FLUX AND DYNAMICS OF IRON AND ALUMINIUM IN WETLANDS OF KUTTANAD AND ITS MANAGEMENT FOR RICE (*Oryza sativa* L.)

by

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THESIS

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DECLARATION

I, hereby declare that this thesis entitled **"Flux and dynamics of iron and aluminium in wetlands of Kuttanad and its management for rice (*Oryza sativa* L.)"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associate ship, fellowship or other similar title, of any other University or Society.

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Certified that this thesis entitled **"Flux and dynamics of iron and aluminium in wetlands of Kuttanad and its management for rice (*Oryza sativa* L.)"** is a record of research work done independently by Ms. Ebimol N. L. under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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Ebimol N. L.

Dedicated to

my beloved

Parents

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LIST OF ABBREVIATIONS

% - Per cent
@ - at the rate of
B - Boron
Ca - Calcium
CD - Critical difference
CEC - Cation exchange capacity
Cl - Chlorine
cm - Centimeter
Cu - Copper
dS m^{-1} - deci Siemens per meter
DAT - Days after transplanting
DAS - Days after Submergence
EC - Electrical conductivity
et al - And others
Fe - Iron
Fig. - Figure
g - Gram
ha^{-1} - Per hectare
K - Potassium
KAU - Kerala Agricultural University
kg - Kilogram
kg ha^{-1} - Kilogram per hectare
L - Litre

m	-	Meter
Mg	-	Magnesium
mg g^{-1}	-	Milli gram per gram
mg kg^{-1}	-	milligram per kilogram
mL	-	Milli litre
mm	-	Milli meter
mmol g^{-1}	-	Milli moles per gram
Mn	-	Manganese
Mo	-	Molybdenum
MT/ha	-	Metric tonnes per hectare
N	-	Nitrogen
NS	-	Not significant
pH	-	Soil reaction
ppm	-	Parts per million
S	-	Sulphur
SEm	-	Standard error mean
viz.	-	Namely
Zn	-	Zinc

Introduction

1. INTRODUCTION

Rice (*Oryza sativa* L.) is the leading cereal of the world and more than half of the human race depends on rice for their daily sustenance. It is the staple food for more than three billion people, over half of the world population. Even though rice is grown in 113 countries, about 95 per cent of the crop is grown and consumed in Asian continent where 59.69 per cent of the world population is residing. In India, rice occupies 23.3 per cent gross cropped area (192 million ha) of the country and contributes 43 per cent of the total food grain production and account for 46 per cent of country's total cereal production. India has the largest area under rice crop (about 45 million ha) and ranks second in production, next to China (DES, 2017).

Rice is the most important cereal and staple food consumed in Kerala though the state's production meets just 16.55 per cent of the demand. Presently Kerala covers an area of 1.99 lakh ha in rice cultivation with an annual production of 5.64 lakh tons and the productivity was marginal with 2827 kg ha^{-1} during 2014- 2015 (DES Kerala, 2016).

Kuttanad of Alleppey district, the rice bowl of Kerala is a unique agricultural tract lying 0.6 to 2.2 m below the mean sea level on the west coast of India. It has a geographic area of 0.85 lakh ha. This comprised of 50,000 ha of rice fields, out of which 14,227 ha belongs to acid sulphate soils (typic sulfaquent) known as the 'Kari' lands which is the most problematic area of rice cultivation. The area in Kuttanad constitutes the largest wetlands of the country and is unique among rice ecologies of the world. Several parts of this area have subsoil layers containing pyrites which on drainage and oxidation produce severe acidity. The rice cultivation in Kuttanad face risks associated with waterlogging, extreme acidity and toxicities of iron and aluminium (Thampatti and Jose, 2000). These problems usually limit the crop production and even crop choice in these soils.

Rice production in acid sulphate soil can be increased by proper management. The extent of acid sulphate soils in the coastal areas of Kerala is about 2.6 lakh hectares (Ray *et al*., 2014). Acid sulphate soil is the common name given to soils and sediments containing iron sulfides, the most common being pyrite. When these soils are exposed to air due to drainage or disturbance, pyrite is oxidized. These results in production of sulphuric acid and subsequent release of toxic quantities of iron, aluminium and heavy metals. The profile of these soils often contains yellow mottle of jarosite which is an important pedological mark in classifying these soils (Rattanapichai *et al.,* 2013). Problems due to presence of toxic quantities of iron and aluminium owing to the acidic condition of soil are widespread in most of the rice growing tracts throughout Kerala.

Iron toxicity commonly occurs in a wide range of acid soils, particularly in lowland rice with permanent flooding. Excess concentration of reduced iron (Fe^{2+}) results in a range of nutrient disorders and results in deficiencies of other major and micro nutrients. Mechanism of iron toxicity in rice might be due to its accumulation in the roots and leaves. In high Fe^{2+} concentrations in soil solution and rice roots being oxygenated the iron precipitates as Fe^{3+} on root surface and coats as a plaque. This makes the roots physiologically inactive or less active. Rice yield losses associated with iron toxicity ranges from 12 to 100% depending on the rice cultivars and the prevailing iron toxicity levels (Abifarin, 1988).

Rice has the characteristic property of forming iron plaque on its root surfaces due to the plant's capability to release oxygen to the rhizosphere. This results in the oxidation of ferrous to ferric iron and the precipitation of iron oxide/hydroxide on the root surface. In wetland fields, iron (Fe^{3+}) forms precipitates on root surfaces, which is predominantly of ferrihydrite (approx. 63%) and goethite (Hansel *et al*., 2001).

Aluminum toxicity is also one of the major concerns of low rice productivity in wetland acid sulphate soils (Fageria and Carvalho, 1982). Aluminum toxicity affects about 40-70% of the world's arable land, which otherwise has the immense potential for food crop and biomass production. Aluminium toxicity impairs productivity in soils having low pH (below 5.0). Free aluminium ions are solubilized at low pH. The primary site of aluminium accumulation and toxicity target in plants was reported to be the root meristem. A severe inhibition of root growth is the direct major effect of aluminium toxicity on plants (Vasconcelos *et al.*, 2002).

The occurrence of metal toxicity predominantly of iron and aluminium in many cases can be overcome by the addition of lime (calcium carbonate), or slaked lime (calcium hydroxide), magnesium carbonate or other alkaline/liming materials to increase the soil pH and precipitate the toxic metals and thus increase plant growth. Phosphorus deficiency is another problem in these areas. This is because of the high P fixation capacity of the soil due to the occurrence of high concentration of iron and aluminium. Availability of phosphorous is decreased in extreme acidic condition. (Suswanto *et al.,* 2007).

Since the acid sulphate soils of Kuttanad is an important problematic area with extreme acidity, toxicity of iron, aluminium coupled with deficiency of phosphorous, application of different amendments and other nutrients should be used for successful cultivation in these area. Keeping all these points in view, the present study on the flux and dynamics of iron and aluminium in wetlands of Kuttanad and its management for rice cultivation has been proposed with the following objectives.

- Investigation of the iron and aluminium toxicity problem in rice grown on acid sulphate soils of 'Kari' lands in Kuttanad
- To evaluate the performance of two popular rice varieties to variable levels of iron and aluminium concentrations at different stages
- To examine suitable amelioration strategies for iron and aluminium toxicity problems

Review of Literature

2. REVIEW OF LITERATURE

Kuttanad is a unique agricultural tract on the west coast of India which is dynamic and lying 0.6 to 2.2 m below the mean sea level. It extends between north latitudes 9° 8' and 9° 52' and east longitudes 76° 19' and 76° 44' (Sreejith, 2013). It is a deltaic formation and the region is crisscrossed by numerous water ways. It has a geographic area of 854 sq. km comprises the area of 54 villages spread over Alappuzha, Kottayam and Pathanamthitta districts in Kerala. The organic matter transported from the high ranges makes Kuttanad a unique ecosystem in the world due to its location near equator, equitable temperature regime, high rainfall and high solar radiation throughout the year. Subsoil layers in many parts of this area contain pyrites which produce severe acidity on drying and oxidation due to formation of sulphuric acid (Nath *et al.,* 2016).

2.1. RICE CULTIVATION IN KUTTANAD

Rice is the most important cereal and staple food consumed in Kerala. Kerala covers an area of 1.99 lakh ha in rice cultivation with a production of 5.64 lakh tons annually and the productivity was 2827 kg/ha in the year 2014- 2015 (DES Kerala, 2016).

Kuttanad is the rice bowl of Kerala. It includes 50,000 ha of rice fields. It is the only system in India that practices rice cultivation below sea level. Kuttanad is a major rice growing belt which has more than 145,000 of wetland fields under cultivation.

Soils in several parts of Kuttanad is having acid sulphate soils which again is having severe other problems like extreme acidity, iron and aluminium toxicity coupled with very low base status (Beena *et al.,* 2007).

The region is experiencing continuous decline in rice production which is mainly attributed to deterioration of soil health. The rice cultivation in Kuttanad face risks associated with water logging, acidity and toxicities of iron and aluminium (Thampatti and Jose, 2000).

Rice production can be increased by proper management of acid sulphate soil. The extent of acid sulphate soils in the coastal areas of Kerala is about 2.6 lakh hectares (Ray *et al.*, 2014).

2.2. ACID SULPHATE SOILS IN KUTTANAD

Acid sulphate soils are problem soils which, however, are suitable for various crops under controlled water logging that keeps the sulphidic horizon reduced, preventing oxidation of pyrite (Dent, 1986). They are usually formed under submerged conditions. When these soils are drained, sulphuric acid is formed by the oxidation of pyrite resulting in acidic pH varying from 2.6 to 4.0 (Attanandana *et al.*, 1986).

There are mainly three types of acid sulphate soils *viz*. actual acid sulphate soils, potential acid sulphate soils and post active acid sulphate soils. Actual acid sulphate soils contain sulphuric acid formed as a result of oxidation of pyrite whereas, potential acid sulphate soils are poorly drained rich in pyrite having the potential to produce sulphuric acid if drained and exposed to oxidised conditions. Hence, upon drainage, these soils become extremely acidic in reaction. Extreme acidity causes pronounced toxicity of iron and aluminium which directly affects the plant growth and indirectly reduces the availability of phosphorous and other plant nutrients (Thampatti and Jose, 2006). Post active acid sulphate soils are soils in which the acid has been leached out or neutralized such that microbiological activation and root development are no longer hampered (Breemen and Pons, 1978).

It is estimated that world over 12.5 million hectare of potential and actual acid sulphate soils are present in the world, out of which about six million hectare (almost half the extent) is found in South East Asia. These soils are mostly located in swampy coastal plains. In India, the acid sulphate soils extents to an area of 0.4 million hectares in the west as well as east coastal lines (Langenhoff, 1986).

