presented in Tables 10 to 15 and Fig . 6 to 8. Mean values are given in Table 14. Fig. 6 relates to iron release from the four soils when submerged under water (control). The Tables and the Fig . indicate

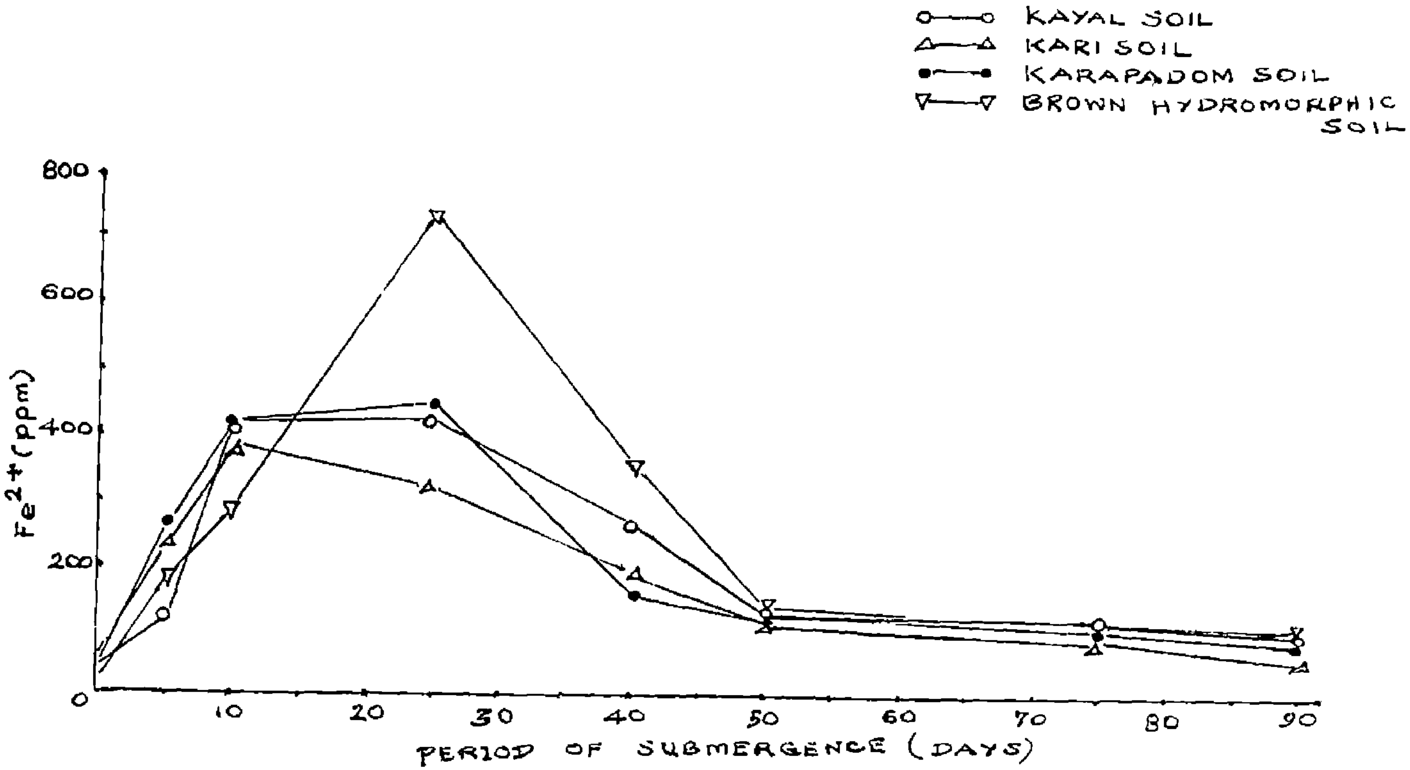

Fig. 6 Effect of Submergence of soil on iron release
(Vide Sl.No. 1, Tables 10-13, 16-19 and 22-25)

that sea water submergence can release Fe^{2+} in to soil solution. The extent of Fe^{2+} release progressively increased with increasing concentration of salt water. Accordingly, sea water mixed with water in the ratio 25:75 released the least Fe^{2+}, while sea water without any dilution could release the maximum Fe^{2+} from the soil. Kari, karapadom and brown hydromorphic soils were found to release maximum iron during the sampling on the 25th day of submergence while kayal soil continued to release Fe^{2+} up to the 40th day, after which progressive decreases were noticed.

Kayal soil

Table 10 and Fig. 7a provide data relating to iron release from kayal soil under the influence of sea water submergence. The Table and Fig. indicate that the rate of release of Fe^{2+} decreased with increasing dilutions of sea water and that sea water submergence resulted in the maximum release of 1868 ppm Fe^{2+} around the 40th day of submergence which decreased to 706 ppm on the 90th day. Submergence with water itself (control) resulted in progressive increases in the Fe^{2+} release attaining a peak value of 420 ppm on the 25th day, which later decreased and reached the level of 100 ppm on the 90th day of submergence. Mixture of 25 per cent sea water and 75 per cent water used for submergence of the soil released

Table 10. Influence of sea water submergence on the release of iron (ppm) (kayal soil)

Sl. No.	Treatments Sea water: Water mixture	Period of submergence - days							
		0	5	10	25	40	50	75	90
1.	Control 0:100	45	120	416	420	268	130	121	100
2.	25:75	45	175	350	720	940	645	456	292
3.	50:50	45	220	385	700	1202	700	605	540
4.	75:25	45	270	496	754	1605	1303	704	603
5.	100:0	45	380	480	856	1868	1695	905	706

Table 11. Influence of sea water submergence on the release of iron (ppm) (kari soil)

Sl. No.	Treatments Sea water: Water mixture	Period of submergence - days							
		0	5	10	25	40	50	75	90
1.	Control 0:100	65	235	384	320	192	120	98	58
2.	25:75	65	350	545	690	475	500	340	350
3.	50:50	65	400	610	888	752	555	495	450
4.	75:25	65	540	675	1080	950	692	605	545
5.	100:0	65	585	800	1825	1305	790	650	575

940 ppm Fe^{2+} on the 40th day which dropped to 292 ppm on the 90th day of submergence. Mixture of sea water and water in the 50:50 ratio caused further release of Fe^{2+} amounting to 1202 ppm on the 40th day while 75:25 mixture of sea water and water released a maximum of 1605 ppm during the same period, after which it got reduced when the submergence was continued with the sea water of the same composition up to 90 days. The mean values for Fe^{2+} release during different periods of submergence also indicated the same trend with maximum release of 1177 ppm Fe^{2+} on the 40th day.

Kari soil

Data on the influence of sea water submergence on the iron release from kari soil with time are furnished in Table 11 and Fig. 7b. Untreated control, where water was used for submergence, gave the peak release of 384 ppm Fe^{2+} even on the 10th day of submergence which decreased to 58 ppm on the 90th day. Mixtures of sea water and water used for submergence were found to result in further increases in the Fe^{2+} release depending on the concentration of ions. Sea water as such used for submergence released a maximum of 1825 ppm Fe^{2+} in 25 days which later subsided to 575 ppm in 90 days. Mean values for the Fe^{2+} release with period of submergence indicated a maximum of 961 ppm Fe^{2+} released on the 25th day.

Karapadom soil

Data relating to the iron release from karapadom soil under the influence of sea water submergence are furnished in Table 12 and Fig. 8a. When the control had released a maximum of 448 ppm Fe^{2+} on the 25th day of submergence with subsequent gradual decrease to 88 ppm on the 90th day, sea water submergence resulted in the peak release of 1241 ppm Fe^{2+} during the same period which later gradually dropped and reached 340 ppm on the 90th day of submergence. It was also noticed that appreciable releases of iron occurred particularly with dilutions of sea water at 50:50 and above. Mean values for Fe^{2+} with period of submergence revealed maximum release of 838 ppm Fe^{2+} on the 25th day.

Brown hydromorphic soil

Data relating to iron release from brown hydromorphic soil as influenced by sea water submergence with time are presented in Table 13 and Fig. 8b. It is seen from the Table that sea water submergence had hastened the iron release from the soil and the rate of release increased with the period of submergence upto 25 days when the peak release of Fe^{2+} occurred. In the control the peak release of Fe^{2+} amounted to 736 ppm which later decreased with time and attained a level of 105 ppm on the 90th day of submergence. The rate of release of

Table 12. Influence of sea water submergence on the release of iron (ppm)
(karapadom soil)

Sl. No.	Treatments Sea water: Water mixture	Period of submergence - days							
		0	5	10	25	40	50	75	90
1.	Control 0:100	56	260	416	448	160	128	110	88
2.	25:75	56	300	505	642	475	302	285	305
3.	50:50	56	545	728	855	756	403	270	252
4.	75:25	56	550	775	1002	985	820	350	320
5.	100:0	56	590	854	1241	1225	902	500	340

Table 13. Influence of sea water submergence on the release of iron (ppm)
(Brown hydromorphic soil)

Sl. No.	Treatments Sea water: Water mixture	Period of submergence - days							
		0	5	10	25	40	50	75	90
1.	Control 0:100	25	180	288	736	360	142	120	105
2.	25:75	25	300	440	782	600	305	202	180
3.	50:50	25	202	375	856	630	270	220	215
4.	75:25	25	335	470	1054	720	380	295	280
5.	100:0	25	388	496	1260	1070	495	380	302

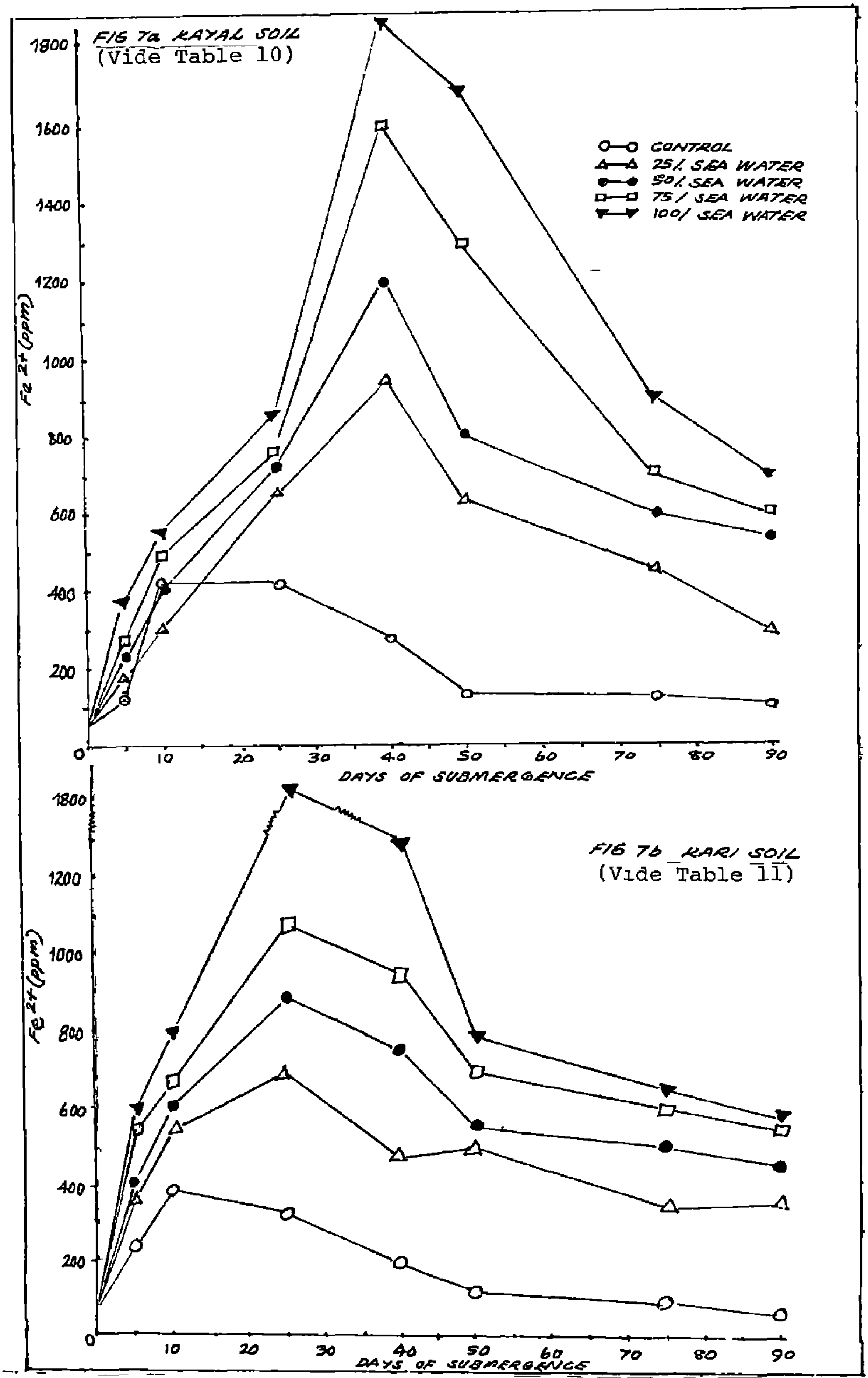

Fig. 7. Effect of sea water submergence on the release of iron

a. Kayal soil b. Kari soil

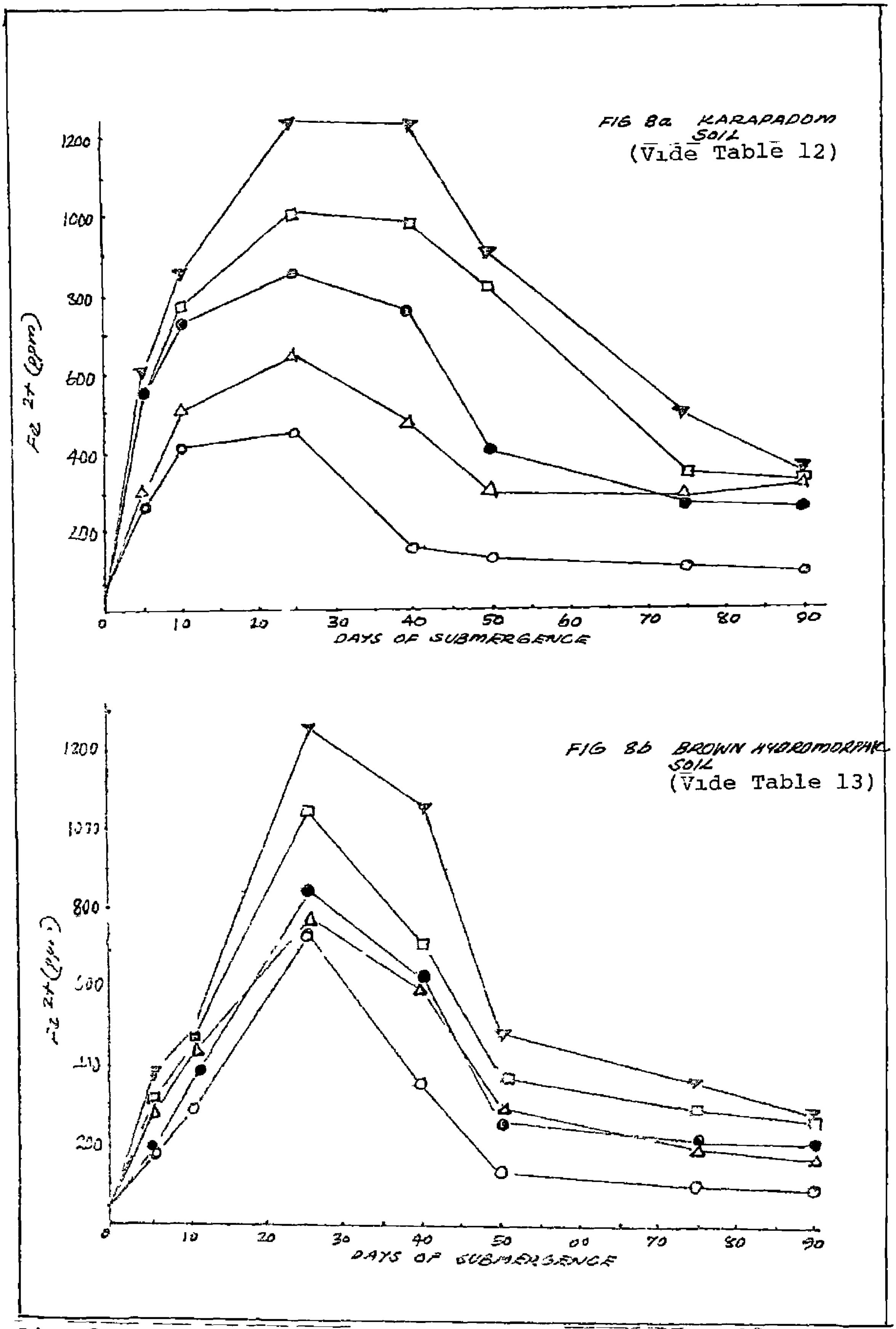

Fig. 8. Effect of sea water submergence on the release of iron

a. Karapadom soil b. Brown hydromorphic soil

Fe^{2+} in the treated soils varied according to the composition of sea water used for the submergence. As with the other soils, sea water: water mixtures appeared to have released iron roughly in proportion to the concentration of the salt. Sea water used for submergence released a maximum of 1260 ppm Fe^{2+} on the 25th day which gradually decreased with further periods of submergence and reached 302 ppm on the 90th day. Mean values for Fe^{2+} on different periods of submergence indicated a maximum of 938 ppm Fe^{2+} released on the 25th day.

