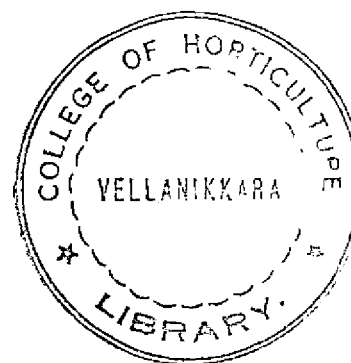


**THE RELEASE OF SOLUBLE ALUMINIUM IN SOILS UNDER
SUBMERGED CONDITIONS AND ITS EFFECT ON RICE**

By
ALICE ABRAHAM



**THESIS SUBMITTED IN PARTIAL FULFILMENT OF
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COLLEGE OF AGRICULTURE
VELLAYANI, TRIVANDRUM**

1984

DECLARATION

I hereby declare that this thesis entitled "The release of soluble aluminium in soils under submerged conditions and its effect on rice" 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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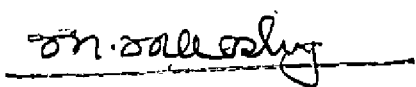
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(M.M. Koshy),
Chairman,
Advisory Committee,
Professor (Research Co-ordination)



Approved by

Chairman

M.M. Koshy
Dr. M.M. Koshy 25/2/85

Members

1. Dr. R.S. Aiyer

R.S. Aiyer
25/2/85

2. Dr. N. Sदानandan

N. Sदानandan

3. Dr. V.K. Sasidhar

V.K. Sasidhar

4. Dr. P. Saraswathi

P. Saraswathi

S. Chandrasekhar
External Examiner. 25/2/85

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Alice Abraham

ALICE ABRAHAM

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INTRODUCTION

INTRODUCTION

Rice, which forms the staple food for more than 80 per cent of the world's population is cultivated over widely varying climatic and edaphic conditions. It is estimated that most of the rice which is currently produced is cultivated in the tropical soils which are often acidic with pH values less than 6.0.

In spite of the introduction of the high yielding varieties of rice and the adoption of improved technology, a break through in rice production has not yet been achieved in many of the tropical countries. A major constraint in limiting the yield of rice has been identified as the prevalence of strongly acidic conditions in the soil which creates innumerable soil fertility problems that prevent the rice crop in expressing its full yield potential (Ponnamperuma, 1978).

It is now well known that in acid soils, the hydrogen ion concentration per se has no direct effect on plant growth except at very low pH values. The poor performance of crops in these soils can be the consequence of an array of complex toxicity factors produced by certain elements over lain with deficiency of several others.

One of the important reasons for the poor performance of rice in acid soils has been attributed to the toxicity

created by the excess of aluminium present in them. Aluminium is an important element in the soil and is a major component of its inorganic fraction. The total content ranges from 2.1 per cent Al_2O_3 in the less weathered soils developed under moist cool climates to 13.8 per cent in the soils developed in hot dry climates. Aluminium remains predominantly a part of the primary and secondary silicate clays and as crystalline gibbsite. Reactive aluminium in the soil is essentially constituted by the free and adsorbed monomer (Al^{3+}) as well as aluminium hydroxy polymers, possessing varying degrees of hydration. When released by the weathering processes, it undergoes hydrolysis with a resultant increase in soil acidity through the release of protons.

Aluminium is not recognized as an essential nutrient since it has no known functions to perform in the plant. However, several plants, especially those growing in the acid soils may contain an appreciable amount of this element in their tissues.

The aluminium removed from the soil by N KCl, designated as "exchangeable aluminium" gives an adequate measure of the minimum amount of reactive aluminium to be neutralised to ensure a soil condition suited for plant growth. The exchangeable aluminium is held very firmly to the negative charged sites of the layer silicate and layer silicate oxide-coated systems.

The work of Coleman et al. (1958) has proved that exchangeable aluminium is the dominant cation associated with soil acidity under most situations and is responsible for the creation of unfavourable soil conditions for plant growth. It has also been observed that the toxicity of a given concentration of aluminium may be greatly influenced by the accompanying cations, which produce an overall decrease in toxic effects with increase in their content. Therefore, the problem of aluminium toxicity in a soil has to be studied in relation to the cation exchange capacity of the soils and the associated cations. Sanchez (1976) has considered the aluminium saturation of the effective CEC to be a more reliable parameter for defining aluminium toxic condition in the soil rather than the absolute values of exchangeable aluminium. An aluminium saturation of more than 20 per cent of the effective CEC has been considered as critical for many sensitive plants including rice.

Unlike the toxicity symptoms produced by iron and H_2S usually common in acid soils, the toxicity by aluminium often goes unnoticed, since the visible symptoms are expressed only in the roots which remain underground and hidden from view. Aluminium toxicity can substantially reduce yields of crops without the manifestation of clearly identifiable symptoms in plant tops. Theoretical and experimental evidence indicates that rice plants suffering from aluminium toxicity may

be affected by a severe deficiency of phosphorus since this element is inactivated nutritionally, although it may be present to an appreciable extent in the plants (Blamey et al., 1983). It is possible that, rice, a crop sensitive to aluminium toxicity, cultivated in the acidic rice soils of Kerala is exposed to varying degrees of aluminium toxicity problems, occasionally aggravated by the drying of soils in summer months in drought years and inundation by sea water in coastal regions. The productivity, as well as the total production, of rice under such conditions may partly or wholly be controlled by the high availability of exchangeable aluminium which is not fully counteracted by the agronomic measures usually adopted in rice cultivation.

Management of acid rice soils with specific emphasis on minimising the stress conditions created by excess aluminium and making them more suitable for rice cultivation is thus highly imperative for the boosting of rice yields in such soils.

Even though aluminium toxicity is considered as one of the important chemical constraints limiting the high productivity in the acid soils of Kerala, no systematic attempt has so far been made to make a thorough investigation of the problem and suggest suitable methods for combating it. A precise knowledge regarding the fundamental nature of the problem in the acid rice soils of Kerala is therefore,

highly desirable for drawing up suitable cultural cum management practices for their improvement.

Tailoring of plants to fit problem acid soils has been conceived as a novel approach in this direction and crop breeding programmes with this objective have been initiated in many of the developed countries. Breeding efforts are also made to incorporate aluminium tolerance into short statured rice varieties with a high yield potential.

Thus, it would appear that the adoption of suitable ameliorative measures, along with the use of aluminium resistant or tolerant varieties will provide a more far reaching solution to this problem.

The present study has therefore been undertaken with a view to making an appraisal of the problem of aluminium toxicity in relation to other important characters in the acid rice soils of Kerala and for evolving a suitable technique that will help to overcome the problem in rice culture. With these objectives in view, the following studies have been carried out.

1. Assessing the extent and magnitude of aluminium toxicity in the acid rice soils of Kerala.
2. Monitoring the changes in the content of exchangeable aluminium in typical soils consequent to changes in soil

conditions during flooding and treatment with ameliorants

3. Studying the effect of different ameliorants in minimising aluminium toxic conditions in a highly acid soil and its effect on the growth, yield and nutrient uptake in rice.
4. Determining the specific effect of graded levels of aluminium on the growth and nutrient composition of rice.
5. Screening of rice varieties for tolerance to aluminium toxicity.

It is hoped that the results from these studies will help to identify the specific soil types where aluminium toxicity is of a serious nature for rice cultivation and to suggest suitable methods for minimising the aluminium toxicity and improving rice yields by a combination of management practices and varieties more tolerant to aluminium toxicity.

REVIEW OF LITERATURE

REVIEW OF LITERATURE

Vast areas in the tropics have acid soils as a result of strong weathering associated with high temperatures and intense leaching consequent to heavy rain fall. The other more important inherent soil factors responsible for producing acidity are occurrence of parent materials with low content of weatherable minerals and accumulated organic sulphur compounds from mangrove vegetation or sulphur rich beds which have been transformed into inorganic forms like iron pyrite and jarosite so common in many acid sulphate soils.

Many of the problems associated with growing crops in highly acid soils were assumed originally as due to the confrontation of H^+ ions with the plant roots. But now it is too clear that aluminium ions have an equal or even a stronger role to play under such situations and that aluminium is directly involved in the production of soil acidity.

Ever since the recognition of aluminium as a potential source of soil acidity and the associated toxicity problems, considerable amount of research has been undertaken for a better understanding of the various facets of this important problem. Some of the earlier work carried out on these aspects, which is of relevance to the present study is reviewed below.

1. Factors affecting release of aluminium into soil solution

The solubility and exchange of aluminium from the clay mineral, extent of acidity so formed and its toxicity to plants are governed by many soil factors.

Coleman et al. (1958) were of the view that electrostatically bound hydrogen ordinarily does not exist in any considerable amount in many acid soils and that the aluminium displaced by neutral salt leaching of such soils was more appreciable than the displaced hydrogen ions. They did not find much of exchangeable H^+ in many acid soils and stated that there was ample evidence to show that hydrogen clays undergo almost spontaneous decomposition to form clays saturated mainly with aluminium ions.

Black (1973) noted that poor crop growth in acid soils was directly correlated with aluminium saturation of soils and that pH had no direct effect on plant growth except at values below 4.2.

In studies on the soils of Tuscany, Lev-Minzi et al. (1971) found that exchangeable aluminium varied from a trace to 370 ppm and was negatively correlated with hydrogen ion concentration. There was no correlation between soluble aluminium and iron. Igue and Fuentes (1972) reported that in soils rich in organic matter, non-exchangeable aluminium resided mostly in the organic fraction and that in mineral

soils especially in their advanced stage of weathering, the inorganic fraction was its main source.

Frink (1973) has discussed evidence supporting the observation that the amount of exchangeable aluminium produced in a soil was related to the concentration of exchangeable hydrogen. It was possible that some exchangeable hydrogen existed on the exchange complex at the pH levels usually found in acid sulphate soils.

The source of exchangeable aluminium formed by the decomposition of hydrogen clays was attributed by Bloomfield and Coulter (1973) mainly to the layer silicates. These silicates had usually coatings of hydroxyl aluminium and iron compounds that were positively charged. Some of these were presumably attacked by the sulphates resulting in the release of aluminium into solution.

Coronel (1980) found that 2:1 clays with aluminium interlayers had on an average $2\frac{1}{2}$ times more of exchangeable aluminium than those with only kaolinite, even though the content of such clays was less. She had also recorded that high levels of cations like calcium, magnesium and potassium decrease aluminium toxicity by non-specific competition for cation exchange sites in the roots and that at high salt concentration, aluminium toxicity was less because salt reduced the activity coefficient of aluminium.

2. Soluble and exchangeable aluminium in relation to soil pH and liming

Notwithstanding a voluminous body of literature on the subject, there is still poor agreement regarding the relative merits of lime requirement indices based on exchangeable aluminium and those based on pH measurements. While it is generally accepted that in the humid tropics, lime requirement should be based on exchangeable aluminium rather than on pH, this parameter still remains the basis for assessing the lime requirement in most subtropical and temperate areas.

There are two schools of thought regarding the liming of acid soils. The original view was that the quantity of lime used should be sufficient to raise the pH of the soil to near neutrality. The other is the one based on the proposal by Kamprath (1970) that aluminium saturation of soils should be the basis for assessing the lime requirement. In either case, the role of aluminium as an important factor in the management of acid soils stands undisputed.

Some of the published literature in favour of the above two schools of thought are reviewed.

Magistad (1925) was probably the first to relate the concentration of aluminium in the soil solution as a function of pH. According to Pavar and Marshall (1934) exchangeable aluminium should be taken as the criterion of soil

acidity rather than the hydrogen ion concentration. That exchange acidity in most soils was contributed by exchangeable aluminium had since been reported by Russel (1950) and McLean et al. (1964).

Nye et al. (1961) and Evans and Kamprath (1970) have shown that the aluminium concentration in the soil solution was generally less than 1 ppm. The increase of aluminium saturation of soil beyond 60 per cent was accompanied by a sharp increase in the rise of aluminium in the soil solution. However, the concentration of aluminium in solution decreased in the presence of organic matter due to the formation of complexes and increased in the presence of salts due to cation exchange.

In a study of some acid soils of Canada, Clark (1966) found no direct relationship between pH and solution aluminium and expressed the view that differences in solubility of $Al(OH)_3$ may have a greater relative effect on the aluminium concentration in the soil solution than on the apparent differences in pH values.

Kamprath (1970) has proposed the content of exchangeable aluminium as a criterion for the liming of leached mineral soils. He found that liming at rates equivalent to the amount of exchangeable aluminium (in KCl extracts) reduced aluminium saturation of the CEC to < 30%, the lime reacting

primarily with the exchangeable aluminium. He concluded that on highly weathered soils, exchangeable aluminium is a valid criterion for determining the rate of liming or reduction of exchangeable aluminium saturation to get uniform pH values.

Studies on lime response, as related to per cent aluminium saturation, solution aluminium and organic matter content by Evans and Kamprath (1970) have shown that aluminium in soil solution of mineral soils was related to per cent aluminium saturation of the effective CEC, while in organic soils it was more related to the amount of exchangeable aluminium. Soil solution aluminium gave an effective estimate of the response to liming, irrespective of soil organic matter content. They have further proposed that for estimating the lime requirement of soils of the same pH but different organic matter contents, the basis can be the extent of decrease of aluminium in soil solution rather than the increase in pH.

The significance of aluminium in liming programmes has been pointed out by Bloomfield and Coulter (1973). They found that when the lime requirement of acid sulphate soils was determined on the basis of pH value, the quantities of lime required were usually enormous and uneconomically large. Hence they have suggested that the percentage aluminium saturation should be the basis for the application of lime.

Amedee and Peech (1976) have examined the validity of the practice of using KCl extractable aluminium for evaluating the lime requirement of acid tropical soils. They found that the amount of lime based on the aluminium removed by extraction with N KCl was appreciably less than the lime requirement as determined by equilibration of soils with lime as in the conventional methods.

While studying the interrelationships between the nature of soil acidity, exchangeable aluminium and per cent aluminium saturation, Sanchez (1976) considered soil acidity as a poorly defined parameter and recommended that per cent aluminium saturation calculated on the basis of effective CEC should be taken as a useful measure of soil acidity. He has recommended the liming of acid soils to pH 5.5 to 6.0 to bring about the precipitation of the exchangeable aluminium as $\text{Al}(\text{OH})_3$.

Further studies by Kamprath (1978) have confirmed the point that the concentration of aluminium in the soil solution was related to the proportion of the effective CEC which was occupied by KCl extractable aluminium.

Bloom et al. (1979) recognized aluminium toxicity in acid soils as a function of the (Al^{3+}) activity in soil solution and (Al^{3+}) in soil solution as a function of pH. Farina et al. (1980) proposed exchangeable aluminium and

pH as indicators of lime requirement for corn in Mollisols.

From studies on soil chemical and crop yield responses to limestone application, Alley (1981) found that the exchangeable aluminium levels in soil differentially affected different crops. Exchangeable aluminium saturation of 18, 11 and 8 per cent of the effective CEC decreased the yield of maize, lucerne and barley respectively. Regression analysis showed that the reduction in exchangeable aluminium was responsible for increase in maize yields and that increase in exchangeable calcium along with a decrease in exchangeable aluminium accounted for increased lucerne yield.

Bache and Crooke (1981) studied the interaction between aluminium, phosphorus and pH in the response of barley to soil acidity. They have reported that the addition of phosphates reduced the exchangeable and soluble aluminium in the soils and lowered the apparent critical pH by 0.35.

In some Canadian acid soils, Webber et al. (1982) found that barley yield was better correlated with aluminium per cent and base saturation, rather than with exchangeable aluminium and pH. As soluble aluminium and per cent base saturation gave equally good prediction of response of aluminium sensitive crops to liming, the soluble aluminium measurement was proposed as more suitable for general diagnostic purpose.

3. Aluminium as a toxic factor

a) Toxicity of aluminium

The infertility associated with acid soils had been recognised for a long time, but it was not known whether this condition was due to the deficiency of calcium or the presence of hydrogen and aluminium ions which were found in relatively high concentration in acid soils. The fact that calcium supplied in the form of gypsum could not remedy the injurious effects of acid soils was taken to mean that calcium deficiency was not probably the only cause for poor plant growth in soils under acid conditions. On the other hand, hydrogen ions in water cultures affected the growth of different species of plants to the same extent, whereas in acid soils some of them were affected more drastically than others. This eliminated the possibility of hydrogen ions being a toxic factor in acid soils and pointed to the occurrence of some other toxic substance to which certain plants were more sensitive than others. Since aluminium ions were present in relatively higher concentrations in the soil solution under acid conditions, the injurious effects of acid soils came to be attributed to this element. Culture solutions to which increasing concentration of aluminium had been added were found to depress the growth of plants to various extents.

In general, it was observed that soils of lower pH

contain more of soluble aluminium than those of higher pH; but it was also evident that hydrogen ion concentration was not the only factor determining the concentration of aluminium in the displaced solution. Thus, at a given pH, the concentration of soluble salts in the soil might affect materially the concentration of active aluminium.

Ideas concerning aluminium toxicity are based in part on earlier findings that aluminium concentration in displaced soil solution, while low at pH values near 6, may become appreciable under more acidic conditions (Pierrie et al., 1932).

A number of scientists who have worked on acid soils have indicated that calcium deficiency is a lesser problem to plant growth in acid soils compared to the toxicity due to aluminium.

Fried and Peech (1946) made the general observation that the addition of CaSO_4 accentuated the problems due to acidity, especially aluminium toxicity, by its neutral salt effect in shifting the exchange equilibrium in favour of aluminium ions in the soil solution. They had also found that addition of 1000 lb of CaSO_4 per acre increased the aluminium content of the soil solution by 50 per cent and that 4000 lb of CaSO_4 , more than doubled it. Plant yields decreased on the addition of CaSO_4 in acid soils, but not in soils limed to pH around 6.3.

Vlamis (1953), based on decisive experiments, found that in view of the universal occurrence of exchangeable aluminium in acid mineral soils, aluminium toxicity is entirely responsible for poor growth of barley in acid soils. He found that if the soil was below pH 5.5 and if the soil contained more than 1 me of exchangeable aluminium, root growth was largely inhibited.

Coleman et al. (1958) have stated that the concentration of aluminium ions in a soil solution will depend on the amount of aluminium present, the nature of the complementary ions, the water content and the electrolyte concentration.

Terelak (1975) has shown that the per cent availability of iron and aluminium decreased with increasing soil depth and in all the soil types studied, pH limited their availability. In loamy and silty soils the content of available aluminium increased at high moisture content.

In a study of corn plants grown in the greenhouse on three highly weathered soils containing substantial quantities of exchangeable aluminium, Farina et al. (1980) found that yield and aluminium content of the tissues were exponentially related irrespective of the level of phosphorus applied ($r^2 = 0.34$ and 0.71). The mechanism by which aluminium becomes increasingly available to the plant as the pH approaches neutrality has not been explained. Strong aluminium-

magnesium and aluminium-phosphorus antagonisms were noticed at both high and low pH values. They further postulated that many of the anomalous results reported in literature concerning yield differences previously ascribed to such factors as micronutrient deficiency or phosphorus unavailability could be explained on the basis of the observed antagonistic effects.

b) Mechanism of aluminium toxicity

The exact mechanism of aluminium toxicity has not been clearly understood. Wright (1943) believed that aluminium interfered with the uptake and translocation of phosphate and that this was the primary cause for the toxicity of aluminium. Schmehl et al. (1952) observed that nutrient solution aluminium at 10 or 100 ppm interfered badly with calcium accumulation and that 10 ppm aluminium, which is a high concentration when compared with levels causing toxicity to many plant species, reduced calcium uptake ninefold. They suggested the interference with calcium accumulation as a possible mechanism for aluminium toxicity.

A similar view was offered as an attractive possibility by Burstrum (1953) on account of the essentiality of calcium for root growth, since a primary symptom of aluminium toxicity is the stunting of the root system. However, Coleman and Kamprath (1958) studied the inhibition of root growth caused by culture solution aluminium and showed that the effects of

aluminium could not be counteracted by raising the calcium concentration of the substrate.

Root injury as a direct result of H^+ ions below pH 4 has been suggested by work in solution culture. Plants may tolerate relatively large concentrations of H^+ ions so long as the concentration of toxic polyvalent cations is low. Thus it appeared that the detrimental effects of aluminium in the soil solution far outweighed those of H^+ ions (Adams and Pearson, 1967).

According to Ota (1968) the bronzing of paddy on poorly drained paddy fields is due to aluminium toxicity along with calcium deficiency. Compost and lime application as well as the substitution of urea for sulphate fertilisers prevented the symptoms.

c) The source of toxic levels of aluminium in soil

Aluminium is normally the major exchangeable cation in many acid soils. Both aluminium and iron exist in fairly accessible hydroxy forms as coatings and on edge sites. Aluminium is appreciably soluble above pH 3.5 and considerable solution aluminium can exist under such conditions. Magistad (1925) gave the solubility of aluminium as 0.3 ppm at pH 4.50 and 76.4 ppm at pH 3.11. This refers to the Al^{3+} ions only, but other aluminium ions (eg. $Al(OH)^{2+}$) may have a less steep increase in solubility with increasing acidity.

Tanaka and Navasero (1966b) found that regardless of the amount of aluminium added, its concentration in culture solution was less than 1 ppm at pH values above 5.5.

Bloomfield and Coulter (1973) were of the view that hydrogen clays underwent almost spontaneous decomposition to form clay saturated mainly with aluminium ions. The source of exchangeable aluminium formed by the decomposition of hydrogen clays was mainly the layer silicates. These silicates usually have coatings of hydroxy aluminium and iron compounds that are positively charged. Some of these were presumably attacked by the sulphates and released aluminium into solution.

Sanchez (1976) has stated that hydrogen ions produced by organic matter decomposition were unstable in mineral soils because they reacted with layer silicate clays releasing exchangeable aluminium and silicic acid.

Aluminium that is exchangeable to neutral salts plays a major role in determining the physical and chemical characteristics of soils and its toxic effect on plants has been widely studied. Both monomeric, $\text{Al}(\text{OH})^{2+}$ and polymeric species (eg. $\text{Al}_6(\text{OH})_{1.5}^{3+}$) of aluminium were reported to occur in the soil solution.

Frink (1973) suggested that simple monomeric hydroxides can be used to calculate the pH and aluminium ion activities

at low basicities. At higher basicities, significant amounts of polynuclear hydroxy aluminium cations might be present. Gibbsite ($\text{Al}(\text{OH})_3$) seemed to control the activity of aluminium in the soil solution at higher pH values.

Recent studies by Kenneth and Kamprath (1983) have shown that a certain amount of non-readily exchangeable aluminium is associated with the organic matter. The amount of this aluminium extracted from the soil depends on the cations present in the extracting solution as well as its pH. They have also indicated that when the organic matter is decomposed, the associated aluminium also may be released.

4. Interrelations between aluminium and the uptake of other nutrient ions

The suppressing effect of aluminium on the availability of soluble phosphates to plants in the slightly acid to highly acid soils is probably the oldest known interrelationship between soil aluminium and other plant nutrients. The majority of investigators suggest the precipitation of phosphorus by aluminium in the soil and link aluminium with phosphorus as an explanation of aluminium toxicity.

Wright (1937) considered internal precipitation of phosphorus in plants by aluminium to play an important role in the poor development of certain plants grown in acid soils. The corrective action of application of superphosphate to acid soils was attributed largely to the internal precipitation

of aluminium by phosphorus, with sufficient phosphorus remaining for metabolic processes of the plant.

Autoradiographs of barley seedlings grown in complete culture solution for a period of four weeks showed that the plants grown in aluminium-free solution contained more P^{32} than those grown in 10 ppm aluminium. From these observations Wright and Donahue (1953) substantiated their earlier hypothesis that phosphorus is largely inactivated on the root surface or within tissues of root systems by the presence of aluminium and that this phosphorus is internally bound and does not reach the top of the plant in any appreciable quantity. Vlamis (1953) also held similar views regarding the precipitation of phosphorus in the growth medium, as well as on the surface and inside of roots.

In acid clay soils possessing various degrees of toxicity due to aluminium and manganese, Clements (1964) found that amelioration with coral stones reduced the amount of phosphorus held by the roots and simultaneously increased the amount of phosphate in the tops. Precipitation of phosphorus in the roots by aluminium resulted in deficiency of phosphorus in the upper portions of plants. Patterson (1965) found a significant fall in the per cent uptake of calcium in corn where the nutrient solution contained 2 or 4 ppm aluminium. The concurrent reduction in calcium translocation

was attributed to the reduction in calcium uptake. Aluminium treatment produced stunted root growth and significantly reduced the cation exchange capacity of the roots. It tended to accumulate more in the roots with only smaller quantities in the tops. As aluminium concentration increased, the level of phosphorus in the roots increased whereas the proportion of magnesium and potassium were little affected. Aluminium treated roots contained low manganese, iron and zinc but copper and boron were not significantly affected. Munns (1965) had reported that on acid sandy loam soils of pH 4 growth of lucerne was little affected by calcium concentration above 5 mM, when aluminium was not added. At concentration of 100 μ M aluminium, its toxicity depressed the yield, root elongation and the calcium and phosphorus levels in roots and shoots. He also noticed that increasing the calcium concentration from 1 to 5 mM slightly alleviated the effects of aluminium except at very toxic levels. Adding EDTA to solution containing 200 μ M aluminium improved the growth of legumes. The chelated portion of the aluminium appeared to have no effect on growth. His studies have also supported the hypothesis that in unlimed soils applied phosphate overcame aluminium toxicity and phosphorus deficiency.

In a study on the differential performance of two barley varieties to varying aluminium concentrations, Maclean and Chiasson (1966) found that phosphorus and calcium levels

decreased in the tops and increased in the roots with increasing aluminium concentration. They attributed this effect to the depressed translocation of these elements in the plant rather than to their decreased uptake by the roots. MacLeod and Jackson (1967) noted a reduction in the potassium, calcium and magnesium content in the tops and roots as well as a depression in the translocation of phosphorus with increasing aluminium concentration in barley.

Cruz et al. (1967) in a study of the phosphorus and aluminium interactions in aluminium sensitive and aluminium tolerant wheat varieties found that 0.2 to 6 ppm aluminium in the nutrient solution had no effect on the translocation of P^{32} in young leaves, but the P/Al ratio in leaves, stems and roots was different for each variety.

Otsuka (1969) found that in nutrient solution at pH 4.1 containing aluminium and low iron levels, aluminium induced iron chlorosis and greatly decreased the growth of acid sensitive wheat and barley varieties.

Growth chamber experiments with soybean by Lund (1970) showed that root growth was reduced when the activity ratios of aluminium to calcium were more than 0.02.

Tripathi and Pande (1975) have obtained convincing evidences to show that at low soil pH, uptake of nutrients, particularly phosphorus, calcium, magnesium and potassium

was reduced in the presence of excess soluble aluminium. Liming helped to reduce the solubility of aluminium and improved the uptake of these nutrients.

A reduction of 40 per cent in the yield of eight varieties of potato has been reported by Lee (1971). The study has also shown that phosphorus, aluminium, manganese, iron and copper accumulated in the roots while phosphorus translocation to the tops was depressed and the absorption of calcium, magnesium and zinc was inhibited. He also noted that the absorption of potassium was stimulated at low aluminium levels (1 to 2 ppm) but inhibited at high levels (5 to 10 ppm).

In a study on the absorption of mineral elements in the presence of aluminium, Guerrier (1979) demonstrated a general inhibitory effect by aluminium on the quantities of potassium, calcium and magnesium absorbed. The inhibition was more effective for calcium, but could not be correlated with indication of sensitivity or tolerance of the plant species studied with respect to aluminium. The study has pointed to the structural modifications of the roots as being responsible for the diminution of the exchange sites of each of these cations.

Brauner and Sarruge (1980a) studied the interrelation between aluminium concentration and tolerance and the

concentration of phosphorus, calcium and magnesium content in the shoot portion of 10 wheat cultivars growing in 0, 2.5, 5.0, 7.5 and 10 ppm aluminium. They could not observe any relationship between the content of phosphorus, calcium and magnesium of the plant and the aluminium concentration in solution or any difference in the extent of tolerance to aluminium by the different wheat cultivars.

In a continuation of the above study, the same authors (1980b) found that calcium uptake was inhibited by aluminium and manganese and that the wheat cultivars differed considerably in the extent of calcium uptake.

In another experiment, Brauner and Sarruge (1980c) reported that phosphorus uptake was stimulated more by aluminium than by manganese in different wheat cultivars.

Mugwira et al. (1980) studied the change in plant composition due to aluminium treatments in terms of the ratio of the concentration of calcium and magnesium, and potassium and phosphorus in plants grown with aluminium to the concentration of these elements in the tissues from control plants. They found that aluminium increased the concentration of phosphorus in the roots and that of potassium in the roots and tops of all cultivars, but reduced the concentration of calcium, magnesium and phosphorus in the tops of wheat and aluminium tolerant triticale. Aluminium sensitive wheat

cultivars accumulated less potassium in the tops but more calcium and phosphorus in the roots than the more tolerant cultivars. They concluded that tolerant cultivars apparently translocated both potassium and calcium more efficiently and the increased phosphorus in the roots of the sensitive cultivars was attributed to the association of phosphorus with larger quantities of aluminium on the root surface, rather than to enhanced phosphorus uptake.

Alam (1981) has reported that in the presence of ferric iron higher levels of aluminium increased the content of aluminium in all plant parts in barley along with a decreased leaf and root phosphorus content. The opposite effect was noted in the presence of ferrous iron.

Memon et al. (1981) in a study of the microdistribution of aluminium and manganese in the tea leaf tissues observed that aluminium uptake was especially high in a soil rich in manganese, but high levels of calcium and magnesium lowered aluminium and manganese uptake. No interaction with phosphorus was noted.

5. Influence of aluminium on plant growth

A. Toxic effects

For acid soils below pH 5.5, the high concentration of aluminium is considered a major limiting factor for production of most field crops. The principal direct effect

of aluminium on plants is a severe inhibition of root growth with consequent decrease in water and nutrient uptake.

Reduction in water uptake makes the crop more susceptible to water stress under drought conditions as well as a diminution in nutrient uptake which leads to growth reduction.

Concentration of soil solution aluminium even at the level of more than 1 ppm has been reported by Sanchez (1976) to cause direct yield reduction.

Symptoms of aluminium toxicity which is of wide spread occurrence in most acid soils show specific variations.

In the majority of crops, sufficiently high concentration of aluminium over a period of time will frequently damage even the most tolerant varieties. Symptoms also express in the plant tops at a later seedling stage and high correlation between weight of roots and tops have been reported by Reid et al. (1969).

It is now quite evident that for aluminium injury to manifest, the pH of the soil solution must be low enough to have sufficient concentration of aluminium in soil solution. Raising the pH of the solution to 5.2-5.5 usually precipitates aluminium and negates injury.

Brown (1963) has pointed out that plant species differed in their susceptibility to aluminium toxicity and that tolerance to aluminium was related to the plant's capacity to

absorb and translocate phosphorus from the growth medium. According to Wright and Donahue (1953) aluminium was precipitated outside the root endodermis which prevented further translocation of aluminium from the roots through the conducting tissues.

Toxicity in cereals

In most of the cereal crops, the symptoms of aluminium injury are first apparent on the roots. Injured roots are slower to elongate. Later they thicken and do not branch normally. The root tip disintegrates and turns brown and the adventitious roots proliferate as long as the crown is alive (Fleming and Foy, 1968; Reid et al., 1971).

Rice

Aluminium toxicity to rice was first reported by Miyake in 1916, who showed that 1.2 ppm of aluminium in solution was toxic. Cate and Sukhai (1964) have summarised the literature on toxic levels of aluminium for rice and have given values varying from 1.2 to 270 ppm.

Tanaka and Navasero (1966a) using water culture found that the critical concentration of aluminium in culture solution was about 25 ppm for plants with adequate contents of other nutrients, particularly phosphorus. Foy et al. (1967) have shown that aluminium sensitive varieties of rice have higher root CEC values and can induce lower pH

levels in nutrient solution than aluminium tolerant varieties.

In a study on the effect of aluminium ions on rice growth in nutrient culture, Chenn (1968) showed that the plant growth was impaired when Al^{3+} concentration in the medium exceeded 2 ppm. The aluminium content in the roots was 2.7 to 4.6 and 3.7 to 9.9 times higher than that in the stems and leaves. In cultures with excised roots the pH of the medium significantly affected aluminium uptake. Aluminium uptake from the solution of higher concentration was greater in rice roots compared to barley roots. These findings were considered to be relevant to the greater adaptability of rice on acid soils.

In Ceylon, a disease of rice known as "bronzing" was found to be caused by aluminium toxicity in combination with calcium deficiency (Ota, 1968). Beye (1971) has reported that the poor growth and low yield of rice in highly acid soils could be correlated with aluminium toxicity in the early stages.

Thawornwong and Diest (1974) reported that the concentration of 2 ppm aluminium was lethal only to young rice seedlings and that plants which had passed the seedling stage were not affected. Instances of seedling injury due to very high aluminium concentration have been observed in

some of the typical acid sulphate soils of the kari region in Kuttanad in Kerala*

Frageria (1982) has demonstrated differential tolerance among rice cultivars to aluminium in nutrient solution. Aluminium injury was indicated by visible symptoms as well as reduction in the dry weight of tops and roots, root length and plant height.

Frageria and Carvalho (1982) further showed that rice varieties responded differentially to aluminium treatments and the critical toxic levels for aluminium in the tops of 21 day old plants varied from 100 to 147 ppm. Increased aluminium concentration reduced the content of all nutrients in the tops.

Blaney et al. (1983) have also reported that aluminium in solution markedly reduced root elongation as well as absorption and translocation of nutrients to the plant tops.

Wheat and Rye

Tolerance of wheat varieties to aluminium and low pH has been the subject of investigation by several workers. Neenan (1960) was probably the first to report varietal differences in wheat to aluminium toxicity. Foy et al. (1964) showed that varieties of wheat and barley widely differed in

* Personal communication - Dr. R.S. Aiyer

their tolerance to acid soils containing high levels of KCl extractable aluminium. Liming of the soils to pH 5.8 reduced the solubility of aluminium to nontoxic levels and thus greatly reduced yield differences between varieties. Cruz et al. (1967) grew aluminium sensitive wheat variety in nutrient solution containing 0 to 60 ppm aluminium and found that root development was inhibited and chlorotic toxicity symptoms appeared in leaves of seedlings grown at higher aluminium concentrations. Increasing aluminium concentration in the nutrient solution also changed the mineral composition of stems, leaves and roots.

Otsuka (1968) demonstrated that rye was extremely tolerant to aluminium toxicity in nutrient solution. Plants injured by aluminium were chlorotic and their roots were stubby with no side branching. In the tops, phosphorus and calcium decreased with external aluminium concentration. The tolerance of plant species and varieties to acid soil corresponded well with their tolerance to aluminium in nutrient solution.

After testing different varieties of wheat from various sources for aluminium toxicity Foy et al. (1974) concluded that older varieties developed on acid, aluminium-toxic soils usually had greater tolerance than those developed on non-toxic soils. He showed that aluminium tolerance in some

plant species and cultivars coincided with their ability to absorb and use phosphorus at low concentration in the growth medium even in the presence or absence of aluminium. From these studies they could find no evidence to indicate that aluminium toxicity factors and favourable yield factors were genetically linked as suggested by Kerridge and Kronsted (1968).

Mugwira et al. (1976) compared several varieties of wheat, rye and triticale in nutrient solution with 6 ppm aluminium and found a range in varietal tolerance within all three species. Such screening experiments have established the fact that tolerance to low pH and aluminium is genetically controlled and that the potential exists for advances in tolerance through isolating superior sources and combining them into acceptable varieties through breeding.

Aniol et al. (1980) tested a total number of 371 spring rye inbred lines, 15 cultivars of wheat and three lines of triticale to aluminium tolerance by exposing seedling roots for 48 hours to aluminium at different concentrations and by measuring the relative root growth. The irreversible inhibition of root growth at a particular level of aluminium concentration in nutrient solution was associated with a significant increase in aluminium concentration in roots.

Barley

A number of investigators have reported differences among barley cultivars in their response to aluminium and/or low pH.

Kenneth et al. (1953) grew barley seedlings in 10 ppm aluminium solutions and produced typical symptoms of aluminium toxicity. The tops were stunted, the leaves contained yellowish streaks and a reddish discoloration was evident at the stem base. Roots were few, much shortened with stubby tips and were brownish and somewhat brittle.

Reid (1970) attributed the tolerance of aluminium in certain winter barley cultivars to a single dominant gene. They further showed that in nutrient solution, aluminium toxicity to barley was characterised by an increase in the number of roots, but a decrease in root length and weight.

Stolen (1973) has reported that the apparent tolerance of some barley varieties to low pH might actually be a result of their tolerance to available or labile aluminium levels in soil.

Based on electron microscopic investigation of aluminium sensitive and insensitive varieties of barley exposed to 9 ppm aluminium in nutrient solution at pH 4.8, Hecht and Foy (1981) observed a rapid autolysis of the affected root tip cells beginning with disorganisation of the

plasmalemma. The changes were similar to those described for calcium deficient tissues and the tolerance was ascribed to a larger resistance of the plasmalemma to aluminium stress.

Alam (1981) reported that high aluminium level decreased the dry matter yield of barley tops and roots and caused the formation of short, thick and brown spotted roots. Aluminium also induced chlorosis in barley when the iron source was ferric but not when it was ferrous.

Bache and Crooke (1981) attributed reduced growth of barley in acid soils to aluminium toxicity which was alleviated in the plant by high levels of soil phosphorus.

Other crops

Bloomfield and Coulter (1973) were of the view that tolerance to aluminium differed greatly between and within species. Except for rice and some other cereals, most of the tropical crops like rubber, oil palm, coconut, banana and pineapple could grow well in soils of pH below 4.0. Cotton alone appeared to be particularly sensitive to aluminium toxicity and/or calcium deficiency.

Foy and Brown (1963) recognized the most characteristic symptom of aluminium toxicity in cotton as phosphorus deficiency and suggested that the toxic effects of aluminium could be reduced or eliminated by raising the pH or adding phosphorus. He also believed that the accumulation of

aluminium compounds in or on the roots were detrimental to both chemical and physical processes in the cotton plant.

With a level of 6 ppm aluminium in nutrient solution, Brown (1963) obtained a reduction of 75 and 93 per cent respectively in the yields of oats and mustard compared to zero aluminium treatments.

Velly (1974) studied the toxic levels of exchangeable aluminium in several crops and reported 25 ppm for cotton, 50 to 60 ppm for groundnut and 120 to 130 ppm for maize in a ferralitic soil.

In a comparative study on the plant nutrition and crop tolerance to soil acidity and aluminium by several species of crops, Tanaka et al. (1975) reported that most species of leguminosae and graminae were tolerant while those of umbelliferae, cruciferae and compositae were susceptible. In field plots, cereals were more tolerant than legumes.

Foy et al. (1980) screened 54 cotton genotypes for aluminium tolerance in an acid aluminium toxic clay soil and found that acid soil sensitive genotypes did not generally differ significantly in the levels of aluminium, manganese, calcium and phosphorus which tended to be higher in chlorotic and/or cupped leaves than in normal leaves.