In the Kuttanad region of Kerala the acid sulphate soils covered an area of 14277.51 ha, comprised of six soil series *viz.*, Ambalpuzha, Purakkad, Thottapally, Thuravur, Kallara and Thakazhi. This area contained within the total of 54,000 ha of wetlands in Kuttanad. Soils of this region are extremely acidic, deep, poorly drained and waterlogged for most part of the year. Among the different soil series, the largest area is occupied by the Kallara series (Beena *et al.,* 2007).

Beena (2013) conducted a study to confirm the acid sulphate condition in Kuttanad soil. Soils from different series were collected and an incubation experiment was carried out. The result revealed the potential acid sulphate condition of the soil increased with reduction in soil pH.

Potential acid sulphate soils are rich in pyrite (FeS_2), which upon drainage and subsequent exposure to air oxidizes to sulphuric acid (H_2SO_4) by sulphur oxidizing microflora and creates actual acid sulphate soils. Resulting from oxidation of reduced sulphur compounds in pyritic mud, these soils are characterized by low pH, high aluminium, iron and sulphate concentrations (Breemen and Pons, 1978).

Acid sulphate soils (typic sulfaquent) of Kuttanad are colloquially known as 'Kari' lands. These are the most problematic cultivated area in the region. The potential acidity of these soils ranged from 13.32 to 112.1 cmol kg^{-1}. The subsoil showed higher potential acidity compared to surface soils. In the surface horizon, potential acidity varied from 32.87 to 110.5 cmol kg^{-1}. The highest value was shown by Thakazhi series (Beena and Thampatty, 2013). The pH values of Kuttanad vary from 2.4 to 5.9 (Thampatti, 1997).

Ferrugineous soils formed under humid tropical climate having high rainfall are characterized by depletion of bases from the solum due to intense leaching and accumulation of acid forming ions like H^+ and Al^{3+} leading to development of soil

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acidity (Beena and Thampatty, 2013). Fe and Al toxicity is very widespread in acid sulphate areas of Kuttanad often leading to a decline of yield of 50 to 70 per cent for rice production (Thampatti *et al.*, 2005).

The total Fe and Al contents ranged from 2.75 to 7.72 and 1.61 to 8.28 per cent, respectively. The dithionite citrate extractable (DCE) Fe and Al also followed the same trend as that of total content of nutrients. The percentage of DCE to total Fe ranged from 62.2 to 90.2 and that of Al from 60.2 to 95.2, indicating majority of Fe and Al exists in free form (Thampatti and Jose, 2000).

2.2.1 Iron toxicity problem in acid sulphate soil

Iron toxicity occurs in a wide range of soils, particularly in lowland rice with permanent flooding. Excess concentration of reduced iron (Fe^{2+}) results in a range of nutrient disorders and deficiencies of other major and micro nutrients. Mechanism of iron toxicity in rice might be due to its accumulation in the roots and leaves in high concentrations. Rice yield losses associated with iron toxicity ranges from 12 to 100% depending on the rice cultivars and the prevailing iron toxicity levels (Abifarin, 1988).

According to Chen *et al.*, (1980) rice plant forms iron plaque on its root surfaces by releasing oxygen to the rhizosphere which is a unique capability of rice plant, which results in the oxidation of ferrous to ferric iron and the precipitation of iron oxide/hydroxide on the root surface. Rice cultivars, growth stage and soil type were significantly related to the amount of iron plaques on field grown rice roots.

Hansel *et al.*, (2001) reported that in wetland fields, iron (Fe^{3+}) forms precipitates on root surfaces, which is predominantly of ferrihydrite and goethite. In field and laboratory conditions, iron plaque was present as a continuous precipitate or as an amorphous coating on roots with an uneven distribution (Batty *et al.*, 2002).

Iron toxicity is recognized as one of the major constraints to rice production in the wetlands. The disorder is caused by excessive amounts of iron in soil solution.

The reduced soil conditions that cause accumulation of soluble ferrous iron also lead to enhanced requirement for nutrients such as P and K needed to overcome the stress (Sahrawat *et al.*, 1996).

Mandal *et al.*, (2003) reported Fe toxicity as one of the major soil constraints of lowland acid soils. Fe toxicity in rice is associated with high concentration of ferrous ion (Fe^{2+}) in the soil solution, mobilized *in situ*.

In humid tropical and subtropical area such as South Asia, Fe^{2+} toxicity is one of the major physiological disorders that limit rice growth (Zhang *et al.*, 2011). Fe^{2+} toxicity injures plants by inhibiting the elongation of rice roots. Batty and Younger (2003) indicated that iron plaque on the surface of rice roots was harmful to the roots. It decreases root activity and inhibited nutrient uptake (Zhang *et al.*, 2010). Moreover, the epidermal and cortex cells within rice roots died when iron plaque was formed (Zhang *et al.*, 2011).

Thuvasan, (2010) reported that phosphogypsum and phosphogypsum-fly ash mixture were effective in decreasing exchangeable Fe, Mn and Al contents in acidic lateritic soil as evidenced in incubation study. Same author showed that ameliorant (phosphogypsum and phosphogypsum-fly ash @ 20:1) treated black pepper plants had superior growth than control in pot and field study. Leaf P, N and K were increased while Fe, Al and Mn contents were reduced.

2.2.2 Aluminum toxicity problem in acid sulphate soil

Aluminum toxicity is also one of the major concerns of low rice productivity in lowland acid sulfate soils (Fageria and Carvalho, 1982). Aluminum toxicity affects about 40-70% of the world's arable land, which has the potential for food crop and biomass production. Aluminium toxicity impairs productivity in soils having low pH (below 5.0). Free aluminium ions are solubilized at low pH. The primary site of aluminium accumulation and toxicity target in plants was reported to be the root meristem. A severe inhibition of root growth is the direct major effect of aluminium on plants (Vasconcelos *et al.*, 2002).

The extreme acidity, iron and aluminium toxicity in acid sulphate areas of Kuttanad leads to a decline in rice yield of 50 to 70 per cent. Even continuous submergence fails to increase the soil pH beyond 4.5 in most of the areas of Kuttanad and has influenced the dynamics and distribution of nutrients especially the micronutrient cations (Thampatti *et al.*, 2005).

According to Thampatti and Jose (2000) the extractable aluminium is very high in Kuttanad soils. The aluminium saturation of total and effective CEC in these soils is also very high and they are above the critical limits for rice. Both the extractable and water soluble aluminium, showed a considerable increase during the post monsoon period. The increase in acidity might have enhanced the solubility of aluminium, which is responsible for its increase.

Azman *et al.*, (2014) showed that the root length of rice seedlings was affected severely by the presence of high Al concentration in the water. Reduction in root length could have resulted in the decrease of nutrient uptake. The root length of rice seedlings was affected by low pH. Rice root length was positively correlated with pH (Azura *et al.*, 2011). They established that the critical Al concentration of the growth of MR 219 was 135 ppm.

2.2.3 Effect of different concentration of iron and aluminium on rice

Yu *et al.*, (2002) conducted a pot culture experiment and reported that addition of iron (Fe^{2+}) to the soil resulted in a retarded growth of rice. Snowden *et al.*, (1995) studied the chemical changes in wetland plant species using different Fe levels (10, 25, 50, 75 and 100 mg l^{-1}), with specific reference to root precipitates and Fe tolerance. The results revealed that there was a significant increase in Fe concentrations of shoots with increase in Fe supply while other elements (except Na and Zn) showed a reduction of concentration in shoot.

Liu *et al.*, (2004) studied the effect of different iron concentrations on forming iron plaque on rice roots and differences in uptake and translocation of arsenate within the rice seedlings in nutrient solution. They used 500 ml of nutrient solution with different iron concentrations (20, 40, 60, 80 and 100 mg L^{-1}) for treating the rice roots for 24 hours. The results showed a significant increase of iron concentration in rice roots with the increase in iron concentration of the treatment solution which also caused formation of iron plaque but did not cause as significant effect in plant growth.

Mehraban *et al.*, (2008) conducted an experiment on iron toxicity in rice under different potassium nutrition. In their study two week old rice seedlings were treated with 10, 50, 100, 250 and 500 mg L^{-1} of iron as Fe- EDTA and 200 and 400 mgl^{-1} of KCl. In the study maximum growth of rice plant occurred at 10 and 50 mg L^{-1} Fe and 250 and 500 mg L^{-1} of Fe caused reduction in plant growth due to Fe toxicity.

Chen *et al.*, (2006) conducted study by growing rice plants in one liter nutrient solution containing iron (30 mgL^{-1} ferrous iron as $FeSO_4.7H_2O$ and Fe (II)-EDTA). The rice root treated with $FeSO_4$ showed yellowish coating indicating the formation of iron plaque and Fe (II)-EDTA caused formation of iron plaque of uneven distribution with a porous structure on the root surfaces. The $FeSO_4$ treated rice roots seemed bulgy and the root tip turned to brown colour which showed that the tips of roots were injured. The study also showed that there was significant enhancement of aluminium after iron pre- treatment.

Olaleye *et al.*, (2001) studied the effect of toxic iron concentrations on the growth of lowland rice in Africa. According to them, in pot culture when different concentrations of iron applied (1000, 3000, and 4000 mg L^{-1} Fe) the total N, available P, Mg, Ca, and Zn levels obtained were below optimum except the exchangeable K in the soil. They also observed that the number of tillers per pot, grain yield, dry matter and plant height were decreased with increase in concentration of iron.

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Sharma and Dubey, (2007) reported that a relative decrease in root and shoot length were caused by increased Al^{3+} uptake when rice seedlings were grown in sand culture with 2.16 and 4.32 mg L^{-1} Al^{3+} for 5-20 days. Aluminium toxicity also causes oxidative stress in rice plant.

Sheela, (2000) carried out a solution culture study using Hoagland solution to identify rice cultivars tolerant to Fe toxicity situation (400, 500 and 600 mg L^{-1} Fe). The study showed that content and uptake of P, K, Ca and Mg decreased in all varieties when the concentration of iron was increased. Iron content in all the varieties increased with increased iron levels in the medium. Maximum iron concentration was obtained in rice roots than other parts. The uptake of iron increased up to 500 mg L^{-1} then decreased in all the varieties.

2.2.4 Phosphorous deficiency in acid sulphate soil

Phosphorus is mostly available for plant uptake between 6.0 to 6.5 soil pH, and decreases outside this pH range. In the acid sulphate soils of Kuttanad the pH levels were less than 3.5, which are categorized as low soil pH (high acidity). Besides that, these soils have high content of iron and aluminium which causes fixation of phosphorus. The applied phosphorus would be unavailable to rice and will remain in place due to its immobilization. This implies that the soluble phosphate fertilizer applied will revert back to its less or insoluble form. Lack of phosphorus in the soil can be somewhat alleviated by applying fused magnesium phosphate (Suswanto *et al.*, 2007).