Among the different Kuttanad soils, it was noticed that kayal soils released the maximum of 1868 ppm Fe^{2+} on the 40th day of submergence followed by kari soil with 1825 ppm Fe^{2+} and karapadom soil releasing the least Fe^{2+} (1241 ppm) on the 25th day of submergence with sea water. Under similar conditions, brown hydromorphic soil had also released 1260 ppm Fe^{2+}. It has to be noted that the Fe^{2+} release on the 90th day did not decrease to much lower values. This is probably due to the continued influence exerted by the ions still present in the soil solution.

Mean Table 14 brings out the results of interaction between soil type x level of treatment x period of submergence. It was noticed that under the conditions of sea water submergence the kayal, kari and karapadom soils released signifi-

Table 14. Effect of sea water submergence on the release of iron in the different soil types : Mean values

(i) Soil type x Level of treatment

Sl. No.	Soil	Composition of sea water					Mean
		0	25%	50%	75%	100%	
1.	Kayal	203	453	550	723	867	559
2.	Kari	184	414	527	644	824	519
3.	Karapadom	208	359	483	607	714	474
4.	Brown hydromorphic	245	354	349	445	552	389
	Mean	210	395	477	605	739	

(ii) Soil type x Period of submergence

Soil	Period of submergence - days								Mean
	0	5	10	25	40	50	75	90	
Kayal	45	233	425	690	1177	895	558	448	559
Kari	65	422	603	961	735	531	438	396	519
Karapadom	56	449	656	838	720	511	303	261	474
Brown hydromorphic	25	281	414	938	676	318	243	216	389
Mean	48	346	524	856	827	564	386	330	

(iii) Level of treatment x Period of submergence

Sl. No.	Period of submergence - days	Composition of sea water					Mean
		0	25%	50%	75%	100%	
1.	0	48	48	48	48	48	48
2.	5	199	281	342	424	486	346
3.	10	376	460	525	604	658	524
4.	25	481	709	825	973	1296	856
5.	40	245	623	835	1065	1367	827
6.	50	130	438	482	799	971	564
7.	75	112	321	398	489	609	386
8.	90	88	282	364	437	481	330
	Mean	210	395	477	605	739	

CD at 5%	for Soil	54
,,	for Treatment	60
,,	for Period	76
,,	for Soil x Treatment	120
,,	for Soil x Period	152
,,	Treatment level x Period	170

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cantly high amounts of Fe^{2+} over the brown hydromorphic soil. Kari and karapadom soils were on par, highest mean release of Fe^{2+} resulted in kayal soil but was not significant. However, between kari, kayal and karapadom soils there was no significant difference. The same trend of significance was noted in the four soils when submerged under 75 per cent and 50 per cent sea water levels. However, in the treatment of 25 per cent sea water submergence and the control, all the four soils behaved similarly.

With regard to the influence of the period of submergence of the four soils on Fe^{2+} release, it was noticed that during the first 50 days of submergence the three Kuttanad soils released significantly higher amounts of Fe^{2+} when compared to brown hydromorphic soils. However, on the 10th day kari and karapadom soils released significantly more Fe^{2+} than the kayal and the brown hydromorphic soils and the two were on par. Period of 25 days submergence resulted in the kari soils releasing the highest amount of Fe^{2+}. Though the kayal soil released lower amount of Fe^{2+} than the kari and karapadom soils till the 25th day, it continued to release more Fe^{2+} with significantly high release on the 40th day and thereafter subsided but still continued to retain significantly higher amounts of released Fe^{2+} than the other 3 soils till the 75th day.

However, after the 75th day no significant difference could be noticed among the four soils. In the kari, karapadom and brown hydromorphic soils the subsidence from the peak release of Fe^{2+} was noted after the 25th day with no significant difference among them throughout the subsidence period. In general, the brown hydromorphic soil gave significantly lower release of Fe^{2+} over kayal, kari and karapadom soils which behaved similarly. Mean values for soils indicated that kayal soil released maximum Fe^{2+} (559 ppm) followed by kari soil (519 ppm) and karapadom soil (474 ppm), brown hydromorphic soil releasing the least Fe^{2+} (389 ppm).

Result of interaction between level of treatment and period of submergence revealed that the maximum release of 1367 ppm Fe^{2+} which occurred on the 40th day of submergence under sea water was on par with the Fe^{2+} release on the 25th day of submergence, irrespective of the soil type.

The results of quadratic regression of the experimental data furnished in Table 15 indicate the maximum days of submergence at which peak release of Fe^{2+} would occur in soils under the influence of submergence under the sea water of different compositions. From the Table it is noticed that kayal soils would need 47 to 51 days for maximum iron release, kari soils would require 44 to 47 days, and the karapadom soils would

Table 15. Days of submergence for maximum release of iron as influenced by levels of sea water in soils

Soil type	Level of treatment* (Sl. No)	Quadratic regression	Period (days)
Kayal	1	$Y = 168.9123+6.362524X-0.0866X^2$	37
	2	$Y = 68.28119+31.02302X-0.3271X^2$	47
	3	$Y = 78.55371+33.298X-0.3259X^2$	51
	4	$Y = 25.15979+51.60518X-0.5192X^2$	50
	5	$Y = -4.714844+63.58737X-0.6345X^2$	50
Kari	1	$Y = 211.3193+2.394383X-0.0498X^2$	24
	2	$Y = 261.3277+13.8248X-0.1536X^2$	45
	3	$Y = 279.5919+20.60623X-0.2208X^2$	47
	4	$Y = 329.4165+26.09402X-0.2739X^2$	47
	5	$Y = 382.7024+41.14287X-0.4632X^2$	44
Karapadom	1	$Y = 235.8378+2.633776X-0.0537X^2$	25
	2	$Y = 248.3495+10.85501X-0.1248X^2$	43
	3	$Y = 374.6582+16.56358X-0.2163X^2$	38
	4	$Y = 330.0733+29.73428X-0.3529X^2$	42
	5	$Y = 343.7941+37.94739X-0.4434X^2$	43
Brown hydromorphic	1	$Y = 155.8141+12.00292X-0.1524X^2$	39
	2	$Y = 207.6395+17.12448X-0.2088X^2$	41
	3	$Y = 161.393+19.05146X-0.2217X^2$	43
	4	$Y = 228.6331+22.20047X-0.2594X^2$	48
	5	$Y = 222.1434+32.53212X-0.3746X^2$	43

X = Period   Y = Iron release

* Tables 10, 11, 12 and 13

require 38 to 43 days while brown hydromorphic soil would need 41 to 43 days for the peak release of Fe^{2+} under the influence of sea water of varying compositions. When the sea water as such was used for submergence, the peak release of Fe^{2+} from kayal soil rose to 50 days, kari soil to 44 days and karapadom and brown hydromorphic soils to 43 days.

2. Influence of organic matter on the release of Fe^{2+}

Data relating to the influence of added organic matter (farm yard manure) on the release of Fe^{2+} from the kayal, kari and karapadom soils of Kuttanad and from the brown hydromorphic soils from Kottarakkara are presented in Tables 16 to 21 and graphically illustrated in Fig . 9 and 10. It was noticed from the Tables and Fig . that even without addition of organic matter, submergence itself resulted in enhanced release Fe^{2+} as evidenced by the changes in Fe^{2+} concentration in the soil solution in the control. Presence of organic matter registered further increases in the concentrations of Fe^{2+} in the soil solution. In all the soil types progressive increase in the levels of added organic matter caused progressive increases in the release of Fe^{2+} with the duration of submergence and this continued upto a peak release of Fe^{2+} and thereafter decreased with further periods of submergence. The peak release of Fe^{2+} was found to be different for different soils.

Kayal soil

Data on the influence of level of organic matter on iron release from a typical kayal soil under submerged conditions are presented in Table 16 and Fig. 9a. It is seen in the Table and Fig. that increased levels of application of organic matter increased the rate of iron solubilisation. In the control, maximum concentration of 420 ppm Fe^{2+} was obtained on the 25th day of submergence after which the Fe^{2+} release into the soil solution subsided. Treated kayal soil alone continued to release Fe^{2+} till the 40th day of submergence after which the concentration of Fe^{2+} in the soil solution dropped of . The maximum release of 2726 ppm Fe^{2+} could be noticed on the 40th day of submergence of the soil which received organic matter at 8 g per pot of the soil, being the highest level studied. This concentration of Fe^{2}, however, decreased to 161 ppm on the 90th day of submergence. Lower levels of organic matter released lower contents of Fe^{2+}.

Kari soil

Table 17 and Fig. 9b pertaining to kari soil indicate that all the treated soils and the control released increasing amounts of Fe^{2+} with period of submergence. Peak release of Fe^{2+} could be noticed around the 25th day of submergence except in the control. As with the kayal soil, increased

Table 16. Effect of levels of organic matter on the release of iron (ppm) (kayal soil)

Sl. No.	Level of organic matter (g per pot of soil)	Period of submergence - days							
		0	5	10	25	40	50	75	90
1	0	45	120	416	420	268	130	120	100
2	1	45	152	320	960	2060	650	404	156
3	2	45	175	280	880	2304	390	296	217
4	4	45	203	495	880	2528	585	260	167
5	8	45	261	420	1048	2726	525	208	161

Table 17. Effect of levels of organic matter on the release of iron (ppm) (kari soil)

Sl. No.	Level of organic matter (g per pot of soil)	Period of submergence - days							
		0	5	10	25	40	50	75	90
1	0	65	235	384	320	192	120	98	57
2	1	65	420	650	1100	450	585	440	153
3	2	65	460	695	1340	925	720	800	256
4	4	65	490	790	1525	560	630	575	316
5	8	65	600	975	2125	825	805	450	384

applications of fresh organic matter resulted in the progressive increase in the Fe^{2+} release in to the soil solution and the highest level of 8 g organic matter applied to the soil released a maximum of 2125 ppm Fe^{2+} on the 25th day of submergence, after which a downward trend in Fe^{2+} release with prolonged submergence to reach 384 ppm on the 90th day could be noticed. The control treatment of the kari soil on submergence was found to release a maximum of 384 ppm even on the 10th day of submergence which was gradually reduced to 57 ppm on the 90th day.

Karapadom soil

Table 18 and Fig. 10a relating to the behaviour of the karapadom soil with respect to iron release under submerged condition in presence of organic matter, indicate that submergence of all the treated samples, as well as the control, resulted in the solubilisation of iron which progressively increased with the time of submergence releasing the maximum concentration of iron on the 25th day of submergence. Increased amounts of organic matter released progressively increasing amounts of Fe^{2+} and the highest level of 8 g organic matter resulted in the maximum release of 1465 ppm Fe^{2+} on the 25th day of submergence which decreased with further periods of submergence to 390 ppm on the 90th day. In the control,

Table 18. Effect of levels of organic matter on the release of iron (ppm) (karapadom soil)

Sl. No.	Level of organic matter (g per pot)	Period of submergence – days							
		0	5	10	25	40	50	75	90
1	0	56	260	416	448	160	128	110	88
2	1	56	455	700	815	650	420	400	325
3	2	56	500	715	950	850	355	370	300
4	4	56	552	805	1215	765	505	350	350
5	8	56	645	985	1465	975	590	480	390

Table 19. Effect of levels of organic matter on the release of iron (ppm) (Brown hydromorphic soil)

Sl. No.	Level of organic matter (g per pot)	Period of submergence – days							
		0	5	10	25	40	50	75	90
1	0	25	180	283	736	360	140	120	105
2	1	25	226	310	832	1016	550	432	217
3	2	25	315	413	904	888	500	326	316
4	4	25	388	510	1100	864	760	360	207
5	8	25	450	620	1632	852	525	402	307

however, the maximum release of 448 ppm Fe^{2+} could be noticed on the 25th day of submergence and later it got reduced progressively to 88 ppm on the 90th day of submergence.

Brown hydromorphic soil

Table 19 and Fig. 10b relating to the influence of organic matter on iron release from brown hydromorphic soil under submerged conditions, indicate that submergence brought about increased solubilisation of iron in the soil. Addition of organic matter enhanced the solubilisation of iron. Increasing levels of organic matter resulted in increased solubilisation of iron and the peak release was noticed between the 25th and 40th days of submergence. In the control, the peak release of 736 ppm Fe^{2+} was noticed on the 25th day which subsequently got reduced with time to reach 105 ppm on the 90th day. The peak release of iron in the treated soil was noticed on the 25th day of submergence except for the lowest level of organic matter which gave a peak release of 1016 ppm iron on the 40th day. The highest release of 1632 ppm iron was noticed in the soil which received the highest level of organic matter and this got decreased progressively after the 25th day and reached 307 ppm on the 90th day of submergence.

Among the Kuttanad soils, in general, the maximum release of Fe^{2+} resulted in all the treated soils during the submergence