In a study of the microdistribution of aluminium and

manganese in the tea leaf tissues in Japan, Memon et al. (1981) reported that tea plants contained large amounts (4457 ppm) of aluminium in their older leaves despite the low level of exchangeable aluminium in the soil. X-ray micrographs showed that aluminium was densely deposited on the cell walls of the adaxial epidermis and palisade parenchyma of old leaf tissues.

B. Beneficial effects

Although aluminium is not generally considered as an essential element, it is often present in large quantities in many plants and along with silicon it has been classed as a "ballast" element by Agarwala and Sharma (1976).

McLean and Gilbert (1927) have reported that plants differed in their sensitivity to aluminium toxicity and that in minute quantities it can act as a growth stimulant.

Bertrand and Wolf (1966) considered aluminium as a dynamic minor element for higher plants and based on experiments with Chlorella vulgaris fixed the optimum concentration as 8.3 µg/l. The same authors (1969) have shown that in a soil containing 0.24 mg ammonium acetate extractable aluminium per kg soil, 1.6 kg/ha aluminium increased the yield of potato by 71.5 per cent.

Frink (1972) has shown that it is aluminium rather than iron which is responsible for cementing soil particles into structural units.

The beneficial effects of non-toxic levels of aluminium on plant growth and mineral uptake has been summarised by Foy (1974).

It has been reported that (Anon., 1980) the addition of aluminium salts to soil promoted the formation of water stable aggregates, lowered the liquid limit and raised the plastic limit. It also reduced the zeta potential, pH and exchangeable cation content and increased the electrical conductivity, water soluble and exchangeable aluminium content as well as phosphate absorption coefficients. The aluminium/OH ratio of the added salt influenced the magnitude of these responses in some soils.

Kumar (1981) reported an increase in the length and dry matter content of shoots of cashew seedlings by treating them with aluminium at 12 mg/l in sand culture compared to the no aluminium treatment which produced the smallest seedlings.

6. Ameliorants to minimise toxic levels of aluminium in soil solution

The solubility of aluminium and the severity of its toxicity to plants are known to be affected by many soil factors such as pH, type of predominant clay mineral, concentration of other cations, total salt concentration, moisture level, organic matter content, etc. Very often

aluminium toxicity is not the only factor limiting productivity in acid soils. Several ameliorative measures are adopted which keep aluminium in sub lethal levels in soil solution along with a moderating effect on other adverse soil conditions. Some of the views regarding the use of different ameliorants to bring about these effects are presented below.

a) Liming

Perhaps liming is the oldest practice to overcome the adverse soil conditions affecting crop production. The beneficial effects of lime in acid soils have been reported by numerous investigators.

The usefulness of lime as an ameliorant for reclaiming acid and acid sulphate soils and for correcting the toxic effects of iron and aluminium has been reported by Allaway (1957), Thomas (1960), Subramoney (1961), Nhung and Ponnamparuma (1966), Kurup (1967), Reeve and Sumner (1971), Coulter (1973) and many others.

Brauner and Catani (1967) conducted an incubation experiment with 11 acid soils using CaCO_3 at 100 and 300 mg/100 g soil and recorded a decrease in exchangeable aluminium and titrable acidity and an increase in the pH of aqueous suspensions and KCl extracts of soils.

Richburg and Adams (1970) were of the view that soils with similar pH values need not be similar in their lime

requirements and that different soils may have to be limed to different critical pH values to eliminate aluminium toxicity.

Helyar and Anderson (1971) reported a response to phosphorus in aluminium toxic soils by increased levels of lime.

In pot trials with barley, to study the effect of liming on the toxicity of aluminium, Ben et al. (1976) drew correlations between an index of aluminium toxicity and yield and showed that applications of lime alleviated aluminium toxicity.

Kamprath (1978) studied the effect of lime in relation to aluminium toxicity in tropical soils and observed that maximum response to lime was obtained when the aluminium saturation of the soils fell below about 20 per cent. The increased yields obtained with deeper liming were attributed to inactivation of aluminium in the deeper soil layers allowing roots to penetrate deeper.

Serda and Gonzalez (1979) proposed the optimum level of lime to minimise aluminium toxicity as 1.5 to 3.0 times the lime required to neutralise the exchange acidity present in acid soils.

Bloom et al. (1979) reported the increase in apparent Al(OH)_3 solubility with increasing pH on liming of acid soils to a greater solubility of amorphous Al(OH)_3 precipitated

by liming. The solution aluminium hydroxide activity product $[Al^{3+}][OH^{-}]^3$ was not found constant for the same soil limed over a range of pH values. Marion et al. (1976) held a similar view and attributed the difference in apparent $Al(OH)_3$ solubility in different soils to the difference in solubility of different crystalline minerals.

Cochrane et al. (1980) have proposed the use of minimum amount of lime on acid soils so as to decrease the aluminium saturation to levels that do not affect production and compensate crop aluminium tolerance.

b) Silicates

Subramoney (1965) has suggested the use of magnesium silicate in acid sulphate soils of Kerala to prevent the production of hydrogen sulphide and other toxic factors.

On an aluminous-ferruginous latosol that was believed to contain toxic amounts of Fe^{+2} and Al^{+3} , Clements et al. (1968) obtained considerable response in sugarcane to application of calcium metasilicates upto 8 tons/acre.

Reeve and Sumner (1970) showed that response to $CaSO_4$ and Ca silicate in oxisols in Natal was due to the elimination of aluminium toxicity and consequent improvement in phosphorus uptake by plants rather than to any improvement in the rate of phosphorus supply to soils.

For the liming of strongly acidic top soils (pH 3.6 to 4.2) slower acting wollastonite (calcium silicate) is considered more suitable than Ca CO_3 at the rate of 3 to 6 tons/ha (Park et al., 1972).

Ameliorative measures like application of lime and repeated flushing with fresh water often improved the acid sulphate soils and produced good grain yield during the ensuing season. But very often, problems like low pH and iron and aluminium toxicity reappeared on drying of the soil after harvest. For such situations Kuruvilla (1974) proposed the use of ameliorants, particularly magnesium carbonate or magnesium silicate, where the resultant sulphates formed by interaction were more soluble than the Ca SO_4 formed when lime alone was applied.

Yong Hwa Shin (1978) considered the application of lime and silicate fertilisers as a general improvement measure for the acid sulphate soils of Korea.

In the Kuttanad area in Kerala, Karunakara Panicker (1980) obtained increased yields of grain and straw in paddy with higher levels of nutrients by the application of magnesium silicate in the form of steatite.

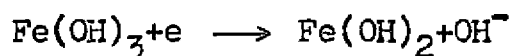
c) Flooding of soils

Rice soils are generally located on relatively imperfectly drained land and are often subject to continuous

periods of flooding for several months of the year. The ensuing physico-chemical changes under the anoxic conditions that initiate a series of changes in the total soil environment possibly make the fields more suited for rice cultivation.

A few of the beneficial influences of flooding in minimising the toxic effects of aluminium in acid soils are briefly reviewed.

Cate and Sukhai (1964) explained the lowering of soil solution aluminium to below critical levels on flooding as a consequence of the precipitation of (Al^{3+}) ions by the hydroxyl ion formed by the reduction of ferric iron as shown by the equation



Tanaka and Navasero (1966b) were of the view that the amount of aluminium in soil solution can be considered very little when such soils are waterlogged for sometime. They have reported the results of a pot experiment in which the initial soil leachate content of 35 ppm aluminium dropped to less than 1 ppm within three weeks of flooding with only an increase in pH of less than half a unit from 3.5 to 3.8, which is a critical range for aluminium. No explanation however, has been offered for the large decrease of aluminium in solution.

Seasonally waterlogged soils had a higher aluminium content in the soil solution than did soils where waterlogging did not occur. Kavrichev et al. (1969) proposed that on flooding water soluble compounds of aluminium and organic matter were produced by interaction of aluminium with fulvic acids and non-specific acid organic substances. Such aluminium organic complexes were considered important for the movement of aluminium during gleying as well as podsolisation. Thus, waterlogging and development of reducing conditions increased the content of water soluble aluminium in soil solutions.

Savant and Kibe (1969) found that when acid soils of pH ranging from 4.7 to 5.4 were subjected to cycles of 30 days of submergence followed by drying, extractable aluminium increased during the first cycle but decreased during the second and third cycles. The changes in extractable aluminium due to submergence and drying were of a chemical nature.

Much greater increase in the pH of soils on flooding for several weeks than given by Tanaka and Navasero has been reported by several workers. Ponnampereuma et al. (1973) found that an increase of pH from 3.5 to 6.1 occurred in 12 weeks of flooding in the acid sulphate soils of Vietnam. Beye (1973) and Kanapathy (1973) have also recorded similar increases in pH of soils from 2.6 to 6.3 and 3.8 to 5.7

respectively on waterlogging of soils for varying periods.

As the critical pH below which aluminium toxicity is expressed is about 4.5, it would appear that this condition cannot be a toxic factor of high magnitude in rice culture, where the land is flooded before and during the crop when the pH may rise beyond the critical point. Under such conditions the rise in pH and associated chemical changes can keep soluble aluminium at a minimum as decided by other soil chemical characteristics.

d) Organic matter

Mattson and Hester (1933) while studying the amphoteric nature of soils in relation to aluminium toxicity apparently recognized that plants growing in soils which were high in organic matter did not exhibit symptoms of aluminium toxicity at the same pH as those grown in soils low in organic matter.

McLean et al. (1964) found that the pH dependent CEC of several top soils decreased drastically as their organic matter was destroyed. They concluded that most of the pH dependent CEC sites were due to organic matter which complexed with aluminium and could be displaced by ammonium acetate and precipitated as $\text{Al}(\text{OH})_3$. Based on field observations, these authors also suggested that at low pH levels crops grew better on peaty acid sulphate soils than on acid mineral soils.

Mutatkar (1965) and Mutatkar and Pritchett (1966) attributed the inhibition of organic matter decomposition in some tropical soils to the high levels of aluminium, the aluminium being either toxic to the saprophytic microflora or due to a greater resistance of the aluminium-organic matter complexes to microbial degradation.

Lefebvre-Drouet (1967) showed that destroying the organic matter in some acid soils liberated complexed aluminium, the amount liberated being significantly correlated with soil organic matter, but was independent of soil pH in the range of 4.1 to 5.5.

Coleman and Thomas (1967) observed that the buffering of most of the acid soils formerly attributed to organic hydrogen ions, might be actually due to the hydrolysis of aluminium on the organic matter exchange sites.

Kavrichev et al. (1969) noted that 65 to 100 per cent of the water soluble aluminium in soil solution was combined with organic matter and could be determined only after the latter was destroyed. Evans and Kamprath (1970) were of the view that increasing amounts of organic matter resulted in lower soil solution aluminium at a given pH and that soil solution aluminium gave an effective estimate of response to liming irrespective of the soil organic matter content. Based on field experiments, they have indicated the beneficial

effects of addition of organic matter to highly acid soils compared to the effect of adjusting the soil pH.

All these evidences therefore point to a strong inter-relationship between aluminium and organic matter in acid soils. Since many of the acid sulphate soils have some amount of organic matter in them and many are known to have organic materials as their parent material, Bloomfield and Coulter (1973) postulated that considerable amounts of aluminium were held absorbed by organic matter in their peaty horizons.

Thomas (1975) has established an inverse relationship between organic matter and exchangeable aluminium in acid soils. He found that at a given pH, the aluminium extracted by N KCl decreased as organic matter content increased.

From a study of the effect of alfalfa meal, sucrose and peat moss in a strongly acid soil on the growth and yield of barley, Hoyt and Turner (1975) reported that the beneficial effects were primarily due to the maintenance of sublethal levels of aluminium by the complexing of exchangeable aluminium by the added organic matter.

Bloom et al. (1979) investigated the factors controlling the relationship between pH and (Al^{3+}) in soil solution by measuring the pH and pAl of individual soil suspensions with different periods of equilibration in the presence of added

organic matter. The results provided direct evidence of the importance of organic matter in controlling Al^{3+} in the soil. The addition of two per cent leaf humus caused about 40 per cent reduction in solution Al^{3+} at a given pH as compared to suspensions with no added humus. It was considered likely that by the addition of humus, the total CEC was increased with a simultaneous decrease in the aluminium saturation of the soil and a resulting fall in solution (Al^{3+}) at a given pH. The exchange of aluminium from the carboxyl sites on organic matter was considered the most important factor in the control of soil solution (Al^{3+}) activity in acid soils low in permanent CEC. Management of organic matter was suggested as effective in lowering (Al^{3+}) activity in acid soils.

Wahab and Lugo-Lopez (1980) compared the effect of adding 7 me $Ca(OH)_2/100$ g soil, 7 per cent finely ground pangola grass and 7 per cent finely ground coffee leaves to some highly acid soils and found that coffee leaves were more efficient in inhibiting aluminium toxicity than the others. Coronel (1980) proposed the addition of organic matter in acid soils to decrease aluminium solubility by the formation of aluminium-organic matter complexes.

7. Screening of plants for aluminium tolerance

The effects of aluminium on plant growth and the differential response of species and cultivars to high levels of

aluminium have been documented in numerous reports.

In 1960, Neenan reported a differential response of wheat cultivars to aluminium and suggested that the adaptability of certain cultivars to strongly acid conditions was due to their ability to tolerate high levels of free aluminium. Since then, a number of tolerance studies within wheat and indications of it in cultivar adaptations have been conducted. It has also been observed that cultivars developed in regions with strongly acid soils often possessed high levels of aluminium tolerance while those developed in other regions seldom had this trait.

Two basic media, viz., acid soils and nutrient solutions have been used in developing screening methods for determining genetic tolerance for aluminium. Because of the complexities and difficulties involved in controlling and measuring complex soil properties, much of the work with aluminium tolerance has been conducted either in green house or by use of nutrient solution techniques, although screening on naturally acid or artificially produced acid soils has also been in practice in some laboratories.

a) Screening trials on acid soils

In Denmark, Stolen (1965) used a field method of selecting barley for low pH tolerance by establishing the desired pH through spraying the soil with dilute sulphuric acid.

Reid et al. (1969) classified winter barley varieties for their tolerance to aluminium in field plots and green house experiments on aluminium-toxic soils. Since his first attempt Stolen (1973) screened aluminium tolerant barley in plastic pots filled with soil where pH was adjusted by adding 0.1 N H₂SO₄, the final adjustments being made by the addition of aluminium sulphate.

In a search for the solution to the problem of low agricultural productivity on the acid infertile soils of the humid and subhumid tropics, CIAT Scientists initiated a screening programme in 1971 at Carimagua in Colombia. The soils were characteristically acidic, aluminium-toxic and of poor fertility status. Based on the results of the study, Foy et al. (1974) reported large differences in tolerance to aluminium among different varieties of wheat, barley, tomato, forage grass, cotton, soybean etc. indicating some degree of variation in all the species. Some of the pulse crops like cowpea, peanut, beans, etc. were relatively well adapted to acid soil environment while corn was poorly adapted to extremely acid conditions.

Spain (1976) carried out a screening programme on these soils by using two major types of experiments, one which involved different lime levels with uniform fertilizer treatments and the other with a combination of different levels of phosphorus and lime. The difference in the tolerance of

crops was attributed to their differential tolerance to aluminium, as well as to their ability for better phosphorus utilization. The studies also pointed out the greater tolerance of upland rice to aluminium toxicity compared to low land rice. A clear correlation between height of rice and tolerance to soil acidity was also noted.

Silva (1976) screened cultivars in a location where the soils were acid with aluminium toxicity strong enough to make a 100 per cent selection pressure. Foy (1976) was of the view that selecting a soil to screen plants specifically for aluminium tolerance can be difficult owing to the difficulty in controlling the soil system to maintain uniform soil solution aluminium. Furthermore, aluminium toxicity may not be the only limiting factor in acid soils, as manganese may also be present as a toxic factor in addition to aluminium. Aluminium and manganese may again interact with other elements in the soil as well as in the plant. At times, the exchangeable calcium content in these soils can also influence the extent of aluminium toxicity. Natural subsoils stabilised at pH 4.5 to 5.0 with poor manganese and calcium contents were considered ideal for screening purpose.

Foy (1976) has further suggested the use of paired indicator plants, an aluminium sensitive and an aluminium tolerant one, grown side by side on the same soil to produce a range

of aluminium toxicity symptoms in the tops, for determining the suitability of a soil as a medium for screening.

b) Screening in nutrient solution

Maclean and Chiasson (1966) compared two commercial spring barley varieties in green house by soil experiments and in nutrient solution and showed that their differential tolerance was the same under both situations. Nutrient solution screening methods have been successfully employed by Kerridge et al. (1971), Reid et al. (1971) and Brown and Clark (1974). The rapid nutrient solution screening methods facilitate screening of a large number of plants and eliminate some of the complexities of field situations. Regression analysis has confirmed the relationship between nutrient solution and field plot data.

A solution paper method was developed by Konzak et al. (1976), wherein, the growing medium was a nutrient solution carried on absorbent paper and they used this technique for screening wheat, barley, rice, sorghum, pulses, etc.

Coronel (1980) studied the absolute root length, root regrowth and hematoxylin staining methods to distinguish the levels of aluminium tolerance in rice.

Kaniska (1981) has reviewed the methods for determining aluminium and manganese toxicity of barley grown at low soil pH and described a method for evaluating the resistance of

spring barley cultivars to aluminium toxicity based on the length of seedling root. Grain yields were correlated with the length and dry weight of seedling roots grown in the presence of aluminium. Aniol (1981) has also reported different methods of determining the aluminium tolerance of cereals and presented data on the length of seedling roots of 12 cultivars and lines of spring wheat along with their yield and 1000 grain weight. Good correlation was shown between the field and nutrient culture techniques for aluminium tolerance. He has further stated that the accumulation of Al^{3+} in plants was a poor indicator of their sensitivity to this element.

Moore et al. (1976) were of the view that methods of screening plants tolerant to aluminium toxicity using acid soils were not usually precise enough as the plant parts most directly affected viz., the roots, are not easily observed. They considered nutrient solution screening techniques to be more precise in that important variables like pH and Al^{3+} activity could be better controlled. For this reason most of the available techniques for selecting varieties for aluminium tolerance are based on observation of the growth of plant roots in solution culture containing aluminium. A common measure of aluminium toxicity is to compare the root lengths of aluminium treated plants with control plants grown in the absence of aluminium. A reasonably

good relationship between relative root length and the degrees of aluminium toxicity has been recorded by Howeler and Cadavid (1976) and Moore et al. (1976). Howeler and Cadavid (1976) measured relative root length at 3 and 30 ppm aluminium and achieved good correlation between this value and grain production in field trials.

Comparisons of cultivar ranking from field and nutrient solution culture studies by Campbell and Lafever (1976) showed that relative root length (8 ppm Al/0 ppm) appeared to be a better index of aluminium tolerance compared to either root weight or top length and weight.

MATERIALS AND METHODS

MATERIALS AND METHODS

The problem envisaged in the present study, namely, "The release of soluble aluminium in soils under submerged conditions and its effect on rice" was investigated by conducting the following interconnected studies:

1. Chemical nature of rice soils with special reference to aluminium saturation.
2. Incubation of typical rice soils under flooded conditions with different ameliorants to follow the pattern of solubilisation of aluminium.
3. Pot culture experiment with different ameliorants added to an acid soil with a high content of exchangeable aluminium to follow the pattern of solubilisation of aluminium and its effect on rice.
4. Solution culture experiment to study the specific effect of graded levels of aluminium on the growth, yield and nutrient uptake in rice.
5. Screening of rice varieties for tolerance to aluminium toxicity.
1. Chemical nature of Rice soils with special reference to Aluminium saturation

A total number of 89 surface soil samples (0-20 cm) ranging in pH from 2.5 to 6.5 collected from the major

wetland rice growing areas of Kerala State were used in this study.

For this, more than 100 samples were first collected, air-dried and the pH determined in the laboratory. These soils were then classified into seven groups in the pH ranges of 2.5 to 3.4, 3.5 to 3.9, 4.0 to 4.4, 4.5 to 4.9, 5.0 to 5.4, 5.5 to 6.0 and 6.1 to 6.5 so as to have a minimum of 12 samples in each group. The number of samples in any one group was limited to 12-15 by rejecting soil samples with identical pH values from nearby locations and soil types.

The chemical analysis of the selected samples was carried out by the following methods:

i) Soil reaction

The pH was determined in water as well as in 0.01 M CaCl_2 solution. (soil:liquid ratio 1:2.5) with a Perkin Elmer pH meter using a glass electrode.

ii) Conductivity

The conductivity of a 1:2 soil water extract was measured using a Solu bridge.

iii) Cation Exchange capacity

This was estimated by the neutral normal ammonium acetate method as described by Jackson (1973).

iv) Exchangeable cations

Exchangeable potassium, calcium, magnesium and aluminium were determined in the ammonium acetate leachate by the methods described by Jackson (1973).

v) Exchangeable hydrogen

The difference between the cation exchange capacity and the sum of total exchangeable potassium, calcium, magnesium and aluminium was reckoned as exchangeable hydrogen (Coleman et al., 1958).

vi) Aluminium saturation

The per cent aluminium saturation was calculated in two ways, namely, on the basis of total cation exchange capacity as suggested by Coleman et al. (1958) and also on the basis of the effective cation exchange capacity (sum of exchangeable potassium, calcium, magnesium and aluminium) as proposed by Sanchez (1976).

vii) Water soluble aluminium

The water soluble aluminium was estimated colorimetrically in the 1:5 soil water extract by the aluminon method (Chenery, 1948).

viii) Lime requirement

Lime requirement was determined by the method suggested by Hutchinson and McLennan (1914).

ix) Base saturation

This was calculated on the basis of the total CEC as suggested by Coleman et al. (1958).

x) Organic carbon

Organic carbon was estimated by Walkley and Black's rapid titration method (Jackson, 1973).

Statistical analysis

The analytical data obtained as above were subjected to statistical analysis to bring about the interrelationships between pH and exchangeable aluminium as well as with other soil chemical characteristics.

2. Incubation of typical rice soils under flooded conditions with different ameliorants and their effect on solubilisation of aluminium

Eleven samples of soil representing the typical rice tracts of the State were used in this study. The details of the soils are given in table 1.

The ameliorants used were ordinary lime and steatite which is a naturally occurring form of magnesium silicate supplied by the Geological Survey of India. The latter material was used in the study in view of its beneficial effects on the growth and yield of rice in acid soils as was revealed in some earlier field experiments (Karunakara Panicker, 1980).

Lime was used @ 600 kg/ha which is the usually recommended level and steatite @ 500 kg/ha. The sample of steatite ($Mg_3Si_4O_{10}(OH)_2$) had a neutralising value of 28.1 per cent and the following composition:

MgO	- 29.0 per cent
CaO	- 1.0 per cent
SiO ₂	- 55.0 per cent

Table 1. Details of soil samples used for the incubation studies

Sl. No.	Location	Order	Local name	Soil group	Texture
1	Vadayar	Entisol	Kari	Acid saline	Clay
2	Vaikom	''	Kari	"	Clay
3	Moncompu	''	Karapadom	"	Clay loam
4	Kumarakom	''	Karapadom	"	Clay loam
5	R. Block	''	Kayal	"	Clay
6	R. Block	''	Kayal	"	Clay
7	Trichur	''	Kole	"	Clay
8	Vyttilla	''	Pokkali	"	Clay
9	Kayamkulam	''	Coastal sandy	Greyish Onattukara	Sandy
10	Pattambi	''	Low Level Laterite	Brown hydromorphic	Clay loam
11	Vellayani	''	Low level laterite	"	Clay loam

Two kg lots of each soil were weighed into three glazed porcelain pots of capacity 2.5 l. In this manner the eleven soils were taken in 33 pots. One series of 11 pots containing the dry soils was kept untreated. The second series received the lime treatment and the third series received steatite at the specified rates.

The required quantities of lime and steatite were weighed and added to the soil in the respective pots and mixed thoroughly. Distilled water was then added into each of the 33 pots and mixed well with a thick glass rod. After ensuring that the soil was mixed properly with the water, an additional quantity of distilled water was added into each pot so as to stand to a height of 6 cm above the soil surface. The level of water was maintained throughout the experimental period by the addition of fresh distilled water.

Soil sampling and analysis

From each pot duplicate samples of the wet soil were removed at intervals of 0, 3, 6, 12, 20, 30 and 60 days by the funnel method proposed by Abichandani and Patnaik (1957). In a sample of the soil removed from the untreated series immediately after mixing with water, the moisture content was determined, which was used for computing the weight of the dry soil in all treatments at the different stages of sampling.

In the soils sampled by the funnel method the pH and EC were determined using a soil water ratio of 1:2.5.

For determining water soluble aluminium and iron a 1:5 soil water extract was used. Exchangeable aluminium and iron were extracted using N KCl in a 1:5 soil solution ratio. Aluminium was determined in the extract by the aluminon method (Chenery, 1948) and iron by the thiocyanate method (Jackson, 1973).

Statistical analysis

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

ANOVA

Source	- df
Between soils (S)	- 10
Between periods (P)	- 6
Between soils within periods (S x P)	- 60
Total	- 76

Since the experiment was single replicated, S x P interaction was treated as error and the soils and periods were tested against this interaction.

Further, a pooled analysis was also carried out to study

the interaction of the different ameliorants in different soils over various periods.

ANOVA

Source	- df
Ameliorants (T)	- 2
Soils (S)	- 10
T x S	- 20
Period (P)	- 6
T x P	- 12
S x P	- 60
T x S x P	-120
Total	-230

The T x S x P interaction was taken as error to test the significance of the effects of different treatments and periods of submergence.

3. Pot culture experiment

The object of this experiment was to follow and monitor the variations in water soluble and exchangeable aluminium and iron as well as the changes in pH and EC brought about by the addition of ameliorants to an acid soil. The soil (a sulfaquent) used in the study was collected from Karumadi in the highly acid kari tract of the State. The ameliorants used were lime, steatite, cattle manure and green leaves (cocoa). Cattle manure and green leaves were used as ameliorants based

on the reports on the beneficial effects of organic materials in decreasing aluminium toxicity in acid soils (Evans and Kamprath, 1970; Hargrove and Thomas, 1981). The experiment was laid out in CRD with the following six treatments and three replications:

- T₀ - No ameliorants (control)
- T₁ - Lime @ 600 kg/ha + steatite @ 500 kg/ha
- T₂ - Lime @ 1200 kg/ha
- T₃ - Lime @ 600 kg/ha + cattle manure @ 5 g/pot
- T₄ - Lime @ 600 kg/ha + green leaves @ 5 g/pot
- T₅ - Lime @ 600 kg/ha

The physico-chemical characters of the soil used for the experiment are given in table 2.

The soil collected from the field was brought to the laboratory, air dried and ground with a wooden mallet. Eighteen earthenware pots (30 x 25 cm) were used in the study. Five kg portions of the ground soil were taken in each pot. In the pots receiving the green leaf treatment, the weighed quantity of cocoa leaves was chopped and mixed with the soil and kept in a puddled condition for ten days before planting. The other ameliorants were added in the required quantities one day prior to planting. Fertilizers as per the package of practices of the Kerala Agricultural University (1982) were added on the day of transplanting of seedlings.

Table 2. Physico-chemical characters of the soil used in the pot culture experiment

Location: Karumadi, Ambalapuzha

pH (water) (1:2.5 soil water suspension)	3.8
pH (0.01 M CaCl ₂) (1:2.5 soil solution ratio)	3.4
E.C. (mmhos/cm ²)	6.8
Total nitrogen (per cent)	0.38
Available nitrogen (kg/ha)	210
Available phosphorus (P) (kg/ha)	12
Available potassium (K) (kg/ha)	78
Water soluble aluminium (ppm)	26
Exchangeable aluminium (me/100 g)	6.8
Exchangeable bases (me/100 g) (K + Ca + Mg)	2.4
Lime requirement (t/ha)	12.5
Organic carbon (per cent)	12.4
Soil texture	Clay
Cation exchange capacity (me/100 g)	17.5
Aluminium saturation of total CEC (per cent)	33.4
Aluminium saturation of effective CEC (per cent)	74.0

The soil in each pot was mixed thoroughly with the various treatments and water and kept in a puddled condition. Three 15 day old seedlings of rice variety 'Triveni' were planted in each pot on 7-3-1983. Water was maintained at a

height of 5 cm on the surface of the soil and the level was maintained by daily irrigation.

From each pot wet soil samples were collected periodically by the funnel method without causing any disturbance to the plants. The first sampling was done on the transplanting day (period 1) followed by sampling at periods corresponding to the important growth stages of the rice plant such as active tillering, maximum tillering, panicle initiation, opening of inflorescence, grain filling and maturity stages (periods 2-7). The harvesting was done on 28-5-1983.

As the roots also had to be collected for analysis, the procedure followed for harvest was as follows:

After noting the plant height and number of productive tillers per plant, each pot was lifted in the hand, gently tilted to drain off the water and then inverted. By carefully shaking the pots, the plants with the soil intact could be retrieved from the pots. A jet of water was then directed onto the soil through a hose so as to remove the soil adhering to the roots. By careful manipulation of the water, the root system could be completely recovered. The roots were washed several times with water to remove even the last traces of clay and allowed to drain. The earheads were removed from the plants, taken in labelled envelopes and kept for air drying.

The shoot and roots from each pot were also air dried and the length of the roots noted by measuring the distance from the base of the stem to the tip of the longest root. After this measurement, the shoot and root were separated and taken in different envelopes and labelled. The grain, straw and roots were then dried in an air-oven at 70°C and their weights recorded. The chaff was separated from the grain and its weight was also noted.

The oven dry plant samples from the different treatments were homogenised and analysed for total nitrogen, phosphorus, potassium, calcium, magnesium, aluminium and iron by standard methods as given by Piper (1966).

Statistical analysis

The data obtained on the plant characters and nutrient content of plant parts were statistically analysed as follows:

ANOVA		
Source	-	df
Treatment (T)	-	5
Error	-	12
Total	-	17

Correlation coefficients were also worked out to estimate the interaction among the different nutrients in the plant.

The soil characters at different time intervals were also correlated with yield and related characters.

4. Solution culture experiment to study the effect of graded levels of aluminium

This experiment was intended to study the specific effect of graded levels of aluminium in the rooting medium on the growth, yield and nutrient uptake pattern in rice. The design was CRD with 11 treatments and three replications.

The 33 porcelein pots required for the study were filled with two litres of the nutrient solution prepared as suggested by Johnson et al. (1957). Its composition is given in table 3.

Table 3. Composition of nutrient solution used in Solution culture experiment

NH_4NO_3	-	50 ppm
$\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$	-	10 "
KCl	-	25 "
CaCl_2 (fused)	-	20 "
$\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$	-	20 "
H_3BO_3		
$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$		
$\text{MnSO}_4 \cdot \text{H}_2\text{O}$	-	2 "
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$		
H_2MoO_4		
Sodium silicate	-	10 "
Ferric citrate	-	2 "
Na EDTA		

The required quantities of aluminium in the form of AlCl_3 solution was added into the respective pots and mixed with a glass rod. The pH of the medium was maintained below 4.5 to ensure that the aluminium remained in solution. The levels of aluminium tried ranged from 0 to 100 ppm as per the treatments shown below.

T ₀	-	0 Al
T ₁	-	10 ppm Al
T ₂	-	20 "
T ₃	-	30 "
T ₄	-	40 "
T ₅	-	50 "
T ₆	-	60 "
T ₇	-	70 "
T ₈	-	80 "
T ₉	-	90 "
T ₁₀	-	100 "

Waxed rattan baskets of suitable size containing washed glass marbles were used to hold the plants. Two 14 day old seedlings of rice, variety "Sabari", were planted in each basket and kept over the top of the solution in each pot. This arrangement helped about 2 cm of the solution to be in contact with the basal parts of the plant. The nutrient solution in each pot was replaced by fresh solution at weekly intervals, after washing the pot as well as roots of plants in water.

The experiment was started on 10-12-1982 and completed on 2-4-1983.

After noting the growth characters such as height of plants, number of productive tillers and length of root, the base and roots were washed several times with fresh water and the plants were separated into root, straw and grain. They were dried in labelled envelopes in an oven at 70°C and the weights noted. The plant materials were ground and kept in labelled bottles and used for the determination of nitrogen, phosphorus, potassium, calcium, magnesium, aluminium and iron by adopting standard procedures as referred to earlier.

Statistical analysis

The effect of different levels of aluminium on the growth and yield characters as well as nutrient composition of the plant parts was studied by the following ANOVA.

ANOVA		
Source	-	df
Treatment	-	10
Error	-	22
Total	-	32

5. Screening of rice varieties for tolerance to aluminium toxicity

Laboratory screening of rice varieties/cultures for tolerance to aluminium toxicity was carried out to group

them into three categories viz., least tolerant, medium tolerant and tolerant.

A total number of 154 varieties/cultures of rice cultivated in the different parts of the State as well as those maintained in the Rice Research Stations under Kerala Agricultural University were used for the study.

Screening technique

The above varieties/cultures were screened in the laboratory for tolerance to aluminium toxicity using the "Solution paper technique" described by Konzak, Polle and Kittrick (1976).

A basal nutrient solution, buffered to pH 4.0 with acid potassium pathallate and mixed with AlCl_3 to give 3.75 mM aluminium in solution was used for the screening. The composition of the basal nutrient solution is given below.

Mg SO_4	-	0.1 mM
K NO_3	-	0.1 mM
$\text{NH}_4 \text{NO}_3$	-	0.15 mM
K H C ₈ H ₄ O ₄	-	8.0 mM
Ca Cl_2	-	0.1 mM

Since the culture period was short, phosphorus was omitted to avoid precipitation of aluminium. Trace elements were also excluded for the sake of simplicity.

The nutrient solution was taken to a depth of 4 cm in

tall (15 x 4 cm) borosilicate glass tubes closely fitted on the inner side with a roll of absorbent filter paper. The base of the filter paper roll dipping in the nutrient solution allowed the paper to be soaked with the nutrient solution throughout the period of study so long as the level of nutrient solution was maintained in the tube.

Eight to ten rice seeds, pre-soaked in water for 24 hours were closely arranged along the mouth of the tube in the space between the filter paper and the sides of the tube. The seeds were arranged with the position of the embryo facing downwards. The tubes were kept erect on a suitable base and the germination and growth were allowed to continue for eight days.

The seedlings were then carefully removed and the average length of roots was measured. Relative root length at 3.75 mM aluminium with reference to the root length in the basal nutrient solution without aluminium was calculated for the 154 varieties/cultures used.

Classification of the varieties

The available varieties/cultures were arranged into three groups based on the normal distribution property (Snedocor and Cochran, 1967) of their relative root length. The mean relative root length (per cent) and standard deviation of relative root length were computed. The varieties

were classified according to the confidence limits given by the means \pm SE (mean)

$$\text{i.e., } \bar{x} \pm \frac{s}{\sqrt{n}}$$

where \bar{x} is the mean relative root length, n is the number of varieties and s the standard deviation of relative root length.

The varieties having root length less than $\bar{x} - \frac{s}{\sqrt{n}}$ were classified as least tolerant, those between $\bar{x} \pm \frac{s}{\sqrt{n}}$ as medium tolerant and those above $\bar{x} + \frac{s}{\sqrt{n}}$ as tolerant to aluminium toxicity.

RESULTS

RESULTS

1. Chemical nature of Rice soils with special reference to Aluminium saturation

The results of the study on soil acidity and exchangeable aluminium in relation to the other soil characteristics for seven groups of soils in the different pH ranges are presented in tables 4a to 4g and the summary of the results are given in Table 5 and fig.(1) and (2). The interrelationships among the different characters for soils of different pH ranges are also briefly indicated.

Soils in the pH range 2.5 to 3.4 (Table 4(a))

The 12 soils of this group represent the acid sulphate and acid saline soils occurring along the west coast of the State. Determination of soil reaction in 0.01 M CaCl_2 has resulted in a lowering of the pH by 0.1-0.5 units. The EC of the two samples from the acid saline area was very high (16.3 and 12.4 mmhos/cm^2) while it ranged only from 4.3 to 6.7 mmhos/cm^2 for the other soils. The mean value of EC was 7.1 mmhos/cm^2 which is much above the critical level suggested for the rice crop. The CEC ranged from 12.4 to 22.2 me/100 g with an average of 16.3 me/100 g. The mean value of the exchangeable hydrogen was 8.6 me/100 g and the average value of the base saturation was 10.6 per cent. Exchangeable aluminium (5.9 me/100 g) accounted for 77.2 per cent of the effective CEC and 36.5 per cent of the total CEC.

Table 4(a) Chemical nature of rice soils (pH 2.5-3.4)

Sl. No.	Location and texture	pH (H ₂ O)	pH (0.01 M CaCl ₂)	EC (mmhos/cm ²)	CEC (me/100 g)	Exchangeable cations (me/100 g)				Al saturation (per cent)		Base saturation (per cent)	Organic carbon (per cent)	LR (t/ha)	Water soluble Al (ppm)
						H	K	Ca+Mg	Al	Total CEC	Effective CEC				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	Vembanakara (clay)	2.9	2.7	6.2	18.0	11.7	0.07	1.3	4.9	27.2	77.7	7.3	8.2	13.1	23
2	Mundar (clay loam)	3.3	3.0	5.8	13.5	6.2	0.12	1.8	5.4	40.0	74.0	13.9	8.6	12.6	26
3	Mundar (clay loam)	2.5	2.3	4.3	12.4	6.3	0.04	1.5	4.6	37.1	75.4	12.5	9.4	13.4	18
4	Kaipadam (clay loam)	3.0	2.6	16.3	12.5	6.4	0.03	1.4	4.7	37.6	77.5	8.6	5.4	11.1	25
5	Orumundakan (clay loam)	3.4	2.9	12.4	13.6	6.8	0.15	1.1	5.6	41.2	82.4	9.4	4.8	13.5	20
6	Vaikom (clay)	3.2	3.0	6.7	14.4	8.2	0.16	1.2	4.8	33.3	77.4	9.5	9.2	12.7	25
7	Mundar (clay)	3.1	2.7	5.7	15.1	9.0	0.21	1.4	4.5	29.8	73.8	10.5	8.6	12.5	27
8	Purakkad (clay)	3.0	2.9	5.5	14.8	6.5	0.24	1.6	6.5	43.9	78.3	12.6	8.3	14.3	30
9	Vadayar (clay)	2.7	2.4	4.8	22.2	9.1	0.35	2.4	10.4	46.8	79.4	12.3	10.9	15.1	28
10	Vadayar (clay)	3.2	2.9	5.5	20.6	12.3	0.18	1.6	6.5	31.6	78.3	8.8	12.6	12.8	31
11	Thottappally (clay)	3.4	3.0	6.2	17.5	10.5	0.23	1.3	5.5	31.4	78.6	8.6	10.8	12.5	22
12	Purakkad (clay)	3.3	2.8	6.0	20.8	10.5	0.31	2.4	7.6	35.6	73.8	12.8	10.6	13.2	24

One of the acid saline soils (Orumundakan) recorded the highest aluminium saturation of 82.4 per cent of the total CEC. The lime requirement of these soils varied from 11.1 to 15.1 t/ha, the organic carbon ranged from 4.8 to 12.6 per cent and the water soluble aluminium varied from 18 to 31 ppm.