2.3 AMELIORATION OF ACID SULPHATE SOILS

The amelioration of acid sulphate soils can be done by chemical neutralization methods like application of lime, dolomite, calcite, magnesite etc.; minimizing the disturbances like human intervention; reducing drainage thereby preventing oxidation of pyrite. Addition of $CaCO_3$ decreases acidity and toxicity due to iron and aluminium (Tho and Egashira, 1976).

2.3.1 Amelioration of acid sulphate soils using lime

The occurrence of metal toxicity predominantly iron and aluminium toxicity in many cases can be overcome by the addition of lime (calcium carbonate), or slaked lime (calcium hydroxide), magnesium carbonate or other alkaline/liming materials to increase the soil pH and precipitate the toxic metal and thus increase plant growth. A common treatment to reduce the solubility of Al, Fe and other heavy metals in soil is to increase the soil pH, which is mostly done by liming (Haby, 2002).

According to Azman *et al.*, (2014) after liming the soluble Al and Fe will decline, while the exchangeable Ca and Mg will increase. Sanchez (1976) found that Al toxicity can be reduced somewhat by the presence of extra calcium and magnesium. The study of Azman *et al.* (2014), also states that application of ground magnesium lime stone would increase the soil pH with the addition of Ca and Mg into the soil.

The critical pH value for rice is 5.5 - 6.0. This can be achieved by applying lime at high rate (>4 t ha^{-1}) under acid sulphate soils (Shamshuddin *et al.*, 2015). Suswanto *et al.,* (2007) reported that liming together with judicious fertilizer management improves rice production on an acid sulfate soil. According to same authors application of ground magnesium lime stone increases the pH and decreases the iron, aluminium toxicity. The exchangeable Ca also increased above the rice requirement. Rice yield was negatively correlated with acid-extractable Fe and was positively correlated with pH and calcium.

The use of lime material together with chemical fertilizer, particularly nitrogen and phosphorus, can increase rice productivity (Rattanapichai, *et al.*, 2013).

According to Ponnamperuma *et al.*, (1973), toxic amounts of Fe^{2+} would be present in the water after two weeks of flooding. This Fe can, to a certain extent, be eliminated by liming. Ponnamperuma and Nhung (1965) reported that activities of water soluble Al^{3+} and Fe^{2+} decreases to 100 fold for each unit increase in pH. The same authors also showed that calcium carbonate alone (@ 0.2% and 0.4%) enhanced the pH of the soil and solution, reduced the redox potential of the soil, which distinctly decreased the Fe^{2+}, Al^{3+}, Mn^{2+} and SO_4^{2-} in the soil solution.

Ponnamperuma and Solivas (1981) studied the effects of MnO_2 (100 kg ha^{-1}) and $CaC0_3$ (5t ha^{-1}) on iron toxicity symptoms and yield of rice varieties on a flooded acid sulphate soil. They reported that MnO_2 coupled with $CaCO_3$, counteracting physiologically the toxic effects of excess iron which can be used as an inexpensive ameliorant for acid sulphate soils.

Toure (1981) reported that combination of lime green manure, and wood ash decreased the toxicity of iron and acidity. Leaching followed by the application of basic slag and lime at different rates excellently increased all the growth and yield parameters of rice (Khan *et al.*, 1994).

The acid sulphate soil was treated with ground magnesium limestone (GML), hydrated lime and liquid lime at specified rates. The study showed that with the application of 4 t GML ha^{-1}, the rice yield was 3.5 t ha^{-1}. Also the ameliorative effects of lime application in the 1st season had continued to the 2nd season Azman *et al.*, (2014).

Khouma and Toure, (1981) conducted a study using two levels of phosphorus and three levels of lime and two varieties. They suggested that triple superphosphate had an overall beneficial effect regardless of soil differences and varieties. Their results showed that with sufficient fresh water and correction of phosphorus deficiency and acidity, rice production is viable on acid sulphate soils.

The major methods used to ameliorate acid sulfate soil infertility are liming using ground magnesium limestone (GML) (Elisa *et al.*, 2016), applying ground basalt (Shamshuddin *et al.*, 2011; Shazana *et al.*, 2013) or putting the soils under continuous submergence (Muhrizal *et al.*, 2006).

Liming is a common approach to raise the pH of acidic soils so as to precipitate aluminum as inert Al hydroxides, thereby reducing its availability to the growing crops (Shamshuddin *et al.*, 2010). Besides increasing pH, GML can supply Ca and Mg, which are needed by crops in large amounts. To some extent, Ca itself is able to detoxify Al^{3+} (Alva *et al.*, 1986). Likewise, ground basalt application can ameliorate acid soil infertility through pH increase and Ca and Mg release when the basalt is dissolved (Shamshuddin and Kapok, 2010; Shazana *et al.*, 2013).

2.3.2 Amelioration of acid sulphate soils using magnesium sources

The presence of extra Mg contributes to alleviation of Al toxicity as had been shown by Shamshuddin *et al.* (1991) for maize.

Using ground magnesium limestone (GML) and organic fertilizer (rice husk-based) at appropriate rate, rice cultivated on acid sulfate soils can produce higher yield. The rice yield could be as high as 7.5 t ha^{-1} using 4 t GML ha^{-1} in combination with an organic fertilizer (Suswanto *et al.*, 2007).

The application of ground magnesium limestone or basalt in combination with organic fertilizer improved the productivity of acid sulphate soils and consequently enhanced rice yield (Shamshuddin *et al.*, 2015). Castro *et al.*, (2016) reported that Ca, Mg content, yield components and yield grains of wheat and maize were increased with application of dolomite and calcium/magnesium silicates. The soil acidity was also corrected significantly by them.

2.3.3 Effect of phosphogypsum as amendment

Phosphogypsum (PG) is a by-product of phosphoric acid plant and also is the residue of phosphate fertilizer industry is effective in correcting the soil acidity in lateritic soil by reducing the exchangeable acidity mainly the exchangeable Al content (Sumner, 1970; Reeve and Sumner, 1972).

Phosphogypsum can alleviate subsoil acidity even when it is applied to surface because the Ca in phosphogypsum is soluble and mobile. Gypsum moves downwards much faster than lime which increases the soil solution activity of calcium ion up to 0.8m depth in five months of initial application. Increase in soil pH to the extent of 0.8 units in dark red latosols after gypsum application was reported by many workers (Ritchey *et al.*, 1980; Bolan *et al.*, 1992).

The application of lime: gypsum combination (25:75 per cent) to groundnut cultivated in acid soil improved the yield more than the application of lime alone (Anitol, 1996). Alva and Sumner (1989) found that application of phosphogypsum alleviated aluminium toxicity and increased soybean root growth in nutrient solutions. Chang and Thomas (1963) showed that the amount of Fe and Al released in to the soil solution depends on the application of gypsum.

Phosphogypsum and mined gypsum can alleviate the aluminium toxicity in the sub soil horizon of highly weathered soil belonging to soil orders ultisols and oxisols) and also in soils such as non allophanic andosols (Saigusa *et al.*, 1996).

The ameliorating effect of mined gypsum or phosphogypsum is due to the supply of calcium and also due to the enhanced mobility of gypsum (Hoveland, 2000). Repeated application of phosphogypsum reduced the exchangeable aluminium (Alva *et al.*, 1990) and increased cation exchange capacity of acid soil (Alva *et al.*, 1991).

Phosphogypsum improves soil structure as a result of increased Ca saturation in soil (Mullins and Mitchell, 1990). The adequate sulphur supply, which can be achieved with phosphogypsum, can protect plants from adverse effects of salinity stress (Astolfi and Zuchi, 2013).

In acidic soils, it has been shown that phosphogypsum improves Ca, Mg, K, Na and S accumulation in plants as a consequence of the intrinsic richness in these elements of the amendment. The effects of phosphogypsum on the geochemistry of nutrients in soil can affect their uptake by plants (Sancho *et al.*, 2009).

Phosphogypsum from the residue of the phosphate fertilizer industry can be applied as a Ca amendment in agriculture (Mrabet *et al.*, 2003). The study of Nayak *et al.*, (2011) showed that 10% PG amendment is optimal for microbial growth and soil enzyme activities. Phosphogypsum usually valorized as amendment for acidic and sodic soils (Quintero *et al.*, 2014).

Lee *et al.*, (2007) used a mixture of fly ash and phosphogypsum (50:50) mixture at 0, 20, 40 and 60 Mg ha^{-1} in rice cultivation. Their result showed that fly ash and phosphogypsum mixture enhance soil fertility and reduce phosphorus loss from rice paddy soils. The amended soils also exhibited increase in pH resulting from increased applications of the mixture. They also suggests that the mixture was a very good alternative soil amendment to increase rice productivity and fertility of paddy soils of South Korea which also reduce loss of phosphorous during the cultivation of rice.

Ayadi, (2015) evaluated the potential use of phosphogypsum as phosphate amendment in soil by growing Arabidopsis. The study was conducted in a greenhouse for 30 days using substrate containing different levels of phosphogypsum (0%, 15%, 25%, 40% and 50%). The results displayed that 15% phosphogypsum improved plant survival and leaf dry weight. There was efficient inorganic phosphate uptake by the plant.

Crusciol *et al.,* 2016 studied the effect of different amendments on soil physical properties with the application of (2.1 Mg ha^{-1} phosphogypsum, 2.0 Mg ha^{-1} lime, and lime + phosphogypsum (2.0 + 2.1 Mg ha^{-1}, respectively). Their results indicated that surface liming effectively enhances the water stable aggregates. Lime in association with phosphogypsum improved the microagregate stability in subsoil layers. Ca, Mg and base saturation were increased with the application of these amendments.

Crusciol *et al.*, (2016) reported that application of phosphogypsum reduced the chemical activity of aluminium ion (Al^{3+}) thereby decreases the Al hydrolysis process and subsequently the displacement of H^+ ion to solution, which causes the reduction in pH.

2.3.4 Potassium - alleviating Fe toxicity

Potassium increases the root oxidation power which converts Fe^{2+} to Fe^{3+} in the rhizosphere and exclusion of this ion from uptake (Tanaka and Yoshida, 1970).

Wang *et al.*, (2013) studied the effect of potassium on plant stature of rice, production, acid metabolism and content in rice plant in a hydroponic study. Different concentrations of potassium (100, 200, and 400 mg L^{-1}) and Fe (250 mg L^{-1}) applied to the nutrient solution. The results showed that addition of potassium can alleviate the iron toxicity. Application of potassium @ 200 and 400 mg L^{-1} increases the shoot length, fresh shoot weight and dry shoot weight of the rice cultivar with 400 mg L^{-1} showing superiority.