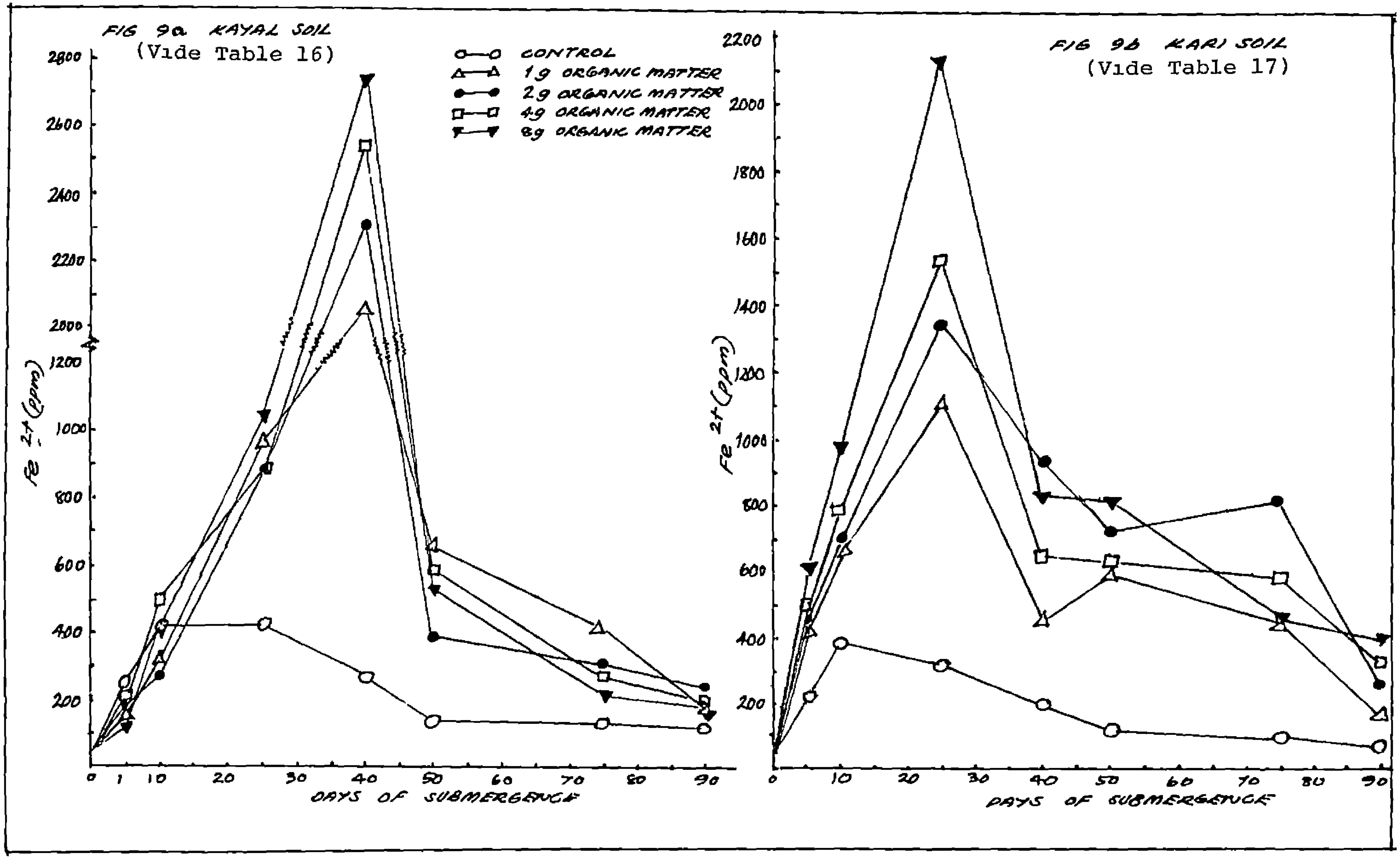

Fig. 9. Effect of levels of organic matter on iron release

a. Kayal soil b. Kari soil

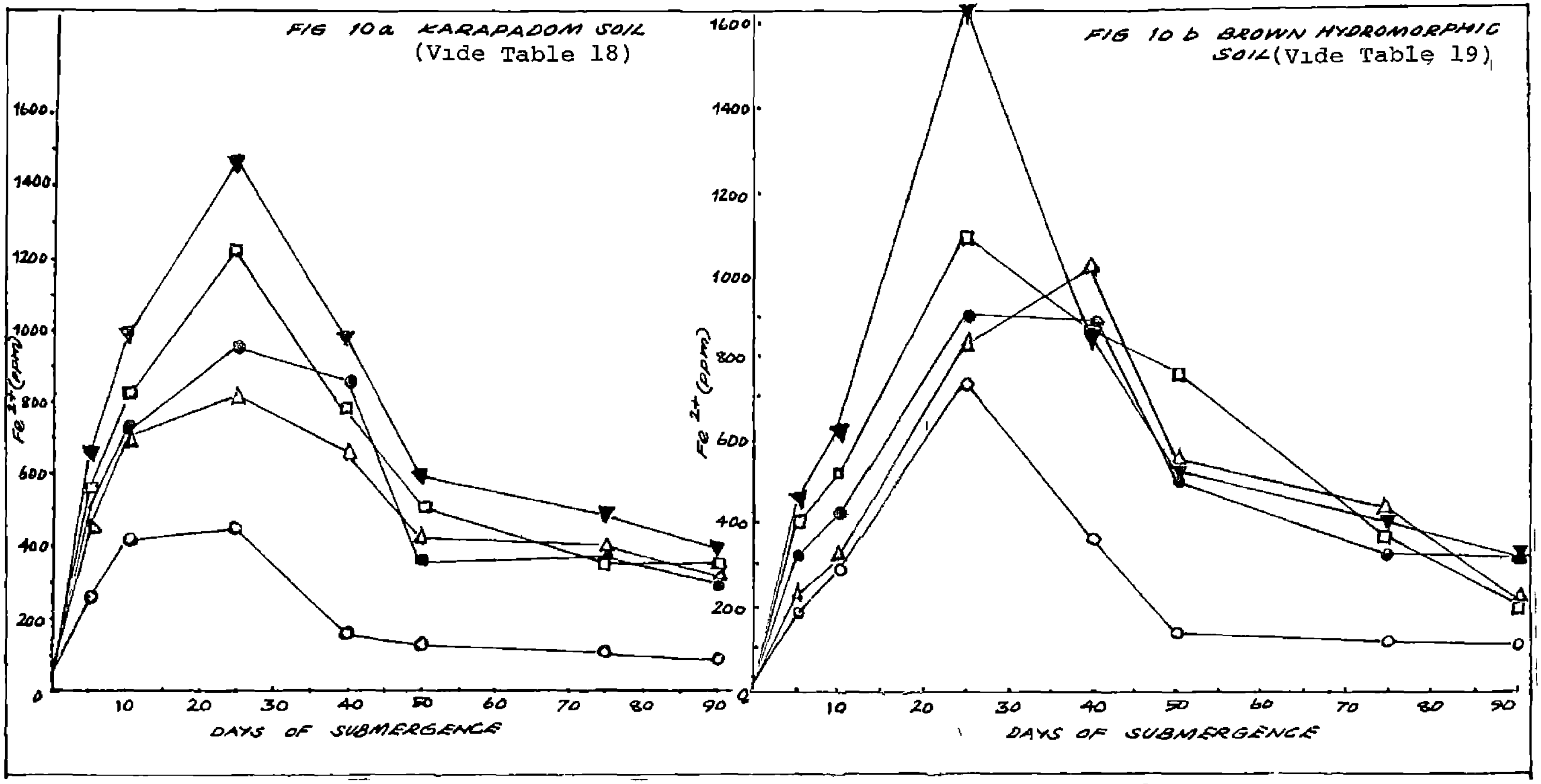

Fig. 10. Effect of levels of organic matter on iron release

a. Karapadom soil b. Brown hydromorphic soil

period between the 25th and 40th days and the peak appeared to be nearer to the 25th day period except for the kayal soil where the period of peak release was around the 40th day. Kayal soil was found to release a maximum of 2726 ppm Fe^{2+} under the influence of 8 g organic matter per pot on the 40th day. This was followed by kari soil which released 2125 ppm Fe^{2+} and karapadom soil releasing 1465 ppm Fe^{2+} both under the influence of 8 g organic matter estimated on the 25th day of submergence. Brown hydromorphic soil released upto 1632 ppm iron on the 25th day in the presence of 8 g organic matter. Comparison of the extent of maximum Fe^{2+} released by levels of organic matter and that of the control indicated that, in general, higher levels of organic matter treatment resulted in much higher rate of Fe^{2+} release in all the soils than the lower level treatments where the rate of Fe^{2+} release was also correspondingly lower. The same trend could be observed in the reverse manner during the post peak periods as well. Among the untreated control of Kuttanad soil types, karapadom soil released the maximum of 448 ppm iron on the 25th day of submergence. This was followed by kayal soil which gave the peak release of 420 ppm Fe^{2+} on the 25th day. In kari soil, the peak concentration of 384 ppm iron was noted on the 10th day of submergence. This being the case with Kuttanad soils, the brown hydromorohic soil released a maximum of 736 ppm iron on the 25th day of submergence.

Mean Table 20 provides results of interaction between soil, level of treatment and period of submergence. The effect of levels of organic matter on the release of Fe^{2+} was not significantly different among the four soils studied. Kari soil released significantly higher amount of Fe^{2+} on the 25th day of submergence which decreased thereafter. However, on the 40th day, the kayal soil released a significantl higher amount of Fe^{2+} with no difference between the other three soils in the lower releases after their peak values on the 25th day. It was also noticed that among the highest releases of Fe^{2+} on the 25th day by the kari soil and 40th day by the kayal soil, there was no significant difference. Beyond the 40th day, subsidence in Fe^{2+} was noted till the 90th day in all the four soils with the kari soil always retaining the higher mean levels of Fe^{2+}, though there was no significant difference. Mean values for soils indicated that the kari soil released maximum Fe^{2+} (547 ppm) followed by kayal soil (538 ppm) and karapadom soil (494 ppm), brown hydromorphic soil releasing the least Fe^{2+} (457 ppm).

Result of interaction between the levels of treatment and period of submergence revealed that the effect of organic matter on Fe^{2+} release was significant with respect to treatments at various periods of submergence.

Table 20. Effect of levels of organic matter on the release of iron in different soils: Mean values

(i) Soil type x treatment level

Sl. No.	Soil type	Treatment level of organic matter (g/pot) 0	1	2	4	8	Mean
1.	Kayal	202	593	573	645	674	538
2.	Kari	184	483	658	630	779	547
3.	Karapadom	208	478	512	575	698	494
4.	Brown hydromorphic	244	451	461	527	602	457
	Mean	210	501	551	594	688	509

(ii) Soil type x period of submergence - days

Soil type	Period of submergence - days 0	5	10	25	40	50	75	90	Mean
Kayal	45	182	386	838	1977	456	253	160	538
Kari	65	441	699	1282	608	572	473	233	547
Karapadom	56	482	724	979	680	400	342	291	494
Brown hydromorphic	25	312	428	1041	796	495	323	230	457
Mean	48	354	559	1035	1021	481	350	229	509

(iii) Treatment level x period of submergence

Sl. No.	Period of submergence - days	Level of treatment of organic matter (g/pot) 0	1	2	4	8	Mean
1.	0	48	48	48	48	43	48
2.	5	199	313	363	408	439	354
3.	10	376	495	526	650	750	559
4.	25	481	927	1019	1180	1563	1035
5.	40	245	1044	1242	1202	1370	1021
6.	50	130	551	491	620	611	481
7.	75	112	419	448	386	335	350
8.	90	88	213	272	260	311	229
Mean		210	501	551	594	638	509

CD at 5% level for Soil	76
,, for Treatment	85
,, for Period	108
,, for Soil x Treatment	171
,, for Soil x Period	216
,, for Treatment x Period	241

Table 21. Days of submergence for maximum release of iron as influenced by levels of organic matter in soils

Soil type	* Level of treatment (Sl No)	Quadratic regression	Period (days)
kayal	1	$Y = 168.9746+6.3571X-0.0866X^2$	37
	2	$Y = -32.50928+56.86296X-0.6335X^2$	45
	3	$Y = -15.19824+53.98169X-0.6038X^2$	45
	4	$Y = 11.26843+60.92097X-0.6944X^2$	44
	5	$Y = 15.80737+64.73808X-0.7445X^2$	43
Kari	1	$Y = 211.2321+2.408596X-0.0500X^2$	24
	2	$Y = 307.6798+21.21271X-0.2614X^2$	41
	3	$Y = 281.2612+35.04127X-0.3944X^2$	44
	4	$Y = 380.975+27.07482X-0.3227X^2$	42
	5	$Y = 485.4573+36.04556X-0.4462X^2$	40
Karapadom	1	$Y = 235.8378+2.633776X-0.0537X^2$	25
	2	$Y = 335.9416+15.48167X-0.1849X^2$	42
	3	$Y = 356.1793+18.92582X-0.2335X^2$	41
	4	$Y = 409.396+21.0751X-0.2635X^2$	40
	5	$Y = 476.32+27.2306X-0.3369X^2$	40
Brown hydromorphic	1	$Y = 156.0572+11.96374X-0.1520X^2$	39
	2	$Y = 73.43634+32.71248X-0.3569X^2$	46
	3	$Y = 170.3616+26.35493X-0.2934X^2$	45
	4	$Y = 193.9661+33.3058X-0.3856X^2$	43
	5	$Y = 305.1658+33.3912X-0.3972X^2$	42

X = Period

Y = Iron release

*Tables 16, 17, 18 and 19

The results of quadratic regression of the experimental data indicating the maximum number of days of submergence at which peak release of Fe^{2+} would occur in soils under the influence of graded levels of applied organic matter are furnished in Table 21. The Table indicates that kayal soil would need 43 to 45 days of submergence for maximum iron solubilisation in presence of organic matter, kari soil would need 40 to 44 days and karapadom soils would require 40 to 42 days. In brown hydromorphic soil, the peak release of Fe^{2+} as influenced by organic matter would occur between 42 and 46 days of submergence. Maximum release of Fe^{2+} under the influence of 8 g organic matter has occurred in kayal soil on the 43rd day, kari soil and karapadom soil on the 40th day and brown hydromorphic soil on the 42nd day of submergence.

3. Influence of ammonium sulphate on the release of Fe^{2+}

Tables 22 to 27 and Fig . 11 and 12 provide data on the release of Fe^{2+} from soils under submerged conditions as influenced by five levels of added ammonium sulphate ranging from 0 to 250 kg N/ha. In all these soils, in general, a progressive increase in the level of ammonium sulphate had resulted in the progressive increase in the release of Fe^{2+} in the soil solution with the duration of submergence and this continued till the fourth week of submergence after which it decreased with further periods of submergence and ultimately tended to approach a more or less steady value.

Kayal soil

Table 22 and Fig. 11a provide data on the influence of graded levels of ammonium sulphate on the release of Fe^{2+} at specified periods of submergence of a typical kayal soil. In the control treatment of the kayal soil length of submergence resulted in the release of Fe^{2+} which progressively increased upto 25 days (third sampling period) after which subsidence from peak value was noticed. It was also noticed that increasing levels of ammonium sulphate application, in general, resulted in the increased solubilisation of iron to attain a peak value around the 25th day of submergence and thereafter the release of Fe^{2+} progressively declined with further periods of submergence. It was observed that while the untreated control under submerged conditions could release a maximum of 412 ppm Fe^{2+}, graded levels of ammonium sulphate added to the soil could release increasing amounts of Fe^{2+} and the highest level of 200 kg N/ha released a maximum of 915 ppm Fe^{2+} during the 25th day of submergence of the kayal soil, which was more than double the Fe^{2+} concentration in the control. After attaining the concentration of Fe^{2+} in the soil solution, iron release decreased and on the 90th day

Table 22. Effect of levels of ammonium sulphate application on the release of iron (ppm) (kayal soil)

Sl. No.	Level of N applied (kg/ha)	Period of submergence - days							
		0	5	10	25	40	50	75	90
1	0	45	120	410	412	256	132	122	102
2	50	45	245	435	504	220	168	156	118
3	100	45	222	408	575	410	202	180	130
4	150	45	350	665	725	290	174	162	158
5	200	45	362	668	915	188	134	123	120

Table 23. Effect of levels of ammonium sulphate application to soils on the release of iron (ppm) (kari soil)

Sl. No.	Level of N applied (kg/ha)	Period of submergence - days							
		0	5	10	25	40	50	75	90
1	0	65	230	382	315	195	125	97	60
2	50	65	235	385	564	225	133	120	68
3	100	65	246	383	1075	356	180	132	115
4	150	65	570	990	695	194	172	156	127
5	200	65	474	860	790	172	150	145	123

of submergence the Fe^{2+} concentration in all the treatments including control attained values around 100 to 160 ppm, with the control having the least concentration of 102 ppm Fe^{2+}.

Kari soil

Data on the influence of added ammonium sulphate on the nature and extent of Fe^{2+} release with period of submergence of a kari soil of pH 3.8 are given in Table 23 and Fig. 11b Kari soil having, in general, higher acidity than the other soil types, gave indications of decrease from the peak release of Fe^{2+} even from the 10th day of submergence (in the control). It was noticed that addition of increased concentrations of ammonium sulphate to kari soil under submerged conditions resulted in progressively increased releases of Fe^{2+}. However, it was found that the maximum Fe^{2+} release was restricted to 100 kg N/ha level. At this level of N, the release of Fe^{2+} was 383 ppm on the 10th day as against the maximum of 382 ppm Fe^{2+} in the control treatment on the same day. However, all the levels of ammonium sulphate except the two highest levels of N could release still more Fe^{2+} with further period of submergence thus releasing the maximum Fe^{2+} around the 25th day of submergence. Ammonium sulphate at the rate of 100 kg N/ha released 1075 ppm Fe^{2+} on the 25th day of submergence, after which this peak concentration of Fe^{2+}

dropped to lower values and reached 115 ppm on the 90th day of submergence. Ammonium sulphate applied at 150 kg N and 200 kg N/ha released a maximum of 990 ppm and 860 ppm Fe^{2+} respectively on the 10th day of submergence and thereafter decreased to lower values to reach a concentration of 127 and 123 ppm Fe^{2+} on the 90th day of submergence. It was also noted that the rate and extent of Fe^{2+} release in the control and in the lower levels of ammonium sulphate treatments upto 100 kg N/ha, was more or less uniform till the 10th day of submergence after which the rate of release changed in the different treatments.

Karapadom soil

The influence of level of added ammonium sulphate on the extent of iron release from a karapadom soil is presented in Table 24 and Fig. 12a. It was noticed that increasing levels of ammonium sulphate resulted in increased releases of Fe^{2+} upto the level of 150 kg N/ha. In all the treatments including the control, release of Fe^{2+} occurred in progressively increasing amounts with time of submergence and reached peak values on the 25th day, except for the highest level of ammonium sulphate, wherein a lesser peak value was obtained on the 10th day of submergence whereafter it diminished to lower values with a tendency towards attaining a more or less steady value

Table 24. Effect of levels of ammonium sulphate application to soils on the release of iron (ppm) (karapadom soil)

Sl. No.	Level of N applied (kg/ha)	Period of submergence - days							
		0	5	10	25	40	50	75	90
1	0	56	260	409	438	157	128	115	92
2	50	56	380	695	795	162	165	140	95
3	100	56	475	850	958	290	130	128	111
4	150	56	344	610	1232	230	132	130	102
5	200	56	535	975	910	195	145	100	98

Table 25. Effect of levels of ammonium sulphate application to to soils on the release of iron (ppm) (Brown hydromorphic soil)

Sl. No.	Level of N applied (kg/ha)	Period of submergence - days							
		0	5	10	25	40	50	75	90
1	0	25	185	275	715	358	130	118	112
2	50	25	430	840	527	510	126	112	96
3	100	25	372	695	868	357	190	181	115
4	150	25	355	690	1050	375	167	161	112
5	200	25	350	666	843	220	145	118	106