Of the different soil characters studied, the pH in water was significantly and negatively correlated to the lime requirement (-0.55) while the relationship was not significant for the pH of soils as determined in 0.01 M CaCl₂. Total CEC was positively and significantly correlated to exchangeable hydrogen (0.76), exchangeable bases (0.64), exchangeable aluminium (0.77) and organic carbon (0.72). The relationship between exchangeable bases and lime requirement was negative and significant (-0.61), while the relation of exchangeable aluminium and organic carbon to lime requirement was significant and positive (0.63 and 0.64). A similar relationship existed between exchangeable hydrogen and organic carbon (0.71).

Soils in the pH range 3.5 to 3.9 (Table 4(b))

These 12 samples also belonged to the acid sulphate soil group and varied in texture from clay or clay loam. The decrease in pH in 0.01 M Ca Cl₂ was 0.1 to 0.6 units. These soils had a high EC which ranged from 4.3 to 8.3 with an average of 6 mmhos/cm².

Table 4(b) Chemical nature of rice soils (pH 3.5-3.9)

Sl. No.	Location and texture	pH (H ₂ O)	pH (0.01 M CaCl ₂)	EC (mmhos/cm ²)	CEC (me/100 g)	Exchangeable cations (me/100 g)				Al saturation (per cent)		Base saturation (per cent)	Organic carbon (per cent)	LR (t/ha)	Water soluble Al (ppm)
						H	K	Ca+Mg	Al	Total CEC	Effective CEC				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	Karuvatta (clay)	3.7	3.5	5.6	13.3	6.8	0.22	1.3	5.0	37.6	78.1	11.1	8.8	10.8	17
2	Mathikayal (clay loam)	3.9	3.3	6.1	13.0	2.0	0.10	4.5	6.4	49.2	58.2	35.4	8.4	10.5	14
3	Sreemoolam (clay loam)	3.6	3.5	5.8	17.0	8.8	0.23	3.8	4.2	24.7	51.2	23.4	9.2	11.7	16
4	Kanjanipadam (clay loam)	3.5	3.1	4.3	14.5	9.0	0.10	2.0	3.4	23.7	61.8	15.2	11.7	11.9	20
5	Kaniakari (clay)	3.8	3.4	5.2	12.7	3.4	0.11	3.1	6.1	48.0	65.6	25.3	6.1	9.8	18
6	Karumadi (clay)	3.9	3.6	6.6	16.0	4.9	0.26	4.4	6.4	40.0	57.7	29.1	12.1	10.2	26
7	Vaikom (clay)	3.7	3.5	6.3	24.2	11.0	0.43	3.6	9.1	37.6	68.9	16.7	8.8	11.5	18
8	Vadayar (clay)	3.8	3.5	6.4	20.2	8.5	0.31	3.0	8.4	41.6	71.8	16.4	10.4	10.6	15
9	Kole (I) (clay)	3.9	3.4	5.7	24.3	16.5	0.38	3.1	4.3	17.7	55.1	14.5	17.5	12.5	17
10	Kole (II) (clay)	3.7	3.1	8.3	18.7	12.0	0.25	1.8	4.7	25.1	70.1	10.7	15.5	11.3	19
11	Ambalapuzha (clay)	3.6	3.3	6.4	14.6	7.3	0.16	3.1	4.0	27.4	53.3	22.0	10.4	14.1	18
12	Mundar (clay)	3.6	3.2	5.1	12.8	5.9	0.22	2.2	4.5	35.2	65.2	19.2	9.6	12.7	18

The chemical characters of the soils in this group were not much different from those of the soils in the pH range 2.5 to 3.4, inspite of the higher average pH of 0.6 units.

Mean values of the total CEC (15.9 me/100 g) and exchangeable hydrogen (7.2 me/100 g) were only slightly lower than that of the previous group. The exchangeable bases (19.9 per cent) on the other hand, showed a tendency to increase with a consequent increase in base saturation. There was not much difference in the per cent aluminium saturation of the total CEC (33.9 per cent) while the aluminium saturation of the effective CEC (62.7 per cent) was significantly lower. Average values for organic carbon in these soils registered a higher value (10.7 per cent) whereas the lime requirement (11.5 t/ha) and the water soluble aluminium (18 ppm) tended to be significantly lower.

As in the former group of soils, the pH in water was significantly and negatively correlated to lime requirement (-0.59) while the pH in salt solution showed no such correlation. A significant positive relationship (0.51) also existed, between pH in water and the exchangeable bases. Exchangeable hydrogen and aluminium were positively related to the total CEC though not significantly. Exchangeable hydrogen showed a significant inverse relationship with per cent aluminium saturation of the total CEC (-0.64) as

well as with the per cent base saturation (-0.70). With organic carbon it showed a high positive correlation (0.88).

The other correlations of importance were those observed between exchangeable calcium and magnesium and per cent base saturation (0.83), exchangeable aluminium and lime requirement (0.53), aluminium saturation of total CEC and per cent base saturation (0.60) and the indirect relation of the base saturation per cent with organic carbon (-0.74) and lime requirement (-0.53).

Soils in the pH range 4.0 to 4.4 (Table 4(c))

The 14 soils of this group were representatives of the brown hydromorphic group of soils in Trivandrum district, the kayal and karapadam soils of Kuttanad and the Orumundakan soils of Alleppey district. The texture of these soils varied from clay to clay loam. A fall of 0.1 to 0.4 units was noted when the pH was determined in 0.01 M CaCl₂ solution.

The tendency of the CEC to decrease with increase in pH continued in this group. It ranged between 9.2 and 27.2 me/100 g with an average of 14.3 me/100 g. However, there was a slight increase in the content of exchangeable hydrogen (7.7 me/100 g). Exchangeable calcium and magnesium were not significantly different from that of the more acidic soils used in this study. Exchangeable aluminium registered a sharp decrease (3.5 me/100 g) compared to the

Table 4(c) Chemical nature of rice soils (pH 4.0-4.4)

Sl. No.	Location and texture	pH (H ₂ O)	pH (0.01 M CaCl ₂)	EC (mmhos/cm ²)	CEC (me/100 g)	Exchangeable cations (me/100 g)				Al saturation (per cent)		Base saturation (per cent)	Organic carbon (per cent)	LR (t/ha)	Water soluble Al (ppm)
						H	K	Ca+Mg	Al	Total CEC	Effective CEC				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	Rajapuram (clay loam)	4.2	3.8	2.1	14.3	8.4	0.18	2.1	3.6	25.2	61.2	15.9	4.8	8.6	15
2	Moncompu (clay loam)	4.3	3.9	2.5	13.9	9.0	0.15	1.8	3.0	21.6	61.2	13.0	6.6	6.4	17
3	Purakkad (clay loam)	4.0	3.8	3.1	14.4	8.7	0.17	3.0	2.5	17.7	43.9	22.0	6.5	8.1	13
4	Thakazhi (clay loam)	4.4	4.1	3.5	17.2	12.4	0.07	2.5	2.2	12.8	38.6	28.0	6.0	7.5	14
5	Alleppey (clay loam)	4.2	4.0	6.6	15.3	7.1	0.15	4.3	3.8	24.8	46.3	28.8	3.8	8.2	18
6	Thakazhi (clay loam)	4.3	4.0	2.9	17.5	11.7	0.13	2.8	2.9	16.6	50.0	16.5	11.8	7.8	15
7	Kumarakom (clay loam)	4.0	3.5	3.6	9.6	3.8	0.15	2.3	3.4	35.4	58.6	25.0	2.8	8.8	16
8	Edathua (clay loam)	4.0	3.8	2.1	15.6	9.2	0.12	2.5	3.8	24.4	65.5	16.9	10.3	7.8	18
9	Purakkad (clay)	4.4	4.2	5.3	27.2	17.2	0.25	3.8	6.0	22.1	60.0	14.7	10.7	6.3	12
10	Moncompu (clay)	4.0	3.7	2.1	11.7	3.7	0.25	3.2	4.6	39.3	57.5	29.5	5.5	7.5	17
11	Vaikom (clay)	4.2	3.9	4.8	10.6	4.5	0.23	2.3	3.6	34.0	59.0	24.2	6.6	8.1	14
12	Neyyattinkara (loam)	4.2	4.0	0.02	9.2	1.8	0.12	2.7	4.6	50.0	71.9	24.7	3.0	6.1	16
13	Ambalapuzha (clay)	4.2	4.1	2.4	11.9	4.2	0.13	4.5	3.1	26.1	40.3	38.9	4.8	6.6	12
14	Attingal (loam)	4.4	4.1	0.01	11.2	3.0	0.14	3.0	5.1	45.5	62.2	27.6	3.5	5.6	8

previous soil samples and the aluminium saturation of both the total and effective CEC also tended to be less (24.5 and 53.5 per cent). The base saturation was consequently higher (22.8 per cent) than that of the more acidic soil groups. Organic carbon varied from 2.8 to 11.8 per cent with an average of 6.6 per cent. The lime requirement ranged from 5.6 to 8.8 t/ha with a mean value of 7.6 t/ha. The variation in water soluble aluminium was between 8 to 18 ppm, the average being 15 ppm.

The pH of the soils of this group as determined in water and in 0.01 M Ca Cl₂ showed a significant negative correlation with lime requirement (-0.57 and -0.65) and to the water soluble aluminium (-0.51 and -0.53). The total CEC of these soils exhibited a high direct correlation to exchangeable hydrogen (0.95) and organic carbon (0.72). The aluminium saturation calculated on the basis of both total and effective CEC was significantly and negatively correlated to the total CEC (-0.63 and -0.95). Exchangeable hydrogen had a negative influence on the per cent base saturation (-0.57) and a positive relation to organic carbon (0.74).

Other correlations of significance were between exchangeable calcium and magnesium and base saturation (0.58), exchangeable aluminium and aluminium saturation of total and effective CEC (0.58 and 0.59) and the indirect effect of organic carbon and lime requirement on base saturation (-0.75 and -0.71).

Soils in the pH range 4.5 to 4.9 (Table 4(d))

The 12 soils included in this group were the coastal alluvial and brown hydromorphic soils of Trivandrum, Alleppey and Ernakulam districts. In texture, most of them were loams and their pH in water and in 0.01 M CaCl_2 varied only by 0.1 to 0.3 units compared to the more acidic soils. The EC of the soils in this group was much lower, with a mean value of 0.8 mmhos/cm². A sample of pokkali soil of this group registered the highest value of 5.6 mmhos/cm².

The CEC was also much lower than that of the earlier groups and the values varied from 6.4 to 16.6 me/100 g with an average of 11.6 me/100 g. Compared to the soils of pH range 4.0 to 4.5, the soils of this group indicated a significant reduction in the exchangeable hydrogen content, the mean value being 5.4 me/100 g. However, there was not much difference in the status of exchangeable bases and aluminium of the soils of this group and that of the previous group.

The aluminium saturation calculated on the basis of total CEC (28.7 per cent) showed a slight increase while it remained rather steady when determined on the basis of the effective CEC (51.8 per cent). The base saturation tended to increase recording values as high as 43.0 per cent with an average of 26.6 per cent. Organic carbon, lime requirement and water soluble aluminium showed a decreasing trend in this group as compared to the earlier groups.

Table 4(d) Chemical nature of rice soils (pH 4.5-4.9)

Sl. No.	Location and texture	pH (H ₂ O)	pH (0.01 M CaCl ₂)	EC (mmhos/cm ²)	CEC (me/100 g)	Exchangeable cations (me/100 g)				Al saturation (per cent)		Base saturation (per cent)	Organic carbon (per cent)	LR (t/ha)	Water soluble Al (ppm)
						H	K	Ca+Mg	Al	Total CEC	Effective CEC				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	Edathua (loam)	4.7	4.5	0.25	10.9	4.3	0.11	2.0	4.5	41.3	68.2	19.4	5.3	7.0	9
2	Alleppey (loam)	4.9	4.8	2.75	13.5	9.3	0.08	1.3	2.8	20.7	66.7	9.8	10.7	6.6	17
3	Vellayani (loam)	4.8	4.6	0.01	11.7	6.4	0.25	2.0	3.1	26.5	58.8	19.2	4.6	6.3	13
4	Attingal (loam)	4.9	4.6	0.02	12.9	5.5	0.12	3.2	4.1	31.8	55.4	25.4	5.9	5.9	11
5	Neyyattinkara (loam)	4.5	4.2	0.05	11.0	4.2	0.18	3.0	3.7	33.6	52.9	28.5	4.8	5.6	10
6	Chirayinkil (loam)	4.7	4.4	0.05	13.3	5.6	0.06	3.5	4.1	30.8	52.6	27.0	5.1	5.1	9
7	Attingal (loam)	4.6	4.5	0.01	11.2	2.1	0.08	4.1	4.9	43.8	53.8	37.3	3.5	5.5	15
8	Venganoor (loam)	4.5	4.3	0.01	9.3	2.4	0.08	3.0	3.8	40.9	48.1	33.4	4.7	6.0	10
9	Pullad (loam)	4.9	4.6	0.15	9.8	4.4	0.20	2.4	2.8	28.6	51.9	26.0	5.5	6.1	7
10	Alleppey (loam)	4.8	4.6	0.25	12.6	7.9	0.32	2.1	2.3	18.3	48.9	23.5	4.1	5.8	12
11	Alleppey (clay)	4.7	4.5	0.28	16.6	11.7	0.04	2.8	2.1	12.7	42.9	27.2	4.7	6.2	12
12	Pokkali (sandy loam)	4.9	4.6	5.69	6.4	2.7	0.25	2.5	1.0	15.6	21.3	43.0	3.6	5.3	14

The significant negative correlation between pH and lime requirement noted in the more acidic soils was not observed in this group. However, there was a significant and indirect correlation between lime requirement and organic carbon (-0.71). A direct relationship between exchangeable hydrogen and CEC (0.69) and an indirect correlation between base status and CEC (-0.55) were noted in this group also. Exchangeable hydrogen was in turn inversely related to exchangeable calcium and magnesium (-0.63) and base saturation (-0.83) and exhibited a strong positive correlation with organic carbon (0.77). The base saturation had a significant direct relation to exchangeable calcium and magnesium (0.69) while it showed an inverse relationship with organic carbon (-0.58) and lime requirement (-0.69).

A similar relationship was evident in the case of per cent aluminium saturation of effective CEC and base saturation (0.69). The per cent aluminium saturation of total CEC expressed a strong correlation with lime requirement in this group of soils alone (0.61) and it showed a correlation with organic carbon as well (0.57). As the aluminium saturation of the effective CEC increased, the base saturation showed a corresponding reduction as seen by the significantly negative relationship existing between these two characters (-0.74). Aluminium saturation was also directly correlated

to organic carbon and lime requirement (0.57 and 0.61). The per cent base saturation, however, revealed a negative correlation with organic carbon, as well as lime requirement (-0.75 and -0.71).

Soils in the pH range 5.0 to 5.4 (Table 4(e))

The 15 soil samples studied in this group belonged to the kayal and karapadam areas of Kuttanad and brown hydromorphic soils of Attingal and Pattambi. Their texture varied from clay to clay loam and loam. The pH of the soils in 0.01 M CaCl₂ was 0.1 to 0.5 units lower than that in water, the average pH in water being 5.2 and that in CaCl₂ 4.9. The EC was very low and ranged from 0.01 to 1.1 mmhos/cm² with a mean value of 0.4 mmhos/cm².

Total CEC and exchangeable hydrogen were low compared to the more acidic soils (9.5 and 3.6 me/100 g). Exchangeable calcium and magnesium ranged from 1.8 to 4.8 me/100 g with a mean value of 3.3 me/100 g. Exchangeable aluminium tended to decrease in these soils as compared to the more acidic soils. The aluminium saturation of total and effective CEC were also lower (25.3 and 40.7 per cent). As compared to the previous group, the soils in this group registered a higher base saturation of the exchange complex (38.5 per cent).

The organic carbon content was almost the same as in the previous groups of soils recording an average of

Table 4(e) Chemical nature of rice soils (pH 5.0-5.4)

Sl. No.	Location and texture	pH (H ₂ O)	pH (0.01 M CaCl ₂)	EC (mmhos/cm ²)	CEC (me/100 g)	Exchangeable cations (me/100 g)				Al saturation (per cent)		Base saturation (per cent)	Organic carbon (per cent)	LR (t/ha)	Water soluble Al (ppm)
						H	K	Ca+Mg	Al	Total CEC	Effective CEC				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	Neyyattinkara (loam)	5.1	4.8	0.5	9.2	2.5	0.07	4.3	2.3	25.0	34.3	47.0	2.6	3.8	4
2	Neyyattinkara (loam)	5.4	4.9	0.7	13.5	7.6	0.12	1.8	4.0	29.6	67.8	13.9	16.7	3.4	12
3	Kayamkulam (loam)	5.2	4.8	0.02	9.4	6.2	0.12	1.9	1.2	12.8	37.5	21.0	5.4	3.5	2
4	Attingal (loam)	5.2	4.6	0.01	11.1	3.3	0.08	4.6	3.1	27.9	39.7	42.4	2.6	2.4	6
5	Attingal (loam)	5.0	4.8	0.01	8.8	2.6	0.08	3.5	2.6	29.5	41.9	40.7	3.8	4.7	3
6	Pattambi (loam)	5.2	5.0	0.04	7.7	3.4	0.14	2.9	1.3	16.9	30.2	39.2	4.9	3.6	12
7	Thakazhi (loam)	5.3	4.8	1.1	7.6	2.8	0.22	3.2	1.4	18.4	29.2	70.8	5.2	4.2	13
8	Mannar (sandy loam)	5.3	5.1	0.4	6.4	1.7	0.13	2.6	2.0	31.3	42.6	43.1	5.8	3.9	6
9	Mavelikara (sandy loam)	5.0	4.9	0.3	6.1	2.0	0.17	1.8	2.1	34.4	51.2	32.8	2.3	2.1	4
10	Moncompu (clay loam)	5.1	4.6	0.8	12.4	3.9	0.25	4.8	3.4	27.6	40.5	40.7	7.2	3.8	17
11	Pullad (clay loam)	5.3	5.0	0.3	10.7	4.8	0.30	3.1	2.5	23.4	42.4	31.8	4.2	3.6	5
12	Champakulam (clay)	5.2	4.8	0.6	12.6	4.0	0.41	4.5	3.7	29.4	43.0	38.6	4.1	3.6	12
13	Thakazhi (clay)	5.3	4.8	0.9	10.0	2.8	0.35	4.3	2.6	26.0	36.1	48.0	3.2	3.0	15
14	Edathua (clay)	5.0	4.7	0.3	9.8	3.6	0.45	3.7	2.1	21.4	33.9	42.5	6.1	3.1	14
15	Moncompu (clay loam)	5.0	4.8	0.6	8.0	2.9	0.33	2.5	2.3	28.8	45.1	35.0	8.0	3.4	14

5.4 per cent for the 15 soils. The soils had a comparatively lower lime requirement value which varied from 2.1 to 4.7 t/ha. Water soluble aluminium was on the decline and registered a mean value of 8 ppm only.

In this group of soils, the pH did not show any significant relationship with the other soil characters. Only a weak inverse correlation was noted between pH and per cent base saturation (-0.48). Total CEC was correlated to exchangeable hydrogen (0.63) and exchangeable aluminium (0.70). Exchangeable hydrogen exhibited a negative relation to base saturation (-0.70) and a direct relation to organic carbon (0.67). Exchangeable bases were directly correlated to per cent base saturation (0.52) and exchangeable aluminium towards the aluminium saturation of the effective CEC (0.60). While the relationship of aluminium saturation of total CEC with organic carbon was weak, there existed a strong relationship between aluminium saturation of the effective CEC and organic carbon content of the soils (0.67). A negative relation between organic carbon and per cent base saturation was also evident (-0.68).

Soils in the pH range 5.5 to 6.0 (Table 4(f))

The 12 soils included in this group were mostly loamy in texture and consisted of the kayal soils from Kuttanad and brown hydromorphic soils from different parts of the State. The pH of these soils in 0.01 M CaCl₂ was nearly

Table 4(f) Chemical nature of rice soils (pH 5.5-6.0)

Sl. No.	Location and texture	pH (H ₂ O)	pH (0.01 M CaCl ₂)	EC (mmhos/cm ²)	CEC (me/100 g)	Exchangeable cations (me/100 g)				Al saturation (per cent)		Base saturation (per cent)	Organic carbon (per cent)	LR (t/ha)	Water soluble Al (ppm)
						H	K	Ca+Mg	Al	Total CEC	Effective CEC				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	Pattanakad (loam)	5.7	5.6	0.02	7.6	3.8	0.25	1.8	1.8	23.7	47.4	26.3	2.6	1.0	3
2	Attingal (loam)	6.0	5.5	0.01	8.5	3.4	0.15	3.8	1.2	14.1	23.5	46.5	3.4	1.8	2
3	Ambalapuzha (loam)	5.8	5.7	0.04	7.8	2.1	0.19	3.4	2.1	26.9	36.8	46.4	2.9	2.2	6
4	Chittoor (loam)	6.0	5.8	0.13	13.7	4.0	0.18	6.4	3.1	22.6	32.0	48.2	6.5	1.8	2
5	Vellayani (loam)	5.8	5.7	0.06	7.5	3.1	0.18	2.5	1.7	22.7	38.6	35.2	4.4	1.5	3
6	Mavelikkara (loam)	5.9	5.8	0.05	7.1	2.0	0.18	2.9	2.0	28.2	40.8	43.7	4.8	0.5	1
7	Chirayinkil (loam)	5.6	5.4	0.05	12.8	2.6	0.17	6.4	3.6	28.1	35.3	51.4	6.0	1.3	2
8	Vellayani (loam)	5.9	5.4	0.00	8.6	3.6	0.25	3.1	1.7	19.8	34.0	39.4	4.7	1.0	3
9	Attingal (loam)	5.7	5.4	0.01	10.5	3.6	0.08	4.6	2.2	21.0	31.9	64.7	4.5	1.1	2
10	Pattambi (loam)	5.8	5.4	0.05	13.4	7.6	0.14	3.7	2.0	14.9	34.5	45.8	5.9	1.4	3
11	Kayamkulam (sandy loam)	6.0	5.5	0.01	5.1	2.6	0.12	1.5	0.9	17.6	36.0	31.4	3.5	0.7	-
12	Karunagappally (sandy loam)	6.0	5.6	0.01	4.8	2.4	0.11	1.2	1.1	22.9	45.8	27.7	2.1	0.8	-

0.1 to 0.3 units lower than that in water. The EC was found to be negligible and was in the range of 0.01 to 0.13 mmhos/cm² with an average of 0.04 mmhos/cm². The CEC of these soils varied from 4.8 to 13.7 me/100 g with a mean value of 9.0 me/100 g.

The mean values of exchangeable hydrogen and calcium and magnesium were 3.4 and 3.5 me/100 g respectively. Exchangeable aluminium was lower than that in the previous group showing a mean value of only 2 me/100 g. Both aluminium saturation of total and effective CEC decreased in this group, recording mean values of 21.9 and 36.4 per cent respectively. The average base saturation was 42.2 per cent and organic carbon content 4.3 per cent, which were lower than the corresponding values in the more acidic groups. Water soluble aluminium ranged from 1 to 6 ppm with an average of 2 ppm and the mean lime requirement was 1.3 t/ha.

The pH in water was indirectly correlated to exchangeable aluminium (-0.56) and to per cent aluminium saturation of total CEC (-0.57). The CEC was correlated with exchangeable calcium and magnesium (0.88), exchangeable aluminium (0.80), per cent base saturation (0.66) and organic carbon (0.85). Exchangeable calcium and magnesium showed high correlation to base saturation (0.78) and organic carbon (0.79), while exchangeable aluminium had a significant correlation with organic carbon (0.73).

Soils in the pH range 6.1 to 6.5 (Table 5(g))

The 12 soils of this group varied from clay loam to sandy loam in texture and represented different parts of the State. The pH of these soils in 0.01 M CaCl₂ was 0.1 to 0.2 units lower as compared to the pH in water. These soils had the least electrical conductivity of the order of 0.03 mmhos/cm² only. The CEC varied from 2.6 to 13.6 me/100 g with a mean value of 7.7 me/100 g. Exchangeable hydrogen and aluminium were also very low with mean values of only 1.5 and 1.0 me/100 g respectively. The status of calcium and magnesium in these soils varied from 0.7 to 10.7 me/100 g with a mean value of 5.1 me/100 g. The soils of this group had the highest base saturation of 60.6 per cent as compared to the more acidic groups of soils.

Organic carbon was also low and showed a mean value of 3.8 per cent. Lime requirement ranged from 0.4 to 1.1 t/ha with an average value of 0.75 t/ha. The level of water soluble aluminium was negligible, the average value being only 1 ppm.

The pH in water was positively and significantly correlated to the exchangeable bases (0.53) and inversely to the aluminium saturation of the total CEC (-0.62). The CEC had a strong positive correlation with exchangeable calcium and magnesium (0.79), exchangeable aluminium (0.78), base saturation (0.84) and a negative correlation with exchangeable

Table 4(g) Chemical nature of rice soils (pH 6.1-6.5)

Sl. No.	Location and texture	pH (H ₂ O)	pH (0.01 M CaCl ₂)	EC (mmhos/cm ²)	CEC (me/100 g)	Exchangeable cations (me/100 g)				Al saturation (per cent)		Base saturation (per cent)	Organic carbon (per cent)	LR (t/ha)	Water soluble Al (ppm)
						H	K	Ca+Mg	Al	Total CEC	Effective CEC				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	Kozhinjampara (clay loam)	6.2	6.0	0.03	13.6	0.6	0.21	10.7	2.1	15.7	16.2	80.2	6.4	0.7	1
2	Palghat (clay loam)	6.5	6.3	0.04	12.6	0.5	0.45	10.6	1.1	8.7	9.2	87.9	3.3	0.3	2
3	Onattukara (sandy)	6.2	6.0	0.03	2.6	1.7	0.12	0.6	0.2	7.7	22.2	28.9	3.1	0.8	-
4	Karunagappally (sandy)	6.1	6.0	0.03	4.5	1.3	0.16	2.1	0.9	20.0	28.1	70.7	4.7	1.0	2
5	Karunagappally (sandy)	6.1	6.0	0.02	4.6	2.2	0.12	1.5	0.8	11.4	33.3	36.1	2.3	1.1	1
6	Palghat (clay loam)	6.4	6.4	0.02	11.5	0.5	0.22	9.8	1.0	8.7	9.1	86.7	2.9	0.8	2
7	Palghat (clay loam)	6.5	6.4	0.02	12.8	1.7	0.26	9.6	1.2	9.4	10.8	77.3	3.5	0.8	-
8	Kayankulam (sandy)	6.3	6.2	0.02	3.0	1.9	0.08	0.7	0.3	10.0	27.3	24.7	1.6	0.4	2
9	Oachira (sandy loam)	6.2	6.0	0.01	3.8	1.9	0.16	1.1	0.6	15.8	31.6	49.5	3.2	0.5	1
10	Melpadom (loam)	6.1	6.0	0.02	9.5	2.2	0.16	5.8	1.3	13.7	17.8	63.7	5.8	0.7	1
11	Venganoor (loam)	6.3	6.1	0.04	7.3	2.0	0.16	4.0	1.2	16.4	22.6	57.0	4.7	1.1	2
12	Venganoor (loam)	6.5	6.3	0.04	6.9	1.3	0.13	4.3	1.2	17.4	21.4	64.8	4.1	0.8	2

Table 5. Chemical nature of rice soils: mean values

Soil group	pH range	pH (H ₂ O)	pH (0.01 M CaCl ₂)	EC (mmhos/cm ²)	CEC (me/100 g)	Exchangeable cations (me/100 g)				Al saturation (per cent)		Base saturation (per cent)	Organic carbon (per cent)	LR (t/ha)	Water soluble Al (ppm)
						H	K	Ca+Mg	Al	Total CEC	Effective CEC				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	2.5-3.4	3.1	2.8	7.1	16.3	8.6	0.18	1.6	5.9	36.5	77.2	10.6	9.0	12.8	25
2	3.5-3.9	3.7	3.4	6.0	15.9	7.2	0.23	3.0	5.5	33.9	62.7	19.9	10.7	11.5	18
3	4.0-4.4	4.2	3.9	3.4	14.3	7.7	0.17	2.9	3.5	24.5	53.3	22.8	6.6	7.6	15
4	4.5-4.9	4.7	4.5	0.8	11.6	5.4	0.15	2.7	3.3	28.7	51.8	26.6	5.2	6.0	12
5	5.0-5.4	5.2	4.9	0.4	9.5	3.6	0.21	3.3	2.4	25.3	40.7	38.5	5.4	3.5	8
6	5.5-6.0	5.9	5.5	0.04	9.0	3.4	0.11	3.5	2.0	21.9	36.4	42.2	4.3	1.3	2
7	6.1-6.5	6.3	6.1	0.03	7.7	1.5	0.18	5.1	1.0	13.0	16.1	60.6	3.8	0.8	1
	C.D.	0.2	0.1	1.39	3.0	2.1	0.07	1.5	1.0	7.1	6.4	9.6	2.1	0.7	2

FIG. 1. VARIATION IN THE CONTENT OF EXCHANGEABLE CATIONS WITH INCREASE IN pH OF SOILS.

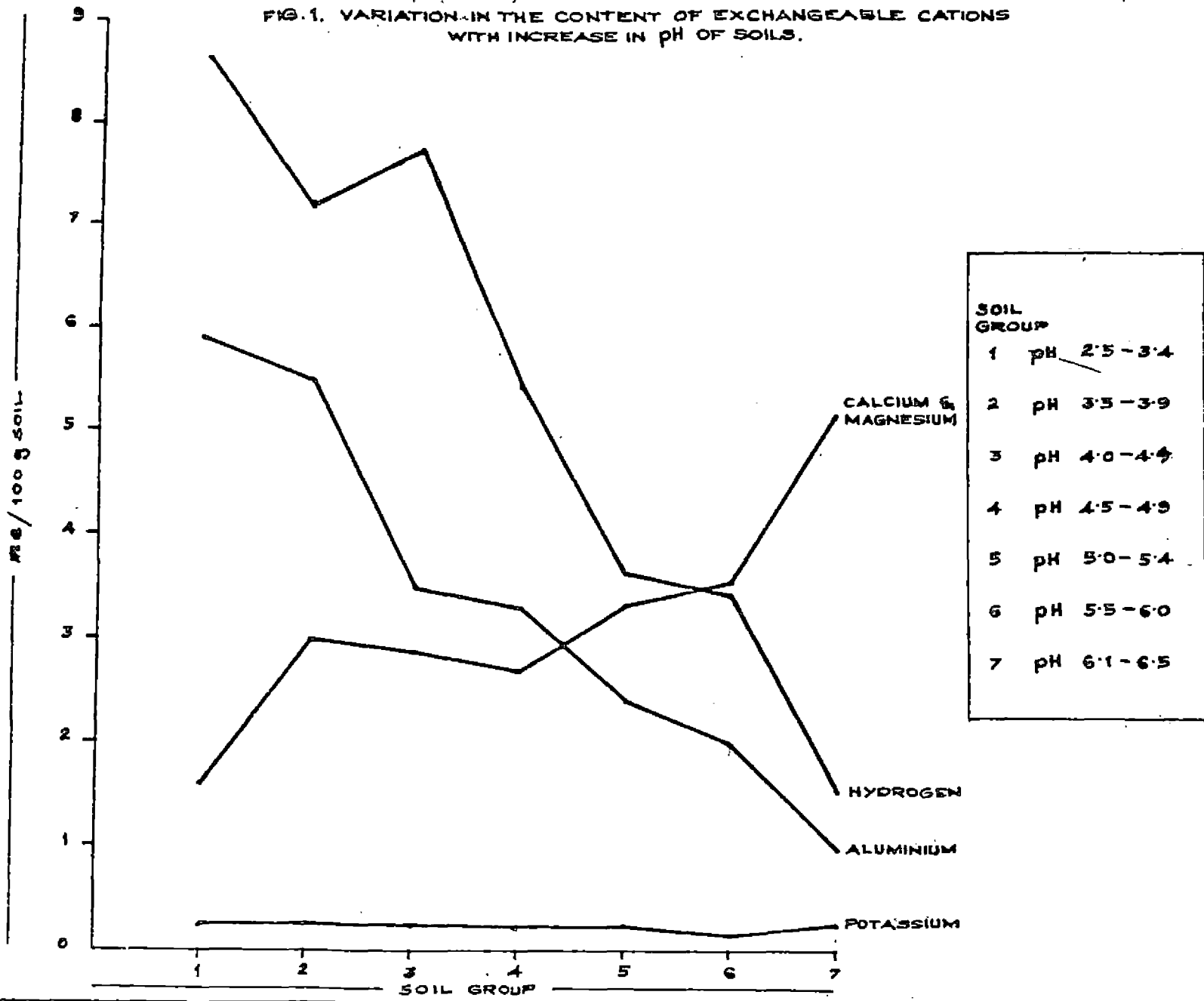
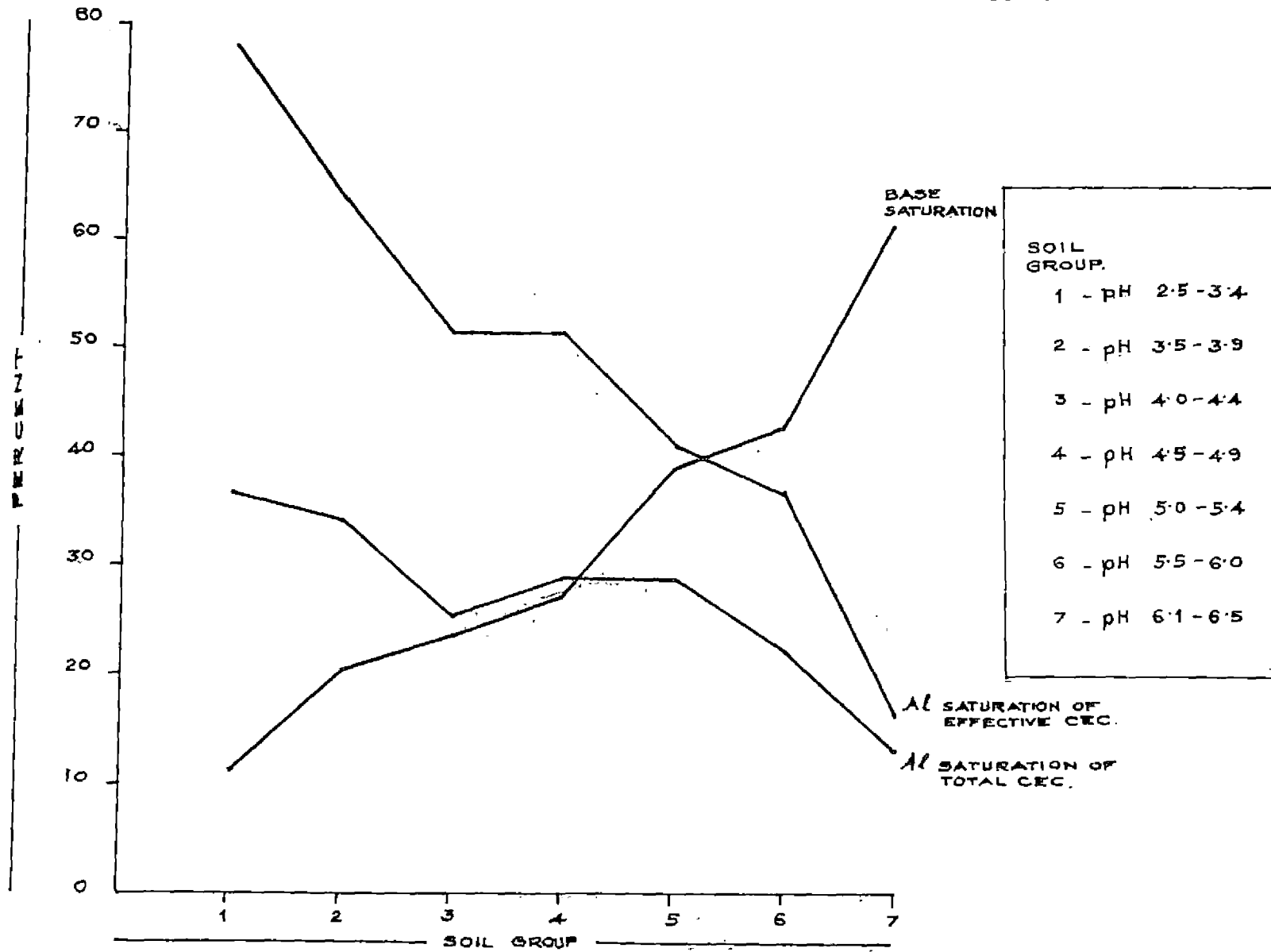


FIG. 2. VARIATION IN BASE SATURATION AND PERCENTAGE ALUMINIUM SATURATION OF THE TOTAL AND EFFECTIVE CEC OF SOILS.



hydrogen (-0.57) and aluminium saturation of the total CEC (-0.85). Exchangeable hydrogen revealed an indirect effect on properties like exchangeable bases (-0.59) and base saturation (-0.60). Exchangeable calcium and magnesium were correlated negatively to the aluminium saturation of total CEC (-0.88) and positively to the per cent base saturation (0.84). The relationship between exchangeable aluminium and organic carbon was positive and significant (0.69).