Ramirez *et al.*, 2002 reported that application of P, K and Zn fertilizers reduces the Fe toxicity in rice. Potassium was applied as KCl in two levels 58 and 116 kg ha^{-1} along with P (22 and 62 kg P ha^{-1}) and Zn (3 and 7 kg ha^{-1}). The appearance of iron toxicity symptoms and concentration of iron in the leaves were reduced with the application of fertilizers.

Li, *et al.*, (2016) reported that potassium plays a critical role in regulating the development of plant roots in Fe toxicity conditions. They also showed that addition of potassium alleviated the suppression of primary root growth and lateral root formation in excess iron condition. Same authors suggests possible reasons for the alleviation mechanism of potassium which are: in the root medium K^+ may alleviate the activity and availability of Fe^{2+} in the root medium their by maintains the root development; the transport of Fe^{2+} root cells may be inhibited by K^+; potassium may act on the target of iron mediated root development or the enzymatic systems that control Fe^{2+} immobilization and detoxification.

2.3.5 Effect of Boron application on rice production

Ehsan-ul-Haq *et al.*, (2009) reported that the application of boron (200-400 mg L^{-1}) improved growth parameters like tillering capacity, shoot and root length, weight in solution culture.

Application of boron to rice improved all growth parameters *i.e.*, tillering capacity, shoot and root length, and shoot and root weight because of external boron application @ 200-400ng mL^{-1} in solution culture (Mehmood *et al.,* 2009).

Several studies conducted reported that application of boron to rice reduced panicle sterility and enhanced the yield (Rashid *et al.*, 2004 and Hussain *et al.*, 2012). Foliar application of boron increased photosynthetic rate and grain filling rate and decreased respiration rate in rice (Yu *et al.,* 2002).

The application of boron through different sources either through soil or foliar spray was found to be beneficial in stimulating plant growth and in increasing yield of rice (Sakal *et al.*, 2002). Rao *et al.,* (2013) reported that application of boron resulted in increase in grain number and reduced the number of unfilled spikelets. Application of 0.4 ppm boron resulted in significant increase in grain yield.

2.3.6 Effect of Silicon application on rice production

Silicon as a beneficial element in the soil can reduce concentration and uptake of iron in the plant (Dufey *et al.*, 2014). Silicon (Si) application can reduce aluminium toxicity to plants including rice (Hara *et al.*, 1999). Silicon enhances the photosynthesis of rice and increases rice resistance to several rice diseases and insects (Ma and Takahashi, 2002).

Okuda and Takahashi (1962) suggested that large amount of Si is important to promote the growth of rice (*Oryza sativa* L.) and to improve the grain yield.

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Application of calcium silicate showed an ameliorative effect on acid sulfate soil, *i.e.*, an increase in soil pH, exchangeable Ca content, and Si content, and a reduction in exchangeable Al in acid sulfate, rice-cropped soils (Elisa *et al.*, 2016).

Gholami and Falah (2013) reported that application of Si enhanced the growth parameters, increased yield, yield attributes and quality of rice crop. According to Agarie *et al.* (1992), the maintenance of photosynthetic activity due to Si fertilization could be one of the reasons for the increased dry matter production. In terms of yield components, silicon increases the number of spikelets per panicle, spikelet fertility (Takahashi, 1990) and the mass of grains. Silicon and boron significantly improved kernel weight, biological yield, protein and starch content in grain (Balastra *et al.*, 1989).

Silicon enhanced the oxidative power of rice roots, resulting in enhanced oxidation of Fe from ferrous iron to insoluble ferric iron. Therefore, excess Fe uptake was indirectly prevented by Si application (Okuda and Takahashi, 1962; Qiang *et al.*, 2012).

Application of soil conditioner which contains calcium compounds and hydrosilicate compounds had effect on tillering of rice, shoot dry matter and grain yield formation especially in the highest rate (Rattanapichai, *et al.*, 2013).

Silicon is usually present in higher amount than other inorganic constituent in grasses (Epstein, 1999). Silicon has a prominent role in plant growth. It improves growth and yield of plants and provide resistance against lodging. Silicon helps in enhancing the photosynthesis, has good effect on surface properties. It offer resistance to disease causing organisms, herbivores, metal toxicity, salinity stress, drought stress and protection against temperature extremes (Epstein, 2001).

Materials and Methods

3. MATERIALS AND METHODS

An investigation entitled "Flux and dynamics of iron and aluminium in wetlands of Kuttanad and its management for rice (*Oryza sativa* L.)" was carried out at College of Agriculture, Padannakkad. The objectives of the study were to investigate the iron and aluminium toxicity problem in rice grown on acid sulphate soils of 'Kari' lands in Kuttanad, to evaluate the performance of two popular rice varieties to variable levels of iron and aluminium concentrations at different stages of the crop and to examine suitable amelioration strategies. The whole experiment was carried out as laboratory and pot studies in three parts:

Part I

Collection of soil sample from the 'Kari' lands of Kuttanad and analysis of their various physical and chemical properties.

As a preparatory study an incubation experiment was also carried out to get an idea about the release of Fe and Al consequent to submergence.

Part II

Solution culture experiment to study the response of two popular varieties of rice to different levels of iron and aluminium.

Part III

Pot culture experiment with two rice varieties

3.1. Collection and analysis of soil sample

Soil samples were collected from the 'Kari' lands of Kuttanad which is included in the ambalappuzha acid sulphate soil series in Karuvatta region of Kuttanad with the GPS coordinates (latitude: 9°:18':56.99'', longitude: 76°:24':30.68''). The soil samples were drawn to a depth of 0 to 25 cm from the surface of a rice field in this region and brought to the College of Agriculture, Padanakkad. Portions of the bulk soil sample were air dried, ground, sieved with 2 mm sieve and stored in air tight container for studying initial soil properties. The soil physical properties bulk density, particle density, particle size distribution and the available nutrients such as N, P, K, Ca, Mg, S, Fe, Cu, Zn, Mn, B, Al and Si was determined as per the standard procedures given in the Table 1.

Using this soil sample iron and aluminium flux as well as soil solution concentration of these two elements were monitored at two levels of submergence *viz.* 5 cm & 10 cm by conducting an incubation study.

Table 1: Analytical methods followed for initial soil analysis

Sl. No	Parameters	Method	Reference
1.	pH	pH meter	Jackson (1958)
2.	EC	Conductivity meter	Jackson (1958)
3.	Organic carbon	Chromic acid wet digestion method	Walkley and Black (1934)
4.	Bulk density	Undisturbed core sample	Black *et al.* (1965)
5.	Particle density	Pycnometer method	Black *et al.* (1965)
6.	Textural analysis	International pipette method	Robinson (1922)
7.	Available N	Alkaline permanganate method	Subbiah and Asija (1956)
8.	Available P	Bray extraction and photoelectric colorimetry	Jackson (1958)
9.	Available K	Flame photometry	Pratt (1965)
10.	Available Ca	Atomic absorption spectroscopy	Jackson (1958)

Table 1: Continued...

11.	Available Mg	Atomic absorption spectroscopy	Jackson (1958)
12.	Available S	Photoelectric colorimetry	Massoumi and Cornfield (1963)
13.	Available Zn (0.1 N HCl)	Atomic absorption spectroscopy	Emmel *et al.* (1977)
14.	Available B	Photoelectric colorimetry	Bingham (1982)
15.	Available Fe (0.1 N HCl)	Atomic absorption spectroscopy	Sims and Johnson (1991)
16.	Available Cu (0.1 N HCl)	Atomic absorption spectroscopy	Emmel *et al.* (1977)
17.	Available Mn (0.1 N HCl)	Atomic absorption spectroscopy	Sims and Johnson (1991)
18.	Available Al (0.1 N HCl)	Atomic absorption spectroscopy	Willis (1965)
19.	Available Si	Photoelectric colorimetry	Korndorfer *et al.*, (2001)

3.2 Incubation experiment

An incubation experiment was conducted using the soil sample collected from 'Kari' lands of Kuttanad at College of Agriculture, Padannakkad as a preliminary study. The study was conducted using four different treatments at two levels of submergence (5 cm and 10 cm). The treatment combinations are given below. The treatments were incorporated and kept under submergence. The analysis of various parameters was done at 30, 60 and 90 days after submergence.

3.2.1 Design and layout

Design: CRD

Treatments: 8 (three treatments and one control in two levels of submergence)

Replications: 3

Treatment details

T_1: Lime as per KAU POP, 2011

T_2: Phosphogypsum @ 500 kg/ha + ½ lime as per KAU POP, 2011

T_3: Magnesium carbonate + ½ lime (as per KAU POP, 2011)

T_4: Control

3.2.2 Experimental soil analysis

Soil samples for laboratory analysis were collected from all the treatments at 30, 60 and 90 days after submergence. The samples were analyzed for pH, available nutrients such as Ca, Mg, Fe and Al as per the standard procedures.

3.3 Solution culture experiment

A solution culture experiment was carried out by maintaining Hoagland's nutrient solution to study the response of two popular varieties of rice Uma and Prathyasa to four levels of iron (200 mgL^{-1}, 400 mgL^{-1}, 800 mgL^{-1} and 1200 mgL^{-1}) and two levels of aluminium (50 mgL^{-1} and 100 mgL^{-1}) and to study the deposition of iron and aluminium in different plant parts. The composition of Hoagland's nutrient solution used in the study is given in the Table 2.

Uma (MO- 16) is the most popular and commonly cultivated variety in Kuttanad which is a medium duration variety released from Rice Research Station (RRS), Moncompu. Prathyasa (MO- 21) is a newly developed variety from RRS, Moncompu, which is a short duration variety that shows iron and aluminium toxicity symptoms in the initial growing period and then recovers without affecting the yield.

The seeds of rice varieties Uma and Prathyasa were placed in the moistened filter paper for germination. After one week the seeds were germinated and these are transferred in to Hoagland's nutrient solution and grown for fourteen days. Fourteen

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days old seedlings with uniform growth were selected and was transferred to Hoagland's nutrient solution (Hoagland and Arnon, 1950) blended with different levels of Fe (200 mg L^{-1}, 400 mg L^{-1}, 800 mg L^{-1} and 1200 mg L^{-1}) using Fe- EDTA and different levels of Al (50 mg L^{-1} and 100 mg L^{-1}) using aluminium sulphate and was maintained for two weeks. The combinations of different levels of iron and aluminium in the Hoagland's solution formed different treatments. The treatment details are shown below. The plants were transferred to the treatment solutions after checking the pH of the solution and confirming the stability of the solution so that there is on formation of precipitates.