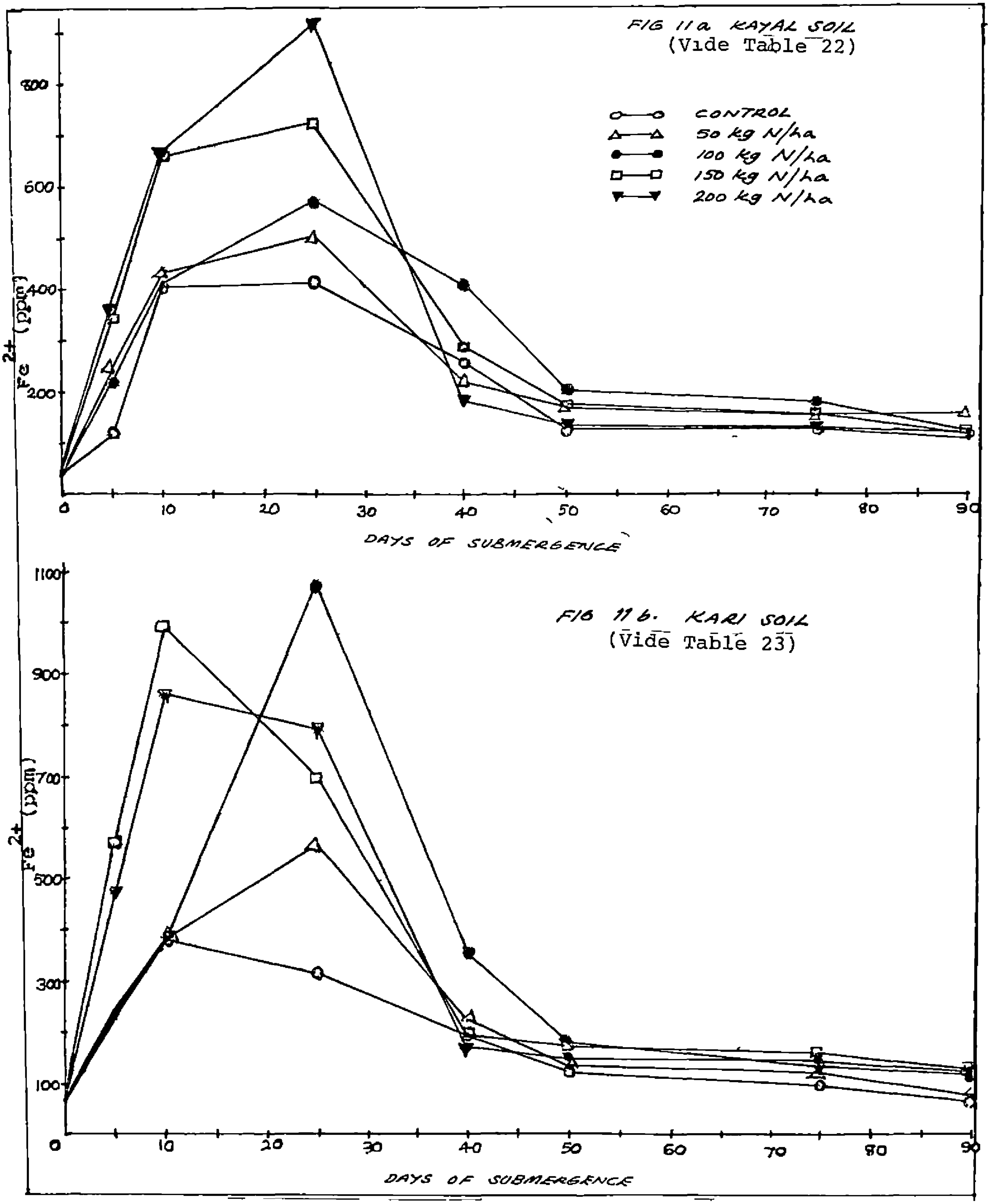

Fig. 11. Effect of levels of ammonium sulphate on iron release

a. Kayal soil b. Kari soil

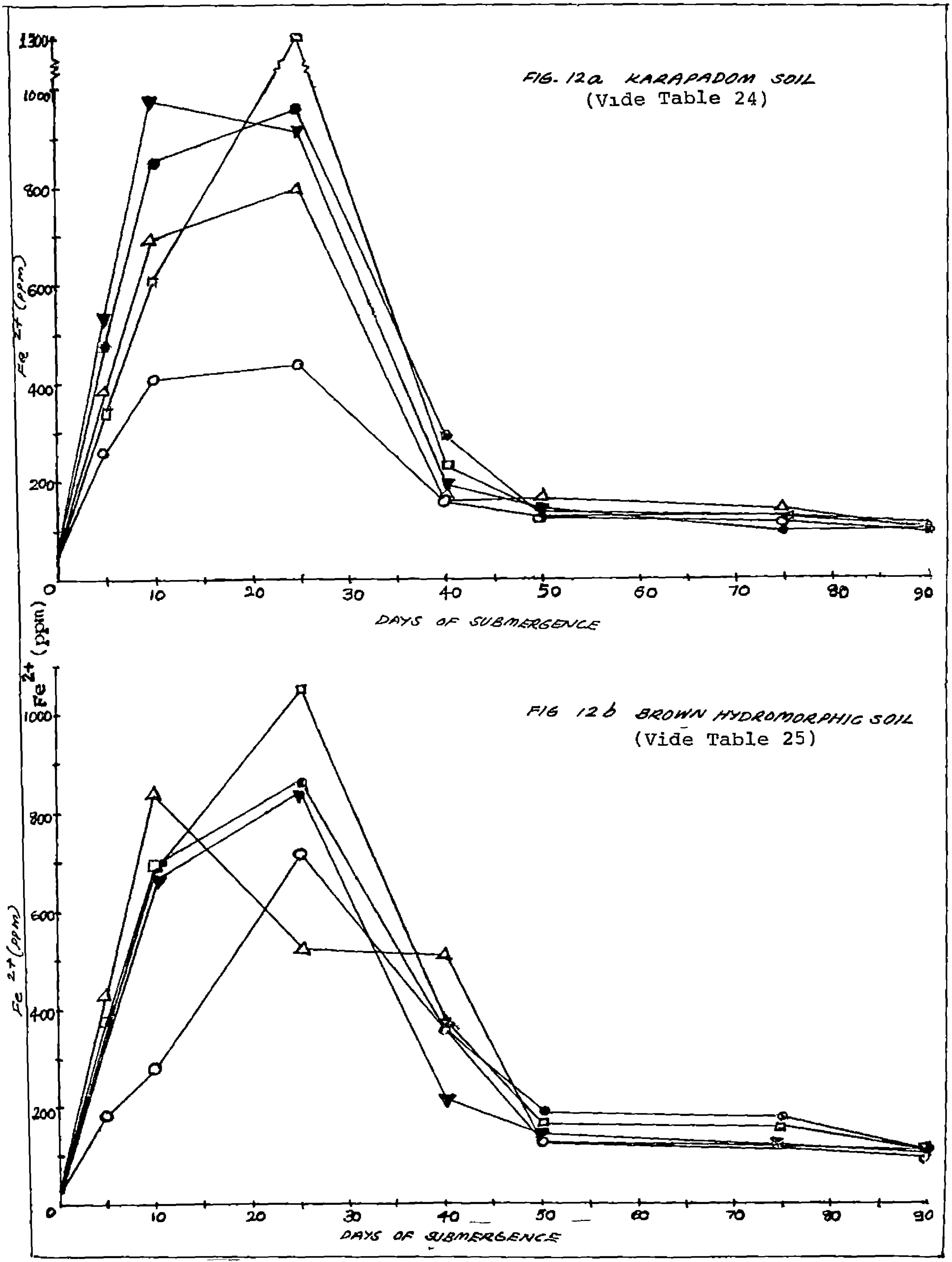

Fig. 12. Effect of levels of ammonium sulphate on iron release
a. Karapadom soil b. Brown hydromorphic soil

on the 90th day of submergence. Ammonium sulphate at 150 kg N/ha could release a maximum of 1232 ppm Fe^{2+} around the 25th day of submergence as against the control which released 438 ppm Fe^{2+} during the same period.

Brown hydromorphic soil

The influence of level of ammonium sulphate application to brown hydromorphic soil on the release of Fe^{2+} under submerged conditions is presented in Table 25 and Fig. 12b. The treatment which received 150 kg N/ha resulted in the maximum of 1050 ppm Fe^{2+} on the 25th day of submergence and decreased thereafter. In the control the iron release on the 25th day of submergence was 715 ppm, which was the maximum, which decreased afterwards. It was also noticed that ammonium sulphate treatment at 200 kg N/ha suppressed iron release to 843 ppm on the 25th day of submergence which later dropped to lower values with further periods of submergence.

Among the four soil types studied karapadom soil with ammonium sulphate applied at 150 kg N/ha recorded the maximum release of 1232 ppm Fe^{2+} in the soil solution during the third sampling period, followed by kari soils with 100 kg N/ha which released upto 1075 ppm Fe^{2+} during the same period and by brown hydromorphic soil with 150 kg N/ha releasing 1050 ppm Fe^{2+}. The peak release of Fe^{2+} was minimum in the kayal soil even with the highest level of 200 kg N/ha. It released only 915 ppm Fe^{2+} during the third sampling period corresponding to the 25th day of submergence. Among the untreated control of the four soils peak release of Fe^{2+} was observed with 412 ppm in kayal soil, 438 ppm in karapadom soil and 715 ppm in brown hydromorphic soil, all measured on the 25th day of submergence while kari soil alone released a maximum of 382 ppm Fe^{2+} on the 10th day of submergence. Mean values for soils indicated that karapadom and brown hydromorphic soils released maximum Fe^{2+} (325 ppm and 320 ppm respectively); the kayal soils releasing least Fe^{2+} (270 ppm) which was on par with kari soil (289 ppm).

The average effects of ammonium sulphate on the release of Fe^{2+} in the different soil types with respect to the levels of treatment and periods of submergence are presented in Table 26. It is noticed from the Table that the treatments behaved consistantly over the different soils with respect to Fe^{2+} release. However, the average Fe^{2+} release varied significantly among the soils and also among the treatments. Among the soils studied, karapadom soil released the maximum of 325 ppm Fe^{2+} followed by brown hydromorphic soil and kari soil wherein mean releases of 320 ppm and 289 ppm respectively of Fe^{2+} were noted. These three were not significantly different. However, the kayal soil resulted in a significantly lower release of Fe^{2+}.

Table 26. Effect of levels of ammonium sulphate on the release of iron in different soil types: Mean values

(i) Soil type x Treatment levels

Sl. No.	Soil type	Level of treatment kg N/ha					Mean
		0	50	100	150	200	
1.	Kayal	200	236	272	321	319	270
2.	Kari	184	224	319	371	347	289
3.	Karapadom	207	311	375	355	377	325
4.	Brown hydromorphic	240	333	350	367	309	320
	Mean	208	276	329	354	338	

(ii) Soil type x Period of submergence

Sl. No.	Soil type	Period of submergence - days								Mean
		0	5	10	25	40	50	75	90	
1.	Kayal	45	260	517	626	273	162	149	126	270
2.	kari	65	351	600	688	228	152	130	99	289
3.	Karapadom	56	399	708	867	207	140	123	100	325
4.	Brown hydromorphic	25	338	633	801	364	152	138	108	320
	Mean	48	337	615	745	268	151	135	108	338

(iii) Treatment level x Period of submergence

Sl. No.	Period of submergence-days	Level of treatment kg N/ha					Mean
		0	50	100	150	200	
1.	0	48	48	48	48	48	48
2.	5	199	323	329	405	430	337
3.	10	369	589	584	739	792	615
4.	25	470	598	869	926	865	745
5.	40	242	279	353	272	194	268
6.	50	129	148	176	161	144	151
7.	75	113	132	155	152	122	135
8.	90	92	94	118	125	112	108
Mean		208	276	329	354	338	

CD at 5% level for Soil	42
,, for Treatment	47
,, for Period	60
,, for Soil x Treatment	94
,, for Soil x Period	119
,, Treatment x Period	134

With regard to the effects of treatment levels and period of submergence it was noticed that 150 kg N/ha applied as ammonium sulphate released maximum Fe^{2+} (354 ppm), but when the nitrogen level was increased further to 200 kg/ha, the average Fe^{2+} release was found lower, though not significant. It has therefore to be inferred that, in general, the Fe^{2+} release increased with the levels of N upto 150 kg/ha and then gradually decreased.

With regard to the effect of interaction between the treatment and the period of submergence it was seen that though the maximum release of Fe^{2+} was on the 25th day it was not significantly different from that on the 10th day of submergence.

The data on the number of days of submergence for the maximum release of Fe^{2+} as influenced by levels of ammonium sulphate in the four soils under study as worked out based on quadratic regression are furnished in Table 27. The Table indicates that higher levels of treatment would need lesser period for maximum release of Fe^{2+}. Thus, in the kayal soil ammonium sulphate added at 200 kg N/ha would need 26 days, in the kari soil 8 days, in the karapadom soil 9 days and in brown hydromorphic soils 28 days of submergence. Application of 50 kg N/ha needed 34 days in kayal soil, 32 days in kari,

Table 27. Days of submergence for maximum release of iron as influenced by levels of ammonium sulphate in soils

Soil type	*Level of N/ha (Sl.No)	Quadratic regression	Period (days)
Kayal	1	$Y = 167.6126+0.1024X-0.0832X^2$	37
	2	$Y = 223.7002+5.2864X-0.0785X^2$	34
	3	$Y = 192.1705+10.6978X-0.1357X^2$	39
	4	$Y = 335.6284+5.8283X-0.0990X^2$	29
	5	$Y = 363.6317+5.3203X-0.1036X^2$	26
Kari	1	$Y = 208.0266+2.5386X-0.0508X^2$	25
	2	$Y = 220.6985+5.8442X-0.0912X^2$	32
	3	$Y = 240.3873+13.9450X-0.1876X^2$	37
	4	$Y = 520.2728+-1.1038X-0.0467X^2$	12
	5	$Y = 458.8502+1.0716X-0.0650X^2$	8
Karapadom	1	$Y = 233.6077+2.4812X-0.0509X^2$	24
	2	$Y = 371.2259+3.9787X-0.0891X^2$	22
	3	$Y = 454.8279+5.0067X0.1140X^2$	22
	4	$Y = 358.9139+10.0833X\ 0.1620X^2$	31
	5	$Y = 515.2199+1.5284X-0.0839X^2$	9
Brown hydromorphic	1	$Y = 155.2255+11.4053X-0.1447X^2$	39
	2	$Y = 379.2877+5.9004X-0.1135X^2$	26
	3	$Y = 338.5545+9.6168X-0.1476X^2$	33
	4	$Y = 343.5178+11.6334X-0.1747X^2$	33
	5	$Y = 340.3683+6.1370X-0.1109X^2$	28

X = Period Y = Iron release

*Tables 22, 23, 24 and 25

22 days in karapadom and 26 days in the brown hydromorphic soils for maximum release of Fe^{2+}. Days required for maximum iron release when 100 kg N/ha was applied to soils, ranged between 33 to 39, in all the soils, except karapadom soil which needed only 22 days of submergence. Application of N at 150 kg N/ha required, 29 days in kayal soil, 12 days in kari soil, 31 days in karapadom soil and 33 days in brown hydromorphic soil.

4. Influence of lime on the suppression of iron release

Data pertaining to the influence of level of applied lime on the release of Fe^{2+} from the kayal, kari and karapadom soils of Kuttanad region and the brown hydromorphic soil of Kottarakkara under the conditions of submergence are presented in Tables 28 to 30 and Fig . 13 and 14. It was noticed from the Table and Fig. that the application of lime had considerably reduced the soluble iron content in the soil solution irrespective of the soil types. The extent of suppression of iron release, however, was different for different soils. Among the two levels tried, lime applied at the rate of 1000 kg/ha released much less iron than the lower level of lime treatment.

Kayal soil

A comparison of the Fe^{2+} content of the treated kayal

Table 28. Effect of levels of lime application to soils on the release of Fe^{2+} (ppm) under submerged conditions

Sl. No.	Soil type	Levels of lime (kg/ha)	Period of sampling (days)							
			0	5	10	25	40	50	75	90
1.	Kayal	0	45	120	416	420	268	124	120	100
		600	45	102	164	410	1327	330	258	133
		1000	45	70	105	302	744	290	137	110
2.	Kari	0	65	235	382	315	193	122	100	60
		600	65	90	162	390	328	312	275	210
		1000	65	80	110	298	165	118	114	112
3.	Karapadom	0	56	260	416	444	160	123	110	88
		600	56	100	120	157	148	128	124	121
		1000	56	70	85	132	120	111	98	96
4.	Brown hydromorphic	0	25	180	236	728	358	135	118	107
		600	25	100	105	133	248	116	68	60
		1000	25	65	65	96	165	77	62	58

Fig. 13 Effect of levels of lime on the suppression of soluble iron in soils

a. Kayal soil

b. Kari soil

Fig. 14 a. Karapadom soil

b. Brown hydromorphic soil

FIG 13a KAYAL SOIL
(Vide Sl.No. 1, Table 28)

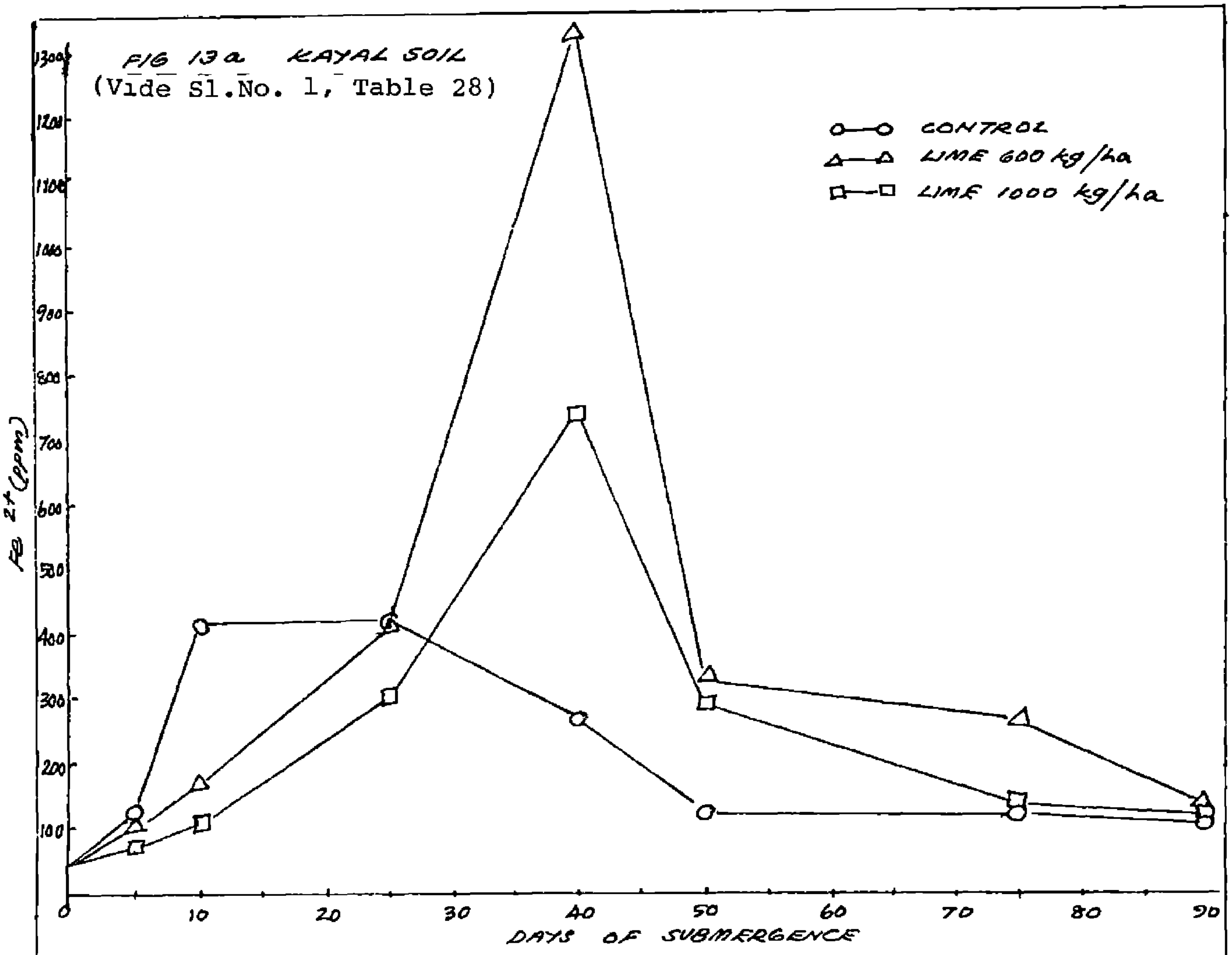

FIG 13b KARI SOIL
(Vide Sl.No. 2, Table 28)