2. Incubation studies on typical Rice Soils

The results of the laboratory incubation studies on the effect of submerging eleven important soil groups of Kerala, under water with and without lime and steatite (as ameliorants) on some of the important physico-chemical properties of the soils are presented:

a) Submerging of the soils in water

The results on changes in pH, EC, watersoluble and exchangeable aluminium and iron due to flooding in water for varying periods of time are presented in tables 6(a) and 6(b), figures 3 to 8 and appendix 1(a).

pH

From the results it may be seen that significant changes in pH were obtained for the different soils due to submergence in water for varying periods of time. Mean values for

Table 6(a) Physico-chemical properties of soils on submergence in water: mean values over a period of two months

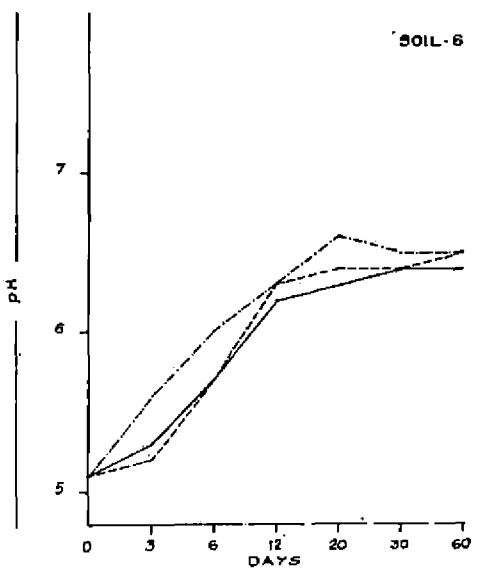
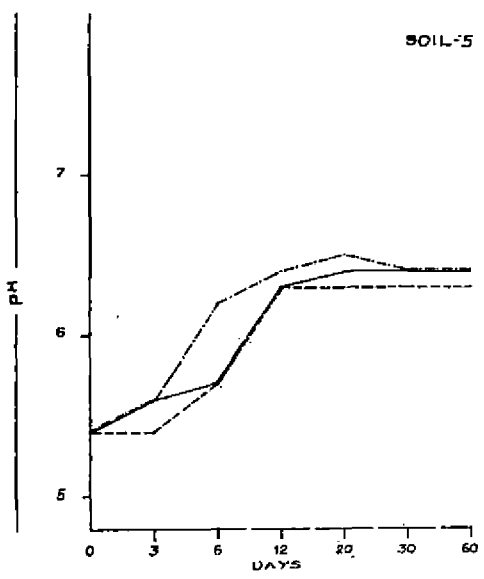
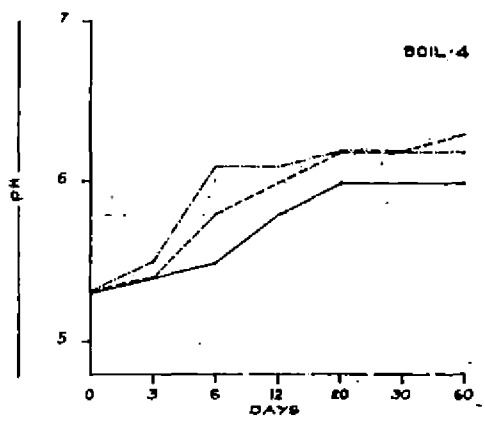
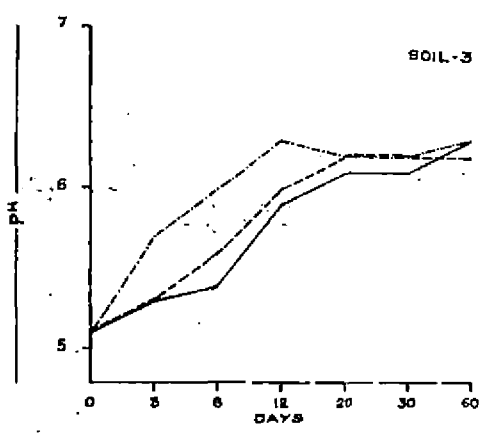
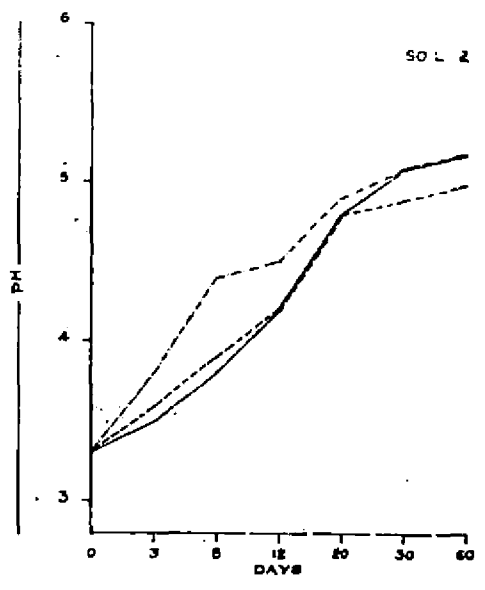
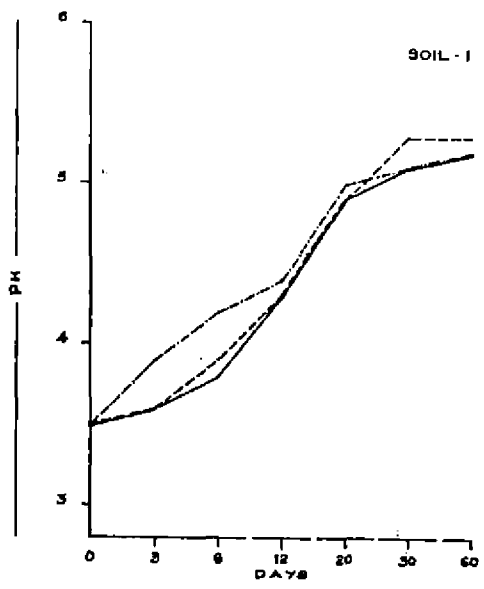
Soil Sl.No.	pH	EC (mmhos/cm ²)	Al(H ₂ O) (ppm)	Al(Exch.) (ppm)	Fe(H ₂ O) (ppm)	Fe(Exch.) (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	4.3	8.3	19	598	64	730
2	4.3	8.4	22	792	63	789
3	5.7	6.3	8	228	30	114
4	5.7	7.3	8	193	25	109
5	6.0	7.6	5	311	33	135
6	5.9	5.7	6	320	29	134
7	5.2	9.6	10	217	36	162
8	4.4	16.9	15	418	58	369
9	6.1	1.0	2	19	4	16
10	5.9	0.7	5	22	30	60
11	6.0	0.4	4	27	22	54
C.D.	0.2	0.1	4	9	14	189

Table 6(b) Physico-chemical properties of soils on submergence in water: mean values for seven periods of sampling over a period of two months

Soil properties (1)	Period (days)							CD (9)
	1(0) (2)	2(3) (3)	3(6) (4)	4(12) (5)	5(20) (6)	6(30) (7)	7(60) (8)	
pH	4.7	4.9	5.1	5.5	5.8	5.9	5.9	0.21
EC (mmhos/cm ²)	5.9	6.4	6.6	6.8	7.0	6.7	6.5	0.1
Al (H ₂ O) (ppm)	15	14	12	10	8	6	4	3.0
Al (Exch) (ppm)	375	370	339	303	217	190	202	7.0
Fe(H ₂ O) (ppm)	6	15	36	49	54	48	39	11.0
Fe (Exch) (ppm)	19	60	240	345	382	349	306	151.0

Fig. 3. Changes in pH of soils with time due to treatment with lime and steatite and flooding

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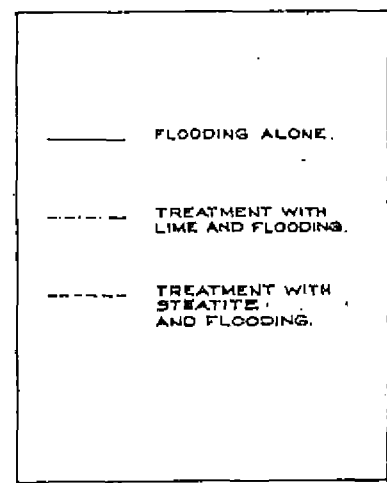
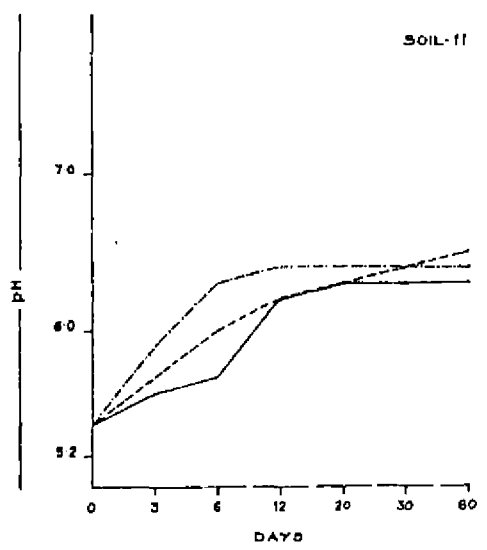
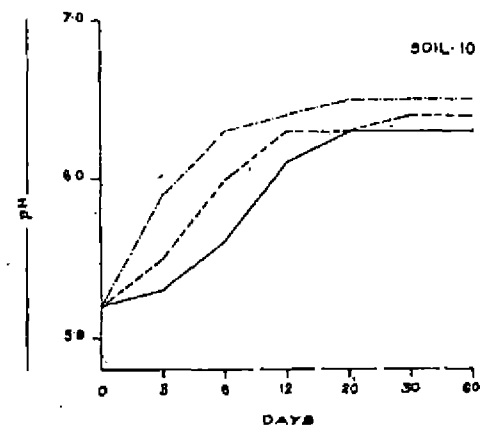
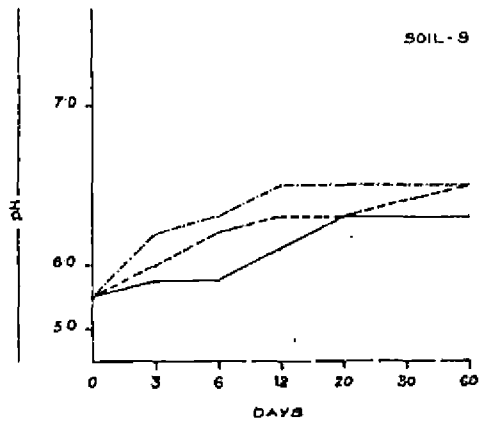
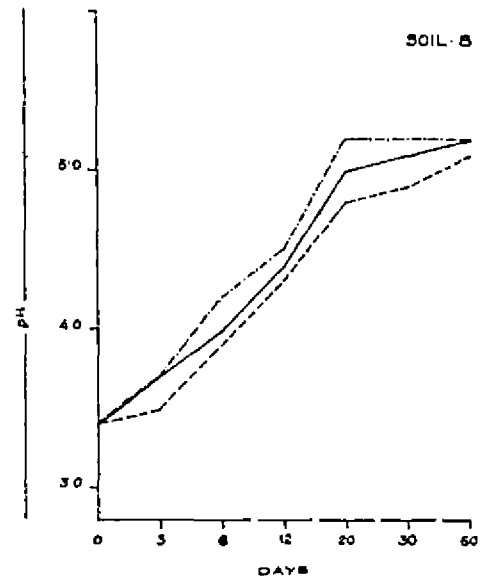
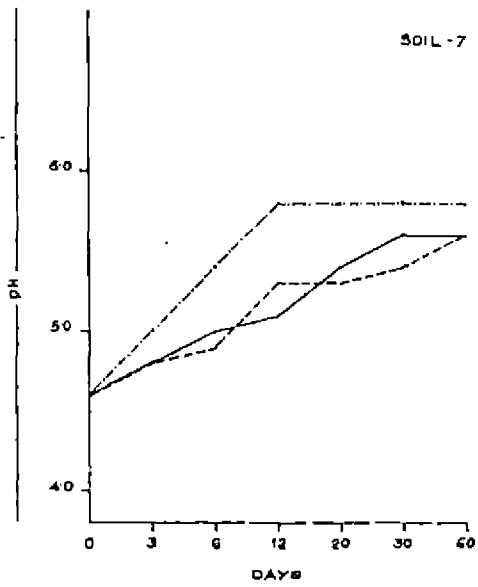
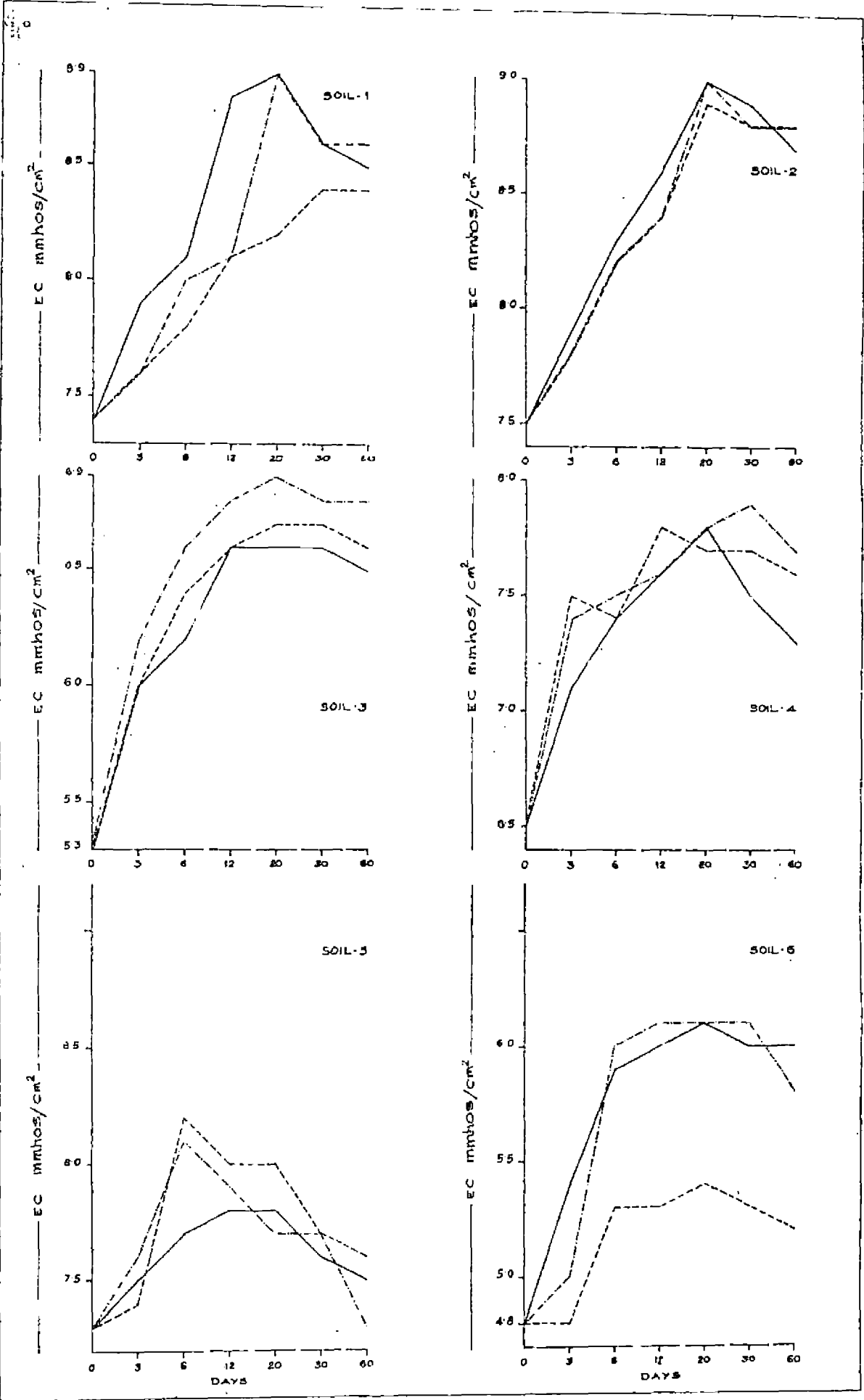
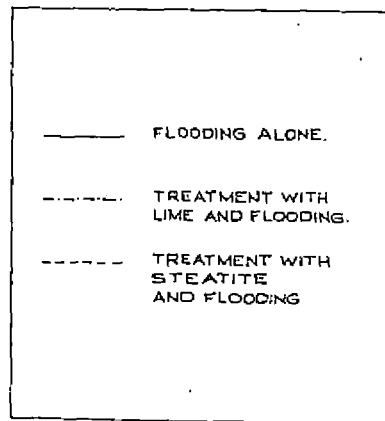
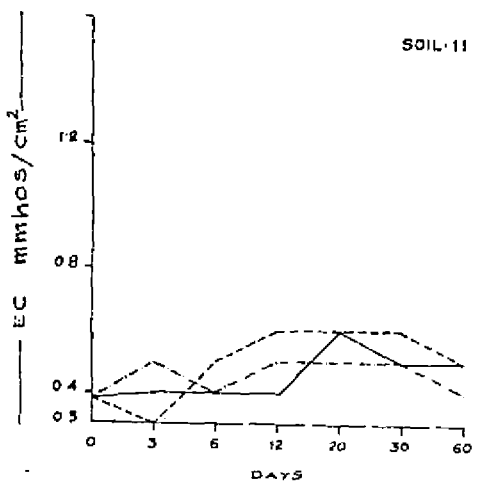
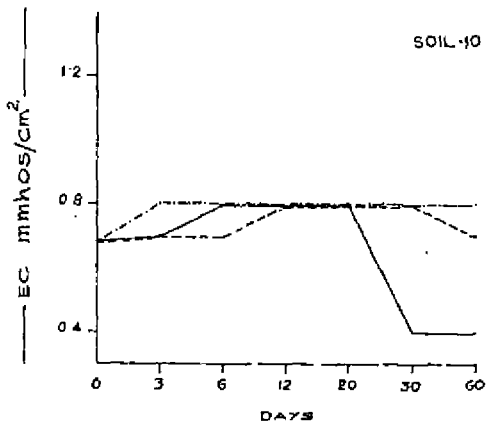
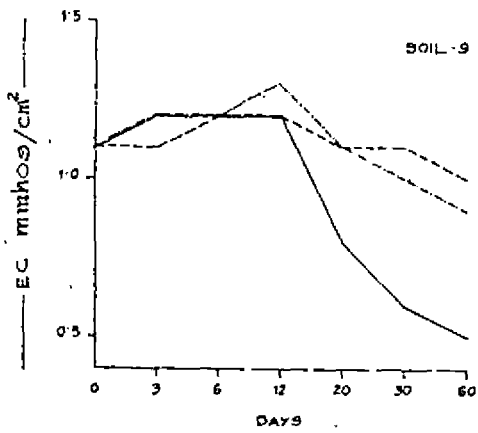
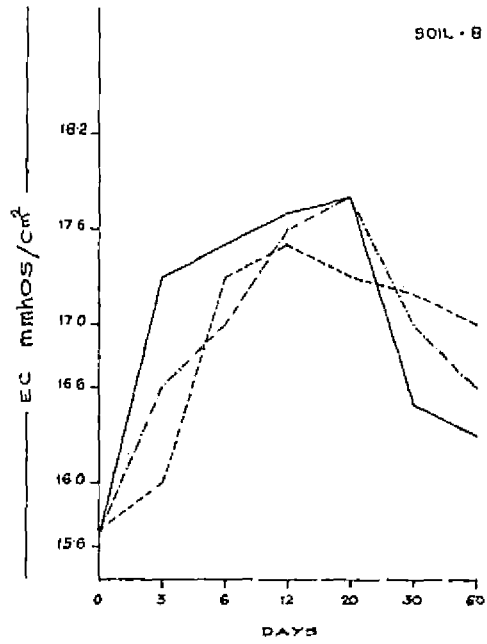
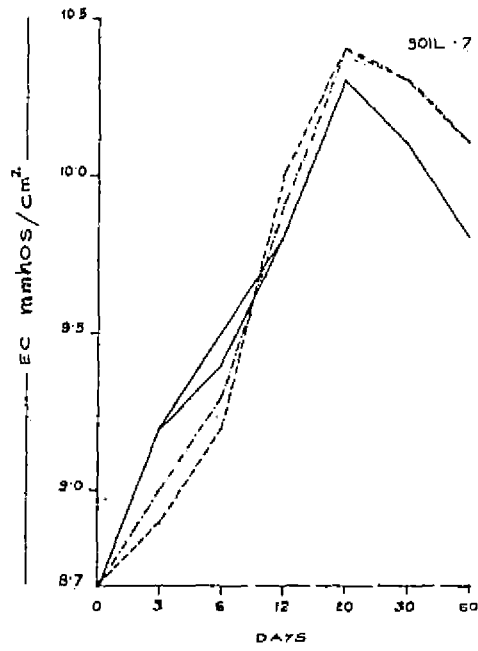


Fig. 4. Changes in EC of soils with time due to treatment with lime and steatite and flooding





pH over a period of flooding for two months was highest for the coastal sandy soils (6.1) while the samples representing the kari and pokkali soils recorded comparatively lower values (4.3 and 4.4). It may be noted that a very high shift in pH from the initial value was recorded for the kari and pokkali soils (1.7 to 1.9 units), while for the remaining soil types the shift was in the range of 0.5 to 1.3 units only, the minimum shift being registered by the coastal sandy soils and the maximum by the kayal soils of Kuttanad.

The rise in pH for the different soils due to flooding in water was significant even after the third day, and it continued to increase significantly till the end of 20 days after which it remained more or less steady.

EC

Changes in EC were also significant in the different soils during submergence. EC was maximum in the pokkali soils (16.9 mmhos/cm²) and minimum in the brown hydromorphic soil from Vellayani (0.4 mmhos/cm²). In most of the soils, maximum rise in EC was observed by the 20th day and after that a significant diminution was observed, which trend persisted till the end of the two month period, showing a quadratic pattern in the sequence of changes. By the 20th day, the maximum rise in EC was obtained in the case of the

pokkali soils (2.1 mmhos/cm²) while the least rise of 0.1 unit for the coastal sandy soils was obtained after three days of submergence itself.

Water soluble aluminium

Submerging the soils in water for a period of two months brought about appreciable reduction in the content of water soluble aluminium in all the soils. The reduction was evident from the third day of flooding and reached a magnitude of significance after the sixth day, registering only marginal changes on further submergence.

Mean values of water soluble aluminium over a period of two months was very high in the two kari and pokkali soils (19, 22 and 15 ppm) and lowest in the coastal sandy soils (2 ppm). Among the different soils used for the study, the fall in water soluble aluminium from the initial level was most prominent for the kari and pokkali soils (11, 14 and 13 ppm) while in all the other samples it ranged from 1 to 6 ppm only.

Exchangeable aluminium

Exchangeable aluminium was highest in the two samples of kari soil (825 and 970 ppm). All other soils except the sandy and low level laterites exhibited high values for exchangeable aluminium ranging from 252 to 480 ppm. As a result of flooding for two months, the mean values over the

different periods came down to 598 and 792 ppm for the kari soils and comparatively lower reduction was noted in the case of the other soils also.

The reduction in exchangeable aluminium in all the soils was noticed from the 6th day of flooding, and it continued till the 30th day and at the end of two months, a slight increase from the values obtained on the 30th day was recorded.

Water soluble iron

Flooding of the soils resulted in a rise in the content of water soluble iron in all the soils, the most significant changes being shown by the kari and pokkali soils. The results presented in table 6(b) show that upto the 20th day the water soluble iron content continued to increase significantly between periods and decreased slowly from the 30th day till the end of two months. The reduction in water soluble iron between the 30th day and the 2 month period was not, however, significant.

The difference in the pattern of solubilisation of iron was not significant for the different soils. Maximum value for water soluble iron was obtained for most of the soils on the 20th day and the values varied from 3 ppm in the coastal sandy soils to as high as 106 ppm in the kari soils.

Exchangeable iron

From the results in tables 6(a) and 6(b), it may be seen that the exchangeable iron content of the soils showed an appreciable increase with increasing periods of submergence. The maximum rise for most of the soils was recorded on the 20th day, after which a gradual decrease was seen. Exchangeable iron was highest for the kari soils (730 and 789 ppm) followed by the pokkali soils (369 ppm). For the other soils, the exchangeable iron ranged between 16 and 162 ppm.

b) Submerging of the soils in water after treatment with lime pH

From the results presented in tables 6(c), 6(d) and appendix 1(b) it may be noted that the pH of all the soils used in the present study showed a significant increase due to submergence in water with the addition of lime, the pH becoming steady by the 20th day. Further changes during the next two periods were not appreciable.

The effect of lime in increasing the pH was more for the kari and pokkali soils (1.7 to 1.9 units) and in the other soils, the increase was in the range of 0.7 to 1.4 units.

EC

For the various soils, the EC remained high at all periods compared to the initial values. The highest value

Table 6(c) Physico-chemical properties of soils after treatment with lime and submergence in water: mean values over a period of two months

Soil Sl.No.	pH	EC	Al (H ₂ O) (ppm)	Al(Exch) (ppm)	Fe (H ₂ O) (ppm)	Fe (Exch) (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	4.5	8.2	20	465	43	480
2	4.5	8.4	22	595	43	577
3	6.0	6.5	8	160	21	74
4	6.0	7.5	8	150	16	97
5	6.1	7.6	8	247	21	111
6	6.1	5.9	10	274	19	96
7	5.5	9.7	14	188	22	117
8	4.5	16.9	18	350	43	265
9	6.3	1.1	1	12	2	9
10	6.2	0.7	1	14	11	29
11	6.2	0.5	3	16	11	32
CD	0.2	0.4	5	86	12	134

Table 6(d) Physico-chemical properties of soils after treatment with lime and submergence in water: mean values for seven periods of sampling over a period of two months

Soil properties (1)	Period (days)							CD (9)
	1(0) (2)	2(3) (3)	3(6) (4)	4(12) (5)	5(20) (6)	6(30) (7)	7(60) (8)	
pH	4.7	5.2	5.6	5.8	6.0	6.0	6.0	0.2
EC (mmhos/cm ²)	5.9	6.3	6.7	6.8	7.0	6.8	6.8	0.3
Al (H ₂ O) (ppm)	15	13	9	13	10	8	8	3.0
Al (Exch) (ppm)	374	270	236	239	153	151	150	7.0
Fe (H ₂ O) (ppm)	6	9	27	30	30	32	27	10
Fe (Exch) (ppm)	19	39	172	236	236	290	212	111

Fig. 5. Changes in water soluble aluminium of soils with time due to treatment with lime and steatite and flooding

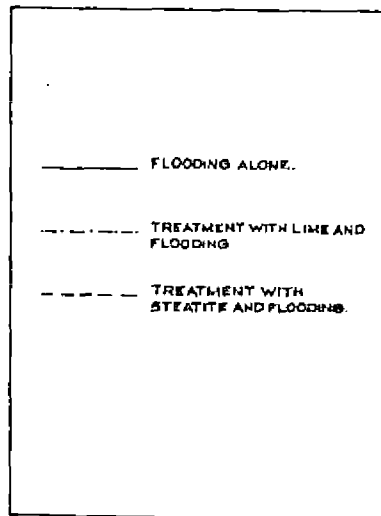
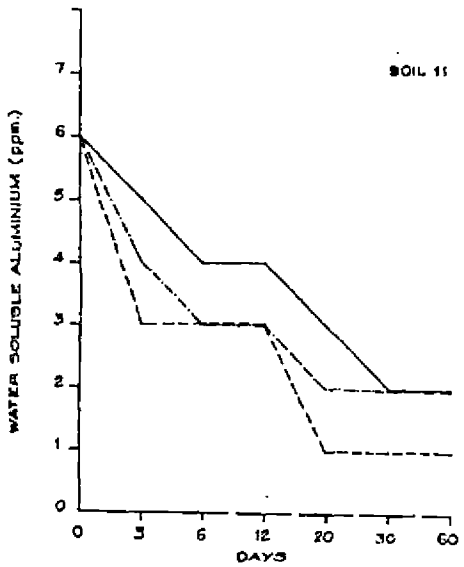
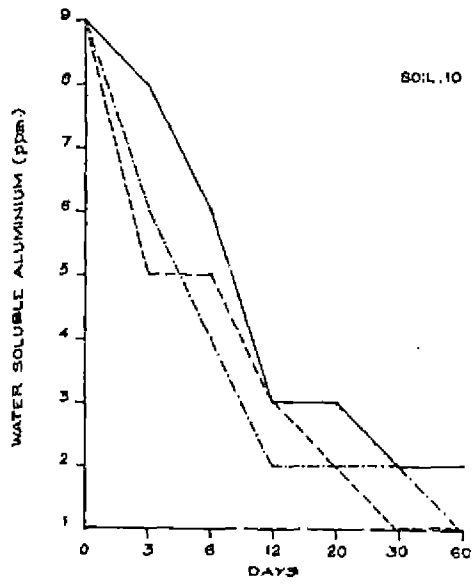
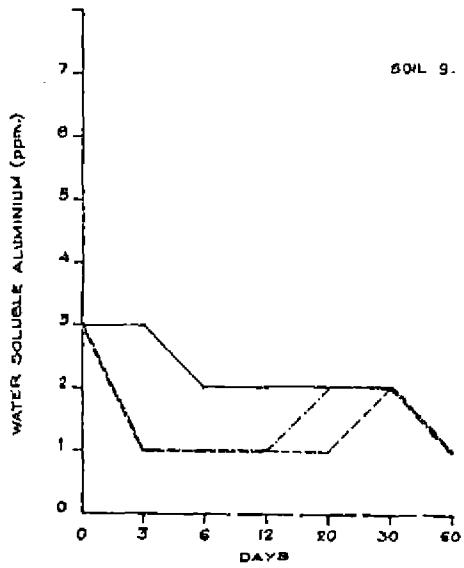
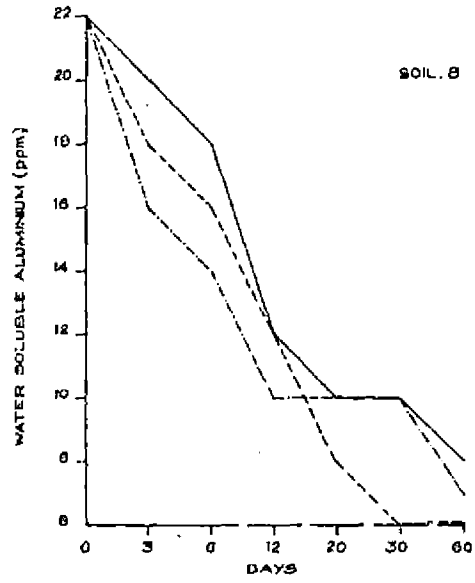
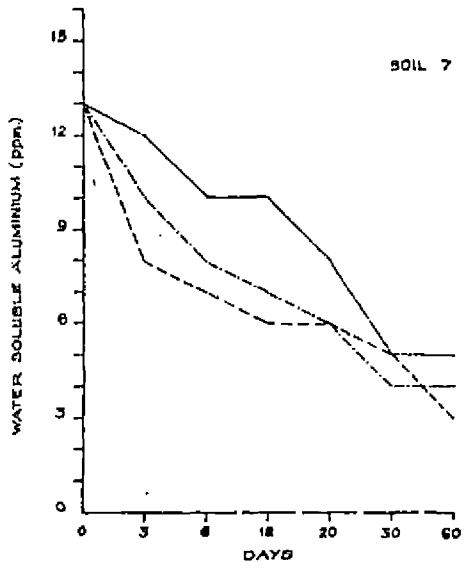
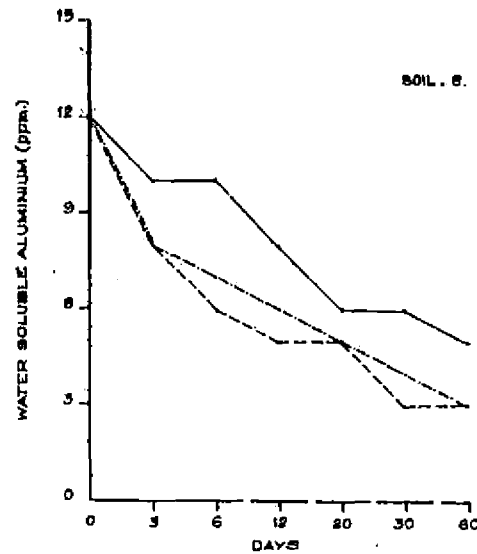
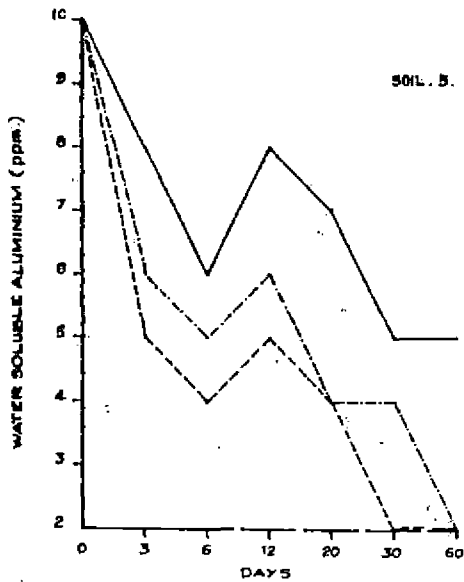
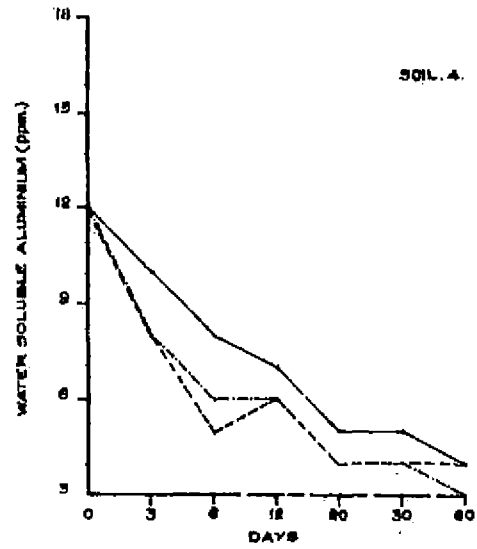
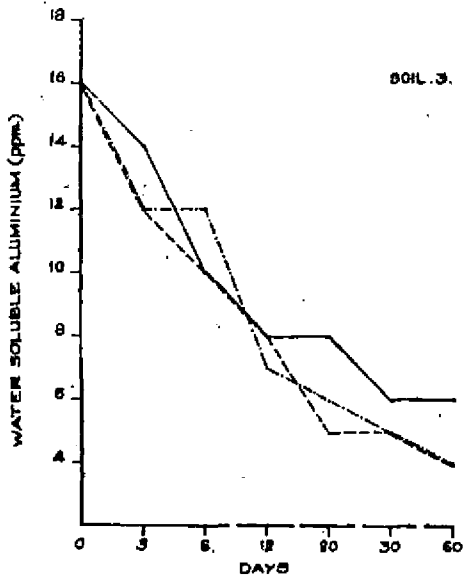
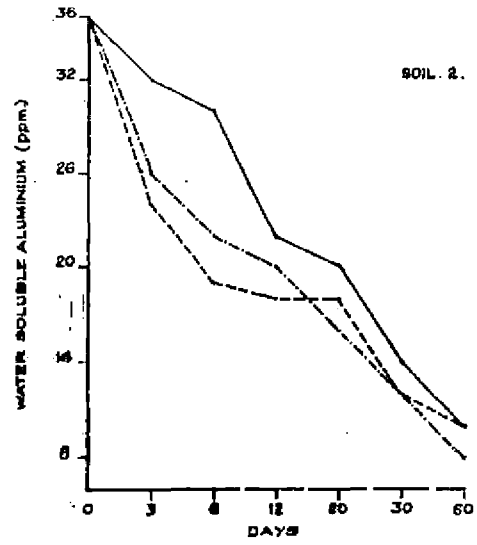
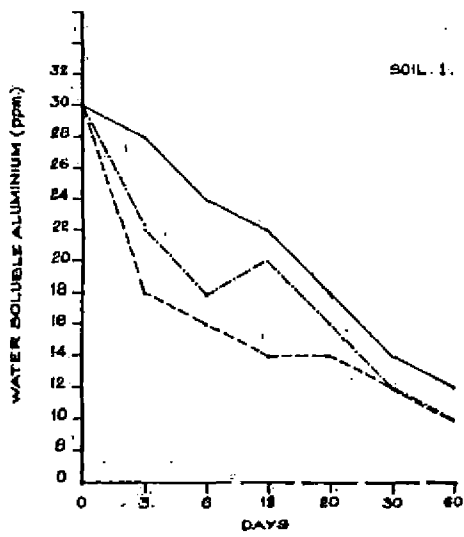
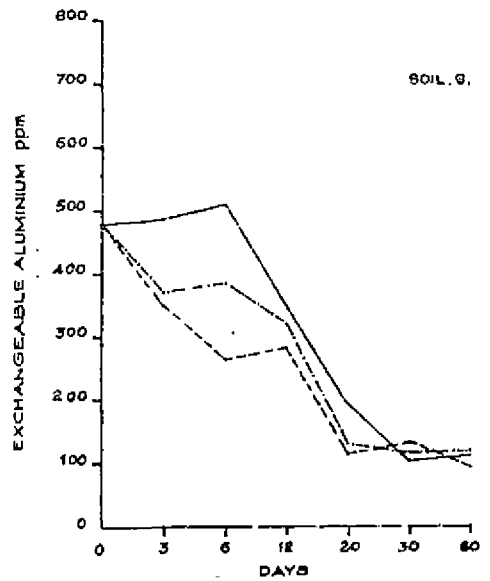
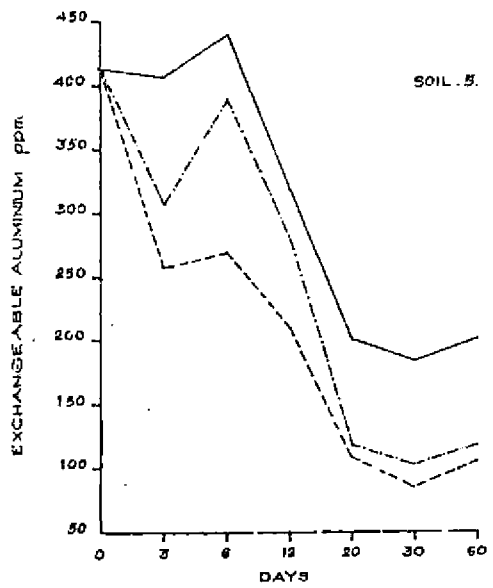
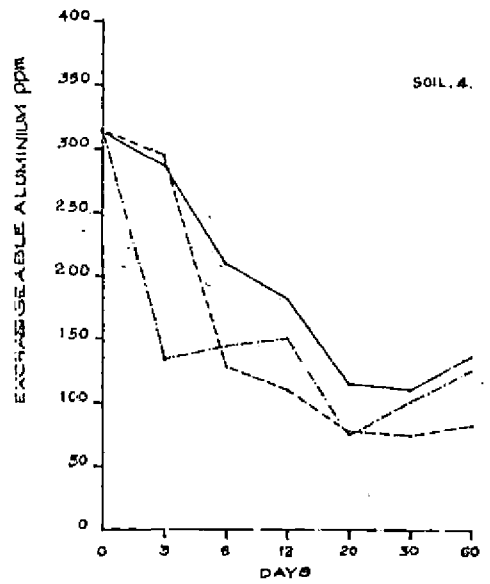
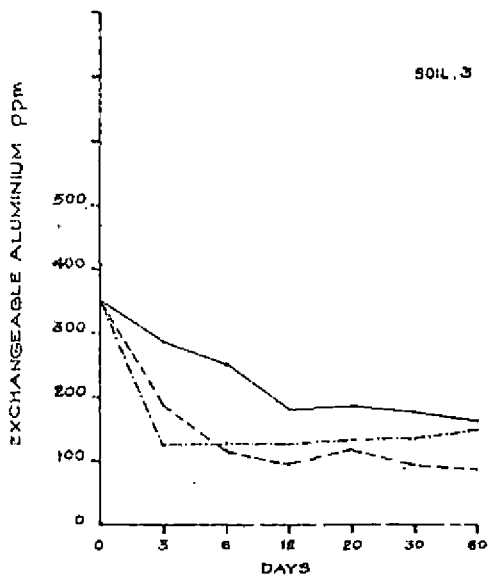
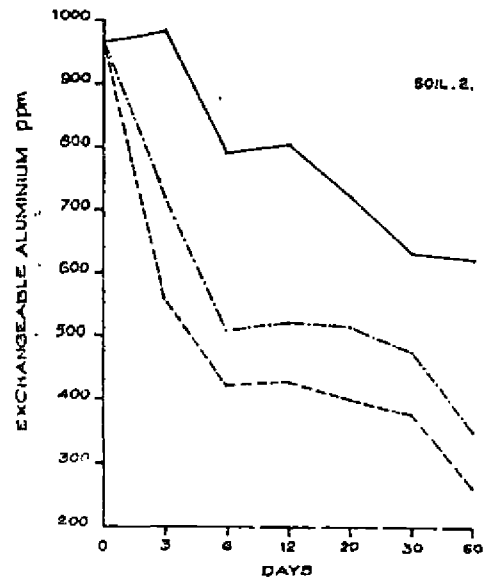
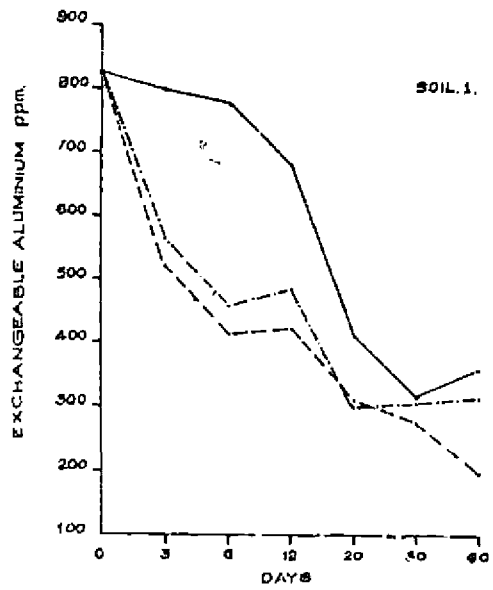
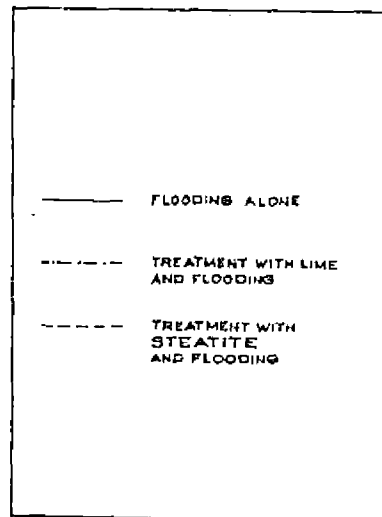
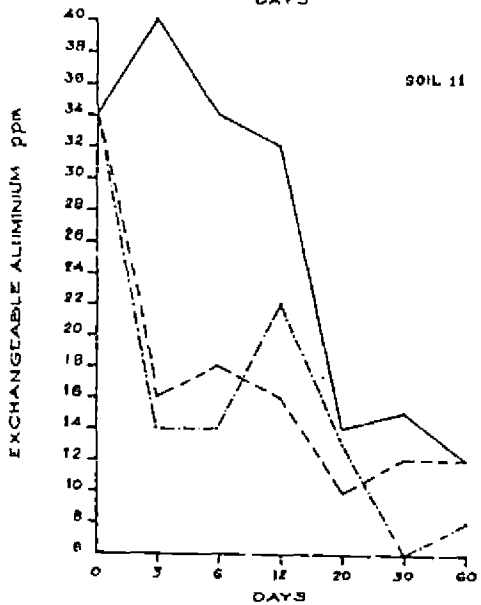
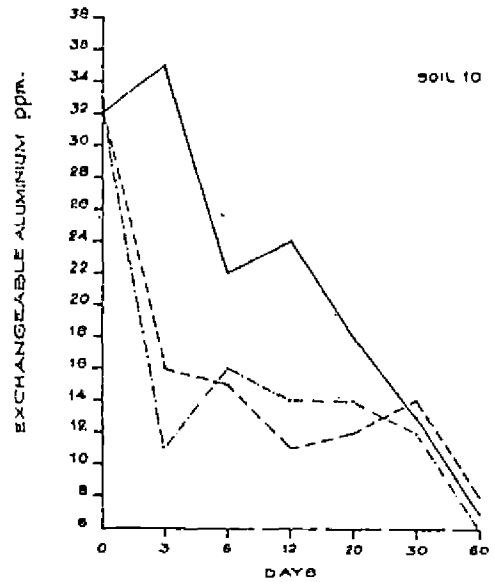
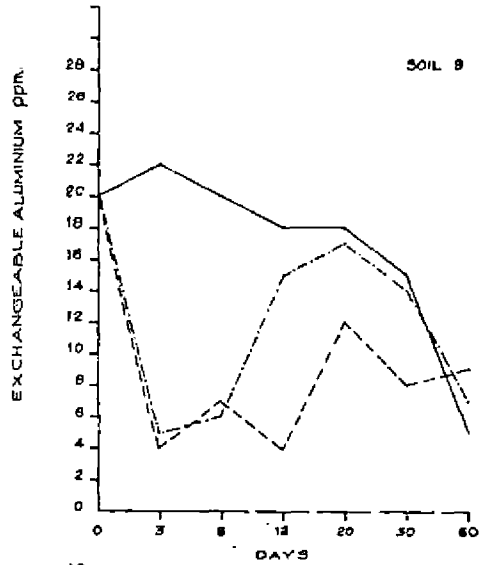
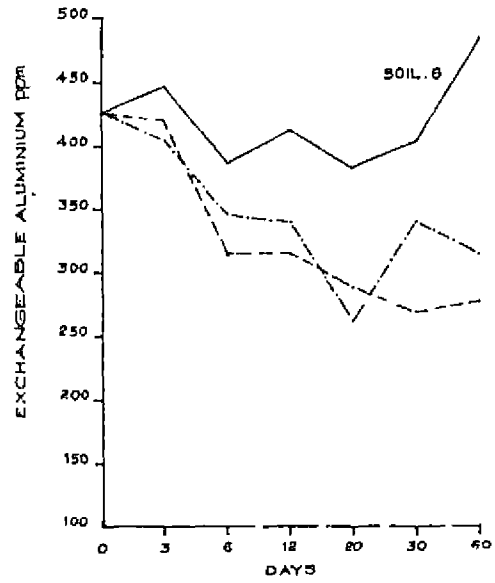
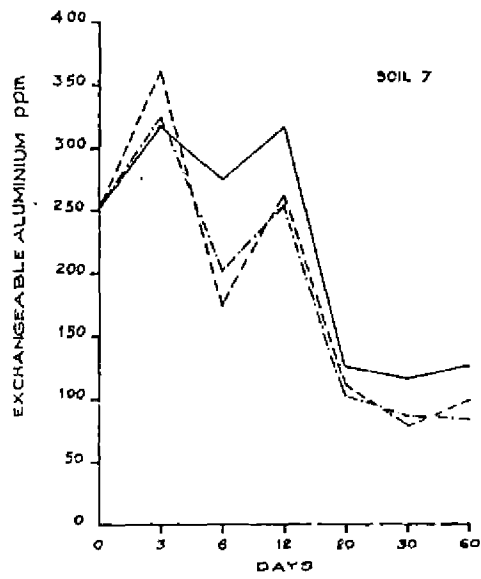