3.3.1 Design and layout

Design: CRD

Treatments: 16 (4 levels of Fe, 2 levels of Al in two varieties)

Replications: 3

Crop: Rice

Varieties: Uma (MO-16) and Prathyasa (MO- 21)

Treatment details

Treatment 1 - Fe 200 mg L^{-1} and Al 50 mg L^{-1}
Treatment 2 - Fe 400 mg $L^{-1}$and Al 50 mg L^{-1}
Treatment 3 - Fe 800 mg $L^{-1}$and Al 50 mg L^{-1}
Treatment 4 - Fe 1200 mg $L^{-1}$and Al 50 mg L^{-1}
Treatment 5 - Fe 200 mg $L^{-1}$and Al 100 mg L^{-1}
Treatment 6 - Fe 400 mg $L^{-1}$and Al 100 mg L^{-1}
Treatment 7 - Fe 800 mg $L^{-1}$and Al 100 mg L^{-1}
Treatment 8 - Fe 1200 mg $L^{-1}$and Al 100 mg L^{-1}
Treatment 9 – control - Hoaglanad's nutrient solution

Table 2: Composition of Hoagland's nutrient solution

Nutrient stock solution	**Formula**	**Per liter of nutrient solution**
Potassium nitrate	KNO_3	5 ml of 1 M
Calcium nitrate	$Ca(NO_3)_2\ 4H_2O$	5 ml of 1 M
Monopotassium phosphate	KH_2PO_4	1 ml of 1 M
Magnesium sulfate	$MgSO_4.7H_2O$	2 ml of 1 M
Micronutrient stock solution		1 ml of stock solution
Iron chelate	Fe-EDTA	1-5 ml of 1000 mg L^{-1}
Micronutrient stock solution		**Per litre**
Boric acid	H_3BO_3	2.86 g
Manganese chloride – 4 hydrate	$MnCl_2\cdot 4H_2O$	1.81 g
Zinc sulfate – 7 hydrate	$ZnSO_4\cdot 7H_2O$	0.22 g
Copper sulfate – 5 hydrate	$CuSO_4\cdot 5H_2O$	0.08 g
85% Molybdic acid	MoO_3	0.02 g

3.3.2 Biometric observations

The important biometric observations like root length, root dry weight and plant length were recorded initially as well as 15 days after the plant's exposure to different treatments.

3.3.2.1 Root length

Root length of the rice plant of each treatment was taken from the base of the plant to the tip of the longest root.

3.3.2.2 Root dry weight

Root dry weight of the plants was taken by separating the roots from the plant and removing its moisture content by keeping it in the oven at 60 ±5°C.

3.3.2.3 Plant height

The plant height was measured from the base of the rice plant stem to the tip of the youngest leaf.

3.3.3 Pattern of iron coating in root

The cross sections of the roots were observed in the microscope and variation in iron coating in the treatments and control was determined using 'Zen' image analyzer. The iron content in the roots was estimated after removing the plants, washing in distilled water and subsequently with 0.1 N HCl extraction. The concentration was measured in AAS (Sims and Johnson, 1991). The cross sections of roots were made and observed for iron coating around the root surface under a microscope.

3.3.4 Root CEC

The cation exchange capacity of the root was determined after washing the roots in distilled water and shaking with KCl and titrating against NaOH as suggested by Mitsui and Ueda, 1963.

3.4 Pot culture experiment

The pot culture experiment was conducted at College of Agriculture, Padanakkad to study the iron and aluminium toxicity problem in rice grown on acid sulphate soils of 'Kari' lands in Kuttanad and to examine the effect of different amelioration strategies. The experiment was conducted in completely randomized design with seven treatments and three replications using two varieties *viz.* Uma and Prathyasa. Uma (MO- 16), the most popular and commonly cultivated variety in Kuttanad is a dwarf, medium tillering and non-lodging variety. This medium duration (120-130 days) variety is having red coloured bran and medium bold grains with an expected yield of 6-7.5 t ha^{-1}. Prathyasa (MO-21) is a short duration variety (100-110 days) with long, bold and red-kernelled grains. It has an expected yield of 5.5 t ha^{-1}.

The soil sample were collected from the 'Kari' lands of Kuttanad and brought to College of Agriculture, Padanakkad. The soil was thoroughly mixed and equal quantity (22.5 kg) of the soil was transferred to different pots of uniform size (40 cm length and 20 cm breadth). Seeds of Uma and Prathyasa were germinated in

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moistened filter paper. After one week the seeds were germinated. The germinated seeds were carefully transferred to nursery containing potting mixture. Different amelioration strategies as amendments were imposed into the pot as per treatment details shown below. The seedlings were maintained for two weeks in the nursery and after that it was transplanted into the already filled pots which contained the soil collected from Kuttanad such that each pot contains two seedlings. Nitrogen, phosphorus and potassium application were followed as per package of practices recommendations, KAU (2011) uniformly for all the treatments. Water level in the pot was maintained as 5 cm from the surface of top soil. A PVC pipe, having a diameter of 5 cm with perforations in the base portion was inserted in each pot to collect the leachate from soil depth. The leachate in the pot enters into the pipe and equilibrates through the holes in its bottom. Leachate samples were collected using a syringe and tube attachment into the perforated PVC pipe in syphoning mechanism and used for analysis.

3.4.1 Design and layout

Design: CRD

Treatments: 14 (six treatment and one control in two varieties)

Replications: 3

Crop: Rice

Varieties: Uma (MO-16) and Prathyasa (MO- 21)

Treatment details:

T_1: Lime @ 600 kg ha^{-1} as per KAU POP, 2011

T_2: Magnesium carbonate @ 50 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} (as per KAU POP, 2011)

T_3: Phosphogypsum @ 500 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} as per KAU POP, 2011

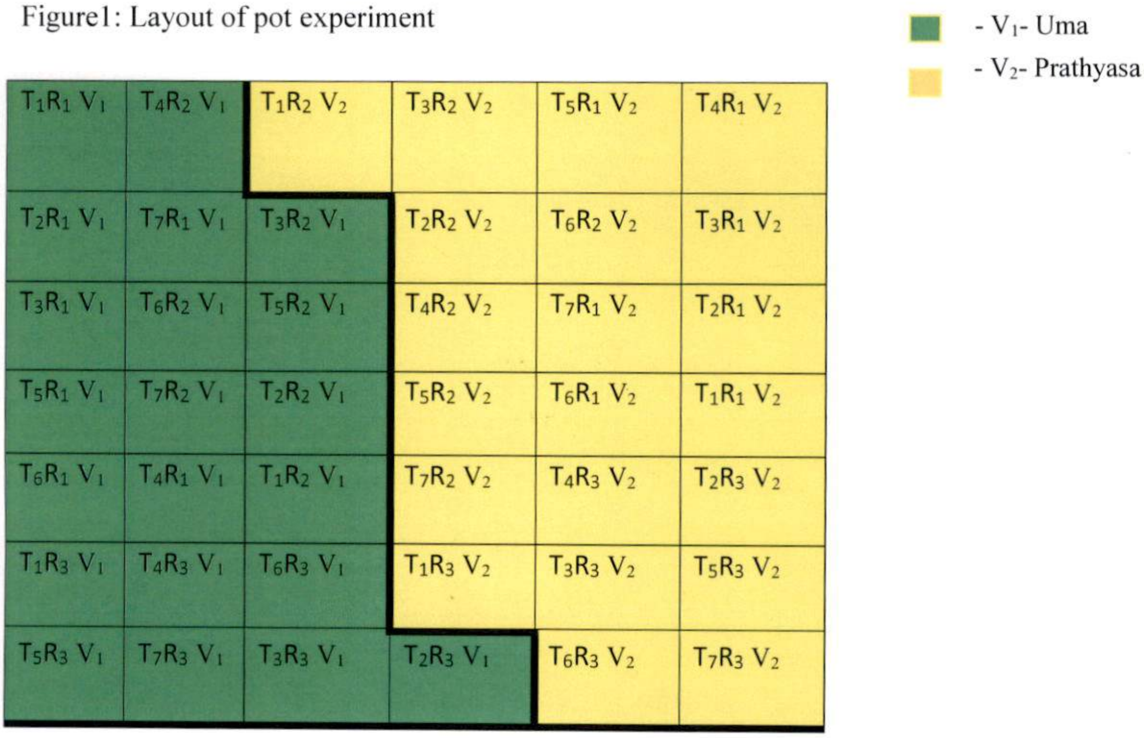
T_4: Lime @ 600 kg ha^{-1} as per KAU POP, 2011 + Potassium silicate 0.25% + 0.25% Boron

T_5: Magnesium carbonate @ 50 kg ha^{-1} + ½ lime (as per KAU POP, 2011) + Potassium silicate 0.25% + 0.25% Boron

T_6: Phosphogypsum @ 500kg ha^{-1} + ½ lime @ 300 kg ha^{-1} as per KAU POP, 2011 + Potassium silicate 0.25% + 0.25% Boron

T_7: Control

Figure1: Layout of pot experiment



🟩 - V_1- Uma

🟨 - V_2- Prathyasa

T_1R_1 V_1	T_4R_2 V_1	T_1R_2 V_2	T_3R_2 V_2	T_5R_1 V_2	T_4R_1 V_2
T_2R_1 V_1	T_7R_1 V_1	T_3R_2 V_1	T_2R_2 V_2	T_6R_2 V_2	T_3R_1 V_2
T_3R_1 V_1	T_6R_2 V_1	T_5R_2 V_1	T_4R_2 V_2	T_7R_1 V_2	T_2R_1 V_2
T_5R_1 V_1	T_7R_2 V_1	T_2R_2 V_1	T_5R_2 V_2	T_6R_1 V_2	T_1R_1 V_2
T_6R_1 V_1	T_4R_1 V_1	T_1R_2 V_1	T_7R_2 V_2	T_4R_3 V_2	T_2R_3 V_2
T_1R_3 V_1	T_4R_3 V_1	T_6R_3 V_1	T_1R_3 V_2	T_3R_3 V_2	T_5R_3 V_2
T_5R_3 V_1	T_7R_3 V_1	T_3R_3 V_1	T_2R_3 V_1	T_6R_3 V_2	T_7R_3 V_2

3.4.3 Biometric observations

Biometric observations like plant height (cm) and number of tillers were taken at 30, 60 and 90 days after transplanting. Emergence of boot leaf or panicle initiation, emergence of panicle, grain filling and incidence of pest and diseases were recorded. Number of panicles, number of grains/panicle, grain yield (g/pot), chaffiness (%), test weight (g) and straw yield (g/pot) were recorded at the time of harvesting.