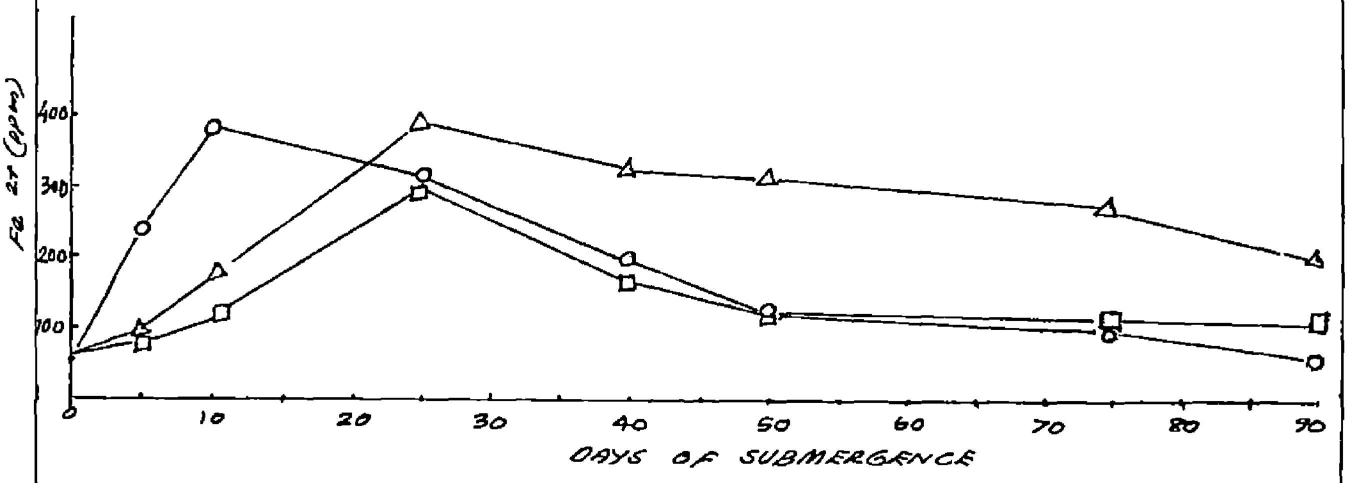

Fig. 13. Effect of levels of lime on the suppression of soluble iron

a. Kayal soil b. Kari soil

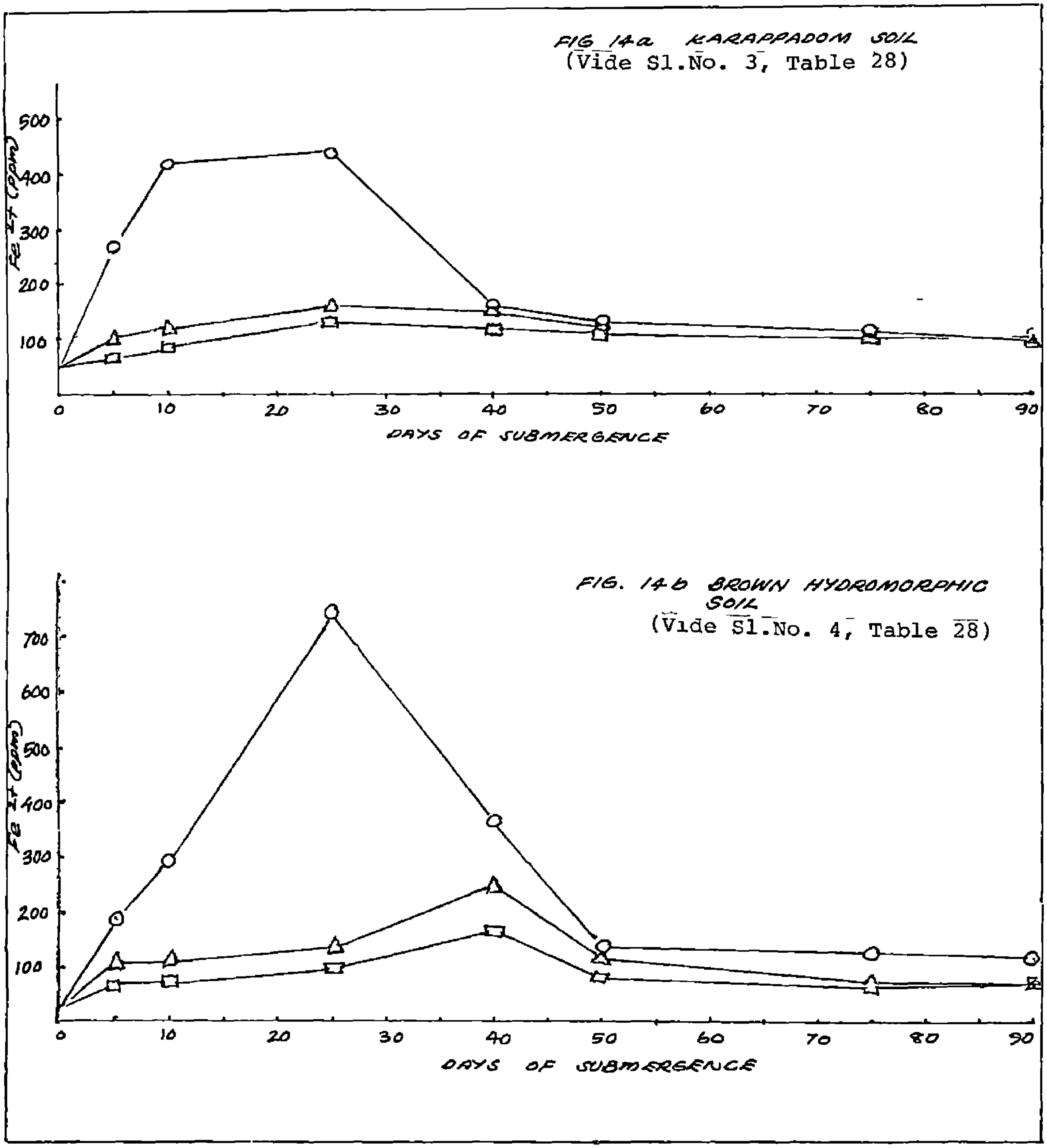

Fig. 14. Effect of levels of lime on the suppression of soluble iron

a. Karapadom soil b. Brown hydromorphic soil

soil with the untreated control (Table 28 and Fig. 13a) would reveal that lime applied at the rate of 600 kg/ha has been helpful in suppressing the iron release from 416 ppm (control) to 164 ppm on the 10th day of submergence. However, on the 25th day lime applied soil released 410 ppm Fe^{2+} as against 420 ppm recorded by the control. Again, on the 40th day the lime treated soil was found to have released as much as 1327 ppm Fe^{2+} while the control itself had released only 268 ppm. These higher value trends for Fe^{2+} resulting from the lime applied soil continued to be retained, though in lesser intensities, throughout the subsequent period of submergence. On the 90th day of sampling, the lime applied soil had 133 ppm Fe^{2+} while the control had only 100 ppm.

Lime applied at 1000 kg/ha was, however, found to have a better effect in reducing the iron release up to the 25th day. A concentration of 105 ppm Fe^{2+} was estimated in the soil solution on the 10th day and 302 ppm on the 25th day. However, further periods of submergence were found to release as high as 744 ppm as against 268 ppm in the control. As in the case of lower level lime, subsequent release of soluble Fe^{2+} continued to remain at higher levels than in the control up to the 90th day of submergence when 110 ppm Fe^{2+} was found in the soil solution as against 100 ppm in the control.

Kari soil

It is clear from Table 28 and Fig. 13b that kari soil which received 600 kg lime/ha released much lower amounts of soluble iron than the untreated control, till the 10th day of submergence. However, on the 25th day the treated soil released 390 ppm Fe^{2+} as against 315 ppm estimated in the control. During the subsequent periods of submergence the Fe^{2+} contents were found to be invariably higher than in the control till the 90th day when 210 ppm Fe^{2+} could be estimated as against 60 ppm in the control. However, the higher level lime treatment was found to be more effective than the lower lime level in bringing down the Fe^{2+} release to 110 ppm on the 10th day, 298 ppm on the 25th day and 165 ppm on the 40th day as against the corresponding releases of 382 ppm, 315 ppm and 193 ppm Fe^{2+} recorded by the control. Those lowered releases of Fe^{2+} in the limed soil continued till the 50th day. However, during the further periods of submergence, Fe^{2+} was released at higher levels than in the control. Thus on the 90th day of submergence there was a release of 112 ppm Fe^{2+} as against 60 ppm estimated in the control.

Karapadom soil

From Table 28 and Fig. 14a, it is clear that lime application was helpful in maintaining reduced concentrations of iron in the soil solution till the 40th day of submergence. Thus, the lower level of lime reduced the iron solubilisation to 100, 120, 157 and 148 ppm as against the corresponding releases of 260, 416, 444 and 160 ppm recorded by the control on the 5th, 10th, 25th and 40th day respectively of submergence. However, from the 50th day onwards, the released Fe^{2+} exceeded the corresponding Fe^{2+} levels in the control, which continued till the 90th day when 121 ppm Fe^{2+} was estimated in the soil solution of the limed soil as compared to 83 ppm in the control.

The soil which received lime at 1000 kg/ha could further improve the situation by maintaining lower levels of iron solubilisation than in the control throughout the period of submergence, except during the last sampling period when 96 pom Fe^{2+} was estimated in the soil solution.

Brown hydromorphic soil

Table 28 and Fig. 14b clearly reveal that both levels of lime were helpful in maintaining reduced iron concentrations in the soil solution throughout the entire period of submergence. Lime applied at 600 kg/ha resulted in lower releases of Fe^{2+} compared to that of the control. Lime applied at 1000 kg/ha brought about further suppression in the concentration of iron in the soil solution.

Table 29 brings out the results of interaction soil type x levels of lime x period of submergence. The mean values indicated that 600 kg lime/ha could not bring about the desired level of suppression of the Fe^{2+} release in kayal and kari soils. However, in karapadom soil and brown hydromorphic soil, more reduced releases of Fe^{2+} could be noticed though not significant. Lime at 1000 kg/ha was also found not very beneficial in kayal soil in relation to suppression of Fe^{2+} release. However, in kari soil some benefits were noticed. Karapadom and brown hydromorphic soils responded more favourably to the higher lime level.

From the mean values of Fe^{2+} release by soils during the different periods of submergence under the influence of lime it could be seen that the suppressing effect on soluble Fe^{2+} was evident only upto 25 days. Beyond 25 days both the levels of lime failed to bring about any control of the Fe^{2+} release. On the contrary, the releases of Fe^{2+} even exceeded those of the control in some soils. Between 25 days and 40 days of submergence there was no significant difference in the Fe^{2+} release due to lime application. Though both the levels of lime were helpful, in general, in prolonging the peak Fe^{2+} release upto 25 days in Kuttanad soils, the higher level of lime was found more effective. Lime treatment at

Table 29. Effect of levels of lime application on the release of iron in different soil types Mean values

(i) Soil type x levels of lime

Sl. No. Soil type	Lime level kg/ha			Mean
	0	600	1000	
1. Kayal	202	346	225	258
2. Kari	184	229	133	182
3. Karapadom	207	119	96	141
4. Brown hydro-	236	107	77	140
Mean	207	200	133	180

(ii) Soil type x period of submergence

Soil type	Period of submergence - days								Mean
	0	5	10	25	40	50	75	90	
Kayal	45	97	228	377	780	248	172	114	258
Kari	65	135	218	334	229	184	163	127	182
Karapadom	56	143	207	244	143	121	111	102	141
Brown hydromorphic	25	115	135	319	257	109	83	75	140
Mean	48	123	197	319	352	166	132	105	180

(iii) Level of lime x period of submergence

Sl. No.	Period of submergence - days	0	600	1000	Mean
1.	0	48	48	48	48
2.	5	199	98	71	123
3.	10	363	138	91	197
4.	25	477	273	207	319
5.	40	245	513	299	352
6.	50	126	222	149	166
7.	75	112	181	103	132
8.	90	89	131	94	105
	Mean	207	200	133	180

CD at 5% for Soil	62
,, for Treatment	53
,, for Period	87
,, for Soil x Treatment	107
,, for Soil x Period	175
,, for Treatment x Period	151

more than the 1000 kg level may probably bring about further suppression of Fe^{2+} release and its toxic level.

The results of quadratic regression of the experimental data indicating the maximum number of days of submergence needed for the peak release of iron in soil solution under the influence of lime are contained in Table 30. The Table indicates that the maximum release of Fe^{2+} from the kayal soils receiving the two lime levels would occur on the 46th day of submergence while the control would need 37 days only. Optimum days required by the lime-treated kari soil would range between 45 and 51 as against 24 days needed by the resoective control. Karapadom soil receiving the two levels of lime would require 51 days of submergence for maximum iron release as compared to control which would require 24 days only. In the brown hydromorphic soils, however, much difference could not be noticed between the control and the lime treated soils and the peak release of Fe^{2+} would result from the treated soil as well as the untreated control between tho 40th and 46th days of submergence.

Table 30. Days of submergence for maximum release of iron as influenced by levels of lime in soils

Soil type	*Level of treatment (Sl No)	Quadratic regression	Period (days)
Kayal	1	$Y = 169.7037+6.239586X-0.0853X^2$	37
	2	$Y = -21.56323+32.04086X-0.3505X^2$	46
	3	$Y = 4775391+19.58001X-0.2141X^2$	46
Kari	1	$Y = 210.211+2.392899X-0.0429X^2$	24
	2	$Y = 68.34134+11.43489X-0.1124X^2$	51
	3	$Y = 82.91127+4.544487X-0.0507X^2$	45
Karapadom	1	$Y = 236.2196+2.493134X-0.0521X^2$	24
	2	$Y = 81.15901+2.714421X-0.0267X^2$	51
	3	$Y = 62.65975+2.398616X-0.0237X^2$	51
Brown hydromorphic	1	$Y = 142.2564+12.00379X-0.1503X^2$	40
	2	$Y = 52.75215+5.416846X-0.0627X^2$	43
	3	$Y = 38.11415+3.383401X-0.0371X^2$	46

*Table 28

X = Period

Y = Iron release

DISCUSSION

DISCUSSION

1. Forms of iron in Kuttanad surface soils as influenced by soil chemical properties

(i) Water soluble iron

The mean Table 5 indicates that the kari soils had the highest mean content of water soluble iron which was significantly higher than that of kayal and karapadom soils. Between the kayal and karapadom soils, however, significant difference in the water soluble iron could not be noticed. The main factor which appears to control the content of water soluble iron is the soil pH. The concentration of water soluble iron is highly sensitive to PH changes. The practical implications of pH-Fe^{2+} relationship for the fertility of submerged soils, brought out by Ponnamperuma (1955, 1972) and IRRI (1968) in the equation $\text{pH}-\frac{1}{2}\text{PFe}^{2+}=5.4$ are that at higher pH values, rice suffers from iron deficiency (as in alkaline soils) and that at low pH values rice is affected by iron toxicity (Tanaka and Yoshida 1970). In the kari soil, the lowest pH and the highest content of reducible iron might have contributed towards the increased iron solubilisation. High content of water soluble iron may be associated with the highest active iron content in the soil which in turn must have influenced the release of soluble iron from the ferruginous mineral constituents of the soil as reported by Kabeerathumma (1975).

It may be observed from the correlation matrix (Table 6) that a significant negative correlation between the pH and water soluble iron exists in all the three soil types of Kuttanad considered individually. The highest significance at 1 per cent level could be obtained when the three soil types were together considered ($r = -0.8464$). Iron is slightly amphoteric in nature and its dissolution requires acid. The Greater the acidity, the greater will be the dissolution. The result is in agreement with the findings of Sukla et al. (1975), Misra and Pande (1975), Patel and Dungarwala (1983) and Sakal et al. (1988).

Benckiser et al. (1982), however, reported that soil iron content and pH values did not appear to be related. In the present study, the kari soil which possessed the highest content of 140 ppm water soluble iron was found to be the most acidic (mean pH 3.8). Kari soil is characterised as a sulphidic soil and its low pH can be ascribed to the presence of sulphuric acid formed through the hydrolysis of ferric sulphate derived mostly by the oxidation of iron pyrites (FeS_2) which occurs abundantly in these soils (Gopalaswamy, 1958; Subramoney, 1960; Money, 1961; Abraham, 1984). Van Breemen and Moorman (1978) and Verma and Neue (1988) reported that a rapid rise in Fe^{2+} is favoured by, among others, a low initial soil pH and the presence of easily reducible ferric oxide (active iron). Experionce with flooding of acid sulphate soil for rice and fish production in Philippines, has shown that once atmospheric oxygen has penetrated into a pyritic substratum, oxidation of pyrite is not stopped instantaneously again on flooding and restoring reduced conditions, because oxidative capacity stored in ferric iron maintains further oxidation of pyrite and production of soluble ferrous iron and sulphate (Van Breemen, 1976). A part of this ferrous sulphate reaches the soil surface and the overlying water where it forms ferric hydroxide and sulphuric acid. Thus, the overlying water keeps acidifying although the acidity of the underlying soil may be decreasing due to chemical reduction caused by flooding.