Fig. 6. Changes in exchangeable aluminium of soils with time due to treatment with lime and steatite and flooding







for mean EC over periods was recorded on the 20th day, whereafter, it decreased. However, the decrease was not significant.

Maximum rise in EC was obtained for the pokkali soils, followed by the kayal, karapadam and kari soils (1.7, 1.7 and 1.5 units).

Water soluble aluminium

The decreasing trend in water soluble aluminium was more marked till the 6th day of submergence and reduction at the later periods was not appreciable between successive periods. High values (22, 20 and 18 ppm) were recorded for the kari and pokkali soils and comparatively lower values (1 to 14 ppm) for the other soil types.

Exchangeable aluminium

A significant decrease in exchangeable aluminium was recorded on the third day of submergence of the soils with lime. Although the negative trend continued till the end of the incubation period, a further significant change was seen on the 20th day, and after that a steady state was attained. Thus, in the soil treated with lime mean value for exchangeable aluminium over the two month period of flooding for the eleven soils decreased from the initial level of 374 ppm to 150 ppm.

The highest decrease in exchangeable aluminium, compared

to the initial level was observed in the case of kari soils followed by the kayal and karapadam soils, while for the pokkali soils, the reduction was not appreciable.

Water soluble iron

Over a period of submergence for two months, the mean value for water soluble iron recorded a nearly five fold increase, the maximum being obtained after 30 days of incubation. The increase was significant from the 12th day and further changes with increasing periods were not appreciable.

Water soluble iron was highest for the kari and pokkali soils (43 ppm each) recording nearly five times increase due to flooding. In the other soils, the water soluble iron ranged from 2 to 22 ppm showing only 2 to 3 fold increase from the initial content.

Exchangeable iron

As in the case of water soluble iron, the mean value for exchangeable iron was highest after 30 days of submergence (290 ppm). Substantial increase in exchangeable iron was observed from the 6th day and the increase continued till the 30th day, after which a decreasing tendency was noted.

Of the eleven soils, the kari soils recorded the maximum content of exchangeable iron followed by the pokkali soils. Although, the initial level of exchangeable iron was similar in these soil types a very high rate of increase was noted

(nearly 20 times) for the kari soils, the increase for the pokkali soils being only about ten times. In the other soils the magnitude of increase was comparatively lower.

c) Submerging of the soils in water after treatment with steatite

pH

Significant changes in pH with respect to the initial values were obtained for the soils treated with steatite and submerged under water. It may be seen from tables 6(e) and 6(f) and appendix 1(c) that the increase in pH between the first two periods of flooding was not much, while that between the 3rd and 4th periods was highly significant (an increase of 0.6 pH units). After the 20th day, however, the rise was slower and not appreciably different between the successive periods. The extent of variation in pH among the soils followed the same pattern as with flooding of the soil with water alone.

EC

The EC was significantly different for the different periods for the various soils. Marked increase in EC was noted from the 6th day onwards and further changes were only meagre.

Among the eleven soils, rise in EC over the two month period was highest in the case of the pokkali and kari soils and in the other soils the rise was not so marked.

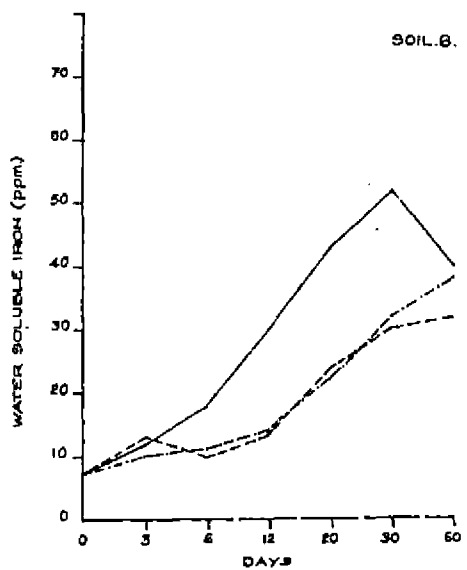
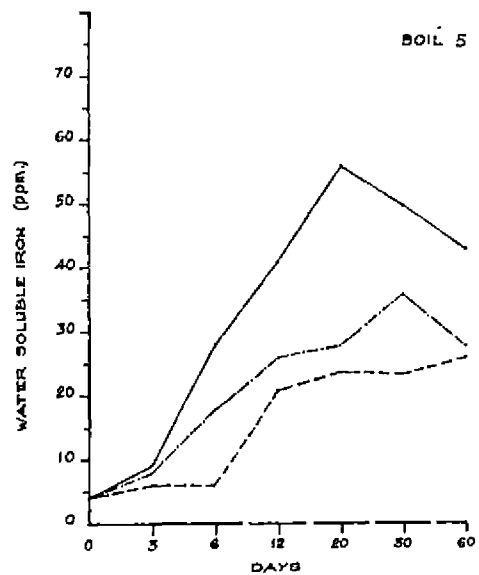
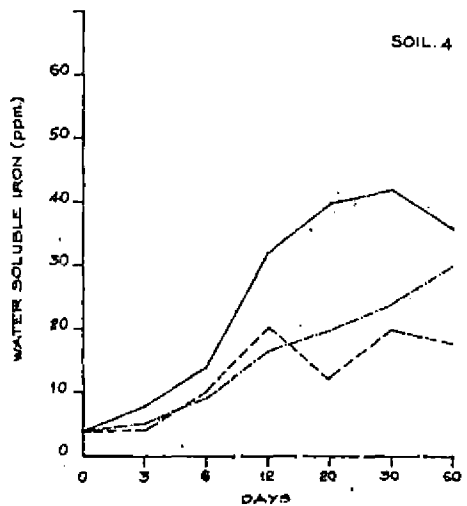
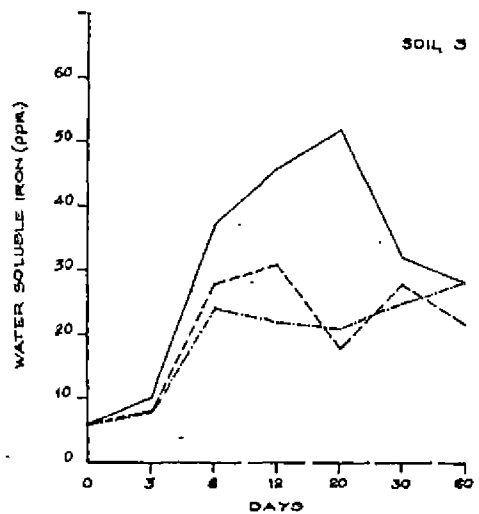
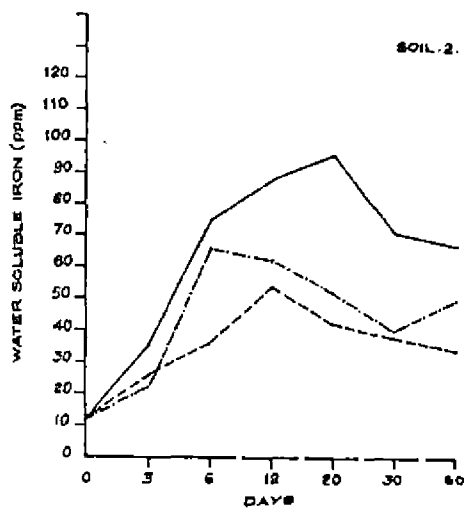
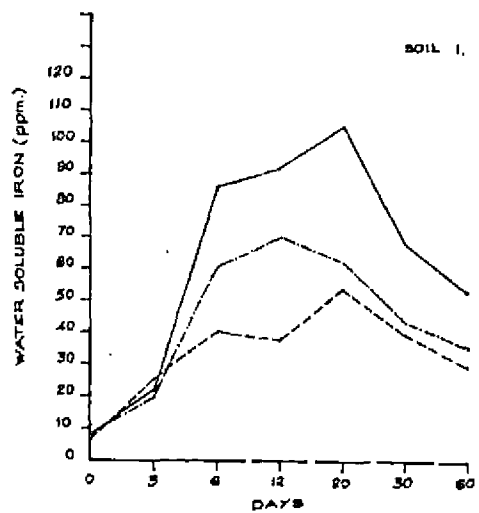
Table 6(e) Physico-chemical properties of soils after treatment with steatite and submergence in water: mean values over a period of two months

Soil Sl.No.	pH	EC (mmhos/cm ²)	Al (H ₂ O) (ppm)	Al(Exch) (ppm)	Fe(H ₂ O) (ppm)	Fe(Exch) (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	4.4	8.0	17	424	34	330
2	4.2	8.3	20	504	35	403
3	5.8	6.3	9	149	18	65
4	5.9	7.5	9	126	13	71
5	6.0	7.8	8	208	16	78
6	6.0	5.2	9	245	18	86
7	5.1	9.7	12	190	19	108
8	4.3	16.9	17	324	31	237
9	6.0	1.1	2	9	2	7
10	6.1	0.7	4	15	6	23
11	6.1	0.5	4	17	11	28
CD	0.3	0.3	10	90	9	95

Table 6(f) Physico-chemical properties of soils after treatment with steatite and submergence in water: mean values for seven periods of sampling over a period of two months

Soil properties (1)	Period (days)							CD (9)
	1(0) (2)	2(3) (3)	3(6) (4)	4(12) (5)	5(20) (6)	6(30) (7)	7(60) (8)	
pH	4.7	4.9	5.0	5.6	5.8	5.9	6.0	0.3
EC (mmhos/cm ²)	5.9	6.2	6.6	6.8	6.8	6.8	6.7	0.2
Al (H ₂ O) (ppm)	15	12	11	11	8	7	7	2.9
Al (Exch) (ppm)	374	254	195	206	139	128	112	7.2
Fe (H ₂ O) (ppm)	6	10	17	20	25	29	25	7
Fe (Exch) (ppm)	19	46	135	143	188	201	182	76

Fig. 7. Changes in water soluble iron of soils with time due to treatment with lime and steatite and flooding



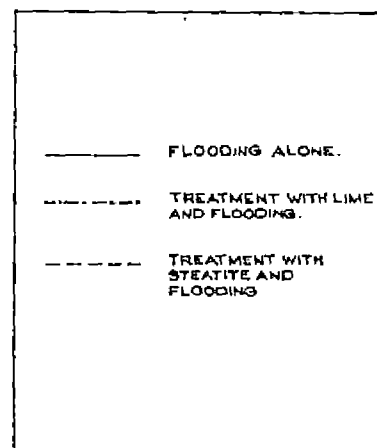
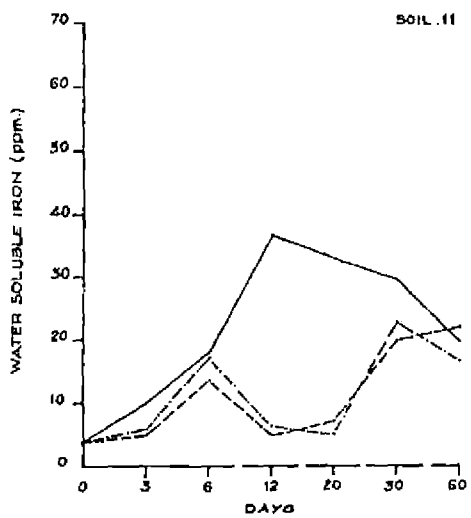
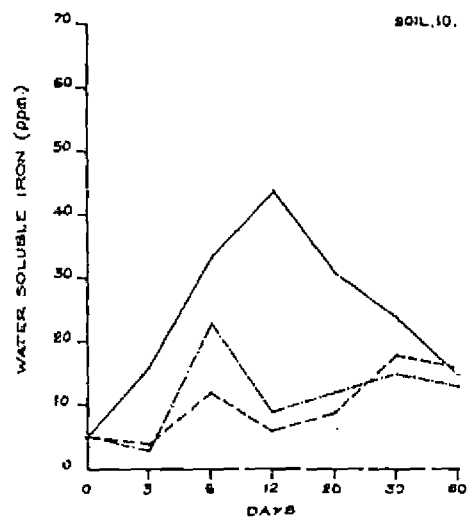
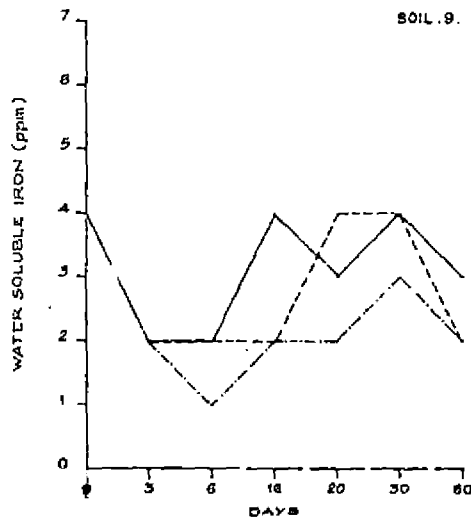
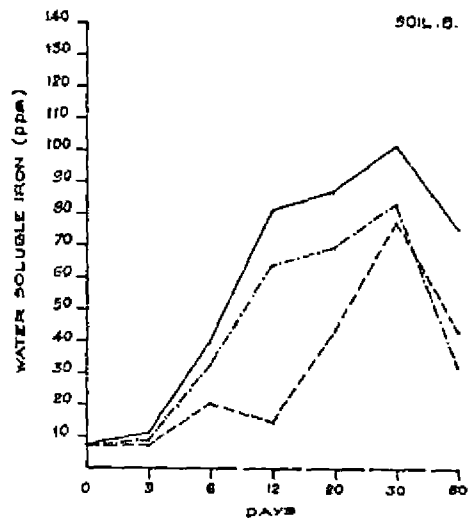
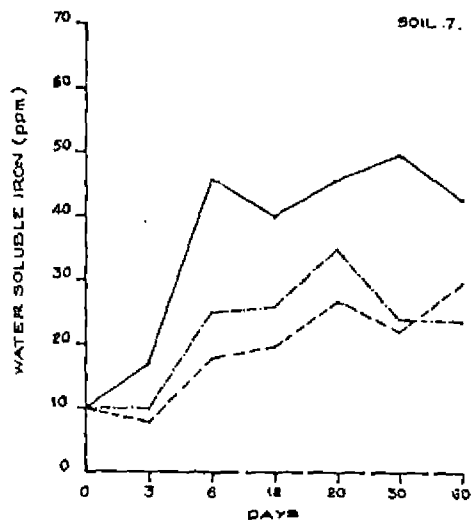
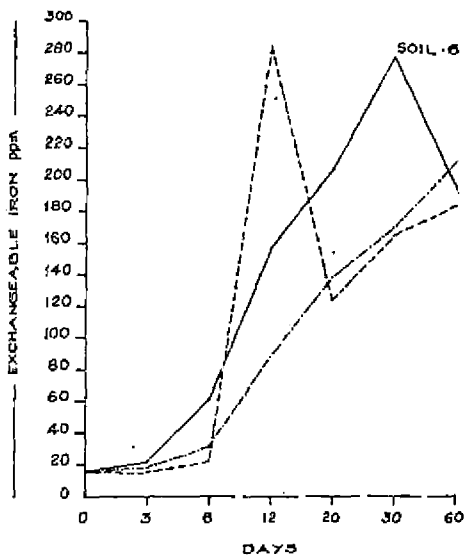
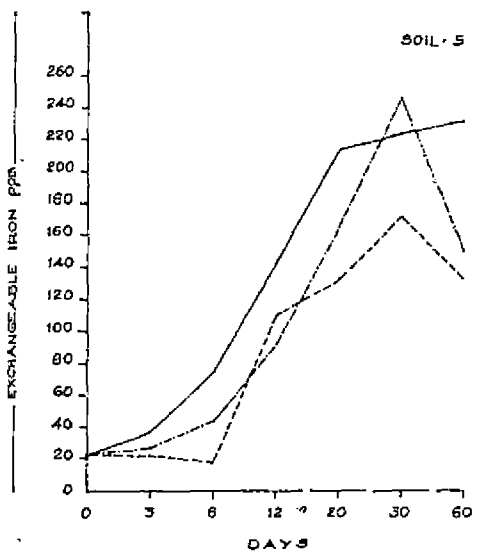
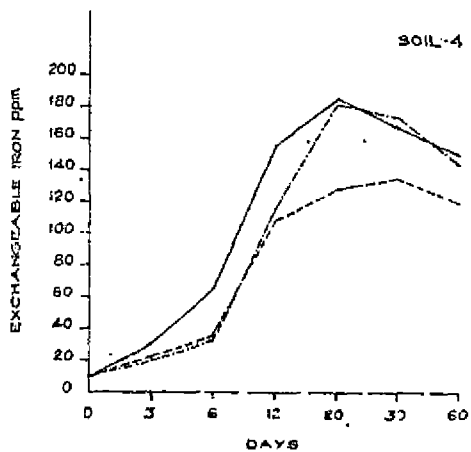
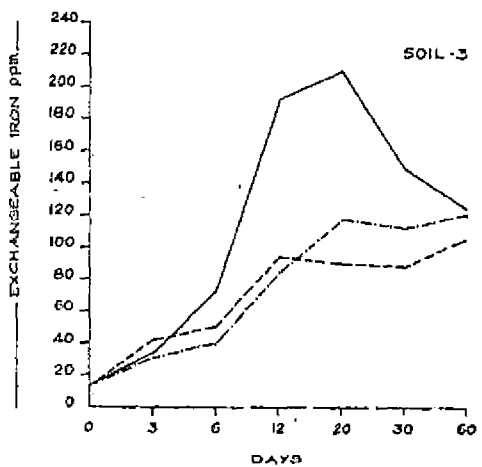
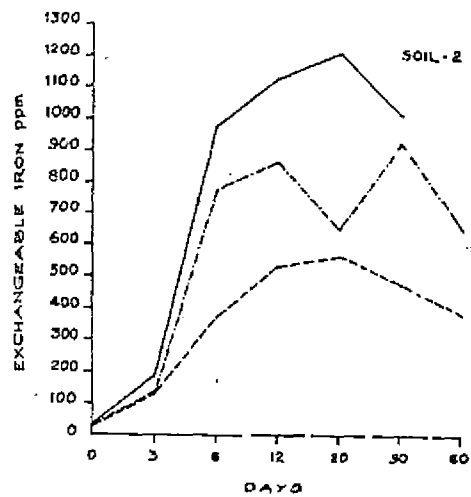
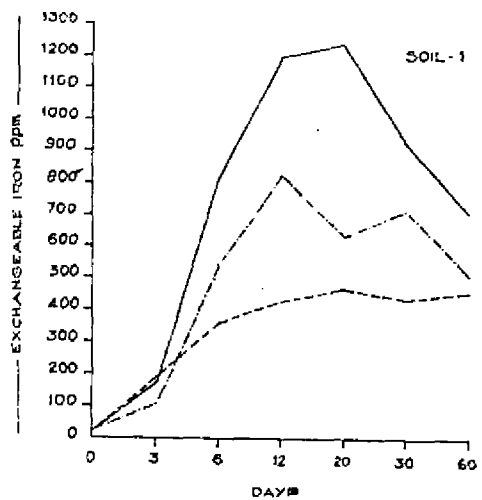
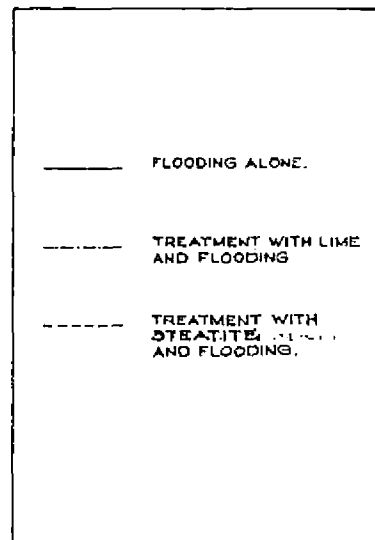
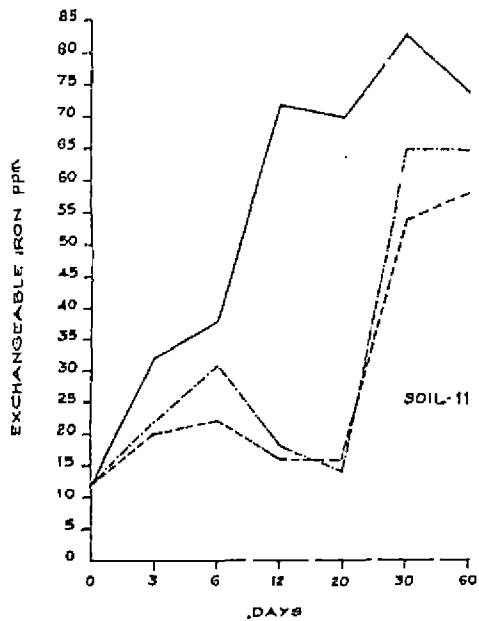
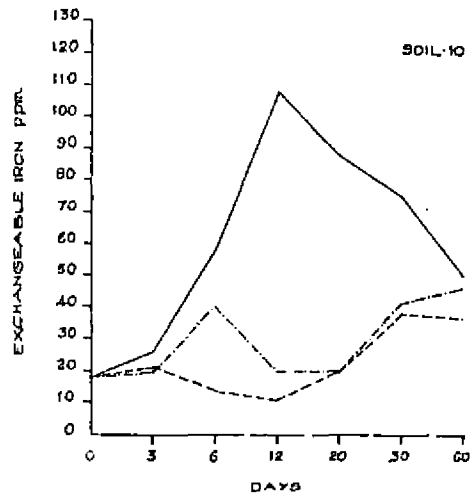
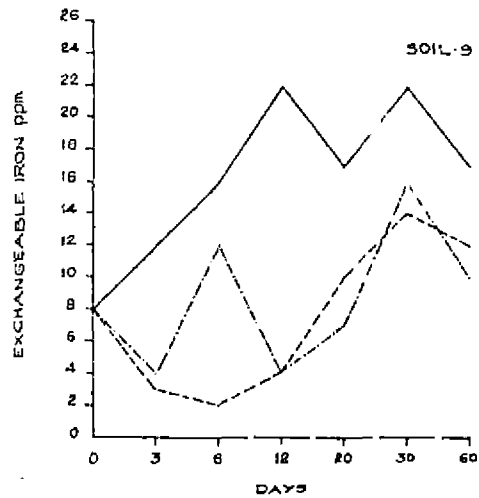
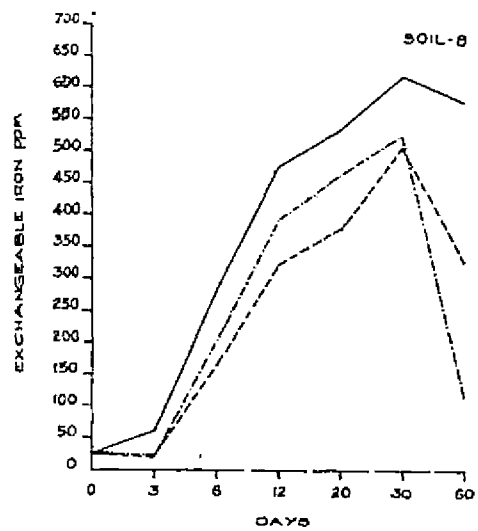
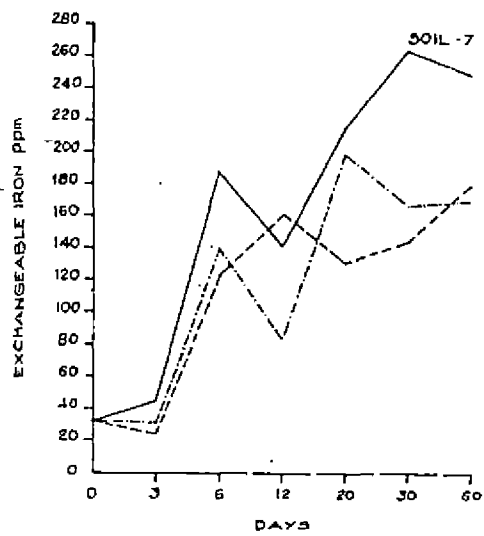


Fig. 8. Changes in exchangeable iron of soils with time due to treatment with lime and steatite and flooding





Water soluble aluminium

A reduction in water soluble aluminium was observed in all the soils on flooding after treatment with steatite. Significant decrease was obtained from the 20th day, but the changes between consecutive periods of flooding were not marked. Reduction in water soluble aluminium was maximum (13 to 16 ppm) in the kari soils as compared to the other soil groups where a reduction of only 4 to 5 ppm were noted.

Exchangeable aluminium

Even from the 3rd day of flooding, a marked decrease in exchangeable aluminium was observed. This decreasing trend continued till the end of the 60 day incubation period, although, the decrease between successive periods was not very marked.

Of the eleven soils studied, the maximum decrease was noted for the kari soils and the least for the coastal sandy and brown hydromorphic soils. In the other soils, the changes were more or less similar.

Water soluble iron

The tendency for water soluble iron to increase with increasing periods of submergence was evident from the results obtained. Significant increase in water soluble iron compared to the initial status was recorded on the 6th day. Changes

between successive periods till the end of the 60th day of incubation, although exhibited a positive trend, were not appreciable. A slight reduction in water soluble iron was also observed after 30 days of flooding. A reddish scum of iron oxide on the surface of the water in the pot, noted in the other treatments was absent in this treatment.

Exchangeable iron

Highly significant increase in the exchangeable iron was observed in all the soils from the 6th day. Although the increasing trend continued during the entire period of flooding, the changes between consecutive periods, were not too large. As in the case with water soluble iron, a slight reduction in exchangeable iron was observed after the 30th day. The two kari and one pokkali soils registered 330, 403 and 237 ppm exchangeable iron, while it was as low as 7 ppm for the coastal sandy soil and ranged only upto 107 ppm in the kayal soils.

d) A comparison of the effect of the three treatments on changes in physico-chemical properties of soils

The results of the pooled analysis of the data obtained by flooding of the soils in water and after treatment with lime and steatite for various periods are given in appendix 1(d).

From the results it may be seen that of the soil properties studied, pH, EC and water soluble aluminium were

not much affected by the different treatments. But significant difference due to the treatments was obtained for exchangeable aluminium, as well as for both water soluble and exchangeable iron.

Exchangeable aluminium

Exchangeable aluminium was significantly lower (225 and 201 ppm) in the soils treated with lime and steatite in comparison to that of the soils flooded in water alone (285 ppm). The content of exchangeable aluminium in the treatments with lime and steatite was not significantly different.

Water soluble iron

Soils flooded with water alone contained 35 ppm water soluble iron while the soils treated with lime and steatite recorded only 23 and 19 ppm respectively, the differences between the three treatments being statistically significant.

Exchangeable iron

Exchangeable iron was also significantly lower in the soils treated with lime and steatite, although between the two treatments no appreciable difference was observed.

The results of the pooled analysis also revealed significant differences between the different soils with respect to the soil properties studied. Significant variation in

soil properties was also revealed for various periods of submergence. No interaction was noted for the treatments either with various types of soils or with period of submergence indicating that the soils responded independently to treatments during different periods of submergence.

3. Pot culture experiment

The results obtained in the pot culture experiment to study the effect of different ameliorative treatments in a highly acidic soil on characters like pH, EC, water soluble and exchangeable forms of aluminium and iron and their effects on the growth and yield of a crop of rice are presented.

A. Effect of the treatments on the physico-chemical properties of soils (Table 7(a) and fig.9)

pH

The mean pH of the soils in the different treatments sampled at specified intervals showed a significant rise in comparison to the untreated soil which registered the lowest pH of 4.9. Lime at 1200 kg/ha (T_2) raised the soil pH to the maximum value of 5.7 which was significantly higher than that in all the other treatments, where it varied between 5.2 and 5.5.

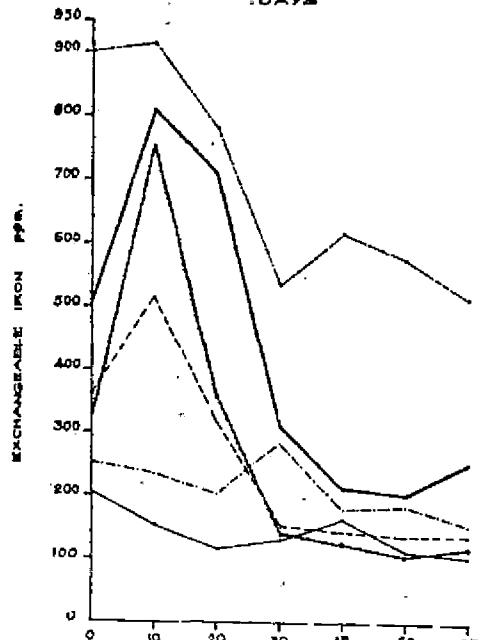
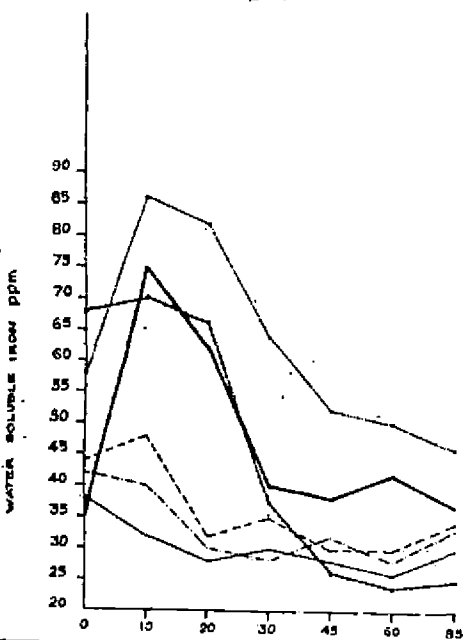
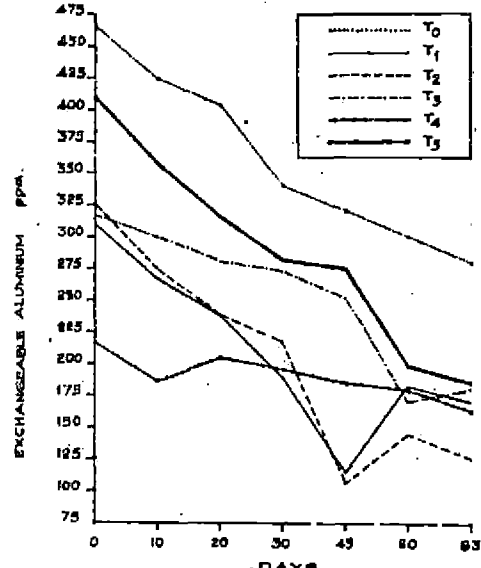
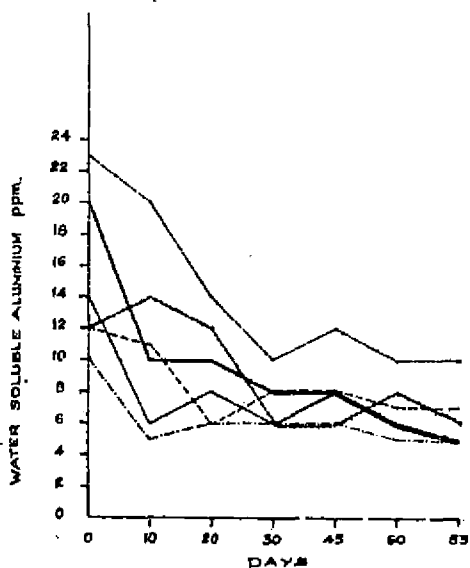
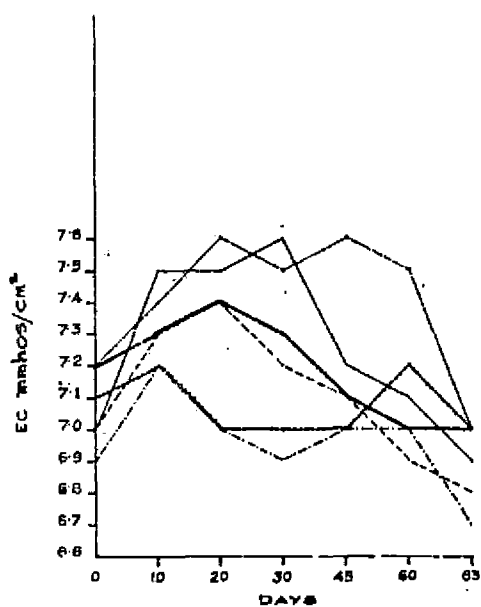
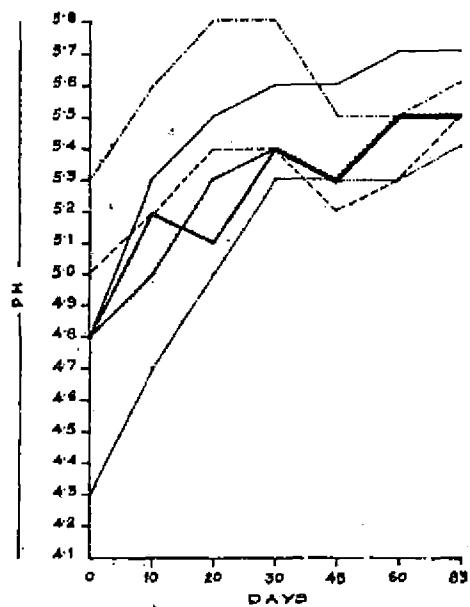
EC

The EC of the soils remained high throughout the period of growth of the crop. The highest EC of 7.5 mmhos/cm² was

Table 7(a) Influence of different treatments on the physico-chemical properties of soils: mean values for seven periods of sampling

Treat- ment	pH	EC (mmhos/ cm ²)	Water- soluble Al (ppm)	Exchan- geable Al (ppm)	Water- soluble Fe (ppm)	Exchang- eable Fe (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
T ₀	4.9	7.5	14	414	61	660
T ₁	5.5	7.3	8	205	25	135
T ₂	5.7	7.0	7	224	31	214
T ₃	5.4	7.1	8	210	32	254
T ₄	5.2	7.2	10	195	39	275
T ₅	5.5	7.2	9	269	46	430
CD	0.2	0.2	5	86	12	122

FIG. 9 EFFECT OF DIFFERENT TREATMENTS ON THE VARIATION IN SOIL CHARACTERS



recorded in the control pot while in the other treatments the conductivity was significantly lowered, the lowest value of 7.0 mmhos/cm² being recorded in T₂. However, the difference in EC between the different treatments was not significant.