3.4.3.1 Germination percentage

Germination percentage of the varieties Uma and Prathyasa were noted at the time of germination of their seeds in moistened filter paper.

3.4.3.2 Plant height

The height of the plant from the base to the tip of the longest leaf was taken at 30, 60 days after transplanting and at harvest.

3.4.3.3 Number of tillers

Number of tillers in each plant of different treatments was taken at 30, 60 days after transplanting and at harvest.

3.4.3.4 Number of grains/panicle

Number of grains/panicle of each treatment was noted at the time of harvest.

3.4.3.5 Grain yield

Total grain yield of each plant in every treatments were taken at the time of harvest.

3.4.3.6 Chaffiness percentage

Chaffiness percentage of each treatment was taken.

3.4.3.7 Test weight

One thousand grains were counted from the harvested grains of each pot at the time of harvest dried and their weight was recorded and expressed in grams.

3.4.3.8 Straw yield

Straw yield of each treatment was taken at the time of harvest by separating the grains.

3.4.4 Root CEC

The cation exchange capacity of the root was determined after washing the roots in distilled water and shaking with KCl and titrating against NaOH as suggested by Mitsui and Ueda, 1963.

3.4.5 Experimental soil analysis

Soil samples for laboratory analysis were collected from all the treatments at the time of harvest. The samples were air dried, ground, sieved with 2 mm sieve and stored in air tight container. They were analyzed for available nutrients such as N, P, K, Ca, Mg, S, Fe, Cu, Zn, Mn, B, Al and Si as per the standard procedures as given in the Table 3.

3.4.6 Plant analysis

Plant samples were collected at harvest and analyzed for various macro and micronutrient content using standard procedures as given in the Table 4.

Table 3: Analytical methods followed for soil analysis

Sl. No	Parameters	Method	Reference
1.	pH	pH meter	Jackson (1958)
2.	EC	Conductivity meter	Jackson (1958)
3.	Organic carbon	Chromic acid wet digestion method	Walkley and Black (1934)
4.	Bulk density	Undisturbed core sample	Black *et al*. (1965)
5.	Particle density	Pycnometer method	Black *et al*. (1965)
6.	Textural analysis	International pipette method	Robinson (1922)
7.	Available N	Alkaline permanganate method	Subbiah and Asija (1956)
8.	Available P	Bray extraction and photoelectric colorimetry	Jackson (1958)
9.	Available K	Flame photometry	Pratt (1965)
10.	Available Ca	Atomic absorption spectroscopy	Jackson (1958)
11.	Available Mg	Atomic absorption spectroscopy	Jackson (1958)

12.	Available S	Photoelectric colorimetry	Massoumi and Cornfield (1963)
13.	Available Zn	Atomic absorption spectroscopy	Emmel *et al*. (1977)
14.	Available B	Photoelectric colorimetry	Bingham (1982)
15.	Available Fe	Atomic absorption spectroscopy	Sims and Johnson (1991)
16.	Available Al	Atomic absorption spectroscopy	Willis (1965)
17.	Available Cu	Atomic absorption spectroscopy	Emmel *et al*. (1977)
17.	Available Mn	Atomic absorption spectroscopy	Sims and Johnson (1991)
18.	Available Si	Photolectric colorimetry	Korndorfer *et al.* (2001)

Table 4: Analytical methods followed for plant analysis

Sl. No	**Parameter**	**Method**	**Reference**
1.	Total N	Modified kjeldhal digestion method	Jackson (1958)
2.	Total P	Vanadomolybdate yellow colour method	Piper (1966)
3.	Total K	Flame photometry	Jackson (1958)
4.	Total Ca	Atomic absorption spectroscopy	Issac and Kerber (1971)

5.	Total Mg	Atomic absorption spectroscopy	Issac and Kerber (1971)
6.	Total S	Turbidimetric method	Bhargava and Raghupathi (1995)
7.	Total Zn	Atomic absorption spectroscopy	Emmel *et al*. (1977)
8.	Total B	Azomethane – H colorimetric method	Bingham (1982)
9.	Total Fe	Atomic absorption spectroscopy	Piper (1966)
10.	Total Cu	Atomic absorption spectroscopy	Emmel *et al*. (1977)
11.	Total Mn	Atomic absorption spectroscopy	Piper (1966)
12.	Total Al	Atomic absorption spectroscopy	Willis (1965)
13.	Total Si	Photolectric colorimetry	Korndorfer *et al*. (2001)

3.3.7. Statistical Analysis

The data obtained from incubation experiment, solution culture and pot culture experiment was analyzed statistically and tested for its significance using WASP 2.0 software given by ICARGOA.

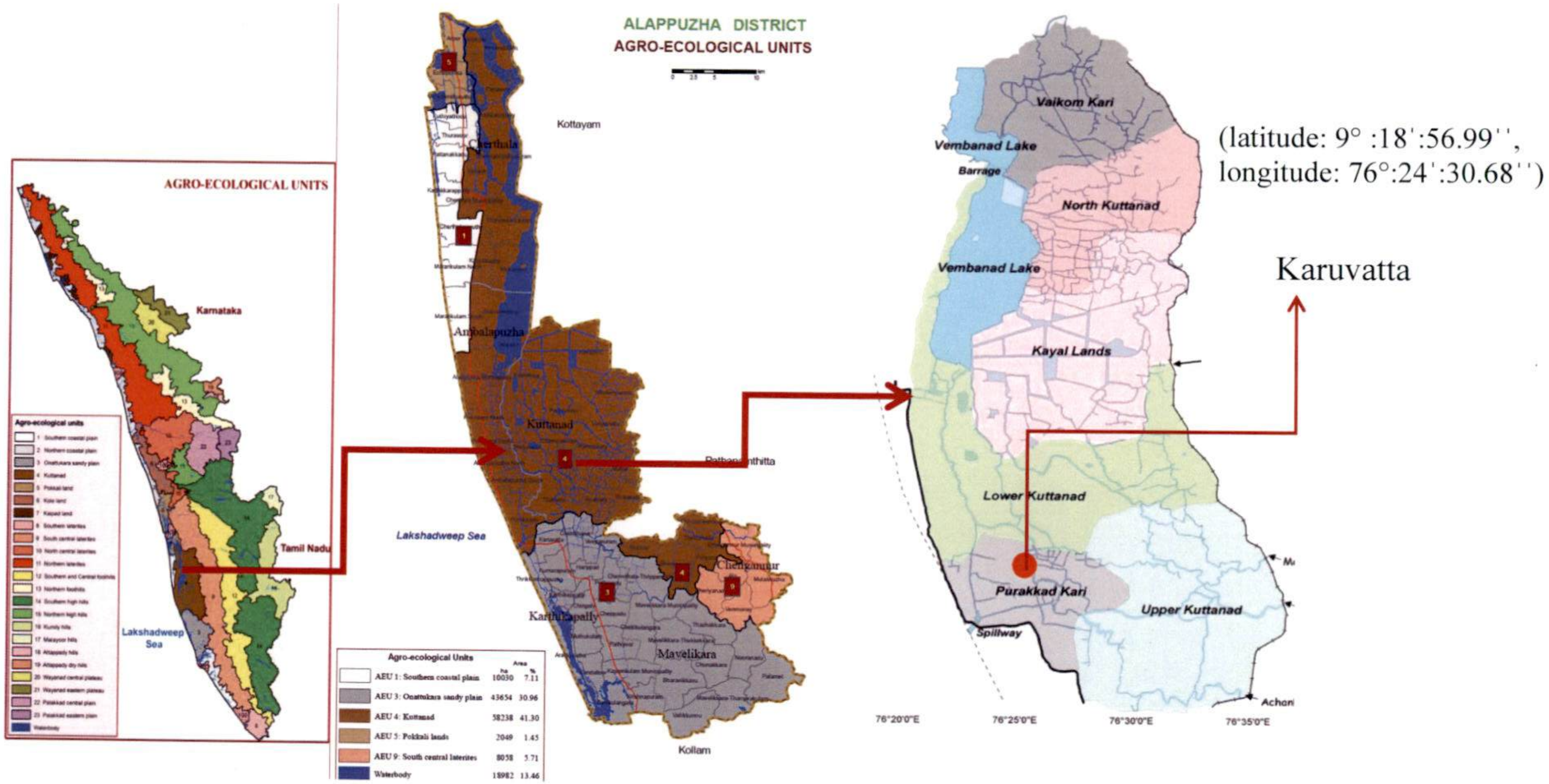


Plate1: Location of soil sample collection

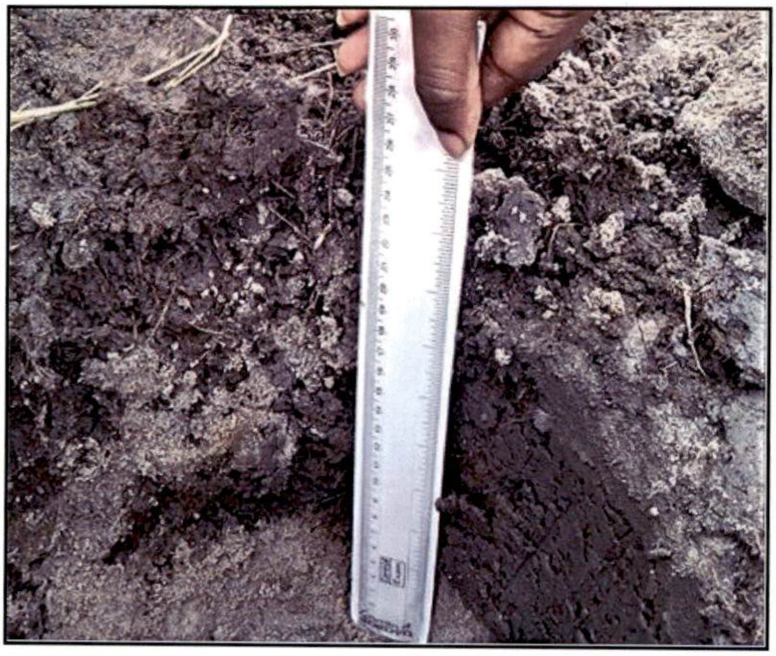


Plate 2: Collection of soil sample from Kuttanad (0-25 cm depth)