Takkar (1969) observed that in acid soils higher amounts of Fe^{2+} was due to high content of free iron and low pH values. This observation is in agreement with Kumada and Asami (1958) who found that the rate of formation of Fe^{2+} depended upon the nature and amount of free Fe compounds, the pH and the organic matter content of the soil. Very low pH values for kari soil have also been reported by Money (1948), Subramoney and Kurup (1961) and Aiyer et al. (1975). The development of acid was found to increase when the kari soil was exposed to air, with wide variations of pH between locations at different periods of the year. The kari soil is characterised by low base status, high organic matter and high exchangeable Al^{3+} which also might have contributed towards the higher acidity.

A significant positive correlation (r = 0.777) exists between the water soluble iron and electrical conductivity in Kuttanad soils. Ponnamperuma (1965, 1972) reported that in normal submerged soils the peak specific conductances are of the order 2-4 mmhos/cm at 25°C. The higher water soluble iron and manganese, at low PE values, along with HCO_3^- increase the specific conductivity of the soil solution and displace large amounts of Ca^{2+}, Mg^{2+} and K^+ by cation exchange reactions and thus may contribute to a higher electrical conductivity of the kari soil to levels (3.97 dSm^{-1}) injurious to the rice crop. At the same time the high content of salt in these soils derived from salt water ingression and seepage from the adjoining Arabian sea, may have a direct effect in releasing more of soluble iron from the soil by the operation of exchange reactions. Pasricha and Ponnamperuma (1976) have proposed that high salinity would favour the production of Fe^{2+} by lowering the activity coefficient of Fe^{2+} causing higher equilibrium concentrations after the peak in water soluble Fe^{2+}. The effect of salt in building up toxic concentrations of Fe^{2+} in strongly acid soils containing adequate amounts of organic matter and reactive iron oxides has been confirmed by Ponnamperuma (1976, 1977b). Bandyopadhyay and Bandyopadhyay (1984) obtained considerable increases in soluble Fe^{2+} fraction due to submergence of coastal saline soil, with more severe effect in the presence of undecomposed organic matter. The findings are in agreement with those of Gerei (1959), Ponnamperuma (1972), Kumar et al. (1981), Menswoort et al. (1985) and Sadana and Takkar (1985). IRRI (1967) has reported that specific conductivity values exceeding 4 mmhos/cm would indicate the presence of too much salt for the healthy growth of rice and values considerably in excess of 4 mmhos/cm are possible in submerged soils that have low CEC and high organic matter contents and in acid sulphate soils.

Water soluble iron was also found positively and significantly correlated with organic carbon ($r = -0.3443$) when the three soil types of Kuttanad were considered together eventhough the relationship with individual soil types was random. Similar positive and significant correlation of available iron with organic carbon could be observed by Sakal (1988). Kari soils of Kuttanad have vast organic deposits as also fossils of timber in varying depths. Anaerobic decomposition of the bulk of the organic matter under waterlogged conditions can lead to the generation of phenolic compounds related to fulvic acids and various organic acids which may reduce ferric oxides as reported by Takijima (1964), IRRI (1971), Okazaki and Wada (1976) and others. This might have naturally resulted in an enhanced iron solubilisation. High active iron content in the soil favoured by organic matter has contributed towards increased water soluble iron in the soil solution.

With regard to the influence of cation exchange capacity on the water soluble iron in the Kuttanad soils, a positive correlation existed but it was not significant.

2. Exchangeable iron

The exchangeable iron content was not significantly different among the three soil types. Highest content of exchangeable iron could be recorded (197 ppm) in the karapadom soil, followed by kari soil with a marginal difference. A positive correlation with pH in the kayal and karapadom soils and significantly negative correlation with pH in the kari soil (r = -0.6327) were noticed. However, in the Kuttanad soils as a whole, a positive correlation between pH and exchangeable iron existed but it was not significant. Significant negative correlations between pH and exchangeable iron and available iron (r = -0.36) have been reported by Pathak et al. (1979).

Exchangeable Fe^{2+} was positively correlated with organic carbon content of the three soil types when the soils were considered individually, as well as when considered together. The relationship was, however, found significant in kari soils alone. Similar correlation has been obtained by Bao et al. (1964) ($r = 0.9554$). High active iron and exchangeable iron contained in the kari soil (Mean Table 5) indicates the relationship between the two forms of iron. Kabeerathumma (1975) reported that exchangeable iron was dependent on the active iron content of the soil. Organic matter added to the soil is known to enhance the availability of soluble forms of iron. It may be noted that kari soil possesses a comparatively higher content of organic carbon than the other soil types. The high CEC of the soil resulting from a high organic matter content in the soil can hold a greater part of soluble iron on the exchange complex, resulting in increased exchangeable iron.

A similar negative and highly significant relationship was noticed between the CEC and the exchangeable iron content of the karapadom soil ($r = -0.8032$). The negative relationship can be attributed to the competition of hydrated aluminium (Al^{3+}, $Al(OH)^{+}$ and $Al(OH)^{2+}$) and monovalent cations of Na^{+} and

K^+ for the exchange positions. In kayal soil also such negative relationship existod but was not significant (Tanaka and Yoshida, 1970). On the other hand, kari soils exhibited a positive non significant correlation between CEC and exchangeable iron. Yu Tian-ren (1980) reported that the amount of exchangeable ferrous iron increases with the cation exchange capacity of tho soil. In the present study, however, when the three soils were together considered the relationship was negative and significant. In low CEC soils which are acidic, exchangeable aluminium and iron will take care of the acidity in the exchange comolex to a greater extent. Where the exchangeable H^+ is high when the pH is less than 5.5 the tendency for exchangeable iron and Al to be present is more. Contradictory reports are available in literature indicating both positive and negative relationships between exchangeable iron and CEC of soils. The influence of CEC on the exchangeable iron and correlation between the amounts of iron extracted from a soil and its organic matter content have been stressed by Bao et al. (1964). The high content of organic carbon in the kari soil, by decomposition can increase the CEC of the soil which in turn must have enhanced the exchangeable cations including Fe^{2+}. On the other hand, a low CEC of a soil implies both a restricted buffering feature as well as a limited supply of available nutrients (Yoshida and Tanaka, 1970). Ottow et al.

(1982) reported from analysis of soils from iron toxic locations, a relatively low CEC with insufficient exchangeable bases, particularly K and Ca and low contents of available P and K. From the results of leaf analysis he ascribed iron toxicity to multiple nutritional soil stress; rather than to a low pH or a high amount of easily reducible iron in the soil. This conclusion was supported by their observation that the pH of the many iron toxic soils in Philippines ranged from neutral (pH 7.4) to acid (pH 4.4) with wide variations in the total iron as well as its 'active' part.

3. Active iron

Active iron content was highest in the kari and least in the kayal soil. Its content differed significantly among the soils.

The active iron content was significantly and negatively correlated with the pH of the Kuttanad soils as a whole. However, when the three soil types were individually considered, the relationship was random and non-significant.

Highly significant and positive correlation could be noticed between the organic carbon and active iron content of the three soil types considered individually and together. Bao et al. (1964) noticed that the amounts of iron extracted from a soil were correlated with the organic matter content of the soil.

Electrical conductivity of the soil was also found to have a significant influence on the active iron content of the soil (r = 0.5215). It has to be noted that in Kuttanad, presence of salt is possible in the irrigation water particularly during the summer months of January to April while during the monsoon months the water is fresh. Submergence brings about an increase in the electrical conductivity of soil solution with time (Ponnamperuma, 1976). In coastal saline soils of EC 13.6 mmhos/cm Bandyopadhyay and Bandyopadhyay (1984) noticed sharp fall in Eh and considerable increases in water soluble iron with more severe effect when the soil was treated with undecomposed organic matter.

II. Distribution of forms of iron in the soil profiles in relation to the physico-chemical properties

a. Physico-chemical features

Kayal soil

Table 7 a and 8 indicate that the kayal soil has dominance of fine sand and silt in the surface layers. Both the profiles had recorded high contents of these two soil fractions. (Mean content 46 per cent and 55 per cent fine sand and 27 per cent and 30 per cent silt in Profiles I and II respectively). The high content of fine sand is ascribed to estuarine influences of the adjoining Vembanad lake on these soils resulting in cumulative depositions of these coarser soil fractions through canals, rivers and flood waters. Electrical conductivity was also fairly high in these profiles throughout the depth examined (4 and 2.5 dSm^{-1} respectively). High conductivity particularly in Profile I must be mainly due to the tidal influences of the adjoining sea. The kayal soils are reclaimed beds of lakes located mainly on the fringes of Vembanad in the Alleppey and Kottayam districts. The rice fields thus reclaimed lie 0.5 - 2 metres below MSL and remain submerged under water for nearly four to five months annually. (May to September) It is seen from the Table that fine sand increased while silt content showed decreasing trend with depth, with nearly 50 per cent decrease in silt in one location. This decrease is seen accompanied by nearly similar rise in clay content with depth. However, in Profile II of the kayal soil, decreases in silt and clay contents were not marked. Organic carbon increased with depth which reveals the possible presence of organic matter in the lower layers. Both the profiles indicated decreases in pH with depth which is attributed to the increased organic matter contents and resultant accumulation of CO_2 and organic acids in the sublayers.

Kari soil

Study of the kari soil profiles indicated high clay content on the surface. However, the clay decreased to nearly one third in the two profiles and coarse sand increased towards the lower horizons which is attributed to estuarine influences over the years. In Profile I this decrease was from 59.0 to 20.7 per cent and increase in coarse sand was from 1.8 to 42.5 per cent. A similar situation was noticeable in Profile II also. The clayey nature of the kari soil thus appeared to be dominant mainly on the surface layers.

As with the kayal soil, a decrease in soil pH with depth was clearly noticeable. The decrease in pH noted in the sub-soil region is due to the acid sulphate nature of these soils and presence of exchangeable aluminium and organic acids accumulated from slow decomposition of vast organic matter reserves characteristic of this soil. The result is in agreement with the findings of Money (1961) that "the lower horizons of most of the profiles have markedly low pH which goes down as low as 2.5". Occurrence of sulphides and the existence of "Sulphur microbial cycle" operating in this soil leading to sulphuric acid have been indicated by Money (1960, 1961). Organic carbon content showed increases with depth. From 8.3 oer cent on the surface the organic carbon rose to 10.4 per cent with depth in Profile I. High organic carbon seen down the profile is indicative of the presence of organic matter in excessive quantities in the sub soil. Presence of partially decomposed organic residues including the wood fossils in the sub soil has been proved. Electrical conductivity increased with depth which indicated the presence of salts in the sub surface layers. These salts must have accumulated over the years as a result of earlier frequent saline intrusions from sea which has been controlled recently by a barrage at Thanneermukkom. Investigations carried out by the adjacent Karumadi Centre of the All India Coordinated Project (ICAR) on Agricultural Drainage has also confirmed high salt content in the sub surface layers.

Karapadom soil

Examination of Profile I of karapadom soil indicated high contents of fine sand and silt. The silt content showed decreases from 45.2 percent to 9.2 percent and clay increased from 10.3 per cent to 42.1 per cent with depth, while Profile II revealed dominance of sand (30.5%) and clay (38.9%) on the surface with considerable decrease in clay in the sublayers. In both the profiles of karapadom soil increase in sand with depth was noticed. In Profile I fine sand increased from 31.6% to 38.4% while in Profile II coarse sand increased from 30.5% to 59.5% with depth. The profiles of this soil type thus showed variation with regard to particle size. Money (1961) has reported that considerable variation existed in the character of the soils in different karapadom regions. Karapadom soils are the slightly raised fields situated on the banks of rivers and other waterways. The soils are enriched by the sand and silt brought down by the rivers and flood waters.

Organic carbon decreased from 5.8 per cent to 4 per cent with depth in Profile I while in Profile II it decreased from 5.1 to 2.4 per cent with depth. The pH decreased from 4.9 to 3.9 in Profile I while slight increase was seen in Profile II. The karapadom soil profiles thus showed variations in pH and texture.

Sandy Onattukara and brown hydromorphic soils

The size fractions remained without much change except ~~in~~ the coarse sand content which appreciably decreased from 14 per cent to 2 per cent with depth. Mean content indicated dominance of fine sand (45.6 per cent) and silt (26.8 per cent). In brown hydromorphic soils the mean values indicated that the soil had high clay content (43.6 per cent) on the surface.

b. Forms of iron in the soil profile

It could be seen in the Table that the total iron content in general, decreased with depth in all the soil profiles of Kuttanad under study except Profile I of kari and Profile II of karapadom soils. Sandy soil profile and the profile of brown hydromorphic soil also showed increases in total iron content with depth, though variations were not marked. They differed from Kuttanad soils in this respect. More accumulation of total iron on the surface soil may be due to the uptake of iron from lower horizons by vegetation and through sediments of eroded materials.

Water soluble and exchangeable iron recorded increases with depth in most of the rice soil profiles of Kuttanad though the pattern of increase slightly varied. Lowest content of water soluble iron was seen in the upper horizon of the kayal soil (105 ppm) while the surface soil of karapadom recorded the highest content (135 ppm). It was however, noticed that among the Kuttanad soils, the variation between profiles with regard to the surface content of water soluble iron was not appreciable. Decreased acidity in the lower layers of the profile is responsible for the increased contents of water soluble iron with depth. In brown hydromorphic soils the content of water soluble iron decreased with depth and in this profile the pH had not changed.

Exchangeable iron was maximum in the upper horizons of kayal and karapadom soil profiles which increased with depth except in Profile II of karapadom soil which showed decreases. In kari soil, however, much variation in exchangeable iron could not be observed. Sandy soil profile recorded the lowest content of 22 ppm which showed increases with depth up to

210 ppm probably due to increased clay content in this profile at lower layers which may lead to higher CEC values. In the brown hydromorphic soils the exchangeable iron decreased with depth.

Increases in active iron content with depth were noticed in all the soil profiles except karapadom soil Profile II.

Low pH and high organic matter in the lower layers have caused increased iron solubilisation, resulting in the higher contents of all forms of iron including active iron which has complexing effect with organic matter. In the kayal and karapadom soils of Kuttanad there is occurrence of jarosite minerals upto a depth of 50 cm together with small amounts of pyrites. The occurrence of small quantities of pyrites beyond 50 cm has been indicated from the studies conducted in the Department of Soil Science and Agricultural Chemistry . Kuttanad soils have thus been shown to be coming under the category of acid sulphate soils. The high release of both water soluble exchangeable iron in the sub surface soils (ie below the plough sole) is thus clearly warranted by the occurrence of Jarosites admixed with pyrites. Active iron was lowest in sandy soil which is traced to its lowest organic carbon content. The increased contents of forms of iron with depth in sandy soil profile might be due to the low water holding capacity of the soil leading to eluviation of soluble iron to lower horizons.

The decreases in all the soluble forms of iron in the Profile II of karapadom soil is explained as due to the increased p^H and decreased organic carbon with depth (Table 7(a)) observed. Moreover, in the various microenvironments in the soil, partial decrease in anaerobicity can occur. Though the soil may be submerged there may be small pockets of aerobic environment existing which can retain the iron in the ferric form.

Water soluble and exchangeable forms of iron together represent the available iron content in the soil which would give indication of toxicity symptoms in plants on immediate planting. Karapadom soils recorded the maximum in this respect whereas in the sandy Onattukara soil, this fraction was negligible. These two forms are dependant very much on soil properties. The increase in the content of these forms in the upper horizons appear to be related to soil acidity, soil organic matter content etc. and these soil properties are found to increase with depth. Moreover, under the conditions of tropical humid climate excessive leaching due to high precipitation may be an additional factor contributing towards the accumulation of these forms in the lower horizons in some of the soil profiles examined. The active iron content also followed the same trend in almost all the profiles studied and it appears to be related to the organic matter content of the soil as is evident from intercorrelation studies conducted.

Correlation studies indicated that the pH and water soluble iron content in the Kuttanad soil profiles (kayal, kari and karapadom soils considered together) were significantly and negatively correlated (r = -0.4278). Significant negative correlation (r = -0.7326) existed between pH and active iron content in the profiles of Kuttanad soils at one per cent level. Significant and positive correlation (r = 0.6292) of organic carbon and active iron content at one per cent level and of electrical conductivity and active iron (r = 0.3664) at 10 per cent level existed in the Kuttanad soil profiles as a whole. Negative correlation between pH and water soluble iron and active iron and positive relationship between organic carbon and active iron and between electrical conductivity and soluble iron have been reported by many workers.

III Influence of added amendments and toxicants on the nature of iron release

Although under the submerged conditions of a soil it has been observed that the presence of certain substances can enhance iron solubilisation to toxic levels in soil solution while some others can suppress it to below the toxic level, the extent and period upto which such Fe^{2+} release or Fe^{2+} suppression continues to occur under the influence of varying levels of added amendments to Kuttanad rice soils have not been investigated earlier and hence the present study was undertaken with Kuttanad soils. For comparison purposes, brown hydromorphic soil was also included in the study.

(i) Effect of submergence on the release of iron

All the soils under study released increasing amounts of Fe^{2+} with the period of submergence (Fig. 6). Peak release was observed 25 days after submergence except in kari soil. Later the iron concentrations dropped gradually to lower values with prolonged submergence upto 90 days. In the kari soil, however, peak release of Fe^{2+} could be noticed on the 10th day of submergence with gradual decrease thereafter. The release of Fe^{2+} during submergence has been demonstrated by different workers. The increase in pCO_2 on flooding is due to accumulation of CO_2 produced by aerobic respiration at the start and followed by anaerobic decomposition of organic matter. Hence PCO_2 in soils high in organic matter is higher. The increase in Fe^{2+} concentration (water soluble) is related to Eh and pH of the $Fe(OH)_3$-Fe system (Ponnamperuma et al. 1967).