Water soluble aluminium

Mean value of water soluble aluminium, throughout the cropping period was significantly higher (14 ppm) in the unamended soil compared to the others, where it varied from 7 to 10 ppm only. No significant difference was noted between the various treatments in controlling the water soluble aluminium in the soil.

Exchangeable aluminium

The exchangeable aluminium in the soil was suppressed to a considerable extent by the treatment with different ameliorants. The level of exchangeable aluminium was brought down from 414 ppm in the unlimed control to the lowest value of 195 ppm in the treatment with green leaves (T₄), followed by 205 ppm in the treatment with steatite (T₁). Lime @ 600 kg/ha (T₅) was not enough to effectively control the exchangeable aluminium level as the other ameliorants. A significantly higher amount (269 ppm) of aluminium was present in this treatment.

Water soluble iron

A significant reduction in the content of water soluble iron was noted for all the treatments, T₁ recording the lowest mean value of 25 ppm followed by T₂ and T₃ with 31 and 32 ppm respectively. In the untreated soil, a mean value of 61 ppm water soluble iron was present during the period of the study.

Exchangeable iron

The amount of exchangeable iron in the differently treated pots also showed significant variations. The maximum value of 660 ppm iron was obtained in the untreated soil (T₀) while all the other treatments recorded much lower values. T₁ (steatite) had 135 ppm exchangeable iron which was on par with T₂ and T₃ with 214 and 254 ppm respectively. The exchangeable iron was, however, significantly higher in treatments T₄ and T₅ (275 and 430 ppm).

B. Plant characters and yield

Table 7(b) and appendix 2(a) present the mean data on the important growth characters and the weight of grain and chaff of rice obtained in the pot culture experiment.

Height of the plant

The average height of the plants in the differently treated pots was significantly higher than that in the un-amended pots. The increase in height was marked in the

Table 7(b) Influence of different treatments on plant characters

Treat- ment	Height of plant (cm)	Number of pro- ductive tillers	Length of roots (cm)	Weight of straw (g)	Weight of root (g)	Weight of grain (g)	Weight of chaff (g)	Grain/ straw ratio	Grain/ chaff ratio
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
T ₀	68.7	14.3	17.0	18.8	4.9	11.2	2.8	0.60	5.1
T ₁	81.7	19.7	28.2	28.6	6.7	17.6	1.3	0.62	14.3
T ₂	79.6	15.0	22.6	23.0	6.0	15.0	1.7	0.68	9.9
T ₃	78.0	17.7	22.3	20.9	6.1	15.8	2.6	0.78	5.9
T ₄	85.1	18.3	26.4	24.7	8.0	18.1	1.8	0.72	9.8
T ₅	73.7	17.0	22.7	23.2	6.2	14.4	2.4	0.62	5.3
CD	11.4	5.5	9.2	6.5	2.5	5.5	1.0	0.22	4.9

treatments with green leaves (85.1 cm) and steatite (81.7 cm) as compared to the other treatments. The minimum height of 68.7 cm was recorded by the plants in the control pot.

Number of productive tillers

An increase in the number of productive tillers, though not significantly different from that in the control pot was recorded in the different treatments. The maximum number of 19.7 productive tillers per plant was obtained for T_1 followed by T_4 with an average of 18.3. In the other treatments, it varied from 14.3 to 17.7.

Weight of straw

The weight of straw was markedly increased by the application of steatite (T_1 , 28.6 g) and green leaves (T_4 , 24.7 g) to the soil. For the other treatments, the increase was not marked and varied from 18.8 g in T_0 to 23.2 g in T_5 which received lime @ 500 kg/ha.

Appearance of roots

The colour of the roots was strikingly different in the plants in the various treatments. The base of the plant and most of the older roots had a dirty black colour. Many of the older roots were in different stages of decay in the control pots (T_0). This condition prevailed to a lesser extent in the plants receiving the other treatments also, except those treated with steatite (T_1). In this case, the

roots were fresh and turgid and the older roots were only slightly brown in colour. Comparatively larger number of white and elongated roots were present and blackening of the base and roots was completely absent.

Length and weight of roots

Significant increase in the length of roots was observed due to the effect of the different treatments, the maximum being observed for T₁ (28.2 cm) followed by T₄ (26.4 cm). The weight of the roots was also higher for treatments T₄ and T₁ which recorded 8.0 g and 6.7 g respectively. The lowest root length of 17.0 cm and lowest weight of 4.9 g were obtained for the plants in the pots which received no treatment.

Weight of grain

An increase in the weight of grain was obtained in all the treatments receiving ameliorants as compared to the control plants. The maximum weight of grain was recorded for T₄ (18.1 g) followed by T₁ (17.6 g) both being significantly higher than that of the control, where only 11.2 g grain was obtained from a pot.

Weight of chaff

A significant reduction in the weight of chaff was observed for treatments T₁, T₂ and T₄ while a slight reduction alone was noted for the other treatments as compared to the

control. Nearly 50 per cent reduction in the weight of chaff was obtained for T_1 (1.3 g as against 2.8 g chaff per pot in the case of T_0).

Grain-straw ratio

The grain straw ratio was not markedly affected by the different ameliorants applied to the soil. The ratio for the various treatments was in the range of 0.62 to 0.78.

C. Influence of different treatments on the nutrient composition and their interaction in the plant

The data on the above are presented in tables 7(c), 7(d), 7(e) and appendix 2(b).

a) Nutrient uptake and interaction in grain (Table 7(c))

Nitrogen

The nitrogen content of the grain was not appreciably affected by the treatments. It ranged from 1.04 per cent in T_0 to 1.16 per cent in T_3 .

Phosphorus

Treatment T_4 recorded the highest content of phosphorus (0.105 per cent) followed by T_1 , T_2 and T_3 (0.097, 0.088 and 0.087 per cent) which were on par. Treatments T_0 and T_5 did not differ from each other in the level of phosphorus in the grain.

Potassium

The content of potassium in the different samples did not show any marked variation between the treatments, and the lowest value was noted for T_0 (0.47 per cent) and the highest for T_1 (0.54 per cent).

Table 7(c) Influence of different treatments on the nutrient composition of grain

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (ppm)	Al (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
T ₀	1.04	0.078	0.47	0.034	0.036	77	38
T ₁	1.14	0.097	0.54	0.050	0.089	31	17
T ₂	1.10	0.088	0.47	0.069	0.060	35	17
T ₃	1.16	0.087	0.49	0.047	0.045	36	22
T ₄	1.10	0.105	0.53	0.046	0.040	34	15
T ₅	1.08	0.078	0.49	0.041	0.039	41	27
CD	0.19	0.02	0.09	0.008	0.008	12	6

Calcium

Highly significant increase in the calcium content of grain was evident in all the treatments, the maximum being recorded in T₂ (0.069 per cent). The other treatments did not differ among themselves and the values ranged between 0.034 per cent for the control and 0.050 for T₁.

Magnesium

A distinctly higher content of magnesium was present in the grain from pots treated with steatite (0.089 per cent). The magnesium content of grain in the other treatments ranged from 0.036 per cent in T₀ to 0.060 per cent in the treatment T₂.

Iron

The level of iron in the grain was significantly reduced due to the effect of the various ameliorative treatments. Maximum reduction in iron was observed in T₁ (31 ppm), compared to 77 ppm iron present in the control (T₀).

Aluminium

The aluminium content in the grain from the different treatments showed that it was highest (38 ppm) in the untreated control pot. For the other treatments, it ranged from 15 ppm in treatment T₄ to 27 ppm in treatment T₅.

Nutrient interaction in grain

Of the different nutrients present in the grain, a significant positive correlation was noticed between phosphorus

and potassium (0.59), calcium and magnesium (0.87) and iron and aluminium (0.83).

b) Nutrient uptake and interaction in straw (Table 7(d))

Nitrogen

Significant variation in the nitrogen content was noticed in the straw samples from the various treatments. The highest content was obtained for T₁ (0.95 per cent) followed in order by T₃, T₂, T₄ and T₅ and the lowest in T₀ (0.66 per cent).

Phosphorus

The phosphorus content of straw was higher than that in the control for all the treatments, although significant differences were not noted between the treatments. The maximum phosphorus content was recorded for T₄ (0.064 per cent) and lowest for the control (0.050 per cent).

Potassium

The potassium content of the straw samples from the various treatments were markedly different from each other. It varied from the lowest value of 0.33 per cent for the control (T₀) to the maximum of 0.46 per cent in the pots treated with steatite (T₁).

Calcium

The highest content of calcium (0.87 per cent) was recorded in the treatment where lime was applied @ 1200 kg/ha (T₂). For the other treatments, the calcium content varied

Table 7(d) Influence of different treatments on the nutrient composition of straw

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (ppm)	Al (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
T ₀	0.66	0.050	0.33	0.44	0.43	1670	513
T ₁	0.95	0.061	0.46	0.71	0.94	1453	289
T ₂	0.81	0.059	0.43	0.87	0.51	1313	387
T ₃	0.88	0.063	0.39	0.51	0.43	1403	459
T ₄	0.73	0.064	0.37	0.59	0.50	1243	333
T ₅	0.69	0.057	0.44	0.58	0.40	1340	333
CD	1.01	0.007	0.04	0.07	0.12	238	105

from 0.44 per cent in the unamended control to 0.71 per cent in the treatment with steatite.

Magnesium

The straw samples from the treatment with steatite (T₁) registered a significantly higher value for magnesium (0.94 per cent) compared to the other treatments where it ranged from 0.40 to 0.51 per cent only.

Iron

Although the difference in iron content of straw among the different treatments was not significant, a marked decrease was noted with respect to the control which recorded the highest value of 1670 ppm. For the other treatments, the content of iron ranged between 1243 ppm in T₄ to 1453 ppm in T₁.

Aluminium

A significant reduction in the content of aluminium in the straw was obtained in T₁ (289 ppm) due to the treatment of the soil with steatite. The reduction in aluminium was less pronounced in the other treatments and was lowest in T₃ (459 ppm) where the aluminium content was not significantly lower than that in the control (513 ppm).

Nutrient interaction in straw

Of the different nutrients in the straw, a significant and positive correlation existed for calcium with nitrogen

and potassium (0.56 and 0.58) and for magnesium with nitrogen and calcium (0.54 and 0.82). Phosphorus was negatively correlated with iron and aluminium (-0.47 and -0.50). Aluminium in its turn was negatively correlated to calcium (-0.67).

c) Nutrient uptake and interaction in root (Table 7(e))

Nitrogen

The effect of different ameliorants in the soil on the nitrogen content showed that treatment with steatite (T_1), lime @ 1200 kg/ha (T_2) and cattle manure (T_3) resulted in a higher uptake and retention of nitrogen in the roots. The roots in these treatments had 0.69, 0.69 and 0.65 per cent nitrogen respectively compared to that in the control pots, where only 0.56 per cent nitrogen was present. Treatments T_4 and T_5 had a higher nitrogen content than the control (0.62 and 0.61 per cent), but the increase was not significant.

Phosphorus

A significantly higher uptake of phosphorus was observed for all the treatments, the maximum uptake being in T_1 (0.062 per cent). The content of phosphorus in T_0 was the lowest (0.046 per cent) and for the other treatments the values were in the range 0.055 to 0.060 per cent.

Potassium

The different treatments had practically no significant effect in increasing the potassium content of the roots over

Table 7(e) Influence of different treatments on the nutrient composition of root

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (ppm)	Al (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
T ₀	0.56	0.046	0.057	0.016	0.017	558	197
T ₁	0.69	0.062	0.067	0.029	0.031	399	131
T ₂	0.69	0.059	0.048	0.028	0.018	420	172
T ₃	0.65	0.057	0.051	0.018	0.015	490	173
T ₄	0.62	0.055	0.051	0.018	0.015	458	133
T ₅	0.61	0.060	0.052	0.019	0.017	487	160
CD	0.09	0.008	0.012	0.005	0.006	50	36

the control. The level of the nutrient varied from 0.048 per cent in T₂ to 0.067 per cent in T₁.

Calcium

The increase in the calcium content of roots was significant for treatments T₁ and T₂ which were on par (0.029 and 0.028 per cent). In all the other treatments, it was only slightly higher than that of the control (0.016 to 0.019 per cent).

Magnesium

A significantly high magnesium content was obtained in T₁ (0.031 per cent) which received the treatment with steatite. The magnesium content of the other treatments including the control was much lower compared to T₁ and was in the range of 0.015 to 0.018 per cent only.

Iron

A significant reduction in the iron content of roots was obtained by the application of the different ameliorants to the soil. The highest reduction was obtained for T₁ followed by T₂ (399 and 420 ppm). Though the iron content of the roots was not significantly different between the various treatments, it was much lower when compared to the control plants which had 558 ppm iron in the roots.

Aluminium

The aluminium content of the roots also exhibited a marked reduction on account of the addition of different

ameliorants to the soil. Treatments T₁ and T₄ recorded the lowest values (131 and 133 ppm) and the variation for the other treatments was not appreciable, although the values were significantly lower than that of the control where 197 ppm aluminium was present.

Nutrient interaction in the root

Nitrogen was significantly and positively correlated with phosphorus and calcium (0.55 and 0.58). Potassium and magnesium also showed a positive correlation, though not significant. A negative relationship was exhibited between nitrogen and iron (-0.59) while the relationship of nitrogen with aluminium was only marginal. The status of phosphorus in the root was negatively associated with iron, the correlation being highly significant (-0.72). Magnesium also positively affected the uptake of potassium and calcium. A positive and significant correlation was observed between aluminium and iron (0.58).

D. Correlation between soil properties and growth and yield of rice crop

The correlation between soil properties at important stages of growth of the rice plant and its growth and yield characters are presented (Table 7(f)).

pH

The pH of the soil at the time of transplanting (period 1) was found to have a significant positive effect on the height

Table 7(f) Correlation between the physico-chemical properties of soils at different periods and plant characters

pH at different periods

Plant characters	1	2	3	4	5	6	7
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Height of plant	0.54*	0.34	0.40	0.53*	0.44	0.48*	0.51*
Length of root	0.54*	0.43	0.30	0.49*	0.61**	0.78**	0.75**
Weight of straw	0.29	0.29	0.13	0.25	0.61**	0.73**	0.64**
Weight of root	0.32	0.04	0.02	0.28	0.24	0.42	0.28
Weight of grain	0.53*	0.29	0.31	0.48*	0.32	0.43	0.50*
Weight of chaff	-0.21	-0.24	-0.38	-0.29	-0.61*	-0.51*	-0.49*

EC at different periods

Plant characters	1	2	3	4	5	6	7
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Height of plant	-0.42	-0.21	-0.16	-0.32	-0.55*	-0.15	-0.40
Length of root	-0.35	-0.30	-0.02	-0.22	-0.60*	-0.16	-0.10
Weight of straw	-0.18	-0.20	-0.06	-0.05	-0.34	-0.01	-0.16
Weight of root	-0.04	-0.28	-0.07	-0.09	-0.44	-0.16	-0.37
Weight of grain	-0.34	-0.20	-0.01	-0.30	-0.58*	-0.22	-0.06
Weight of chaff	-0.45	-0.18	-0.15	-0.02	-0.12	-0.17	-0.17

(contd.)

Table 7(f)

Water soluble aluminium at different periods

Plant characters	1	2	3	4	5	6	7
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Height of plant	-0.61*	-0.38	-0.34	-0.26	-0.40	-0.30	-0.59**
Length of root	-0.56*	-0.52*	-0.27	-0.23	-0.75**	-0.64**	-0.76**
Weight of straw	-0.28	-0.42	-0.10	-0.06	-0.74**	-0.65**	-0.60**
Weight of root	-0.34	-0.09	-0.09	-0.10	-0.48*	-0.40	-0.44
Weight of grain	-0.60*	-0.31	-0.32	-0.24	-0.39	-0.27	-0.53*
Weight of chaff	0.37	0.37	0.29	0.10	0.41	0.38	0.48*

Exchangeable aluminium at different periods

Plant characters	1	2	3	4	5	6	7
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Height of plant	-0.66**	-0.67**	-0.64**	-0.56**	-0.62**	-0.67**	-0.54*
Length of root	-0.87**	-0.76**	-0.87**	-0.83**	-0.76**	-0.80**	-0.79**
Weight of straw	-0.66**	-0.50*	-0.71**	-0.64**	-0.48**	-0.52**	-0.57**
Weight of root	-0.52*	-0.45	-0.49*	-0.59**	-0.42	-0.52*	-0.50*
Weight of grain	-0.79**	-0.70**	-0.66**	-0.71**	-0.73**	-0.78**	-0.69**
Weight of chaff	0.46	0.39	0.56**	0.34	0.54*	0.60*	0.61*

(contd.)

Table 7(f)

Water soluble iron at different periods

Plant characters	1	2	3	4	5	6	7
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Height of plant	-0.06	-0.42	-0.55**	-0.68**	-0.64**	-0.63**	-0.63**
Length of root	-0.26	-0.47	-0.66**	-0.72**	-0.69**	-0.68**	-0.82**
Weight of straw	-0.32	-0.35	-0.44	-0.50*	-0.38	-0.41	-0.59*
Weight of root	0.23	-0.21	-0.25	-0.53*	-0.51*	-0.35	-0.43
Weight of grain	0.02	-0.35	-0.58*	-0.64**	-0.77**	-0.71**	-0.73**
Weight of chaff	0.29	0.45	0.33	0.34	0.18	0.35	0.04

Exchangeable iron at different periods

Plant characters	1	2	3	4	5	6	7
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Height of plant	-0.62**	-0.39	-0.46	-0.63**	-0.61**	-0.62**	-0.66**
Length of root	-0.72**	-0.48	-0.68**	-0.80**	-0.76**	-0.77**	-0.79**
Weight of straw	-0.54*	-0.40	-0.53*	-0.53*	-0.51*	-0.51*	-0.53*
Weight of root	-0.35	-0.29	-0.26	-0.46	-0.43	-0.44	-0.45
Weight of grain	-0.58**	-0.30	-0.47	-0.76**	-0.68**	-0.70**	-0.72**
Weight of chaff	0.58**	0.56*	0.27	0.27	0.24	0.23	0.35

* Significant at 5% level

** Significant at 1% level

of the plant, length of roots and grain yield. The pH of the soil after the maximum tillering stage (period 3) also exhibited a significant correlation with the weight of straw as well, in addition to the above characters. A significant negative correlation was also observed between the weight of chaff and the pH of the soil from the time of opening of the flowers till the maturity of the grain (periods 5 to 7).

EC

Generally, the high EC of the soil at every stage of the cropping period showed an adverse effect on the yield and growth characters of the rice plant. The EC in the soil at the stage corresponding to the time of opening of inflorescence and fertilization of flowers (period 5), exhibited a highly significant negative correlation with the weight of grain (-0.58).

Water soluble aluminium

From the results of the correlation analysis it may be seen that the water soluble aluminium in the soil throughout the growth of the rice crop exhibited a negative influence on all parameters of growth and yield except the weight of chaff. Water soluble aluminium in the soil at all stages of growth was positively correlated to the weight of chaff and the relationship was more pronounced from the time of opening of the inflorescence till the grain filling stage (periods 5, 6 and 7).

Exchangeable aluminium

The level of exchangeable aluminium in the soil from transplanting till harvest exhibited a very significant negative correlation with all the desirable plant characters. The correlation between exchangeable aluminium and chaff was always positive and was significant at the maximum tillering stage of the plant (period 3) and also from the opening of inflorescence (periods 5, 6 and 7).

Water soluble iron

Soluble iron in the soil exerted a very unfavourable influence on all the growth and yield characters of the rice plant except the chaff content. The relationship between water soluble iron and chaff though positive, was not significant, at any of the growth stages of the rice plant.

Exchangeable iron

The level of exchangeable iron in the soil at all stages of growth of the rice plant showed a similar significant negative relationship with the height of plant, length of root and weight of straw and grain. Its effect on the weight of root, though negative, was not significant as in the case of the other plant characters. The positive relationship observed between exchangeable iron at transplanting and the weight of chaff was significant. After this stage, the correlation became weaker and did not further attain a level of significance.

4. Solution culture experiment

A. The general appearance of the plants

No visible symptoms of aluminium toxicity were seen in the tops in any of the plants during the entire period of growth, although a reduction in the number of productive tillers was noticed in plants receiving more than 70 ppm of aluminium in solution. The most remarkable evidence of the toxic effect of aluminium was a progressive reduction in root length and weight observed from the seventh day onwards in plants receiving more than 20 ppm aluminium. At higher levels of aluminium (above 40 ppm) the root length was considerably reduced and the roots showed a prominent tendency for repeated branching at short distances and presented the appearance of a dicot root system (Plates 1 and 2). The root anatomy was also distinctly different (Fig. 10 and 11). In transverse sections these roots showed three to four vascular traces distributed in the cortex in addition to the usual single central vascular bundle in a normal root. The air spaces in these roots were much reduced due to overgrowth of round cortical cells.

B. Influence of graded levels of aluminium on the growth and yield characters of the Rice plant

Plant height (Table 8(a) and appendix 3(a))

In general, much difference in the height of plants was

Plate 1. Rice plants grown with graded levels of aluminium

Plate 2. Root of rice in the absence and presence of
aluminium



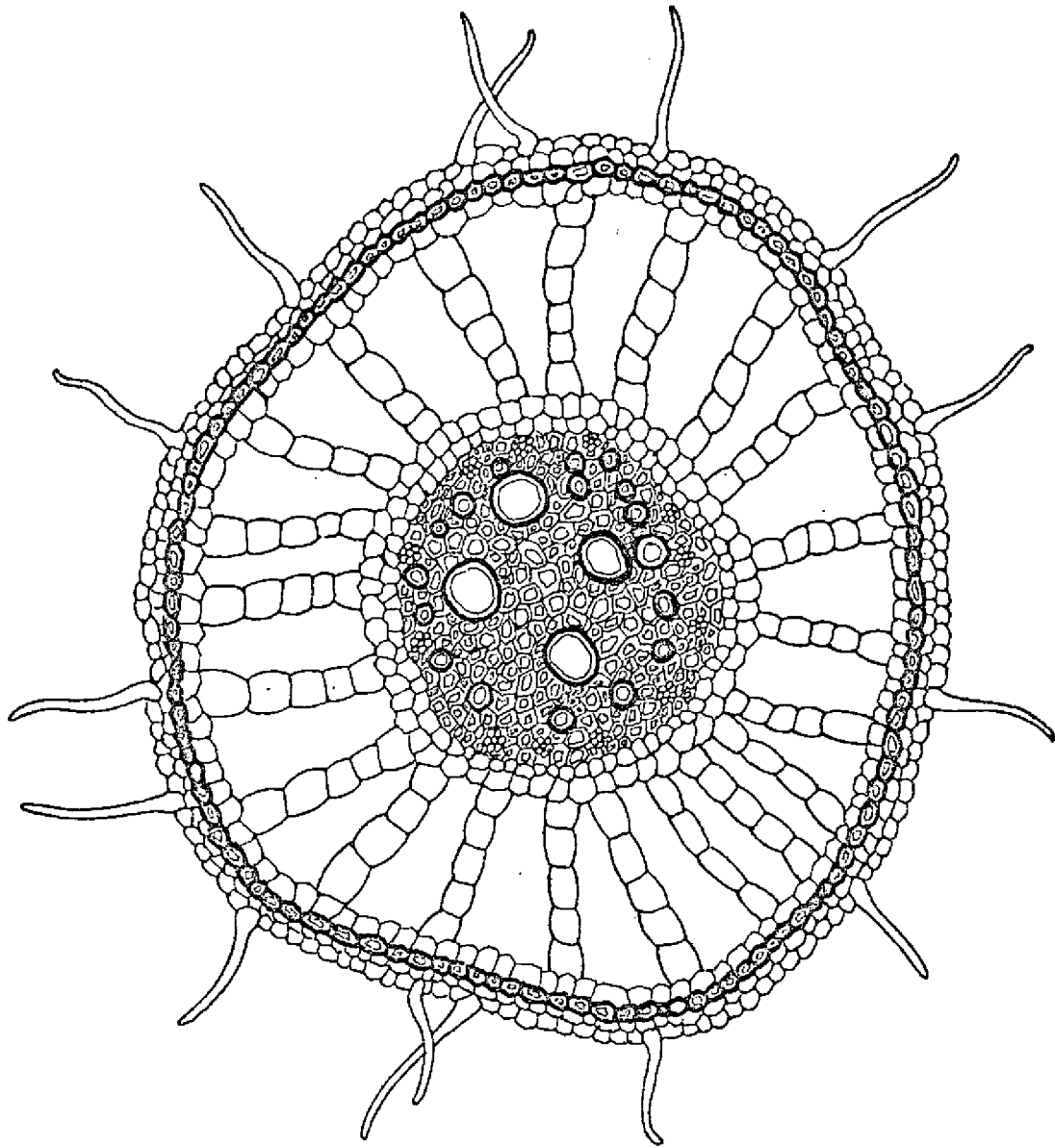


FIG. 10.
TRANSVERSE SECTION OF ROOT OF RICE IN THE ABSENCE
OF ALUMINIUM.

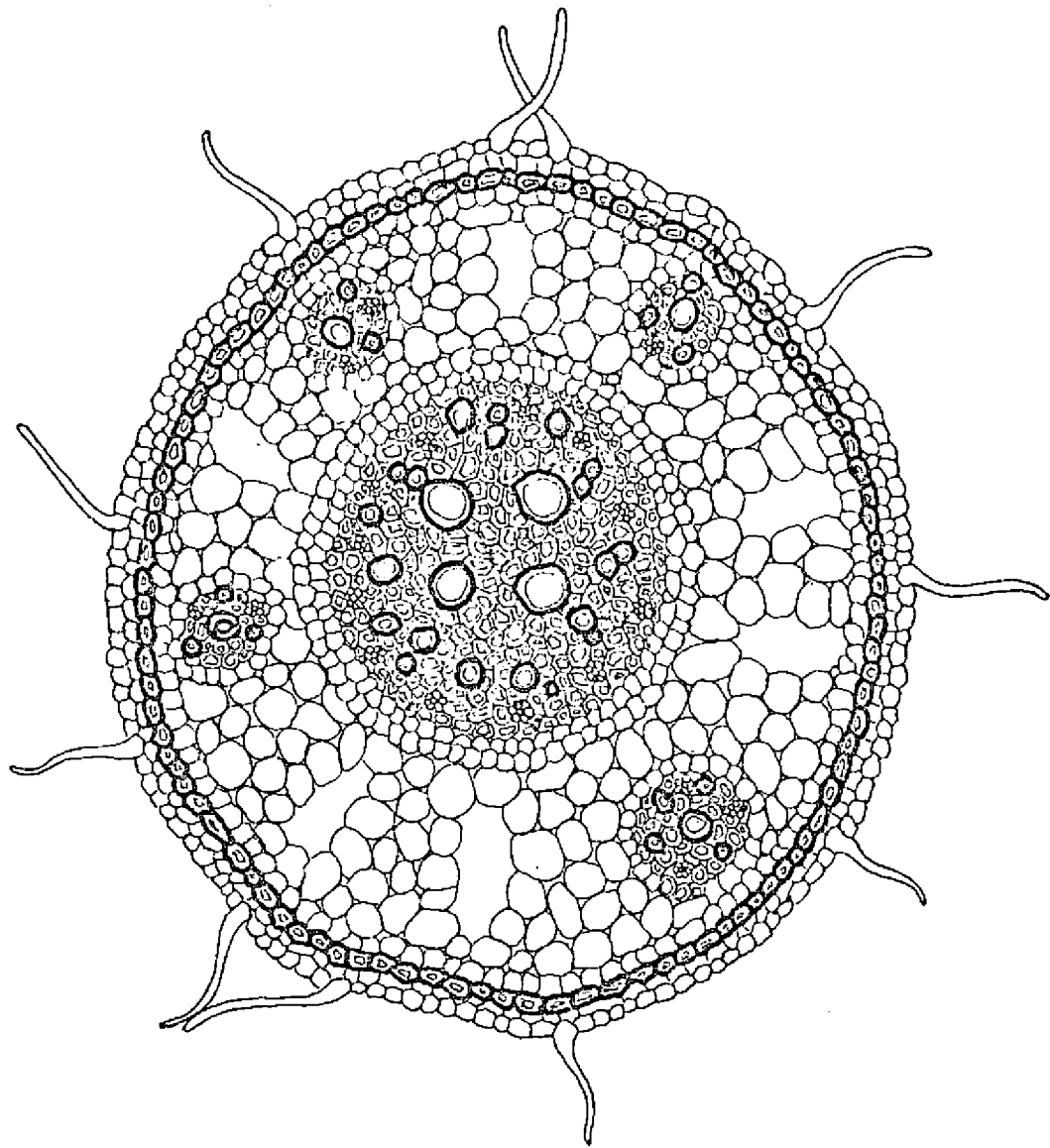


FIG. 11.
TRANSVERSE SECTION OF ROOT OF RICE IN THE PRESENCE
OF ALUMINIUM (50 ppm)
(SHOWING REDUCED AIR SPACES AND ADDITIONAL VASCULAR TRACES)

Table 8(a) Influence of graded levels of aluminium on plant characters

Treat- ment	Plant height (cm)	Number of produc- tive tillers	Root length (cm)	Weight of straw (g)	Weight of root (g)	Weight of grain (g)	Weight of chaff (g)	Grain/ chaff	Grain/ straw
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
T ₀	30.5	23.0	15.5	43.2	12.7	33.7	4.9	7.1	0.78
T ₁	29.3	24.3	14.7	42.5	12.9	30.7	4.8	6.5	0.75
T ₂	29.0	23.0	9.8	42.0	9.3	31.1	2.6	12.0	0.76
T ₃	28.5	22.0	7.7	40.6	7.5	28.0	5.1	5.4	0.68
T ₄	29.5	22.7	7.5	41.0	4.6	28.7	4.3	7.2	0.68
T ₅	29.3	23.3	6.9	41.2	4.7	28.5	3.3	9.3	0.72
T ₆	30.5	21.3	7.1	41.3	5.1	27.5	5.6	5.0	0.67
T ₇	30.6	19.3	6.7	39.7	4.9	26.2	5.4	4.9	0.66
T ₈	30.2	18.3	6.3	37.8	4.8	25.3	6.7	3.8	0.65
T ₉	30.1	18.3	6.2	37.2	4.7	21.4	5.8	3.8	0.57
T ₁₀	29.2	18.0	6.2	37.1	4.3	21.5	6.2	3.5	0.59
CD	1.8	3.0	1.3	1.9	1.3	2.8	1.6	2.2	0.07

not noticed and it varied from 28.5 to 30.6 cm for the different treatments.

Number of productive tillers

The number of productive tillers in the various treatments ranged from 24.3 in T₁ to 18.0 in T₁₀. A significant reduction in the number, compared to the control was observed only in treatments T₇, T₈, T₉ and T₁₀.

Length of root

A highly significant and linear reduction in the length of roots was observed from the treatment with 20 ppm aluminium onwards, although a suppression in root elongation was evident at 10 ppm aluminium. The maximum length of the roots was 15.5 cm in T₀ while it was only 6.2 cm in treatments T₉ and T₁₀, showing a reduction of nearly 60 per cent compared to the plants that were not treated with aluminium.

Weight of straw

Most of the treatments responded negatively towards the weight of straw, which was highest (43.2 g) for the control (zero aluminium treatment) and lowest (37.1 g) for treatment T₁₀. But when the treatments were compared independently, the difference in the weight of straw between successive incremental levels of aluminium was not appreciable.

Weight of root

A significant reduction in the weight of roots was noted

from T₂ onwards. The highest reduction of 66 per cent in weight over the control was recorded for T₁₀. The weight of roots varied from 12.7 g in T₀ to 4.3 g for the treatment where 100 ppm aluminium was applied in solution.

Weight of grain

The weight of grain was also significantly affected by the application of aluminium in graded levels. A reduction of 8 to 36 per cent in grain weight was obtained for treatments T₁ to T₁₀ as compared to the control (T₀).

Weight of chaff

Though a significant increase in the weight of chaff was obtained by the application of various levels of aluminium, the effect did not show any regularity for the different treatments. Thus, the lowest weight of chaff was recorded for T₂ (2.6 g) and the highest weight (6.7 g) for T₈.

Grain to chaff ratio

Eventhough the grain to chaff ratio was low for most of the treatments, a significant increase was noted for treatments T₂ and T₅ (12.0 and 9.3). At higher levels of aluminium, it was much lower compared to the control and the ratio ranged from 7.1 in the control to 3.5 in the treatment with 100 ppm aluminium.

Grain to straw ratio

Appreciable difference in the grain to straw ratio was

observed from T_3 onwards, compared to the control. The ratio ranged from 0.78 in T_0 to 0.57 in T_9 .

C. Nutrient uptake

The uptake of nutrients in the grain, straw and root of rice in the solution culture experiment are presented in tables 8(b), 8(c) and 8(d) and appendix 3(b).

a) Nutrient uptake in Grain

It may be noted that the accumulation of various nutrients in the grain was significantly affected by the levels of aluminium tried in the solution culture experiment.

Nitrogen

The tendency of grain nitrogen to decrease with levels of added aluminium was significant only in treatment T_{10} . It decreased from 1.32 per cent in T_0 to 0.76 per cent in T_{10} .

Phosphorus

The phosphorus content in grain also decreased from treatments T_0 to T_{10} , showing a fall from 0.22 per cent in T_0 to 0.13 per cent in T_{10} , the decrease becoming significant from T_2 onwards. A rapid fall in the phosphorus content of grain was noted in T_9 and T_{10} as compared to the other treatments.

Potassium

Significant difference in potassium content was noticed for the various levels of aluminium. From treatment T_2

Table 8(b) Influence of graded levels of aluminium on nutrient composition of grain

Treat- ment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Al* (ppm)	Fe* (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
T ₀	1.32	0.22	0.30	0.045	0.042	-	53 (1.724)
T ₁	1.29	0.21	0.28	0.036	0.039	15 (1.176)	54 (1.734)
T ₂	1.31	0.19	0.27	0.038	0.038	21 (1.315)	54 (1.732)
T ₃	1.23	0.18	0.26	0.035	0.031	25 (1.398)	62 (1.792)
T ₄	1.14	0.17	0.24	0.031	0.033	26 (1.415)	66 (1.819)
T ₅	1.09	0.17	0.23	0.031	0.031	38 (1.579)	65 (1.813)
T ₆	1.13	0.16	0.22	0.028	0.029	42 (1.623)	63 (1.799)
T ₇	1.11	0.15	0.22	0.026	0.029	45 (1.653)	66 (1.819)
T ₈	1.07	0.15	0.21	0.025	0.030	45 (1.653)	62 (1.792)
T ₉	1.07	0.13	0.21	0.021	0.028	49 (1.690)	63 (1.799)
T ₁₀	0.76	0.13	0.20	0.019	0.022	50 (1.699)	61 (1.785)
CD	0.31	0.02	0.03	0.008	0.006	0.067	0.045

*log (x+1) was used to analyse the data since the results were not additive in nature.

onwards, a linear decrease in potassium with increasing levels of aluminium was evident, recording a decrease from 0.30 per cent in T_0 to 0.20 per cent in T_{10} .

Calcium

The decrease in the content of grain calcium due to treatment with aluminium was more marked from treatment T_3 onwards. The lowest value of 0.019 per cent was recorded in treatment T_{10} , while the control plants had the highest content of 0.045 per cent calcium.

Magnesium

As in the case of calcium, significant reduction in magnesium content of grain was evident from 30 ppm aluminium onwards. The content of magnesium decreased from 0.031 to 0.022 per cent in treatments T_3 to T_{10} . The control plants showed the highest value of 0.042 per cent magnesium in the grain.

Aluminium

Increasing the concentration of aluminium in the rooting medium has resulted in a rise in the level of aluminium in the grain. Maximum accumulation of aluminium (50 ppm) was for treatment T_{10} compared to 15 ppm aluminium in plants grown with 10 ppm aluminium in solution.

Iron

The iron content of the grain also showed an increase

from treatment T₃ onwards. Compared to 53 ppm iron in the zero aluminium treatment, the range in iron content for the other treatments was only from 54 to 66 ppm, the highest values being shown by treatments T₄ and T₇. The increase in iron content of the grain showed only an irregular pattern for the different levels of aluminium applied.

b) Nutrient uptake in straw

Significant difference in the content of the various plant nutrient elements was observed in the straw samples from paddy plants exposed to different levels of aluminium.

Nitrogen

A reduction in the nitrogen content of straw was observed with increasing levels of aluminium. The differences were not marked between treatments T₀ to T₃ (1.55 to 1.45 per cent) while significant reduction was obtained for levels of aluminium beyond 40 ppm, where the values decreased from 1.39 per cent in T₄ to 1.15 per cent in T₁₀.

Phosphorus

With the different levels of aluminium, the uptake of phosphorus in straw showed a linear negative trend. The phosphorus content was reduced from 0.049 per cent in T₀ to 0.030 per cent in T₁₀, significant reduction from T₀ being observed only in treatments T₆ to T₁₀.