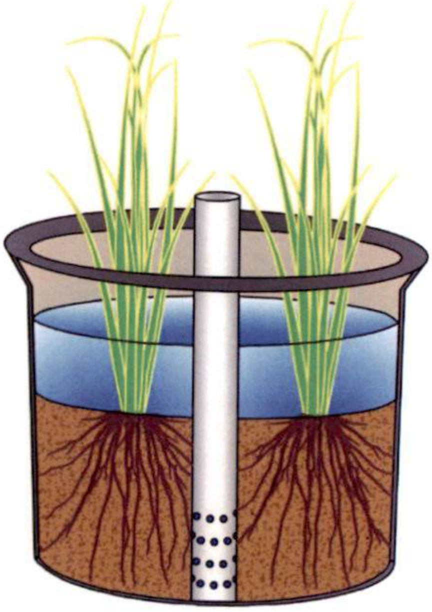


Plate 3: Pot with PVC pipe arrangement for collecting leachate

Plate 4 a: View of incubation experiment with submergence level

Plate 4 b: View of incubation experiment with different treatments

Plate 4: Incubation experiment

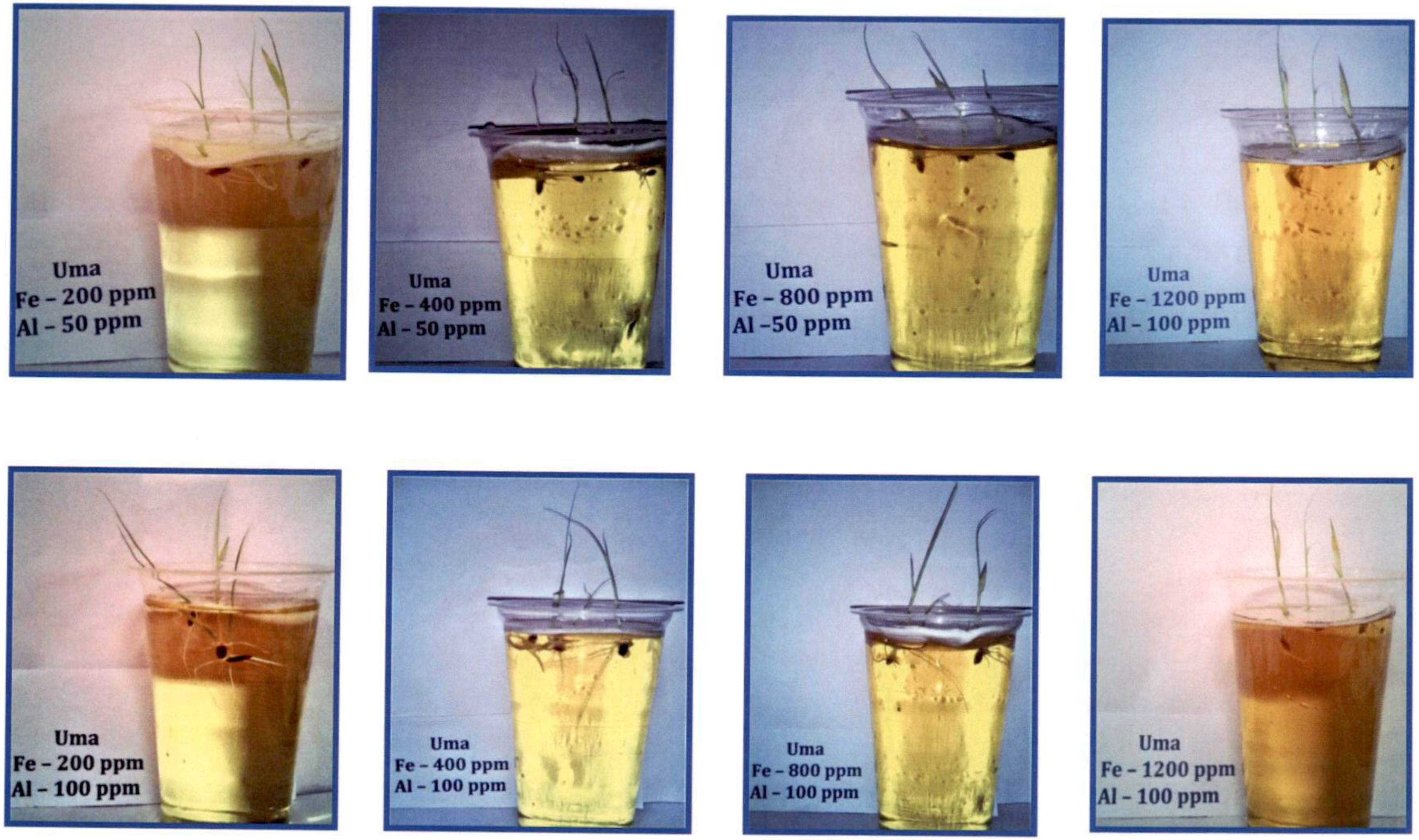


Plate 5: Solution culture experiment with different treatment combinations in Uma variety

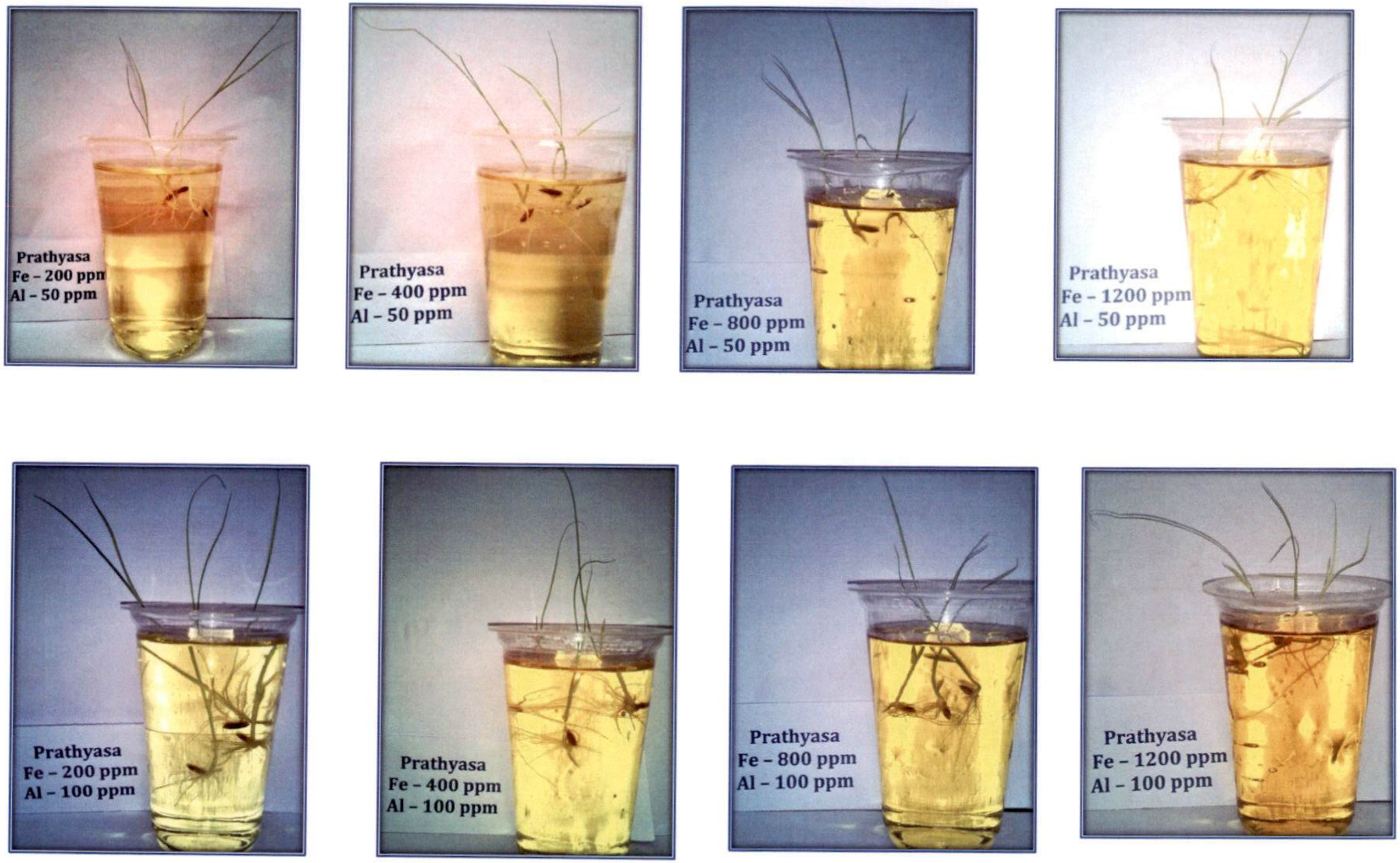


Plate 6: Solution culture experiment with different treatment combinations in Prathyasa variety

Plate 7a: Planting

Plate 7b: 60 DAT

Plate 7c: 80 DAT

Plate 7d: Harvessting stge

Plate 7: Pot culture experiment

Results

4. RESULTS

An investigation was carried out at College of Agriculture, Padannakkad during 2015- 17 to study the toxicity problems of iron and aluminium in wet land rice grown on acid sulphate soils of 'Kari' lands in Kuttanad. The study was undertaken to evaluate the performance of two popular rice varieties to variable levels of iron and aluminium concentrations at different stages and to examine suitable amelioration strategies. The experiment was carried out in three parts, which included collection and analysis of soil sample from Kuttanad, solution culture and pot culture experiments. An incubation experiment was also done as a preparatory study.

The results of analysis of various parameters of incubation study, the leachate collected from the pot culture experiment and solution culture were statistically analyzed and the results are explained below. Along with this soil analysis, biometric observations recorded and plant analysis values were also done, tabulated and results interpreted.

4.1 CHARACTERISTICS OF KUTTANAD SOIL

The soil sample collected from Kuttanad were analysed for various physical and chemical properties. The soil physical properties *viz.* bulk density, particle density, particle size distribution and the chemical properties *viz.* pH, EC, OC and available nutrients such as N, P, K, Ca, Mg, S, Fe, Cu, Zn, Mn, B, Al and Si are given in the Table 5.

The soil was sandy clay with extreme acidity for dry soil which is indicative of typical acid sulphate soil. There was no indication of salinity and the content of 0.1 N HCl extractable Fe and Al were higher. The available K, Ca and Mg were also good whereas available N was medium. Available P and the water soluble B indicated low while the available S content was high.