Soil reduction under flooded conditions is a direct consequence of exclusion of oxygen. This culminates in the release of several reduced ions such as Fe^{2+}, Mn^{2+}, NH_4^+, HCO_3^- and other displaced cations. The concentration of ions in the soil solution thus increases and is characterised by a rise in specific conductivity. Thus, there is close similarity between the kinetics of specific conductance and those of Fe^{2+} and Mn^{2+} and other cations (Ponnamperuma, 1972).

The reduction of iron and increase in its solubility is a consequence of the anerobic metabolism of bacteria and it appears to be due to the chemical reduction of Fe^{3+} by bacterial metabolites (Ponnamperuma, 1955). Direct bacterial reduction coupled with respiration might be involved in the process (Kumura et al. 1963). At low redox potential ferric hydroxide is reduced to ferrous hydroxide according to the equation

$Fe(OH)_3 + e \rightarrow Fe(OH)_2 + OH^-$ (Patrick 1964, Mahapatra, 1968). The distribution of reduced Fe^{2+} between the solid and solution phase is controlled by pH, organic matter, cation exchange capacity and the duration of submergence.

The role of ferrous-ferric hydroxides as the principal redox system in submerged soil has been illustrated with thermodynamic evidences by Ponnamperuma (1967). It is noticed that the reduction process involving chemical transfermation is most active during the initial periods of submergence. More rapid solubilisation of iron has occurred in the kari soils as compared to the kayal, karapadom and brown hydromorphic soils. Soils rich in organic matter and low in pH are known to undergo rapid reduction due to submergence (Mandal, 1961; Motomura, 1962) with a concurrent increase in CO_2 (Ponnamperuma, 1965). The kari soils are characterised by an organic carbon content of 6.2 per cent and pH value 3.8. These two factors have influenced the more rapid release of Fe^{2+} during submergence. High amount of organic matter and increased CO_2 production during the rapid decomposition of organic matter during waterlogging are favourable factors in kari soil for the early formation of $FeCO_3$ (Ann. Report IRRI, 1967) and $Fe_3(CH)_8$ (Ann. Report IRRI, 1966). In kari soil therefore the reduction process is most active within 10 days of submergence after which the rate of reduction slows down. Compared to the kari soil, the kayal, karapadom and brown hydromorphic soils have only a lower organic carbon and slightly higher pH values which has resulted in a slower release of soluble iron.

A gradual decrease in Fe^{2+} could be noticed in all the soils after attaining peak values for Fe^{2+}. According to

Ponnamperuma (1967) the subsequent decrease of Fe^{2+} concentration is due to the precipitation of iron as $Fe_3(OH)_8$ or $Fe_3O_4nH_2O$ brought about by increase in pH following a decline in pCO_2 and that the final stable concentration appear to be regulated by the pH and Eh of the system. The decline in pCO_2 after the peak value of Fe^{2+} release may be ascribed to escape or diluting effect of CH_4 produced in the later stages of organic mattor decomposition, bacterial reduction of CO_2 to CH_2 or leaching losses or removal of CO_2 as insoluble carbonates. The Eh-PH diagrams as proposed by Ponnamperuma et al. (1967) would indicate that $Fe(OH)_3$ and $Fe_3(OH)_8$ were the possible iron compounds in equilibrium with Fe^{2+} in the soil solution. Though $Fe_3(OH)_8$-Fe^{2+}, $Fe(OH)_3$-Fe^{2+} and $Fe_3(OH)_8$-$Fe(OH)_3$ are the three major iron hydroxide redox systems operating in submerged soils $Fe(OH)_3$-Fe^{2+} equilibria would alone operate throughout the period of submergence while $Fe_3(OH)_8$-Fe^{2+} and $Fe_3(OH)_8$-$Fe(OH)_3$ equilibria would operate at the beginning of the peak or plateau of water soluble iron when $Fe_3(OH)_8$ is precipitated.

(ii) Salinity

Marine salinisation resulting from tidal variations of the Arabian sea is the major source of salt contamination in Kuttanad soils due to the low lying terrain of the region.

In these soils the variations in salt content is mostly seasonal. The dominant salts in Kuttanad soils are those of chloride, sulohate, carbonate and bicarbonate. The sulphate owes its origin to the acid sulphate soil itself while carbonate and bicarbonate originate from the organic matter decomposition. The effect of seasonal saline intrusion and consequent submergence on the release of soluble Fe^{2+} has not been investigated earlier.

Tables 10 to 13 and Fig . 7 to 8 would reveal that sea water submergence released significantly higher contents of Fe^{2+} in the soil solution. This observation is in general agreement with the findings of Pasricha and Ponnamperuma (1976). The release of Fe^{2+} appears to be influenced by the concentration of salt in the sea water treatment.

Sea water submergence of all the soil types except the kayal soil resulted in the peak release of Fe^{2+} on the 25th day of submergence while in kayal soil the release of iron continued till the 40th day and declined thereafter. Maximum release of Fe^{2+} could be noticed in the sea water submerged kayal soil with 1868 ppm in the drainage water collected on the 40th day. On the 25th day it was only 856 ppm. In kari soil also the release of Fe^{2+} was more or less the same. Karapadom soil released 1241 ppm iron on the 25th day under the influence of 100 per cent sea water. Brown hydromorphic soils behaved almost similarly as karapadom with a marginal increase in the Fe^{2+} release on the 25th day of sampling eventhough its control released higher amounts of Fe^{2+} compared to other soil types.

The increase in specific conductance of acid sulphate soils when submerged (Ponnamperuma 1955, 1977) may get aggravated by the use of salt containing irrigation water for the second crop of paddy in Kuttanad during the months January to April. Increase in conductivity during waterlogging of a soil is the result of displacement of the cations from the soil colloids by Fe^{2+} formed by the reduction of Fe^{3+}. IRRI (1965) reported that low pH and high salinity due to NaCl or $MgCl_2$ could aggravate iron toxicity to rice. According to Ponnamperuma (1977) the accumulation of ions on submergence of a soil increases the ionic strength and alters the ionic composition of the soil solution, which affects the ionic equilibria involving plant nutrients and uptake of ions by the rice root. In Maahas clay of pH 6.6 amended with NaCl to give initial specific conductances of 5, 10, 20 and 25 mmhos/cm, it was revealed that as the salt content increased the concentrations of cations also increased. This increase in cation concentration is attributed to the displacement of cations from soil colloids by Na^+, decrease in pH caused by the presence of extra electrolyte and effect of increased ionic strength on the solubility of soil minerals. In addition to the direct injurious effect of excess salt, a high specific conductance of submerged soil may imply the presence of injurious amounts of Fe^{2+} and ionic antagonisms that hinter the uptake of ions. Thus iron toxicity is aggravated by adding sodium chloride Ponnamperuma (1977). Bandyopadhyay and Bandyopadhyay (1984) in coastal saline soil and Sadana and Takkar (1985) in a sandy loam soil obtained a fall in Eh and increased releases of both soluble and exchangeable forms of iron under the influence of different concentrations of salt. The Kuttanad region lies in close proximity to the sea coast at one to two metres below the mean sea level. In addition to the submergence of the paddy fields in Kuttanad under water for three to four months annually, the tidal influence of the sea can cause salinity problems in these low lying acid sulphate soils. The problem has of late become less serious on account of the Thaneermukkom salt water barrage constructed across the Vembanad lake which has access to the sea, but still salinity problems do arise occasionally.

(iii) Organic matter

Submergence causes reducing conditions which are aggravated by organic matter. The intensity of the soil reduction varies depending upon the amount and nature of the decomposable organic matter applied to the soil and the duration of submergence. Hence different levels of organic matter in the form of farm yard manure were tried. It is clear from the Tables 16 to 19 and Fig . 9 and 10 that organic matter application to soils under submerged conditions has favoured Fe^{2+} release in the soil solution. In all the soil types, progressive increases in the release of Fe^{2+} were noted when the concentration of organic matter in the soil increased. Peak release of Fe^{2+} has occurred during the 25th day sampling in all the soils except the kayal soil where the release of Fe^{2+} continued till the 40th day to attain the peak value. When organic matter is added, the soil gets more and more buffered and the CEC increases. The consequence is that release of Fe^{2+} is delayed and prolonged till the 40th day in the kayal soil. After the peak concentration of Fe^{2+} in the soil solution, the release of Fe^{2+} gradually subsided with further periods of submergence of the soil due to fall in the concentration of CO_2 and precipitation of iron as $Fe_3(OH)_8$ or $Fe_3O_4nH_2O$. The maximum release of 2726 ppm Fe^{2+} has occurred in the kayal soil on the 40th day, followed by kari soil with 2125 ppm Fe^{2+} on the 25th day and and karapadom soil with 1465 ppm Fe^{2+} on the 25th day of submergence. In brown hydromorphic soils peak concentrations of 1632 ppm Fe^{2+} were noted on the 25th day. All the above peak values have resulted from the application of the highest level of organic matter. It has been reported that iron concentration in the soil solution may reach toxic proportions on submergence of the soil and aggravated by the addition of organic matter. Tables 16 to 19 and Figs. 9 and 10 give sufficient evidence supporting such earlier findings. (Islam and Elahi, 1954; Gopal Rao, 1956; Mandal, 1961; Motomura, 1961, 1962; Patnaik and Bhadrachalam 1965; Meek et al. 1968; Takkar, 1969; Mandal and Nandi, 1971; Ponnamperuma, 1972; Jaggi and Russel, 1973; He Xun and Xu Zu-yi, 1980; Khind et al. 1987 and many others. However, it could be seen from the Figs. 9 and 10 that the pattern of Fe^{2+} release caused by levels of organic matter was more or less identical for a particular soil. It could also be noticed in the Table that, in general, the higher level treatments resulted in much higher rates of Fe^{2+} release in all the soils than the lower levels where the rate of Fe^{2+} release was also correspondingly lower. The same trend could be observed during the subsidence of the peak values also. Higher amounts of Fe^{2+} due to addition of organic matter to acid soil may be due to the high content of free iron and low pH values (Takkar, 1969). Formation of Fe^{2+} in waterlogged soils in presence of organic matter is also attributed to the reducing compounds present and CO_2 produced in the course of anaerobic decomposition or fermentation of organic matter. Such substances dissolve insoluble ferric iron compounds in the soil and reduce them to soluble Fe^{2+} form. This observation is in agreement with those of Islam and Elahi (1954), Mandal (1961, 1962) and Motomura (1962) and Takkar (1969).

In general, the intensity of Fe (II) formation increased under the influence of higher amounts of easily mineralisable organic substances added to the soil. In the absence of oxygen, the Fe^{3+} compounds are used as H-acceptors in the course of microbial metabolic energy conservation (ATP synthesis).

Mineralisation:

$$\text{Organic substances} \xrightarrow[\text{(ADP + Pi)}]{\text{Dehydrogeses of micro organisms}} ATP + H^+ + e^- + \text{metabolites}$$

Fe (III) oxides act as H-acceptors (hydrogenation)

$$Fe(OH)_3 + H^+ + e^- \xrightarrow{\text{Ferrireductase}} Fe(OH)_2 + H_2O$$

The reductive transformation of Fe^{3+} oxides and hydroxides in submerged soils has been reported as a direct enzymatic process linked to specific reductases of many facultative and obligately anaerobic bacteria (Ottow and Glathe, 1973). These grow using such oxidised soil components as NO_3^-, MnO_2, hydrated oxides of Fe (III), SO_4^{2-} and even their own metabolites as electron acceptors in their respiration. According to Takijima (1964), IRRI (1971) and Okasaki and Wada (1976), this reduction may also evidently be due to the increased formation of CO_2 in the course of decomposition of organic matter and the decrease towards the later period of the experiment may be due to the fall in the concentration of CO_2 in soil solution. Tables 16 to 19 reveal this fact clearly. As the levels of organic matter is increased there is a concomittant increase in the concentration of Fe^{2+} in soil solution, the maximum corresponding to the peak period of organic matter decomposition. After the 4g (per pot) level of organic matter tried, the influence was not so much as it was in the previous level slabs. The difference in the soil types has no definite or clear out role in deciding the influence of added organic matter on the released iron. The bulk of the reducing dissolved organic substances in the solution of flooded soils, formed by the microbial action on the organic matter often consists of phenolic compounds perhaps relating to fulvic acid and other chelating agents which can reduce oxide to soluble iron complexes and aggravate iron toxicity by hampering the oxidising capacity of the rice roots. The inhibitory effects on plant growth due to organic acids and phenols have been indicated by Chandrasekharan and Yoshida (1973) and Govindaswamy and Chandrasekharan (1979). High concentrations of reducing organic substances are common in peaty soils. Patnaik and Bhadrachalam (1965) considered that organic or green manure can not only aggravate soil reduction, but also lead to the accumulation of toxic decomposition products. They have, therefore, cautioned against the application of organic or green manures to low land areas with imperfect drainage Leachate analysis conducted by Mandal (1961) and Singh and Patiram (1979) in soils waterlogged in pots showed sharp rise of insoluble Fe^{2+} which later with increase in CO_2 concentration in the soil solution entered into the exchange complex and still later with further increase of CO_2 it appeared in the drainage water in the soluble form. Mandal (1961) observed that in the presence of organic matter the reduction process was more intensive and CO_2 production much higher. Under such situations, he noticed much larger quantities of insoluble, exchangeable and soluble forms of iron much earlier. Mandal (1962) further found that Fe and Mn concentrations in drainage water were highest in soil when kept under an atmosphere containing 10 per cent oxygen concentration by volume.

(iv) Fertilisers - Ammonium sulphate

Tables 22 to 25 and Figs. 11 to 12 revealed that the acid forming fertilisers have a definite influence in releasing Fe^{2+} as the fertiliser level is increased from 0 to 250 kg N/ha. It is noticed from the Tables and Figs. that in the karapadom and brown hydromorphic soils maximum Fe^{2+} occurred on the 25th day of submergence from ammonium sulphate applied at the rate of 150 kg N/ha; while in kari soils peak release of Fe^{2+} resulted from the application of ammonium sulphate at 100 kg N/ha. In kayal soils, however, the maximum Fe^{2+} release occurred from ammonium sulphate applied at the rate of 200 kg N/ha.

The recommended dose of nitrogen as per the package of practices recommendations of the Kerala Agricultural University (1986) is 40 kg N/ha for local rice varieties, 70 kg N/ha for short duration and 90 kg N/ha for medium and long duration varieties, irrespective of the soil type in the State. It can be seen from the Table that even with the package dose, the concentration of Fe^{2+} in the soil solution reached toxic levels within the first three sampling periods invariably in all the four soil types studied, indicating thereby the need to avoid application of such acid forming fertilisers to submerged acid rice soils of Kuttanad, which might lead to increase in soil acidity followed by the development of iron toxicity. In case ammonium sulphate itself has to be applied sufficient time should be given after application of such fertilisers. After the 5th week, however, the concentration of Fe^{2+} was coming down to reach more or less stable value. It was noticed that the progressive release of Fe^{2+} continued till the 5th week of submergence after which it decreased tending to reach a more or less steady value. Kari soils which are the most acidic, gave indications of decrease from peak release of Fe^{2+} even from the 10th day of submergence (in the control) while the other soil types showed progressive subsidence from peak release of Fe^{2+} after the 25th day. Of the different soils studied, karapadom soil with N at 150 kg N/ha registered the maximum iron release of 1232 ppm on the 25th day of submergence followed by kari soils with 100 kg N/ha releasing 1075 ppm Fe^{2+} and by brown hydromorphic soils fertilised with 150 kg N/ha releasing 1050 ppm Fe^{2+} during the same period. The peak period of Fe^{2+} release in all the soils studied was noticed around the 3rd sampling period, ie; 25th day and the peak release of Fe^{2+} was found minimum in the kayal soil even with the highest level of 200 kg N/ha tried. The increased releases of Fe^{2+} must have resulted from the promotion of microbiological activity by the NH_4^+ ion. Ammonium sulphate being an acid forming fertiliser can induce more acidity to the soil if the fertiliser is continuously used as is being done by some farmers in Kuttanad. Similar increases in the iron concentration in soil solution to toxic levels have been reported by Sahu (1968) in Orissa soils, who also found that urea application alleviated it. Subramoney and Kurup (1961) observed that ammonium sulphate favoured scum formation in Kuttanad soils resulting from iron solubilisation. Tanaka and Yoshida (1970) have referred to the 'Mainsha' disorder in rice in Orissa as being similar to bronzing due to iron toxicity which was shown to be aggravated by the application of ammonium sulphate. Sharma and Banerjee (1983) noted that soil application of ammonium sulphate favoured iron release at a very high rate due to chemical reduction along with boosted microbial activity.