Table 8(c) Influence of graded levels of aluminium on nutrient composition of straw

Treat- ment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Al* (ppm)	Fe* (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
T ₀	1.55	0.049	0.34	0.82	0.55	-	735 (2.866)
T ₁	1.53	0.052	0.35	0.76	0.49	27 (1.431)	898 (2.953)
T ₂	1.53	0.049	0.33	0.57	0.48	131 (2.117)	682 (2.833)
T ₃	1.45	0.048	0.30	0.45	0.44	153 (2.185)	683 (2.834)
T ₄	1.39	0.047	0.30	0.34	0.41	249 (2.396)	813 (2.910)
T ₅	1.35	0.043	0.27	0.35	0.38	385 (2.586)	766 (2.884)
T ₆	1.26	0.037	0.24	0.33	0.37	410 (2.613)	1023 (3.009)
T ₇	1.29	0.033	0.24	0.33	0.37	436 (2.639)	1046 (3.019)
T ₈	1.18	0.032	0.26	0.30	0.30	488 (2.688)	1006 (3.003)
T ₉	1.17	0.030	0.22	0.27	0.29	587 (2.767)	973 (2.988)
T ₁₀	1.15	0.030	0.23	0.24	0.30	695 (2.842)	1093 (3.039)
CD	0.15	0.007	0.11	0.06	0.06	0.057	0.077

* log (x+1) was used to analyse the data since the results were not additive in nature.

Potassium

Reduction in the potassium content of the straw also followed a pattern similar to that of nitrogen and phosphorus, marked differences being evident from treatment T_3 onwards. The difference in potassium content was not appreciable between successive levels of aluminium. The content of potassium varied from 0.34 in the control (T_0) to 0.23 per cent in T_{10} in which the highest level of aluminium (100 ppm) was applied.

Calcium

A marked diminution in the calcium content of straw was observed in treatments T_2 to T_{10} . The values varied from 0.82 per cent in T_0 to 0.24 per cent in T_{10} .

Magnesium

The reduction in magnesium content of straw was also significant only from T_2 . From T_4 to T_{10} , much difference was not noticed between treatments, although the differences were appreciable when compared to the zero aluminium treatment.

Aluminium

A positive linear increase in the aluminium content of straw was obtained with increasing aluminium level in the culture solution. It steadily increased from 27 ppm in 10 ppm aluminium solution to 695 ppm in the treatment with 100 ppm aluminium.

Iron

Iron content of straw also followed the same pattern as that of aluminium, registering the highest value of 1093 ppm in T₁₀ and the lowest value of 735 ppm in T₀. The variation from the control was significant in the case of treatments T₆ to T₁₀.

c) Nutrient uptake in root

Nitrogen

Significant difference in the nitrogen content of root was observed only for the application of higher levels of aluminium in solution. Nitrogen content did not differ much at the initial levels of T₀ to T₄ and was in the range 1.09 to 1.15 per cent. The content of nitrogen in T₅, T₆ and T₇ was significantly lower and was on par with one another (1.02, 0.97 and 0.97 per cent). Compared to the other treatments, the nitrogen content was very low for T₈, T₉ and T₁₀ (0.88, 0.90 and 0.79 per cent) indicating that higher levels of aluminium had a profound negative influence on the uptake and retention of nitrogen in the roots.

Phosphorus

The phosphorus content of the roots of the rice plants treated with the different levels of aluminium showed a gradual decrease from T₁ (0.18 per cent) to T₅ (0.14 per cent) and then it slowly increased from T₆ (0.16 per cent) and reached the highest level (0.20 per cent) in T₁₀. Significant

Table 8(d) Influence of graded levels of aluminium on nutrient composition of root

Treat- ment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Al* (ppm)	Fe* (ppm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
T ₀	1.15	0.18	0.13	0.94	0.54	-	382 (2.582)
T ₁	1.15	0.18	0.11	0.93	0.48	33 (1.519)	418 (2.621)
T ₂	1.15	0.18	0.11	0.89	0.41	161 (2.204)	461 (2.660)
T ₃	1.13	0.17	0.10	0.78	0.40	166 (2.220)	504 (2.702)
T ₄	1.09	0.16	0.10	0.62	0.34	221 (2.344)	575 (2.760)
T ₅	1.02	0.14	0.10	0.59	0.35	483 (2.684)	612 (2.786)
T ₆	0.97	0.16	0.11	0.44	0.32	593 (2.773)	732 (2.865)
T ₇	0.97	0.18	0.11	0.38	0.31	647 (2.811)	863 (2.935)
T ₈	0.88	0.18	0.11	0.35	0.29	675 (2.830)	987 (2.994)
T ₉	0.90	0.19	0.10	0.36	0.28	815 (2.912)	1136 (3.055)
T ₁₀	0.79	0.20	0.10	0.32	0.27	1077 (3.032)	1218 (3.085)
CD	0.12	0.02	0.02	0.11	0.06	0.047	0.072

* log ($\bar{x}+1$) was used to analyse the data since the results were not additive in nature.

reduction in root phosphorus was noted only for T₅ and T₆ compared to the control. In the other treatments, the phosphorus content did not appreciably differ from that in the control.

Potassium

The different levels of aluminium in solution produced appreciable difference in the potassium content of roots. Although a reduction in potassium content (from 0.13 in T₀ to 0.10 in T₅) was observed for various treatments, the variation was rather irregular and did not reveal any definite relationship with the level of aluminium applied.

Calcium

Significant variation in the content of root calcium was noted for the different levels of aluminium in solution. Between the first two levels of aluminium and the control the differences were not appreciable (0.94 to 0.89 per cent) and the decreasing trend in the calcium content was more evident at the higher aluminium levels. Calcium content was much lower and on par for treatments T₇, T₈, T₉ and T₁₀ and it was only 0.32 per cent in treatment T₁₀ as against 0.94 per cent in the zero aluminium treatment.

Magnesium

High levels of aluminium in solution significantly diminished the uptake and retention of magnesium in the roots.

Thus the content of magnesium decreased gradually from 0.54 per cent in the control to 0.27 per cent in T₁₀ which meant a reduction of 50 per cent in the uptake.

Aluminium

A comparatively higher content of aluminium was present in the roots of rice plants grown with the various levels of aluminium in solution, the values showing a positive linear relationship between application and uptake. Thus, the content of aluminium in the treatment with 10 ppm aluminium was only 33 ppm while it was 1077 ppm with 100 ppm aluminium applied in solution.

Iron

The iron content of the roots also showed a linear increase with increasing levels of aluminium in solution. A very high uptake of iron was noticed in treatment T₁₀ compared to the control, the increase becoming more prominent from T₄ onwards. The values for iron varied from 382 ppm in the control (T₀) to 1218 ppm in plants grown with the highest level of aluminium in solution (T₁₀).

5. Screening of rice varieties for tolerance to aluminium toxicity

A total number of 154 varieties/cultures of rice were screened for resistance to aluminium toxicity in nutrient solution. Their relative root length (per cent) in the presence of 3.75 mM aluminium with reference to zero aluminium

was calculated and the mean relative root length (RRL) and standard deviation from the RRL were computed. Based on 95 per cent confidence limits given by the means \pm standard error, the varieties were classified into three groups.

Varieties/cultures possessing RRL below 53 were treated as least tolerant, those between 53 and 62 as medium tolerant and those above 62 as tolerant to aluminium toxicity. The names of varieties/cultures falling under the three categories, showing their absolute root length and relative root length are presented in tables 9(a), 9(b) and 9(c).

The mean value of the absolute root length of all the varieties in the three tolerance classes were 5.3, 5.2 and 5.1 cm respectively indicating no appreciable difference in the length of roots of the varieties/cultures used in the study.

The mean root length of the varieties/cultures in the presence of 3.75 mM aluminium in respect of the above classes were 1.9, 3.0 and 3.9 cm respectively, bringing out the specific effect of aluminium in restricting the root growth among the rice varieties.

Based on the results 79 rice varieties/cultures were classified as least tolerant, 14 as medium tolerant and 61 as tolerant to aluminium toxicity.

Table 9(a) Rice varieties/cultures least tolerant to aluminium toxicity

Sl. No.	Name	Root length (cm)		
		0 Al	3.75 mM Al	RRL
(1)	(2)	(3)	(4)	(5)
1	Jamuna	9.0	3.5	39
2	BR 51	6.0	2.4	39
3	Cul-82279	3.7	1.0	26
4	Cul-1180	3.5	1.4	39
5	Sabari	7.3	1.3	18
6	Hema	6.1	1.0	16
7	PTB-30	8.6	2.6	30
8	MBL-9	4.3	1.1	26
9	PTB-8	4.9	2.2	50
10	PTB-31	5.0	2.2	44
11	PTB-1	3.9	2.0	51
12	IR-20	2.9	1.0	36
13	Cul MA 54-42	4.0	1.4	35
14	Cul-3	6.8	2.1	31
15	Soorya	6.5	3.1	48
16	Kalyan V	5.4	2.2	40
17	IR 32	8.4	2.2	27
18	Kumar	7.2	0	0
19	Kannaki	7.8	2.2	28
20	H 4	5.0	1.6	32
21	PTB-7	8.3	2.2	26
22	Cul-25064	8.0	2.8	35
23	Suvarnamodan	7.8	0	0
24	Malinya	5.3	0.5	85
25	Kauveri	6.6	3.1	46
26	Purajit	5.9	2.1	35
27	Pankaj	7.8	3.0	38

(contd.)

1	2	3	4	5
28	Jagannath	7.1	1.5	21
29	Sakthi	5.9	1.2	20
30	Rajeswari	5.5	1.5	26
31	Pennai	6.9	2.3	34
32	Cul-169	4.8	0	0
33	Cul-204	8.6	2.9	34
34	H-105	5.9	0.9	15
35	IR 8	4.0	1.0	25
36	PTB-32	5.4	1.1	21
37	Cul-124	5.4	0	0
38	HT-4	6.0	2.3	37
39	Panamkurava	7.0	2.9	41
40	Kutticheradi	6.2	2.3	43
41	Cul 54-1-3	4.8	0.6	13
42	Cul-172	3.8	1.8	47
43	Cul-1322-1	5.5	1.8	32
44	Cul-43-1-6	8.1	0	0
45	Cul-1336-3	6.1	3.1	51
46	Cul-1424-2	6.1	3.0	49
47	Lekshmi	3.9	1.9	48
48	Cul-4-4	4.4	2.2	49
49	Ponkaruka	6.3	2.0	32
50	Cul-2533	5.2	2.6	49
51	Cul-26-1-1	4.0	2.4	61
52	Chettivirippu	2.6	1.2	47
53	Cul-3	6.5	2.1	32
54	MN-54-42	8.1	3.6	45
55	Vyttilla-1	7.1	3.5	50
56	IR-5	8.1	3.1	38
57	PTB-29	6.0	2.2	36
58	PTB-10	10.5	3.5	33

(contd.)

1	2	3	4	5
59	Cul 1954	7.8	2.7	35
60	Taichung Native-1	3.5	1.1	32
61	Triveni	7.5	1.4	19
62	Supriya	7.8	1.9	25
63	PTB-7	9.3	2.1	22
64	Annapoorna	5.3	2.1	40
65	Cul-25316	6.0	2.3	39
66	Jaya	5.8	2.9	50
67	Cul-25315	5.5	1.7	31
68	PTB-2	5.8	1.9	33
69	Mahsoori	4.4	1.6	37
70	Cul-25331	7.7	2.8	37
71	Cul-1999	7.2	2.6	36
72	Cul-25335	8.5	3.8	44
73	Cul-1907	6.6	1.4	22
74	Deejee wojong	4.3	1.2	27
75	Cul-25333	6.8	2.2	32
76	PTB-22	6.5	2.2	34
77	Cul-25336	0.5	0.2	41
78	Rohini	6.4	1.4	22
79	Purple	4.8	2.3	48

Table 9(b) Rice varieties/cultures medium tolerant to aluminium toxicity

Sl. No.	Name	Root length (cm)		
		0 Al	3.75 mM Al	RRL
(1)	(2)	(3)	(4)	(5)
1	Suphala	2.4	1.4	56
2	IR-42	5.8	3.1	54
3	Kanchi	4.9	3.0	61
4	Rajendra	2.3	1.9	60
5	Pokkali	9.9	5.9	60
6	Cul-204	6.7	4.0	59
7	Aluvella	5.5	3.1	56
8	PTB-28	6.6	4.0	60
9	Rasi	4.1	2.5	61
10	Chennellu	7.4	4.4	60
11	Cul-12814	4.7	2.9	60
12	Vyttilla-II	3.3	1.9	59
13	Kalinga	3.4	2.0	61
14	MO-5	5.6	3.4	59

Table 9(c) Rice varieties/cultures tolerant to aluminium toxicity

Sl. No.	Name	Root length (cm)		
		0 Al	3.75 mM Al	RRL
(1)	(2)	(3)	(4)	(5)
1	Cul-25337	4.5	2.9	64
2	Cul-23372	4.4	3.3	75
3	PR 106	2.4	2.2	94
4	Cul-87248	5.6	5.4	96
5	PTB-26	6.2	4.4	72
6	Cul-1999	5.7	4.5	80
7	1-5-4	6.6	4.9	72
8	Cul-7944	4.9	3.8	77
9	IR-28	3.8	3.3	87
10	Padma	3.9	2.5	64
11	IR-30	3.1	2.5	80
12	PTB-9	5.5	4.0	73
13	Ratna	6.8	4.8	72
14	Jyothi	6.2	4.4	71
15	IR-8-68	2.6	1.8	69
16	IR-34	6.7	4.9	74
17	Subhashini	4.5	3.5	77
18	Kolapala	6.2	5.5	88
19	Karuna	4.5	4.0	89
20	Bhavani	6.1	4.4	72
21	Basmathy	2.6	1.6	64
22	Cul-1537-2	4.2	4.0	96
23	MO 6	6.2	5.0	81
24	Cul-168	6.3	4.6	74
25	Cul-93	6.6	4.9	74
26	MO 4	9.5	8.2	87

(contd.)

1	2	3	4	5
27	Cul-129	7.7	5.4	70
28	Cul-199	3.6	2.7	74
29	Cul-1361-2	5.7	5.5	96
30	Cul-1332-3	5.2	4.4	85
31	Cul-1358-2	5.8	5.6	96
32	Cul-1328-1	5.9	4.1	71
33	Cul-1311-1	5.7	3.7	65
34	Cul-1344-4	3.3	2.2	65
35	Cul-1338-B	6.6	4.9	74
36	Cul-1405-1	5.5	4.2	78
37	Cul-200	5.3	4.8	92
38	Cul-203	4.1	2.9	70
39	Cul-1334-1	6.3	4.4	70
40	Cul-5-1	4.3	2.8	65
41	Bharathi	3.8	2.4	65
42	Cul-23332-2	4.0	3.2	79
43	BR-51-46-1	6.4	4.2	66
44	Aswathi	3.6	3.0	83
45	PTB-26	6.6	5.0	76
46	PTB-42	0.6	0.5	87
47	Vijaya	6.3	4.1	65
48	Cul-233322	4.5	2.8	62
49	IR-36	5.1	3.7	73
50	Vani	5.8	3.7	64
51	Cul-198	6.8	4.5	66
52	Cul-1424-1	5.2	3.6	69
53	Cul-1325-4	4.6	3.1	67
54	Cul-1357-1	5.3	3.5	66
55	Cul-154	5.6	4.0	71
56	Cul-1423-5	6.5	4.1	63
57	Cul-1423-4	6.3	4.2	67

(contd.)

1	2	3	4	5
58	Karuka	6.8	4.4	64
59	Orpandi	4.3	2.7	63
60	Virippu	4.1	2.8	68
61	Thulunadan	4.5	2.8	62

DISCUSSION

DISCUSSION

Chemical nature of Rice soils

The large majority of the rice growing soils of the Kerala State are characteristically acidic in reaction. They include the mildly acidic coastal sandy and alluvial soils, the moderately acidic brown hydromorphic soils and the strongly acidic acid sulphate and acid saline soils. Though the area covered by the acid sulphate soils is comparatively low, the problems of management practices presented by them are enormous.

The pH of the acid rice soils of Kerala vary widely, ranging from 2.5 to 6.5. The productivity pattern of these soils also varies widely from place to place. Apart from the yield differences due to variety, climatic and other environmental factors, inherent soil properties like the fertility status and toxic parameters such as acidity and the consequently high levels of aluminium and iron as well as salt content, very often affect the soil-plant relationships to an extent that leads to substantial reduction of yield and at times even crop failures.

Soil acidity is not an unmanageable problem in the moderately acidic rice soils, while it was not so in the strongly acidic soils such as the acid sulphate soils. The poor performance of rice varieties in such soils has often

been attributed to the harmful effects of acidity, direct as well as indirect. The high H^+ ion concentration associated with acidity per se may not be responsible for poor crop yields (Arnon and Johnson, 1942) in acid soils. Toxicity due to aluminium, iron and manganese, low availability of plant nutrient elements, especially calcium and magnesium and decreased activity or even absence of beneficial microorganisms have been indicated as other reasons for their low productivity.

Erico et al. (1979) have attributed high aluminium saturation as the most significant limiting factor to crop production in many acid soils. Yield response to liming was considered to be due to improved calcium nutrition and the neutralisation of the toxic levels of aluminium.

Eventhough the pH of soils has long been used to evaluate the intensity of soil acidity and has been accepted as one of the standard criteria for soil characterisation, it does not, nevertheless, give a true picture of the potential sources of acidity in soils, especially those linked to exchangeable forms of hydrogen and aluminium. It is more important to keep under control the content of exchangeable aluminium that slowly goes into soil solution generating acidity by its stepwise hydrolysis to yield protons.

The exchangeable hydrogen and aluminium that directly contribute to soil acidity and the extent of aluminium

saturation of the exchange complex which largely control the productivity of acidic rice soils have to be studied in relation to the pH and other soil characters like total CEC, exchangeable bases, base saturation and organic matter status so that we may obtain a clearer picture of the factors governing the productivity of the acidic rice soils.

The mean values of these chemical characters for the seven groups of soils presented in table 5 reveal a steady gradation with increase in pH as could be expected from theoretical considerations.

The variations in properties such as CEC, exchangeable hydrogen and aluminium, base and aluminium saturation, organic carbon and lime requirement of soils with pH and their intercorrelations are discussed below:

Cation Exchange Capacity

The highest CEC was noted for the three groups of soils which were the most acidic (pH below 4.5). The CEC in these soils was positively and significantly correlated to the organic carbon content which indicated that an appreciable proportion of the exchange sites was contributed by the organic matter along with those which originated from clay minerals. Schnitzer and Khan (1972), Flaig et al. (1975) and Hargrove and Thomas (1981) have stressed the significance of organic matter in their contribution to the total CEC of soils.

The CEC of the other soils was not directly related to organic carbon except in the soils with pH between 5.5 and 6.0 indicating a greater preponderance of negative charges to be located in the inorganic soil material rather than in organic matter.

Exchangeable hydrogen

Exchangeable hydrogen was highest in the three groups of soils of pH below 4.5. It decreased steadily as the pH increased in the remaining three soil groups and was negligible in the least acidic group.

Exchangeable hydrogen was highly correlated to the CEC in the soils upto a pH of 5.4. As the pH increased, the positive correlation between CEC and exchangeable hydrogen tended to get weaker and in the least acidic soils the relationship was negative.

A high degree of positive correlation was also observed between organic carbon and exchangeable hydrogen in all soil groups upto a pH of 5.4. This probably means that, the negative sites on the organic matter might act as the seat for a large part of the exchangeable hydrogen present in these soils. The lack of such a correlation in the remaining groups of soil might indicate a lesser role for organic matter in its contribution to exchange acidity.

The results generally indicate a dominance of the exchangeable hydrogen ions in the more acidic soils with a

tendency to decrease in the moderately acid soils upto a pH of 6.5.

It is to be noted that in the soils of pH below 4.4 nearly 50 per cent of the exchange sites was saturated with H^+ ions resulting in a much lower effective CEC. This indicates the significance of hydrogen held on the exchanger as a potential source of soil acidity in the more acidic soils.

Base saturation

It has been noted that the base saturation of the different groups of soils increased with decrease in acidity. Thus it was found that exchangeable calcium and magnesium increased steadily with rise in pH. The soils of the group with pH between 3.5 and 4.4 were seen to be associated with molluscan lime shells in the lower depths which may be one of the reasons for a higher content of the bases in them. However, the extremely acidic soils were generally characterised by a very high status of exchangeable hydrogen coupled with a low per cent base saturation (10.6 per cent). As the pH rose to neutrality, the base saturation also increased to a value as high as 60.6 per cent, with a correspondingly low status of exchangeable hydrogen.

Aluminium saturation

The exchangeable aluminium status in the various groups

of soils also showed a diminishing trend with increase in pH. In soils of pH below 4.0 it had an average value of 5.9 and 5.5 me/100 g while it was 3.5 and 3.3 me/100 g in the soils upto a pH 4.9 and between 2.4 and 1 me/100 g in soils above pH 5.0. Black (1973) and Sanchez (1976) have reported similar appreciable decrease in the content of exchangeable aluminium with decrease in soil acidity.

The aluminium saturation of the total CEC showed comparable values for the two groups of soils of pH 2.5 to 3.4 and 3.5 to 3.9 (36.0 and 33.9 per cent respectively). For the next three groups in the pH range of 4.0 to 5.4, it varied from 24.3 to 26.7 per cent and in the remaining groups the range was between 21.9 and 13.6 per cent.

On the other hand, the aluminium saturation with respect to the effective CEC of soils presented a different picture. In this case, the variation was more marked and it ranged from 77.2 per cent in the most acidic soils to as low as 16.1 per cent in the least acidic soils.

In spite of the higher absolute values of exchangeable aluminium even in the most acidic soils, the aluminium saturation has tended to be low because of the higher CEC. However, due to the higher content of the exchangeable hydrogen and a consequently lower effective CEC, aluminium saturation calculated on the basis of the effective CEC has been found to be rather high (77.2 per cent). It may be noted that,

all the soils except those below pH 6.0 had more than 36.4 per cent of their effective CEC saturated with exchangeable aluminium, which is a condition not very favourable for rice culture.

A high aluminium saturation of the effective CEC of soils is associated with severe conditions of aluminium toxicity and it has been considered to be a better and more effective practice to apply as much lime as is required to bring down the effective CEC to below critical levels.

Poor growth of several crops in acid soils has been considered to be the direct consequence of a high degree of saturation of the exchange complex with aluminium (Black, 1973; Sanchez, 1976; and Kamprath, 1978) and application of large quantities of lime to precipitate excess aluminium is essential for improving crop yields in such soils. However, in soils with a low content of exchangeable aluminium, the amount of lime could be just enough to neutralise the acidity produced by the addition of nitrogenous fertilizers and to provide sufficient calcium for the nutrition of the crop (Lathwell, 1979).

As there exists a large variation in the degree of sensitivity of various crops to aluminium saturation of the soil (Alley, 1981) the liming practice may be further guided by this factor and liming rates could be fixed for lowering

the aluminium saturation of the soil to below critical level for each crop (Cochrane et al., 1980; and Webber et al., 1982).

Farina and Sumner (1980) considered aluminium saturation of soils as a better index of lime requirement and they argued that maintaining aluminium in soil solution at levels below critical to the plant may be beneficial in producing a slightly acidic condition which permits most of the nutrients to be in solution and their consequent uptake.

Among the soils of different pH range used in this study, a significant and positive correlation between aluminium saturation per cent and lime requirement was obtained only in the case of soils in the range of pH 4.5 to 4.9.

Aluminium in soil solution

Nye et al. (1961) and Evans and Kamprath (1970) have shown that when the aluminium saturation rises above 60 per cent, the aluminium in soil solution also rises sharply subject to the opposing action of organic matter and salt content. The organic matter generally tends to decrease the soil solution aluminium by forming very strong organic matter aluminium complexes while the salt content, because of the displacement of exchangeable aluminium by mass action, tends to increase the aluminium in solution. These two factors appear to be relevant in the case of the

extremely acid soils used in the present study, which contain high amounts of both organic matter and salt. The high EC observed in these soils has been correlated to the exchangeable aluminium content, while there was no significant correlation between soluble aluminium, EC and organic carbon. A lower value of soil solution aluminium was obtained in the present study as compared to the higher values reported in literature for soils of pH less than 4.0 (Sanchez, 1976). This appears in all probability to be due to the attainment of an equilibrium between the two opposing interactions of soluble salts with aluminium resulting in its release and this being complexed by organic matter. The equilibrium appears to be more in favour of the latter, explaining the observed low concentration of aluminium in spite of the low pH.

The results of the present study reveal an inverse relation in all the soil groups between total CEC and aluminium saturation. The poor base status coupled with the high exchangeable hydrogen has resulted in a higher degree of aluminium saturation of the effective CEC in the acidic soils compared to the less acidic soils low in exchangeable hydrogen and high in exchangeable bases. The inverse relationship between these two soil characters was more significant for the soils in the pH range of 4.0 to 5.9. Thus the significance of the interaction between exchangeable

hydrogen and aluminium on the one hand, and bases on the other with the CEC of the soils and its effect on the aluminium saturation of the total and effective CEC has been clearly brought out by the results of the present study. Further, the influence of the pH of the soil on this relationship has also been brought out. The interactions have been more evident in the soils of the pH group 4.0 to 5.9. In the more acidic soils, the relationship between these parameters has been only of a weaker nature, probably indicating the involvement of other soil chemical factors controlling this relationship.

Organic carbon

In general, the content of organic matter in the soils showed a decrease with decrease in acidity. The relatively high content of organic matter in the extremely acidic soils might be due to the fact that they have originated from a mangrove vegetation characteristic of similar situations. Some of the soils with extremely low pH in Kuttanad area are believed to have such an origin (Velu Pillay, 1940). The extreme acidic condition prevalent in the soils with its low rate of mineralisation associated with low microbial activity might have caused such an accumulation of organic matter in these soils.

Organic matter seems to bear a very significant and direct relationship with the content of exchangeable hydrogen

in the soils upto a pH of 5.4 after which it becomes weak and indicates a negative relation in the near neutral soils. The observed correlation indicates that the major source of exchangeable hydrogen in these soils might be the carboxylic acid groups bound to organic matter, which on ionisation releases H^+ ions as is mostly found in acid soils below pH 5.4 (Hargrove and Thomas, 1981). The rapid oxidation of organic matter under more favourable conditions in the weakly acidic soils might be responsible for the decreased role of organic matter and hence the observed weaker correlation.

This type of a relationship between organic matter and exchangeable aluminium was evident to a lesser extent only in the more acidic soil which incidentally possessed a high organic matter status, and to a significant extent in the soils above pH 5.5. Thomas (1975) has shown that exchangeable aluminium was lower at any given pH as organic matter increased. Clark and Nichol (1966) and Evans and Kamprath (1970) have also found much less exchangeable aluminium in organic soils than in mineral soils eventhough the pH of the organic soils was quite low. The observations of the earlier mentioned authors lend support to the relationship shown in the present study between organic matter and exchangeable aluminium.

The correlation between base saturation and organic matter, however, did not present any distinct pattern. It showed a random relationship in the soils between pH 3.5 to 5.4, while in the others, there was a direct relationship. This might be due to the difference in the nature of cation bonding on the exchange sites of organic matter, which was less pronounced in the soils of pH 3.5 to 5.4 while it might not have been so in the case of the other soils.

Lime requirement

Lime requirement value was highest in the most acidic soils and it slowly diminished in magnitude with the lowering of acidity. It showed a positive correlation with organic matter in soils below pH 3.5, probably accounting for the neutralisation of a larger part of the acidity dependent on organic matter. The weaker correlation between these factors with increase in pH of the soil, probably suggests a minor role of organic matter in contributing to soil acidity. Keeny and Corey (1963) obtained close correlation between the organic matter content and lime requirement value for 26 Wisconsin soils rich in organic matter.

No significant correlation was observed in any of the soil groups between exchangeable hydrogen and lime requirement. The lime requirement values were found to be significantly correlated to exchangeable aluminium in soils below

pH 4.5 and with increasing pH, the relationship tended to be of a weaker nature.

Exchangeable aluminium has been considered as the basis of predicting the lime requirement values in preference to the amount of limestone determined for neutralisation of free acidity. Thus, Lathwell (1979) recommended 2 t lime/ha to be applied for each milli equivalent of exchangeable aluminium.

The results obtained in the present study indicate that in the majority of soils, the lime requirement values (t/ha) are much more than twice the content of exchangeable aluminium present in them. Thus it appears that in the highly acid soils liming rates based on exchangeable aluminium content may be more useful in preventing problems due to both overliming as well as underliming. Lime just sufficient to suppress excess of exchangeable aluminium may be used, which will be more economical.

From the results of analysis of a large number of rice growing soils of the State, it is clear that, eventhough the content of water soluble aluminium in them is not very high, the soils below pH 5.5 have more than 2 milli equivalent of exchangeable aluminium and an aluminium saturation of more than 20 per cent of both the total and effective CEC. While there has been some inconsistency in the tolerance

limit fixed for aluminium in the soil solution, the exchangeable aluminium content of more than 2 me/100 g soil and an aluminium saturation of more than 20 per cent of the effective CEC has generally been considered as critical enough for limiting the productivity of rice (Lathwell, 1979).

Because aluminium concentrations are harmful even before they cause visible toxicity symptoms and the aluminium content of plants does not necessarily reflect aluminium toxicity, the disorder is sometimes overlooked.

It has been reported that (Tanaka and Yoshida, 1970) during the flooding of soils for wetland rice culture, aluminium toxicity ceases to be a problem of high magnitude, due to the onset of reductive reactions which cause a decrease in the soil acidity and the precipitation of excess aluminium as aluminium hydroxide. The decrease in the content of exchangeable aluminium under such situations, however, will depend on several soil chemical characters that control the release of aluminium from the exchange complex and its subsequent precipitation as hydroxide. Thus the possibility exists that in all situations submergence alone may not be a solution to reduce or minimise aluminium toxicity. Therefore it is important to find out how flooding for rice culture alters the chemical behaviour of exchangeable and soluble forms of aluminium in the typical rice soils of the State,

since most of the factors that control these processes are likely to differ from soil to soil.

Incubation of selected soils from various pH groups with and without different types of amendments has given useful indications for the management of these soils, especially for keeping down the levels of aluminium both soluble and exchangeable to below critical levels.

Changes in the physico-chemical properties of rice soils on flooding in water with and without ameliorants

From the results presented in Chapter 3 (Tables 6(a) to 6(f). it may be seen that in all the soils flooding for a continuous period of 60 days has brought about significant rise in pH and EC, a decrease in water soluble and exchangeable aluminium and an increase in the contents of both water soluble and exchangeable forms of iron. The change in magnitude of each factor and the time taken to reach the peak levels, however, varied depending on the inherent physico-chemical characters of the individual soils.

pH

The two kari and one pokkali soils representing the acid sulphate and acid saline soils of the State, which had the lowest initial pH (3.3 to 3.5) were raised to a maximum pH of 5.2 only, while all the other soils with initial pH values ranging from 4.6 to 5.8 recorded peak values of

6.0 to 6.4 during the two month period of flooding. The resistance of the three highly acid soils to attain a higher pH might be attributed to differences in the process of "soil metabolism" which vary strongly with the soil pH (Etherington, 1975). Increase in soil pH consequent to flooding has been ascribed partly to an increase in $\text{NH}_4\text{-N}$ (Karunakar and Daniel, 1950; Rodrigo, 1962), reduction of ferric and manganic compounds and release of bases like potassium, calcium and magnesium due to hydrolysis (Ponnamperuma, 1955; Chatterjee, 1964; Rodrigo, 1967). A large segment of these reactions occur under the anoxic conditions that follow on waterlogging and are triggered by biochemical agencies which are highly sensitive to a low initial pH (Brinkman and Pons, 1973). Further, the presence of a large amount of undecomposed organic matter in these soils might have released organic acids and phenols which keep the soil pH at a low level. Similar resistance to the raising of the pH of acid sulphate soils has been reported from IRRI (1964), by Nhung and Ponnamperuma (1966) and by Kabeerathumma (1975).

It may be noted that application of lime and steatite has not resulted in any appreciable variation in the maximum pH value attained in any of the soils studied. This is suggestive of a possible minor role to them as agents for raising the pH of soils under continuously flooded situations.

Electrical conductivity

With the onset of reducing conditions consequent to flooding, the specific conductance in all the soils both amended and unamended showed an appreciable increase during the first 20 days and then diminished to values which were only slightly higher than the initial value. The comparatively larger increase in specific conductance observed in the highly saline pokkali soils (2.1 units) might be due to the effect of a part of the soluble ions in the soil solution exchanging with ions of higher conductance present in the exchange complex.

The rise in specific conductance might be attributed to an increase in the content of soluble iron on reduction which gets re-oxidised or precipitated later, as suggested by Ponnampereuma (1973). Thus, it may be seen from the results that maximum specific conductance coincides with the highest content of soluble ions and a lowering in the EC corresponds to a parallel fall in the level of both water soluble and exchangeable ions with progressive flooding. The decline in specific conductance after a steep increase was found to be in striking similarity to the kinetics of water-soluble iron and manganese worked out by Ponnampereuma (1973). Lack of appreciable rise in EC in the low level laterites and coastal sandy soils might be due to a lower rate of release of soluble ions.

Water soluble aluminium

Water soluble aluminium in all the soils showed a steady and significant decrease with progressive flooding, the reduction being more prominent in the three acidic soils. Treatment of the soils with lime and steatite did not bring about much differences in the content of soluble aluminium. The decrease in soluble aluminium in all the soils may be seen to coincide with a rise in pH.

The lowering of soil solution aluminium on flooding can be a consequence of the precipitation of $(Al)^{3+}$ ions at a higher pH value by the hydroxyl ions formed by the reduction of ferric iron as $Fe(OH)_3 + e \longrightarrow Fe(OH)_2 + OH^-$ as proposed by Cate and Sukhai (1964).

Tanaka and Navasero (1966a) also considered that the amount of aluminium in soil solution can be considered very little when such soils are waterlogged for some time. They reported a drop in aluminium from 35 to 1 ppm within three weeks of flooding, with only an increase in pH of less than half a unit from 3.5 to 3.8. The results obtained in the present study are however, not consistent with the above findings where, in spite of the maximum rise in pH of 1.9 units, the corresponding fall in soluble aluminium was only from 36 to 8 ppm in the most acidic soil. The kayal, karapadom and kole soils also recorded appreciable fall in soluble aluminium and in all soils the levels were much below

the initial level by the 20th day. The initial level itself, however, was lower than the critical level of 27 ppm fixed by Tanaka (1966b) for rice.

Exchangeable aluminium

The exchangeable aluminium content in all the soils dropped considerably due to flooding and the reduction was more remarkable in treatments with lime and magnesium silicate. It was more pronounced in the two kari soils and less so in the other soils.

The decrease in exchangeable aluminium can be an indirect effect of the increase in pH beyond 4.5 which has been fixed as critical for expressing aluminium toxicity (Ponnamperuma, 1978). As suggested by Nhung and Ponnamperuma (1966), the aluminium is likely to get precipitated as $Al(OH)_3$ in the higher pH ranges prevalent in flooded soil systems. McLean et al. (1964) and Jackson (1973) proposed that these polymerised forms were not replaced by N KCl.

Another reason for the lowering of exchangeable aluminium on flooding might be due to the utilization of the $Al(OH)_3$ for the process of chlorotisation of some of the minor 2:1 minerals present in the soils as indicated by Gopalaswamy (1969) who has detected the presence of chlorite in some of the acid sulphate soils of the State.

The beneficial effects of liming in decreasing exchangeable aluminium can be attributed to the differential

solubility of amorphous $\text{Al}(\text{OH})_3$ precipitated by liming as proposed by Marion et al. (1976) and Bloom et al. (1979). The ability of magnesium silicate to suppress toxic factors in acid and acid sulphate soils has been reported by Reeve and Sumner (1970). However, the possible causes for the ameliorating effect of magnesium silicate have not been made clear by them.

It is very likely that the partly precipitated $\text{Al}(\text{OH})_3$, along with the silicate anions made available from steatite, in presence of various ionic species in the soil solution undergo layer silicate formation. Evidences have not been adduced either for their formation or for defining clearly the conditions which might result in their formation, though the possibilities of their formation cannot be precluded. In fact, it would be theoretically interesting to follow up this aspect of the study.

Water soluble and exchangeable iron

Flooding of the soils has led to an appreciable increase in the content of the above two forms of iron in all the soils, the magnitude being highest in the two kari soils followed by the pokkali soil. The results of the pooled analysis of the three treatments showed a significant effect of steatite in keeping the water soluble iron as low as 19 ppm while it was 35 ppm in soils flooded with water only.

Both lime and steatite exerted a similar effect in maintaining a lower level of exchangeable iron compared to flooding the soils in water.

The increase in the content of both forms of iron can be the direct result of the massive reduction of the oxides of iron that take place immediately after the onset of anoxic conditions. Subramoney and Kurup (1961) showed that considerable iron was brought into solution by iron reducing bacteria in the soil, while Ponnampetuma et al. (1967) considered these reductive reactions to be guided by physico-chemical processes.

Decrease in the content of both forms of iron on continued flooding beyond the period of their peak concentration might be the result ensuing from a re-oxidation at the interface of the water and atmosphere and consequent precipitation.

The results of the incubation studies show that even in the highly acidic soils, water soluble aluminium was much below the critical levels for rice, while it was not so in the case of exchangeable aluminium in almost all soil types except the coastal sandy and brown hydromorphic soils. Even though a reduction in exchangeable aluminium was observed after three days of flooding and the decreasing trend continued till the 30th day, the soils still had about 1.5 to 6 milli equivalent exchangeable aluminium in them at the

end of two months incubation. During the earlier periods of submergence, the content was even much higher in many of the soils. Kabeerathumma (1975) in her studies with aluminium saturated bentonite clay has shown that 2 milli equivalent exchangeable aluminium in soils may be considered as the safe limit for normal rice growth, but in the presence of high levels of phosphorus the crop may be able to withstand more of exchangeable aluminium (Vlams, 1953).

It has therefore to be presumed that wet land rice cultivated in the above types of soil, in spite of the usual liming practices may pose serious problems due to high contents of exchangeable aluminium in them. It is likely that the buffering properties imparted by the native organic matter of the soil along with the added phosphorus may offset the adverse conditions to a certain extent. The presence of high iron and aluminium can inactivate the applied phosphorus by precipitation and render it less available, while the adverse effects of iron and aluminium are averted to a certain extent. Thus, it appears that in the highly acid soils the adverse effects of aluminium and iron can be overcome only at the expense of the availability of phosphorus to the crop.

It is quite possible that unless the level of exchangeable aluminium in the soil is maintained below critical levels, the rice crop will be exposed to the unfavourable

effects of both aluminium toxicity as well as phosphorus deficiency leading to a drastic reduction in rice yield.

The results of the study on the incubation of typical rice soils in water and with lime and steatite as ameliorants has clearly indicated that, the level of exchangeable aluminium continued to be above critical limits in most of the soils in spite of its suppression due to flooding and treatment with ameliorants. The need for the adoption of more effective management practices other than liming are necessary under such circumstances.

Effect of different ameliorants on changes in soil properties and its effect on the growth, yield and nutrient uptake in rice

The effect of different ameliorative treatments on changes in pH, EC, water soluble and exchangeable aluminium and iron in a highly acidic soil at different periods corresponding to the important growth stages of the rice plant was determined and these characters were correlated with the yield and growth characters, as well as nutrient accumulation. The nutrient contents in the plants and their interaction in the different plant parts were also studied.

It may be seen from the results (Table 7(b) that for the plants grown in soil with the treatment of steatite and green leaves, a higher dry matter content in terms of the yield of grain, straw and root was obtained. The roots of

the rice plants especially those that were grown in the steatite treated soil were longer and healthier and did not show any identified symptoms associated with adverse soil conditions as was observed in the case of the rice plants in the other treatments. A lower content of exchangeable aluminium as well as iron in the soils treated with steatite might be considered as the main reason for the observed healthy root system. It may be noted that, even though the exchangeable aluminium has been controlled to a significant extent by the treatment with green leaves and cattle manure, it was not so effective in keeping exchangeable iron at a lower level in the soil. The blackening of the roots observed in these treatments, in spite of a lower exchangeable aluminium content might possibly be due to the effect of injurious level of iron in the soil.

Tanaka and Yoshida (1970) have reported similar blackening of roots of rice plants grown under flooded conditions in soils rich in reduced iron.

Treatment of the soil with steatite and organic materials has also positively influenced the uptake and accumulation of nutrients in the different plant parts. Although the nitrogen content in the different plant parts was not significantly altered by the various treatments, an appreciable increase in phosphorus, calcium and potassium contents of the grain and straw could be obtained. The levels

of iron and aluminium in the grain, straw and root of the plants in the different treatments was also appreciably lower.

A lower level of exchangeable aluminium in the soil might have promoted better root proliferation leading to an increased absorption and translocation of nutrients. Obviously, this has resulted in a higher nutrient status and a lower iron and aluminium content in these plant parts.

Data on the nutrient status of the straw and root show that the phosphorus content was very low in them and that it was negatively correlated to the iron and aluminium contents. Calcium was also negatively influenced by aluminium and positively by phosphorus indicating a possible interaction between phosphorus, calcium and aluminium, the latter tending to decrease the content of the other two.

The interaction between the above nutrients thus indicates that the presence of excess aluminium can produce a negative influence on the accumulation of calcium and phosphorus. Such antagonistic effects of aluminium towards phosphorus and calcium have been reported in literature by several workers (Cruz et al., 1967; Brauner and Sarruge, 1980(a); Alam, 1981). The findings from the present study are also in agreement with the views generally prevalent on aluminium-phosphorus interactions.

Another interesting result obtained in the present study

is the appreciable reduction in the proportion of unfilled grains, resulting in a high grain to chaff ratio (14:1) in the treatment with steatite. It may be noted that this particular treatment has helped to maintain the lowest mean value for exchangeable aluminium throughout the cropping period. The high positive correlation observed (Table 7(f) between the chaff content and the water soluble and exchangeable aluminium at the time of opening and fertilisation of the inflorescence till the maturity of the grain probably indicates a very critical role played by this element during the process of grain filling.

A similar relationship between exchangeable and water-soluble iron and chaff weight, though present, was not so significant as in the case of exchangeable and soluble aluminium. This reveals the more specific effect of soluble and exchangeable aluminium in the soil than of iron in decreasing the proportion of filled grains on the earhead. The importance of keeping a low level of exchangeable and soluble aluminium in the soil for better yields in rice is made apparent.

The chemical composition of the rice grain from the differently treated pots also showed that the grain obtained from the plants receiving steatite and organic materials contained a higher level of the nutrients. A high nutrient content in the paddy seed is desirable since it is a very

critical factor in deciding the quality of the grain either as seed or for food. Thus the results have indicated the usefulness of organic materials and steatite in suppressing toxic soil factors in highly acid soils at critical growth stages of the rice plant ultimately leading to increased yields of better quality grain.

The incubation study with different soil types of Kerala has shown that toxicity problems due to iron and aluminium were highest in the acid sulphate and acid saline soils, relatively lower in the karapadam and reclaimed kayal soils and a minimum in the brown hydromorphic and coastal alluvial soils. Very often, rice production in the acid soils of the State is curtailed by injurious soil conditions which prevail during the cropping period, either due to environmental or managerial differences.

The amount of lime usually applied to the acid soils (600 kg/ha) during rice cultivation is quite insufficient to maintain soil iron and aluminium below toxic levels. Lime at such rates may barely help to neutralise the derived acidity from the acidic fertilizers applied to these soils. Under such situations, the rice crop, although inherently adapted to the adverse conditions prevailing in submerged soils, will still be exposed to a complexity of stress situations due to toxicity and nutrient deficiency though specific symptoms may not often manifest or may not be discerned.

Since the rice soils below pH 4.5 were found to possess a high aluminium saturation of the effective CEC and comparatively low base saturation, much larger amounts of lime are needed to suppress the exchangeable aluminium content and provide a high base saturation.

Richburg and Adams (1970) proposed that soil solution Al^{3+} activities in different soils with similar pH values are not necessarily similar and that different soils may be limed to different critical values to eliminate aluminium toxicity.

In this context, the relative values and merits of the different lime requirement indices may be considered. The soil reaction (pH) cannot be a reliable liming index because, the amount of lime required to raise the pH of a soil to neutrality will depend not only on the initial pH, but also on several other factors, especially the nature of the clay complex. At the same time, the lime requirement values determined by conventional methods often reveal such impractically high figures that they are totally uneconomic. It has therefore been generally accepted that in the humid tropics, liming recommendation should be based on exchangeable aluminium rather than on the pH per se. (Farina et al., 1980).

The results from the present experiment show that amelioration of acid soils with organic materials and

steatite along with 600 kg lime can effectively control the release of soluble and exchangeable iron and aluminium in a better manner than by the use of lime at the rate of 1200 kg/ha. Soils amended with the above materials recorded lower values for exchangeable aluminium in the soil at all periods, corresponding to the stages critical to the growth of the rice crop. The increase in the yield of grain and straw, as well as nutrient uptake obtained in the plants receiving the above treatments can, no doubt, be the result of a more favourable soil condition especially at stages critical to the growth and development of the crop.

The significant negative correlation between soluble and exchangeable forms of iron and aluminium in the soil and the growth and yield characters, as well as the significant positive effect of these elements in increasing the proportion of unfilled grains indicate how these soil characters can adversely affect the productivity of a rice crop.

The beneficial effect of steatite in increasing the yield of rice in the acid sulphate soils of Kerala has been reported by several authors (Subramoney, 1965; Kuruvilla, 1974; Karunakara Panickar, 1980). This phenomenon has generally been explained as due to the effect of silica as a possible nutrient element or its effect in imparting strength to the straw and making it more resistant to the attack of pests and diseases. It is also possible that the exchangeable

aluminium and the Al_2O_3 coating of the clay particles react with the magnesium silicate in steatite to form aluminosilicate compounds which get precipitated in the pH range 4.0 to 8.0 (Bear, 1965).

The effect of organic matter in keeping exchangeable aluminium at a low level was found to be more significant in the case of green leaves as compared to cattle manure. This might possibly be due to a priming effect of green leaves on the soil microflora (Alexander, 1978) which act upon the native organic matter also and produce several intermediate organic compounds that might have helped in complexing some of the exchangeable and soluble aluminium and iron. Such a priming effect cannot be expected from well rotted cattle manure and hence its lower efficiency in suppressing the concentration of aluminium and iron in the soil solution.

Santiago (1972) obtained a reduction in solution aluminium at a given soil pH by the addition of coffee leaf humus which, because of its high content of calcium, was effective in increasing the base saturation, as well as in raising the soil pH.

Similar decrease in the concentration of soluble aluminium by the application of organic materials has been reported (Hoyt and Turner, 1975; Bloom et al., 1979 and Hargrove and Thomas, 1981).

It is possible that in such instances, the reduction of soil solution aluminium might be due to an enhancement of the total CEC of soils by the humus leading to a corresponding decrease in the aluminium saturation of the total CEC. The increase in base saturation of soils due to the application of organic materials rich in bases (Bloom et al., 1979) might also partly be responsible for decreasing the aluminium saturation of soils that subsequently bring about a reduction in the content of soluble aluminium in the soil.

Interaction of aluminium with fulvic acids and non-specific acid organic substances derived from the decomposition of organic materials (Kavrichev et al., 1969) can be considered as another probable cause for the inactivation of soluble aluminium in acid soils.

Aluminium-organic matter interactions have been characterised by Hargrove and Thomas (1981) and they have shown that increasing soil organic matter tended to lower the exchangeable aluminium content at any given soil pH at which aluminium toxicity occurred. Continued addition of organic materials like animal manure or sewage sludge to acid tropical soils was found to reduce aluminium toxicity problems.

The findings from the present study on the beneficial effects of organic materials like green leaves and cattle manure in alleviating aluminium toxicity in the acid soils

of Kerala seem to deserve greater attention under field conditions. The results also open up scope for new approaches in the management of the highly acidic soils of Kerala for rice cultivation.

In addition to the toxicity of aluminium, stress conditions arising out of nutrient deficiency and toxicity due to iron and manganese may complicate the situation and mask the specific effects of the toxicity due to aluminium under field conditions. It was this specific effect of aluminium toxicity on the rice plant that was investigated in the solution culture experiment.

Specific effect of aluminium on the growth, yield and nutrient uptake in rice

The study in nutrient solution culture with graded levels of applied aluminium has revealed a significant depressing effect on all plant growth and nutrient uptake characters from concentrations of 30 ppm and beyond.

Growth and yield characters

The general appearance of even those experimental plants which received 100 ppm aluminium did not show any visible symptoms except a comparatively thinner foliage. None of the symptoms usually attributed to aluminium toxicity and described in literature such as chlorosis (Cruz et al., 1967), dark purplish discolouration of leaves (Tanaka and Yoshida, 1970)

stunted growth or delayed maturity (Foy, 1976) could be observed in any of the experimental plants in the present study. The only visible symptom noted was a drastic stunting of the roots, their characteristic branching and differences in anatomical structures as described earlier.

The fact that the general appearance of even those plants grown in the presence of the highest concentration (100 ppm) of applied aluminium in the nutrient solution was not strikingly different from that of the plants grown in the complete absence of aluminium illustrates how the toxicity by aluminium can go unnoticed under practical field conditions. The more prominent effect of aluminium in decreasing the grain yield compared to the length and weight of the straw, coupled with its effect on increasing the content of chaff (Table 8(a)) suggest a more specific effect of aluminium in decreasing the total grain yield in rice. The significant negative correlation between the content of chaff and exchangeable aluminium from the time of opening of flowers till maturity of grain in rice (obtained in the pot culture experiment) suggests a possible involvement of aluminium in interfering with some of the processes during the grain filling stage.

Nutrient uptake

From the data on the analysis of different plant parts

presented in tables 8(b) to 8(d) it is very clear that high levels of aluminium in solution had interfered with the mineral nutrition of the plants to a considerable extent. The levels of the various elements in the plants except iron and aluminium showed a negative relationship with increasing levels of aluminium.

A drastic reduction in the volume and weight of the roots as obtained in plants treated with more than 20 ppm aluminium in the nutrient solution, if occur under field conditions can produce a more severe influence on nutrient uptake and translocation in view of the lesser volume of the soil in contact with the roots. The overgrowth of root tissues (Fig. (1) and (2) may also result in a constriction of the air channels that help in the transport of atmospheric air to the root zone. Blocking of the movement of air may in turn reduce the oxidising capacity of the roots (Etherington, 1975) and lead to an injurious condition due to the building up of several reduced compounds in the rhizosphere. Therefore, it is possible that the rice crop growing under stress of aluminium toxicity might be exposed to both nutrient deficiency as well as toxicity problems. The reduction in grain yield and other growth parameters could be explained on the basis of a lower nutrient status in them, as growth is an exponential function of the available nutrients.

It may be noted that, even though the plants grown in the presence of high levels of aluminium were able to carry out normal growth activities without the expression of any visible toxicity symptom, the total nutrient uptake in dry matter produced under each treatment was affected considerably (Tables 8(b) to 8(d)).

The adverse effect on nutrient uptake, in spite of an assured supply of nutrients in the rooting medium, might be due either to direct interactional effects of high aluminium or to an impaired absorption and translocation in view of the reduction in root growth and the observed anatomical aberration of the roots.

Injury to roots has been reported as the primary symptom of aluminium toxicity in all sensitive crops like paddy, barley, wheat, legumes, etc. (Vlamis, 1953; Abruna et al., 1970; Villagarcia, 1973).

It is worthwhile to note in this connection that the pattern of mineral nutrition of crops grown in situations of high aluminium has been studied based on the differential uptake and translocation of nutrient elements by plant species tolerant to aluminium toxicity. Aluminium resistant wheat plants have been shown to use an avoidance mechanism like increasing the pH around the roots (Foy et al., 1965), a retention of ions in the roots (Ouellette and Dessureaux, 1958) and more specifically ion retention within the cell

wall of roots (Turner and Gregory, 1967). Chen (1968) obtained 2.7 to 4.6 and 3.7 to 9.9 times higher aluminium in the roots than in the stems and leaves of rice and barley respectively. A proportionate increase in root aluminium with applied aluminium has been reported by Niatsumoto and Hirasawa (1979) in peas.

In the present study also, a very high content of aluminium that was present in the roots of plants grown in a high aluminium containing solution might be considered as a result of an avoidance mechanism presented by the plant. Heller (1974) and Epstein (1976) have postulated that tri-valent aluminium can penetrate in a passive and irreversible manner in the free space of the roots. Possibly this was the reason for aluminium being named as a "ballast" element in plant nutrition (Agarwala and Sarma, 1976). Guerrier (1979) in a study on the excised roots of lupine, sorghum and horsegram grown in nutrient medium with high aluminium showed that aluminium possessing the strongest valence saturated the root's cation exchange capacity. Consequently as the concentration of aluminium increased the adsorption of phosphorus, calcium and magnesium was diminished as a function of their respective valences. The general decrease in the content of various nutrient ions observed in the present experiment might also be explained as a consequence

of the decreased uptake due to an over saturation of the root CEC with aluminium in an avoidance mechanism to overcome the excessive aluminium in solution from being translocated to the straw and grains.

A substantial decrease in the nitrogen content of plants grown in high aluminium has been observed in the present study. It is likely that the low uptake of other essential elements under the influence of a high level of aluminium might have limited the absorption and metabolism of nitrogenous compounds in these plants resulting in their lower nitrogen content. Mesdag et al. (1970) found a weak association between tolerance of soil acidity and aluminium toxicity and protein content in wheat. Absence of nitrate reductase activity in the plants due to poor utilisation of molybdenum at the very low pH in the nutrient solution can be another probable reason for the lower assimilation of nitrogen in these plants.

A similar decrease in the content of phosphorus in the different plant parts is obtained at the higher levels of aluminium.

The interrelationship between phosphorus deficiency and aluminium toxicity has been reported in literature and a deficiency of phosphorus has often been considered as a characteristic symptom of aluminium toxicity. Encouraging results also have been reported for the correction of

aluminium toxicity by phosphorus fertilisation (Wright, 1937). Foy and Brown (1963, 1964) expressed the view that plant species possessing abilities to absorb and utilise phosphorus in the presence of excess aluminium were tolerant to aluminium. More recently, Foy (1974) found aluminium to accumulate in the roots and impede the uptake and translocation of calcium and phosphorus to the tops, thus accentuating both phosphorus as well as calcium deficiency.

Similar reduction in the uptake and translocation of phosphorus has been reported by Sanchez (1976), Bringer (1980), Mugwira et al. (1980) and Alam (1981). Mugwira et al. (1980) attributed the increased phosphorus content in the roots of sensitive cultivars to the association of phosphorus with larger quantities of aluminium on the root surface, rather than to enhanced phosphorus uptake.

Unlike the content of phosphorus in the grain and straw root phosphorus recorded a decrease till 40 ppm aluminium and then gradually increased upto 100 ppm indicating a tendency for phosphorus to accumulate in the roots with increasing aluminium, as reported by Brauner and Sarruge (1980a). They attributed this increase in phosphorus uptake to a stimulatory effect of aluminium. A perusal of the data presented in table 8(d) reveal that the level of aluminium in the roots also show a large increase beyond 50 ppm aluminium in solution.

It is possible to associate the high content of both aluminium and phosphorus in the root tissues with the formation of insoluble aluminium phosphate which is accumulated in the roots and prevented from translocation to the aerial parts, where only lower contents of both these elements are noticed. Sanchez (1976) had reported similar situations in the case of aluminium resistant varieties of rice, corn and wheat.

A perusal of the composition of rice plants grown with graded levels of aluminium in solution reveal a steady decrease in the content of all nutrient elements with increasing levels of applied aluminium. Such a high depletion of nutrient levels in plant tissues might be attributed to an impeded metabolism of the plant resulting under aluminium toxic conditions.

A level of even 10 ppm aluminium in nutrient solution has been found to interfere appreciably with the uptake of calcium and under such conditions as much as a nine fold decrease in calcium uptake has been reported (Schmehl et al., 1952). Since the primary symptom of aluminium toxicity is a stunting of the root system and it could be counteracted by raising the calcium concentration (Burstrum, 1953), it is possible that the interference with calcium uptake might be a consequence of the impairment of the metabolism of calcium in the plants due to aluminium toxicity.

By expressing changes in plant composition due to aluminium in terms of the concentration of calcium, magnesium, potassium and phosphorus in plants grown with and without aluminium in nutrient solution, Mugwira et al. (1980) showed that these elements were more concentrated in the root system and that tolerant cultivars apparently translocated potassium and calcium more efficiently. The results obtained in the present study on the nutrient composition of plants grown in high aluminium are consistent with several of the earlier findings where such a decrease in nutrient uptake has been reported (Tripathi and Pande, 1975; Ben et al., 1976; Cruz et al., 1976; Kamprath, 1978; Mugwira et al., 1980).

Further, in all cases, it was observed that the reduction in nutrient content became appreciable beyond 30 ppm aluminium, confirming the critical level of 27 ppm for rice fixed by Tanaka (1966b).

An enhanced uptake of iron, especially in the roots and straw, suggests a positive relationship of iron with aluminium, but previous reports on this aspect are lacking.

The significance of the pH of the rooting medium that was around 4.8 in the control and 3.8 in the high aluminium containing solution cannot be ignored while considering the nutrient composition of the plants. Since the graded levels of aluminium in the medium were obtained by the addition of

AlCl_3 solution to the basal nutrient solution, a fall in pH was expected, as at least a part of the Al^{3+} ions might undergo hydrolysis liberating H^+ ions. It is possible that the resultant acidity maintained a high level of Al^{3+} ions in solution and created an unfavourable effect on the uptake and utilisation of all other nutrient ions except iron and aluminium.

Aluminium toxicity can thus, be considered as one of the major constraints to the production of rice in the majority of acid soils in the humid tropics. The results obtained from the present study point to the fact that the usual management practices followed for rice cultivation such as liming and maintaining the field under flooded conditions, can only bring about a partial elimination of the problems due to aluminium toxicity. Another practical approach to this problem in the field would be the selection of rice varieties that are tolerant to aluminium toxicity. Such varieties will, no doubt, be more suited for cultivation under highly acid situations, as they will be able to withstand the toxic effects of aluminium and utilize the available soil resources in a better manner.

Screening of Rice varieties for tolerance to Aluminium toxicity

The screening study has revealed that a large number of rice varieties cultivated in Kerala are sensitive to

aluminium toxicity, while an equally large number showed appreciable tolerance to aluminium toxicity.

Nutrient solution screening studies conducted at IRRI (Coronel, 1980) showed that the rice varieties commonly cultivated in the acid soils of Brazil were characteristically tolerant and most other lines from Philippines, specifically the IR varieties were sensitive to aluminium in solution.

The degree of tolerance of the rice varieties/cultures used in the present study, however, did not exhibit any such specificity with regard to any location, even though a few varieties like MO 4, MO 5 and MO 6 developed at the Moncompu rice research station, where the soils are characteristically acidic and aluminium toxicity problems do exist, showed marked tolerance to aluminium toxicity. At the same time, some of the PTB varieties evolved in the less acidic soils of Pattambi where aluminium toxicity is not encountered, were more sensitive. Some of the IR varieties (IR-42, IR-28, IR-30 and IR-34) used in the present study also showed marked tolerance to aluminium toxicity, while IR-8 and IR-20 were sensitive.

The screening studies at IRRI have indicated a correlation between root length and resistance to toxicity by aluminium. Rice varieties recording a shorter root length

in the absence of aluminium were more sensitive to aluminium toxicity while those with longer roots were less sensitive. The results from the present study, however, did not reveal any such relationship between root length and sensitivity to aluminium. The mean root length of the rice varieties in the less tolerant, medium tolerant and tolerant categories were 5.3, 5.2 and 5.1 cm respectively and exhibited no marked variation in root elongation in the absence of aluminium and no characterisation could be based upon root length as observed by Coronel (1980) at the IRRI.

Since root elongation is highly restricted in the aluminium sensitive cultivars, nutrient absorption, especially that of phosphorus is likely to be limited to a great extent in them. Phosphorus being an immobile nutrient element in the soil, most of it has to be taken up by root interception rather than by diffusion or mass flow (Clark, 1976). Therefore, the volume of the root that has to remain in contact with the surrounding soil also must be sufficiently large to facilitate an effective phosphorus uptake.

A differential response of rice varieties to phosphorus has been reported in literature (Dev et al., 1971; Ponnampereuma, 1972; Gupta et al., 1975; Subba Rao et al., 1979). Mahendran (1979) reported a decreased length, weight, volume and surface area for the roots of some of the rice varieties which did not respond to phosphorus, compared to

the medium and high responders. These observations bring out the importance of a larger root volume and surface area in enhancing phosphorus absorption in rice.

In the light of the above evidence, it might be presumed that the aluminium tolerant rice varieties whose relative root length is higher under comparable conditions of aluminium toxicity than the sensitive ones might be able to explore more efficiently, a larger soil volume for their phosphorus nutrition. The poor uptake of phosphorus, observed in aluminium toxic situations might partly be explained on the basis of a restricted root growth limiting the feeding volume of the soil for phosphorus. Thus, it is likely that the aluminium tolerant varieties might perform better with a lower input of phosphorus fertilizers compared to the sensitive varieties under acid soil situations because of the comparatively greater volume of root in contact with the soil.

Dev et al. (1971) have reported IR-8 and Jaya to be relatively less efficient in utilising soil phosphorus. Mahendran (1979) identified PTB 31, Rohini, Annapoorna, Triveni, Jaya, IR-8, IR-5 and IR-20 as moderate responders to phosphorus. It may be noted that the screening technique has shown these varieties to be sensitive to aluminium toxicity. The poor response of these rice varieties to phosphorus in a soil of pH 4.8 might be due to a restricted

root growth which has prevented the plants from a better utilization of the applied phosphorus.

At the same time, varieties Aswathi and Bharathi which under similar conditions showed a linear response to applied phosphorus (Mahendran, 1979) were identified as tolerant to aluminium toxicity by the nutrient solution screening technique.

Thus, it is possible that the rice varieties identified to be less affected by excess aluminium might possess yet another favourable character like a responsiveness to phosphorus which will enable the plant to express a higher yield potential under stress of aluminium toxicity, as well as phosphorus deficiency in acid soil situations.

SUMMARY

SUMMARY AND CONCLUSIONS

A study has been made on the extent of aluminium toxicity in relation to other important characters in the acid rice soils of Kerala with a view to evolving suitable ameliorative measures. The investigation was carried out in the following five parts:

1. Chemical nature of the rice soils with special reference to aluminium saturation.
2. The pattern of solubilization of aluminium when rice soils are incubated under flooded conditions with different ameliorants.
3. Pot culture experiment with different ameliorants added to an acid rice soil to follow the pattern of solubilization of aluminium and its effect on rice.
4. Solution culture experiment to study the specific effect of graded levels of aluminium on the growth, yield and nutrient uptake in rice.
5. Screening of rice varieties for tolerance to aluminium toxicity.

The first part of the investigation was carried out by analysing 89 samples of typical wet land rice soils, ranging in pH from 2.5 to 6.5. The various properties of these soils, which are known to be related to the expression of aluminium

toxicity, were determined and their interrelationships studied.

By incubating selected rice soils under flooded conditions for a period of two months, with and without ameliorants, the periodical changes in the release of exchangeable aluminium was determined. The study was followed by a pot culture experiment using a highly acid soil treated with different ameliorants like lime, steatite, cattle manure and green leaves. The comparative efficiency of these materials in suppressing the release of exchangeable aluminium and its consequent effect on the growth, yield and nutrient uptake in rice was studied.

Since the toxic effects of aluminium to rice under field conditions are likely to be affected by several other adverse soil conditions, a solution culture experiment was designed to study this aspect. The specific effect of aluminium on the growth, yield and uptake of nutrients in rice was obtained by growing rice in a complete nutrient solution containing graded levels of aluminium.

The concluding part of the investigation was aimed at selecting rice varieties more suited for cultivation under conditions of aluminium toxicity. By a rapid screening method, a large number of rice cultivars were classified as tolerant, medium tolerant and least tolerant to aluminium toxicity.

The important findings from the above studies are given below:

1. A very high content of exchangeable aluminium is present in the rice soils of Kerala whose pH value is less than 6.0. The aluminium saturation of the total and effective CEC in these soils were also very high and above critical limits for rice.
2. Exchangeable hydrogen was comparatively higher in the soils below pH 4.5 and this accounted for the large variation observed between total and effective CEC in them.
3. A significant negative correlation between pH and exchangeable aluminium was observed only in the near neutral soils of pH between 5.5 and 6.0.
4. In soils recording pH values lower than 4.0, there existed a significant and positive relationship between lime requirement values and exchangeable aluminium. This relationship became weaker with decreasing acidity.
5. Organic carbon was significantly and positively correlated to exchangeable hydrogen in soils below pH 5.4. In soils above this pH organic carbon showed a positive and significant relationship with exchangeable aluminium. These relationships reveal the importance of organic matter in controlling the exchange acidity in the more acidic soils

and that of exchangeable aluminium in the less acidic soils.

6. Flooding for a period of two months resulted in a rise in pH and EC of all the typical rice soils of the State. The maximum rise was obtained after 20 to 30 days of flooding. The kari and pokkali soils recorded the maximum shift in pH value, but it did not rise beyond 5.2. In all the other soils, the pH remained more or less steady after reaching the peak value, whereas, the EC of these soils showed a decreasing tendency with time, owing to the precipitation of some of the dissolved ions, especially ferrous iron.
7. Water soluble and exchangeable aluminium in all the soils showed a progressive decrease with increase in the period of flooding. The reduction in the content of water soluble aluminium was evident from the 3rd day and became significantly lower than the original content by the 6th day. Only marginal changes were recorded thereafter. The reduction in the case of exchangeable aluminium started from the 6th day and continued till the 30th day.
8. A rapid rise in the contents of both water soluble and exchangeable iron was observed in all the soils. The highest values were recorded by the end of 20 to 30 days of flooding, after which it slowly decreased.

9. Treatment of the soils with lime and steatite and subsequent flooding resulted in a significantly lower content of exchangeable aluminium as well as water soluble and exchangeable iron in all the soils, when compared to flooding in water alone.
10. Treatment with lime and steatite and flooding, however, did not bring down the mean values for exchangeable aluminium to below critical limits for rice except in the sandy and brown hydromorphic soils.
11. Use of steatite and organic materials along with lime was found to be very effective in suppressing the release of exchangeable aluminium in a highly acid soil.
12. The yield of grain and straw as well as the uptake of nutrients in them were more favourably influenced by the treatment of the soils with steatite and organic matter than by the use of lime at twice the recommended level.
13. Correlation studies between soil properties at important growth stages of the plant and various plant characters showed a significant positive influence of the pH of the soil, especially at the transplanting and maturity stages, on all plant characters except the content of chaff.
14. The slightly high EC prevalent in the soils produced a

negative influence on all plant characters except the weight of chaff.

15. Both water soluble and exchangeable forms of iron and aluminium exerted a significantly negative influence on all favourable plant characters. The weight of chaff, however, was positively correlated with these chemical parameters.
16. The specific effect of aluminium in suppressing root elongation of rice in nutrient solution culture was evident from the 20 ppm level. With increase in aluminium concentration the root elongation was drastically affected. Shortening and branching of roots and onset of anatomical modifications were more conspicuous from the 40 ppm level of aluminium.
17. A significant reduction in the number of productive tillers, as well as the yield of grain and straw, was observed from 30 ppm of applied aluminium.
18. An appreciable reduction in the uptake of all nutrients was noted from 30 ppm applied aluminium. However, a higher content of aluminium in the nutrient solution led to a higher uptake of aluminium as well as iron in the plant. The maximum content of aluminium and iron was present in the roots.

19. Screening of rice varieties for tolerance to aluminium toxicity revealed that a large number of rice cultivars in Kerala show considerable tolerance to aluminium toxicity, while an equally large number does not.
20. It is possible that the rice varieties showing tolerance to aluminium toxicity are capable of adopting in a better manner to soil conditions where aluminium toxicity is a serious problem for rice cultivation.

From the investigation carried out in the present study, it has been possible to obtain a systematic account of the extent and nature of the problem of aluminium toxicity in the wet land rice soils of Kerala. The study has revealed that the majority of rice soils contain appreciable levels of exchangeable aluminium capable of producing aluminium toxicity conditions of a variable degree. The usual practice of flooding the soil after treatment with lime, though reduces the severity of the problem, does not completely eliminate it. The rice crop under such situations can produce only a lower yield of grain and straw, having a comparatively lower nutrient content.

Treatment of acid soils with steatite and organic materials like green leaves and cattle manure along with lime was found to be more effective in suppressing the release of exchangeable aluminium than by the treatment with lime alone.

The resultant soil conditions might have created a more favourable effect on the rice plant and enhanced the yield of grain and straw, having a higher nutrient content.

It is to be concluded that rice varieties identified as tolerant to aluminium toxicity will perform better under acid soil conditions. Thus, it should be possible to counteract the ill effects of aluminium toxicity by a judicious combination of selected rice varieties and suitable management practices.

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* Originals not seen

APPENDICES

Appendix 1(a) Physico-chemical properties of soils on submergence in water -
Abstract of ANOVA

Source	df	pH	EC	Al (H ₂ O)	Al (KCl)	Fe (H ₂ O)	Fe (KCl)
Period (P)	6	2.791**	1.210**	226.445**	72718.333**	3579.528**	235802.690**
Soil (S)	10	3.569**	161.399**	325.836**	418102.184**	2566.293**	514816.696**
P x S (error)	60	0.056	0.011	11.366	62.838	178.932	315729.120

** Significant at 1% level

Appendix 1(b) Physico-chemical properties of soils after treatment with lime and submergence
in water - Abstract of ANOVA

Source	df	pH	EC	Al (H ₂ O)	Al (KCl)	Fe (H ₂ O)	Fe (KCl)
Period (P)	6	2.645**	1.643**	91.203**	75236.056**	1221.601**	118829.636**
Soil (S)	10	4.069**	158.338**	336.556**	250372.909**	1417.379**	253479.927**
P x S (error)	60	0.037	0.109	8.623	6753.852	129.406	17035.936

** Significant at 1% level

Appendix 1(c) Physico-chemical properties of soils after treatment with steatite and submergence in water - Abstract of ANOVA

Source	df	pH	EC	Al (H ₂ O)	Al (Exch)	Fe (H ₂ O)	Fe (Exch)
Period (P)	6	2.959**	1.320**	108.330	91826.630**	774.660**	56333.650**
Soil (S)	10	4.098**	157.700**	238.824**	190361.230**	755.170**	122902.350**
P x S (error)	60	0.098	0.080	78.360	7087.650	75.310	7936.400

** Significant at 1% level

Appendix 1(d) Physico-chemical properties of soils on submergence in water. Pooled ANOVA for eleven soils and three treatments

Source	df	pH	EC	Al (H ₂ O)	Al (Exch)	Fe (H ₂ O)	Fe (Exch)
Treatments (T)	2	0.795	0.252	0.252	14713.450*	5559.946**	250491.159*
Soils (S)	10	11.853**	478.513**	868.748**	672788.648**	4369.208**	710328.361**
T x S	20	0.024	0.112	15.979	1636.875	260.598	17715.546
T x P	12	0.077	0.085	0.085	6753.690	392.773	19136.885
S x P	60	0.001	0.002	0.189	1.047	2.982	5262.152
T x S x P	120	0.476	0.466	31.577	38076.375	283.651	76963.405
Total	230						
CD for comparison of treatments (T)		0.08 ⁺	0.08 ⁺	0.64 ⁺	62.90	5.43	89.42
CD for comparison of treatments (S)		9.44	0.42	346.83	120.44	10.39	171.23
-do- (P)		0.34	0.33	2.77	96.08	8.29	136.59

+ SE of treatment means

* Significant at 5% level

** Significant at 1% level

Appendix 2(a) Influence of different treatments on plant characters - Abstract of ANOVA

Source	df	Height of plants	Number of ear heads	Length of root	Weight of straw	Weight of root	Weight of grain	Weight of chaff	Grain/ straw	Grain/ chaff
Treatment	5	102.44**	12.27	45.12**	39.41**	3.17*	18.72*	1.050**	0.0095	38.25**
Error	12	41.23	9.56	5.64	13.30	2.03	9.43	0.329	0.0150	7.56

Appendix 2(b) Influence of different treatments on the nutrient composition of plant parts - Abstract of ANOVA

Source	df	N	P	K	Ca	Mg	Fe	Al
<u>Grain</u>								
Treatment	5	61x10 ⁻⁴ **	369x10 ⁻⁷ **	373x10 ⁻⁵ *	418x10 ⁻⁶ **	124x10 ⁻⁵ **	903.07**	354.80*
Error	12	119x10 ⁻⁴	85 x10 ⁻⁷	262x10 ⁻⁵	20x10 ⁻⁶	2x10 ⁻⁵	42.56	145.00
<u>Straw</u>								
Treatment	5	367x10 ⁻⁴ **	71x10 ⁻⁶ **	66x10 ⁻⁴ **	709x10 ⁻⁴ **	1206x10 ⁻⁴ **	66792.22**	22202.89**
Error	12	55x10 ⁻⁴	16x10 ⁻⁶	6x10 ⁻⁴	14x10 ⁻⁴	44x10 ⁻⁴	17905.56	3494.67
<u>Root</u>								
Treatment	5	84x10 ⁻⁴ **	101x10 ⁻⁵	141x10 ⁻⁶ *	98x10 ⁻⁶	11x10 ⁻⁵ **	9226.46**	1898.89**
Error	12	280x10 ⁻⁴	2x10 ⁻⁵	47x10 ⁻⁵	78x10 ⁻⁶	1x10 ⁻⁵	803.61	402.78

* Significant at 5% level

** Significant at 1% level

Appendix 3(a) Influence of graded levels of aluminium on plant characters - Abstract of ANOVA

Source	df	Plant height	Number of ear heads	Root length	Weight of straw	Weight of root	Weight of grain	Weight of chaff	Grain/chaff	Straw/grain
Treatment	10	2.522*	26.659**	27.277**	10.553**	32.709**	45.759**	4.520**	20.913**	0.013**
Error	22	1.118	4.333	0.582	1.316	0.594	2.640	0.916	1.630	0.0016

Appendix 3(b) Influence of graded levels of Aluminium on nutrient composition of plant parts - Abstract of ANOVA

Source	df	N	P	K	Ca	Mg	Al	Fe
<u>Grain</u>								
Treatment	10	747×10^{-4} *	276×10^{-5} *	340×10^{-5} **	179×10^{-6} **	99×10^{-6} **	5105×10^{-4} *	385×10^{-4} **
Error	22	324×10^{-4}	21×10^{-5}	25×10^{-5}	22×10^{-6}	13×10^{-6}	16×10^{-4}	70×10^{-4}
<u>Straw</u>								
Treatment	10	89×10^{-4} **	194×10^{-6} **	643×10^{-5} **	1166×10^{-4} **	253×10^{-4} **	1.7240**	1792×10^{-5} **
Error	22	81×10^{-4}	15×10^{-6}	54×10^{-5}	45×10^{-4}	30×10^{-4}	113×10^{-5}	208×10^{-5}
<u>Root</u>								
Treatment	10	482×10^{-4} **	71×10^{-5} *	223×10^{-6}	1837×10^{-4} **	2263×10^{-5} **	1.9123	940×10^{-4}
Error	22	48×10^{-4}	15×10^{-5}	177×10^{-6}	42×10^{-4}	118×10^{-5}	76×10^{-5}	18×10^{-4}

* Significant at 5% level

** Significant at 1% level

**THE RELEASE OF SOLUBLE ALUMINIUM IN SOILS UNDER
SUBMERGED CONDITIONS AND ITS EFFECT ON RICE**

By
ALICE ABRAHAM

**ABSTRACT OF THE
THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENT FOR THE DEGREE
DOCTOR OF PHILOSOPHY IN AGRICULTURE
FACULTY OF AGRICULTURE
KERALA AGRICULTURAL UNIVERSITY**

**DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY
COLLEGE OF AGRICULTURE
VELLAYANI, TRIVANDRUM**

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ABSTRACT

A study has been made of the extent of aluminium toxicity in relation to other important characters in the acid Rice soils of Kerala with a view to evolving suitable ameliorative measures.

The submerged wet-land rice soils of Kerala showing a pH value of less than 6.0 were found to contain appreciable amounts of exchangeable aluminium. The aluminium saturation of the total and effective CEC of these soils were also very high and above the critical limits for rice.

Flooding of these soils in water resulted in a rise in pH and EC, as well as water soluble and exchangeable iron. Peak values for these parameters were obtained by 20-30 days of flooding, after which the pH remained steady while EC and iron showed a decreasing trend. Water soluble and exchangeable aluminium, on the other hand, registered a significantly lower content after the 6th day and the trend continued till the 30th day.

Flooding of the soils after treatment with lime and steatite also produced similar effects. Even though the release of iron and aluminium was controlled to a great extent, the mean values for exchangeable aluminium still remained above critical limits in the highly acidic samples of kari, karapadam, kaval, kole and pokkali soils.

The use of steatite and organic materials like cattle manure and green leaves, along with lime at recommended levels, was found to be very effective in suppressing the release of exchangeable aluminium in a highly acid soil from the kari region of Kuttanad. These treatments were able to create a more favourable soil condition and produced a better yield of rice and straw having a higher nutrient content.

The specific effect of graded levels of aluminium in solution culture on the growth of rice was revealed by a drastic reduction in root growth. The shortening and branching of roots and the onset of anatomical changes were more conspicuous from the 40 ppm level of aluminium.

Transverse sections of these roots showed an overgrowth of cells in the cortex leading to a considerable reduction in the air spaces. The constriction of air channels in the roots can impede the transport of atmospheric air to the rhizosphere and lead to an accumulation of several reduced compounds in the vicinity of the roots. Such a condition arising out of the toxicity due to aluminium can affect the normal growth of rice under flooded conditions.

High levels of aluminium in the nutrient solution led to a reduction in the yield of grain and straw, as well as

a decrease in the uptake of all the nutrients. However, the aluminium and iron contents in the plant were higher, the maximum content being present in the roots.

Screening of rice varieties for tolerance to aluminium toxicity has revealed that a large number of rice cultivars shows considerable tolerance to aluminium toxicity while an equally large number does not.

It is to be concluded that rice varieties identified as tolerant to aluminium toxicity will perform better under acid soil conditions. Thus, it should be possible to counteract the ill effects of aluminium toxicity by a judicious combination of selected rice varieties and suitable management practices.