(v) Amelioration of iron toxicity by the application of lime

Iron solubilisation occurs mainly due to the high soil acidity. Effect of lime was therefore attempted to find out its efficacy in the control of excess iron solubilisation from soils. Table 28 and Fig . 13 to 14 indicate the usefulness of lime in suppressing iron releases. Ponnamperuma (1958, 1960) Nhung and Ponnamperuma (1966), Sahu (1968), Subramoney and Kurup (1961), Sahu (1968), Tanaka and Tadano (1972), Ponnamperuma and Solivas (1981), Freire et al. (1985). Bishnoi et al. (1988) and several others have reported the effectiveness of lime in relation to reduction in Fe^{2+} toxicity. Kabeerathumma (1975) ascribed the reduction of soluble Fe^{2+} in waterlogged soil by lime application to lowering of pH and precipitation of iron as insoluble hydroxide. It was noticed from the Table that though lime could suppress iron release from soils, complete prevention or alleviation of excess release of Fe^{2+} from soils was not possible. In the present study it was noticed that lime could prolong the iron release from some soil types for a few days, but thereafter the release of Fe^{2+}

occurred equally as in the control treatment or even in higher amounts. It may be noted that only two levels of lime viz. 600 kg and 1000 kg/ha, were tried. The usefulness of lime treatment in the prolonged suppression of soluble Fe^{2+} in soils was not much evident in Kuttanad soils probably due to the insufficiency of the lime levels tried. It is likely that increased levels of lime beyond 1000 kg/ha might be able to bring about the suppression of acidity and soluble iron concentration in these soils more efficiently. In kayal soils it is clear from the Table 35 that lime application at 600 kg/ha could retard iron release from soil for 25 days but after this period lime failed to prevent iron solubilisation. During the 25th day of sampling the suppression of soluble iron in the soil was only marginal. Lime level at 1000 kg/ha had much more favourable effect upto 25 days, but beyond this period it again failed to keep more iron in the insoluble form. Moreover, the releases of Fe^{2+} in quantities substantially more than that in the control could be seen during the advanced stages of the study with both the levels of lime. However, at the close of the experiment the iron levels, in general, showed a tendency to get stabilised. In the kari soil also the effect of liming on the suppression of iron release from the soil to an extent of more than 50 per cent was evident till the sampling period between the 10th and 25th days. Beyond this period, the lower level of lime was not helpful in controlling iron solubilisation. However, the higher level of lime could prolong the suppression of iron release for a few more days and after 50 days of submergence even the higher lime level was not found helpful. It is to be noted that the release of soluble Fe^{2+} in kari soil was low up to the 10th day only. However, in lowland paddy cultivation the available evidence would suggest that the susceptibility of the rice plant to iron toxicity is much more during the initial stages of its growth and maximum tillering (Tanaka and Yoshida, 1970; Haque, 1977) than in the advanced stages. In such a situation it is likely that the purpose of applying lime to iron toxic soils in quantities affordable by the marginal farmers would only be to prolong the Fe^{2+} release for a few days so that the plant may be able at its advanced growth stages to resist the hazards due to excess soluble iron from the soil through the efficient operation of its root oxidation mechanism, provided the plant is maintained under proper nutrition management as indicated by Ottow et al. (1981), (1982) and Benckiser et al. (1984). Brady (1980) reported that iron toxicity could be ameliorated by liming, but quantities required are often prohibitive.

Conceptually, the rate of soil acidification should be measured in terms of change in H^+ activity per unit time. The sources and sinks of proton (H^+) in soil are numerous and complicated. This is much more so in Kuttanad soils which are known to be acid sulphate soils containing pyrites and Jarosites. The sub-soils themselves in view of the pyrites, act as source of protons to the other layers.

Under the environmental conditions in Kuttanad, drainage occurs and any process which produces protons and leachable anions other than OH^- will result in soil acidification. This is due to the replacement of exchangeable cations by H^+.

Some soil processes which result in the soil acidification are nitrification, respiration of carbon dioxide, mineralisation of organic matter producing organic acids, oxidation of sulphidic material to mineral sulphuric acid as in acid sulphate soils etc. Liming on acid soils would thus favour these very processes and result in the accelerated formation of various products including more of protons. Thus, theoritically, though it appears to be reasonable that liming should result in the decrease in H^+ activity per unit of time, the neutralisation process by itself can activate the sources of protons and suppress the sinks as well. This complicates the reverse phenomena to such an extent as to preclude possibilities of making generalised predictions. The above findings of Marykutty (1986) in relation to the pattern of residual action of liming to some extent explains the present apparantly paradoxical observation of liming that induces the greater release of Fe^{2+} in the kayal and kari soils for a more enhanced period of time than the unlimed treatment. Thus the higher rates of reacidification consequent to liming has activated the sources of proton as to liberate more hydrogen. The suppression of the proton sinks by the liming itself makes the sinks non-operative. This makes the protons release more Fe^{2+}.

In the present study with karapadom soil, however, lime had a more favourable effect. Lime at 600 kg/ha could suppress iron release up to 50 days while 1000 kg/ha could suppress excessive iron release throughout the period of study. The extents to which the releases of Fe^{2+} were suppressed in the karapadom soil during each sampling period were found to be more than in kayal and kari soils. In brown hydromorphic soils the effect on iron suppression by both the levels of lime was clearly evident throughout the period of study, with more benefit accrued from the higher level lime treatment, wherein the release of Fe^{2+} at each sampling period was found reduced to nearly two thirds from that of the control. The results of the present study are supported by the findings of Nhung and Ponnamperuma (1966) that 4 per cent $CaCO_3$ increased the pH 3.7 to 4.6, depressed Fe^{2+} concentration in soil solution from 490 to 190 ppm at planting and prevented death of plants but later high iron concentrations in the soil solution caused iron toxicity. However, 8 per cent $CaCO_3$ raised the pH 3.7 to 5.5 at planting and depressed Fe^{2+} concentration to 133 ppm and prevented iron toxicity and enabled the plant to produce yield double that of 4 per cent $CaCO_3$ treatment. Field experiments conducted in iron toxic sandy loam at the Agronomic Research Station, Chalakudy (1981) and brown hydromorphic soil at Vellayani (1984) to compare the effectiveness of soil ameliorants in the alleviation of iron toxicity revealed the usefulness of lime, magnesium silicate (steatite) and potassium chloride in improved grain yield of paddy (Kerala Agricultural University Ann. Rep. 1982 & 1984). Verma and Tripathy (1984) reported that although liming did not alleviate bronzing it delayed the appearance of symptoms about 25 days. Thus at flowering stage, the plants grown under submergence with lime application also started bronzing. The use of lime as an ameliorant for the acid sulphate and other acid soils is widely known. By correcting soil acidity and bringing about a more favourable soil environment for plant and microbial growth, lime also indirectly alleviates the toxic concentrations of Fe^{2+}.

Though the practice of liming acid soils and washing out the toxic soluble iron is popular in Kuttanad, the prohibitive cost of lime and lack of local availability of the material have dissuaded some marginal rice farmers from this practice. The per hectare profitable and economical doses of lime needed for the amelioration of iron toxic rice soils have therefore to be worked out for the different soil types. Improvement of drainage, use of cheaper and indigenous soil ameliorants such as steatite, prescription of the critical levels of iron in the soil and in the plant tissue and screening of the presently popular traditional and high yielding rice varieties for tolerance to iron toxicity need attention by soil scientists.

SUMMARY

SUMMARY AND CONCLUSIONS

A study was made of the extent of solubilisation of iron in the submerged acid rice soils of Kerala State where iron toxicity is likely to be a serious field problem during rice cultivation. The kayal, kari and karapadom soils of Kuttanad, sandy soils of Onattukara and the brown hydromorphic soils of the midland lateritic zone were included in the study. Chemical characterisation of the soils and soil profiles in relation to forms of iron and the studies on the release of soluble iron from these soils under submerged conditions as affected by organic matter, sea water and ammonium sulphate as well as on the methods of amelioration of such iron toxic soils were attempted, with a view to obtain a better understanding of the dynamic aspects of iron in these submerged soils.

The major findings from the above study are given below:

1. Among the submerged soils studied kari soil was the most acidic with a significantly high organic carbon content, CEC and electrical conductivity compared to the kayal and karapadom soils of Kuttanad.

2. The water soluble iron content in the Kuttanad rice soils ranged from 79-165 ppm. Significant positive correlation existed between the electrical conductivity and water soluble iron. Significant negative correlation existed between the pH and water soluble iron.

3. The exchangeable iron content in Kuttanad soils ranged from 144-310 ppm and it was significantly and positively correlated with the CEC.

4. The active iron content constituted the major form of iron and it varied between 1460 and 5200 ppm. A significant and positive correlation was observed between active iron and organic carbon content and electrical conductivity. Significant negative correlation existed between pH and active iron

   In general, the forms of iron such as water soluble and exchangeable which are responsible for producing iron toxicity in transplanted rice exist in sufficiently high amounts in the Kuttanad soils

5. A comparison of the distribution of the different forms of iron in the orofiles of Kuttanad, sandy (Onattukara) and the brown hydromorphic soil revealed that while the total iron content decreased with depth, the water soluble, exchangeable and active iron increased in all the soil profiles except one profile of the karapadom soil and the profile of brown hydromorphic soil where the water soluble and exchangeable iron decreased with depth

6. Submergence of the soils of Kuttanad and brown hydromorphic soils invariably resulted in an increase in the soluble iron content. Maximum release of soluble iron was noticed on the 10th day of submergence in the case of kari soil and on the 25th day in the other soils.

Highest iron release was observed in brown hydromorphic soil. After the peak release the soluble iron declined to lower values with time and reached fairly stable values on the 90th day

7. Submergence of the soil under sea water of different dilutions resulted in the enhancement of iron release, the pattern of release being more or less similar in all soils. The release of soluble iron was influenced by the dilution of the sea water used for submergence of the soil. The highest concentration of sea water resulted in the maximum release of iron from all the soils. The peak release of iron was observed on the 25th day in the kari, karapadom and brown hydromorphic soil, while kayal soil alone registered peak concentration of iron on the 40th day of submergence. Further periods of submergence up to 90 days resulted in a decrease in soluble iron concentration, which did not, however, reach the lowest value attained in the control soil

8. Highest release of 1868 ppm soluble iron under the influence of undiluted sea water was obtained in the kayal soil on the 40th day of submergence

9. Under the conditions of sea water submergence, the kayal, kari and karapadom soils released significantly higher

amounts of iron compared to brown hydromorphic soil. The same trend was noticed when these soils were submerged under 75 per cent and 50 per cent sea water levels also. However, at the lowest level of 25 per cent sea water submergence, all the four soils behaved similarly.

10. Addition of organic matter in the form of farm yard manure to soils under submerged conditions influenced iron solubilisation considerably. Increasing levels of organic matter resulted in the progressive increase in the concentration of soluble iron in the soil solution in all the soils with time. In the presence of organic matter kari soil released significantly higher amount of soluble iron on the 25th day of submergence which decreased rapidly thereafter. However, on the 40th day the kayal soil released significantly higher amount of iron.

11. During the post peak periods of gradual decline in soluble iron under the influence of submergence and organic matter, the kari soil alone maintained higher concentration of iron compared to other soils, eventhough the difference was not significant.

12. Addition of ammonium sulphate to soils under submerged conditions resulted in increased release of soluble iron

in the soil solution with time. Peak release of iron was noticed on the 25th day in all the soils. After the peak period the concentration of iron dropped to lower values and got stabilised around the 90th day

13. The level of ammonium sulphate required to release maximum soluble iron was different for the four soils. Maximum release of soluble iron in the kari soil was obtained with ammonium sulphate applied at 100 kg N/ha level, in the karapadom and the brown hydromorphic soils with 150 kg N/ha and the kayal soil with 200 kg N/ha level

14. Application of lime had considerably reduced the soluble iron content in the different soils; higher lime levels always showing better suppression of iron release

15. In the kayal soils, addition of 600 kg lime/ha level, was helpful in suppressing the release of iron only up to 10 days. However, lime at 1000 kg/ha level could keep more soluble iron under control up to the 25th day. In both the lime treatments after the 40th day, the soluble iron concentration considerably exceeded that of the control

16. In the kari soils the effect of both the levels of lime was evident only up to the 10th day of submergence. After this period, the release of iron continued and exceeded that of the control

17. In karapadom and brown hydromorphic soil, lime application was helpful in maintaining reduced iron concentration till the 40th day. Lime at 1000 kg/ha however, could maintain a lower level of soluble iron throughout the period of submergence in these two soils.

From the investigation carried out in the present study it has been possible to obtain useful information on the relationship between soil chemical properties and the forms of iron in the Kuttanad acid rice soils where iron toxicity frequently poses field problems for the farmers. In Kuttanad surface soils, the ranges of forms of Fe^{2+} are 79 - 165 ppm water soluble iron, 144 - 310 ppm exchangeable iron and 1460 - 5200 ppm active iron. Water soluble and exchangeable forms of iron together represent the available iron content in the soil which would give indication of toxicity symptoms in plants on immediate planting.

A comparison of kayal, kari and karapadom soils indicated that Kuttanad soils in the submerged conditions, in general, contain appreciable levels of soluble iron and that the kari soil has significantly higher soluble iron contents enough to produce toxicity to the rice plant. The rice crop under such situations can produce only a lower yield of grain and straw. From the incubation trials on soils it was found that among the treatments, the treatment with organic matter resulted in the highest release of Fe^{2+} (1568 ppm) on the 25th day.

Though in the kayal and kari soils lime at 1000 kg/ha succeeded in suppressing the iron release for 10 to 25 days, and gave indications of possible better performance if applied at higher levels, in the karapadom and brown hydromorphic soils lime at the level of 1000 kg/ha was sufficient enough to bring out an atmost complete control over iron solubilisation. The usual practice of the farmers in flooding the soil after treatment with lime is helpful in suppressing the Fe^{2+} release from soils under submerged conditions. Very often the high degree of potential acidity in acid sulphate soils makes reclamation through liming economically impractical. Proper drainage and water management practices will be useful in such situations. Flooding the field for 25 days to enable maximum release of Fe^{2+} and then washing out can therefore be recommended for the submerged rice soils to minimise the iron toxicity.

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*Original not seen

STUDIES ON THE SOLUBILISATION OF IRON IN SUBMERGED SOILS AND METHODS TO MINIMISE ITS SOLUBILITY AND TOXIC CONCENTRATION TO PADDY

BY

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ABSTRACT OF THE
THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENT FOR THE DEGREE
DOCTOR OF PHILOSOPHY IN AGRICULTURE
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ABSTRACT

A study has been made of the extent of solubilisation of iron in the submerged acid rice soils of Kerala State where iron toxicity is likely to be a serious field problem during rice cultivation. The kayal, kari and karapadom soils of Kuttanad, brown hydromorphic soils of the midland lateritic zone and the sandy soils of Onattukara were included in the study. Chemical characterisation of the soils and soil profiles in relation to forms of iron were investigated with a view to obtain a better understanding of the dynamic aspects of iron in these soils. The nature, and extent of periodical variations in soluble iron as influenced by levels of sea water, organic matter (farm yard manure) and ammonium sulphate added to kayal, kari, karapadom and brown hydromorphic soils under submerged conditions were also studied along with the influence of levels of applied lime on the amelioration of iron toxicity.

Among the Kuttanad soils, kari soil was most acidic with a mean pH of 3.77, high organic carbon content and CEC compared to others. The water soluble iron ranged from 79-165 ppm in the Kuttanad soils. This form of iron and pH were negatively correlated. Electrical conductivity and water soluble iron were significantly and positively correlated. The exchangeable iron varied between 144-310 ppm and was positively correlated with CEC. Active iron ranged between 1460 and 5200 ppm. Active iron had a significant positive correlation with organic carbon and electrical conductivity. Kuttanad soils contained high contents of water soluble and exchangeable iron, together known to contribute towards the development of iron toxicity to transplanted rice in these soils.

High contents of water soluble, exchangeable and active iron were noticed in the profiles of Kuttanad soils as well. Compared to these. the brown hydromorphic and sandy (Onattukara) soils had much lower contents of soluble iron. Total iron content decreased with depth in most of the profiles while water soluble, exchangeable and active iron, increased with depth studied upto 100 cm. In brown hydromorphic soil the water soluble and exchangeable iron were found to decrease with depth.

Incubation studies under laboratory conditions indicated that submergence of soils resulted in an increase in the soluble iron with time, reached a peak value on the 10th day in kari soil and 25th day in the other soils, after which the soluble Fe^{2+} decreased to lower values.

Sea water submergence resulted in enhanced releases of Fe^{2+} with time to reach peak value around the 25th day followed by decrease. Kayal soil alone, however, needed 40 days for peak release of Fe^{2+}. The release of Fe^{2+} was influenced by the dilution of sea water used. Kayal, kari and karapadom soils released significantly higher amounts of Fe^{2+} compared to brown hydromorphic soils. However, at the lowest level of 25 per cent sea water all soils behaved similarly.

Presence of organic matter under the submerged conditions enhanced the Fe^{2+} release considerably depending on the content of organic matter in the soil. Kari soil on the 25th day and kayal soil on the 40th day of submergence released significantly higher amounts of Fe^{2+}.

Addition of ammonium sulphate to soils under submerged conditions resulted in increased releases of Fe^{2+} in the soil solution with time. Peak releases of Fe^{2+} were noticed on the 25th day in all the soils. Maximum release by kari soil was influenced by ammonium sulphate applied at 100 kg N/ha, in the karapadom and brown hydromorphic soils by 200 kg N/ha.

The beneficial effect of lime on the suppression of iron release was clearly evident in the soils though to varying extents. In kayal soil 600 kg lime/ha suppressed iron release upto 10 days and 1000 kg/ha could suppress more soluble iron for 25 days. However, after the 40th day, soluble iron exceeded that of the control. In kari soil the iron suppressing effect of both the levels of lime was evident only up to the 10th day after which the release of soluble iron exceeded that of the control. In karapadom and brown hydromorphic soils, lime at 600 kg/ha was helpful in suppressing the release of Fe^{2+} till the 40th day. Lime at 1000 kg/ha, however, could suppress more of the soluble Fe^{2+} throughout the period of submergence. In kayal and kari soils, levels of lime upto 1000 kg/ha appear to be inadequate in controlling iron toxicity.

Flooding the field for 25 days and leaching out the released Fe^{2+} just before planting of rice is suggested as an alternate solution to minimise iron toxicity to rice in Kuttanad soils.