Table 5: Properties of the Kuttanad soil (initial soil sample)

Sl. No.	**Parameter**	**Value**
I. Physical properties		
1.	Bulk density (g cm^{-3})	1.19
2.	Particle density (g cm^{-3})	2.68
II. Mechanical composition		
1.	Sand (%)	48
2.	Silt (%)	10
3.	Clay (%)	42
4.	Textural class	Sandy clay
III. Chemical properties		
1.	pH (dry)	3.01
2.	EC (dS m^{-1})	0.43
3.	Organic carbon (%)	1.38
4.	Organic matter (%)	2.37
5.	Available N (kg/ha)	489
6.	Available P(kg/ha)	8.20
7.	Available K(kg/ha)	292

8.	Available Ca (mg/kg)	245
9.	Available Mg (mg/kg)	20
10.	Available S (mg/kg)	198.35
11.	Available Zn (mg/kg)	2.01
12.	Available B (mg/kg)	0.41
13.	Available Fe (mg/kg)	192.00
14.	Available Cu (mg/kg)	0.65
15.	Available Mn (mg/kg)	27.10
16.	Al (mg/kg)	93.00
17.	Available Si (mg/kg)	21.40

4.2. INCUBATION EXPERIMENT WITH SUBMERGENCE

An incubation experiment was conducted using the soil sample collected from 'Kari' lands of Kuttanad at College of Agriculture, Padannakkad as a preliminary study prior to the pot culture experiment. The study was conducted using four different treatments at two levels of submergence (5 cm and 10 cm). The treatment combinations are given below:

T_1: Lime @ 600 kg ha^{-1} as per KAU POP, 2011

T_2: Phosphogypsum @ 500kg/ha + ½ lime @ 300 kg ha^{-1} as per KAU POP, 2011

T_3: Magnesium carbonate @ 50 kg ha^{-1} + ½ lime@ 300 kg ha^{-1} (as per KAU POP, 2011)

T_4: Control

The treatments were incorporated kept under submergence. The analysis of various parameters was done at 30, 60 and 90 days after submergence and the results obtained were statistically analyzed and the results are presented below.

4.2.1 pH

The effect of different treatments on pH of the soil in the incubation study at 30, 60 and 90 days are given in Table 6. The soil pH was increased from highly acidic to near neutral pH after the incubation period. There was no significant effect with respect to the two levels (5 cm and 10 cm) of submergence on soil pH. Level of submergence at 5 cm (L_1) showed higher pH (5.08) compared to 10 cm level (L_2) (4.88) on 30 days of incubation. But after 60 and 90 days of submergence with 10 cm level showed higher value of pH than 5 cm level.

The treatments however had a profound effect on the soil pH values recorded at 30, 60 and 90 days of submergence. Application of amendments significantly increased the soil pH throughout the submergence period. T_1 was found to record significantly higher pH (5.85) which was on par with T_2 (5.53) at 30 days after incubation. At 60 and 90 days of incubation the treatment T_2 was found to be dominated over other treatments. At 60 days of incubation T_2 showed a pH of 5.82 which was on par with T_1 (5.79) and T_3 (5.22). After 90 days of incubation T_2 showed a pH of 6.61 which was on par with T_1 (6.34). The lowest value of pH was shown by T_4 (control) at these periods of submergence and these values were significantly lower to all the ameliorant mixed treatments.

The interaction of treatments and levels of submergence did not show any significant effect. The treatment T_1 give higher pH for both L_1 (5.75) and L_2 (5.94) at 30 days after incubation, whereas the treatment T_2 showed higher pH for L_1 and L_2 during later periods of 60 and 90 days.

4.2.2 Available Calcium

The available calcium content of the soil in different treatments at 30, 60 and 90 days after incubation are presented in the Table 7. The Ca content was increased impressively during the submergence period. There was no significant effect with respect to two level of submergence L_1 and L_2 on the available Ca in the soil on 30, 60 and 90 days after submergence. The level of submergence L_2 dominated over L_1 throughout all the submergence periods.

The treatments showed profound effect on the available Ca content in soil during the incubation period. Among the treatment T_2 showed significantly higher amount of available Ca throughout the incubation period. After the first 30 days of incubation the treatment T_2 showed 475.33 mg kg^{-1} Ca and at 60 days it increased to 543.87 mg kg^{-1} which was on par with T_1 and T_3. After 90 days of incubation T_2 give 653.63 mg kg^{-1} of available Ca which was on par with that of T_1 (576.67 mg kg^{-1}). The control T_7 showed the lowest value during the entire course of incubation period.

There was no significant effect with respect to interaction between treatments and level of submergence. The treatment T_2 showed higher Ca content in both level of submergence L_1 and L_2 at all the periods of submergence.

4.2.3 Available Magnesium

The effect of different amendments on available magnesium content in the soil at different days of incubation study is given in the Table 8. The available Mg was increased after the submergence period. The two different level of submergence is non-significant in case of available magnesium. Level L_1 (5 cm) showed higher Mg content in soil over L_2 (10 cm) throughout the incubation period.

The treatments exhibit a remarkable difference in magnesium content. T_3 which used $MgCO_3$ showed higher magnesium content (75.41 mg kg^{-1}), (89.18 mg kg^{-1}) and (82.83 mg kg^{-1}) at 30, 60 and 90 days of incubation respectively. The available Mg content increased during the 30 days of period. T_4 control showed the lowest Mg content in soil during the course of study.

Table 6: Change in pH of soil incorporated with different amendments

Treatments	30 DAS			60 DAS			90 DAS		
	L_1	L_2	Mean	L_1	L_2	Mean	L_1	L_2	Mean
T_1	5.75	5.94	5.85	5.79	5.79	5.79	6.25	6.43	6.34
T_2	5.74	5.32	5.53	5.84	5.81	5.82	6.52	6.71	6.61
T_3	5.26	4.79	5.03	5.15	5.28	5.22	6.23	6.12	6.17
T_4	3.57	3.48	3.53	4.25	4.49	4.37	5.51	5.81	5.66
Mean	5.08	4.88		5.26	5.34		6.13	6.27	
Comparison	**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**	
L	0.095	NS		0.16	NS		0.096	NS	
T	0.14	0.41		0.23	0.69		0.14	0.41	
Lx T	0.19	NS		0.32	NS		0.19	NS	

Note: T_1: Lime as per KAU POP, 2011; T_2: Phosphogypsum @ 500 kg ha^{-1} + ½ lime as per KAU POP, 2011; T_3: Magnesium carbonate + ½ lime (as per KAU POP, 2011); T_4: Control; DAS: Days after submergence.

Table 7: Change in available Ca (mg kg^{-1}) of soil incorporated with different amendments

Treatments	30 DAS			60 DAS			90 DAS		
	L_1	L_2	Mean	L_1	L_2	Mean	L_1	L_2	Mean
T_1	342.50	344.58	343.54	526.70	529.98	528.34	553.97	599.38	576.67
T_2	478.17	472.50	475.33	536.50	551.23	543.87	617.30	690.63	653.97
T_3	343.75	364.58	354.17	492.48	493.32	492.90	521.88	532.72	527.30
T_4	311.50	334.42	322.96	392.90	394.05	393.47	378.97	381.88	380.43
Mean	368.98	379.02		487.15	492.15		518.03	551.15	
Comparison	**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**	
L	13.12	NS		18.46	NS		29.45	NS	
T	18.56	56.12		26.11	78.96		41.65	125.93	
Lx T	26.24	NS		36.93	NS		58.89	NS	

Note: T_1: Lime as per KAU POP, 2011; T_2: Phosphogypsum @ 500 kg ha^{-1} + ½ lime as per KAU POP, 2011; T_3: Magnesium carbonate + ½ lime (as per KAU POP, 2011); T_4: Control; DAS: Days after submergence.

Table 8: Changes in available magnesium (mg kg^{-1}) of soil incorporated with different amendments

Treatments	**30 DAS**			**60 DAS**			**90 DAS**		
	L_1	L_2	Mean	L_1	L_2	Mean	L_1	L_2	Mean
T_1	55.50	58.00	56.75	57.30	55.10	56.20	52.73	53.17	52.95
T_2	69.17	64.87	67.02	62.07	58.80	60.43	64.83	62.67	63.75
T_3	79.33	71.48	75.41	89.367	89.00	89.18	82.33	83.33	82.83
T_4	38.13	37.33	37.73	43.40	35.97	39.68	33.83	33.67	33.75
Mean	60.53	57.92		63.03	59.72		58.43	58.21	
Comparison	**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**	
L	1.452	NS		2.28	NS		1.30	NS	
T	2.054	6.21		3.23	9.76		1.84	5.56	
Lx T	2.904	NS		4.56	NS		2.60	NS	

Note: T_1: Lime as per KAU POP, 2011; T_2: Phosphogypsum @ 500 kg ha^{-1} + ½ lime as per KAU POP, 2011; T_3: Magnesium carbonate + ½ lime (as per KAU POP, 2011); T_4: Control; DAS: Days after submergence.

There was no significant difference between the interaction of treatments and level of submergence. T_3 (Magnesium carbonate + ½ lime) in both L_1 (5 cm) and L_2 (10 cm) showed maximum available magnesium content throughout the study and T_4 (control) showed the lowest.

4.2.4 Available Iron

The available iron content in the soil at 30, 60 and 90 days after submergence experiment are presented in Table 9. The Fe content increased to three fold from the dry soil which was 192 mg kg^{-1}. Different level of submergence (L_1 and L_2) did not express any significant effect on the soluble iron content throughout the incubation study. The level of submergence L_1 was found to be dominant over L_2 at 30 days of incubation period. After 60 days of incubation L_2 showed higher level of available iron content than L_1. Again after 90 days of submergence L_1 showed higher Fe content than L_2.

The treatments exhibit an introspective effect on available iron content throughout the incubation study. The control, (T_4) showed higher amount of available Fe at 30, 60 and 90 days of incubation experiment. The treatment T_2 showed lowest amount of available iron in the incubation period. The available iron content was found to be decreasing after the incubation period. At 30 days of incubation T_2 showed lowest value for iron content (316 mg kg^{-1}) which was on par with T_1 (347 mg kg^{-1}) and T_3 (441 mg kg^{-1}). After 60 days the treatment T_2 recorded a decrease in iron content (260 mg kg^{-1}) on par with T_1 (280 mg kg^{-1}) and T_3 (421 mg kg^{-1}). The treatment T_2 again show the least value for iron content (159 mg kg^{-1}) which was on par with T_2 (161 mg kg^{-1}) and T_3 (294 mg kg^{-1}).

The interaction effect between treatments and level of submergence did not show any significant effect on the available iron content. The treatment T_2 showed the least value which was on par with T_1 and T_3 in both L_1 and L_2 level of submergence throughout the incubation period.

4.2.5 Extractable Aluminium

The aluminium content in the soil in the incubation experiment is given in the Table 10. The result showed increase in concentration of Al from dry soil upon submergence. The different level of submergence (L_1 and L_2) did not show any significant effect on the available Al content at 30, 60 and 90 days of incubation. The level of submergence L_1 (5 cm) recorded higher aluminium content than L_2 throughout the incubation experiment.

The treatments had a substantial effect on the soluble 0.1N HCl extractable aluminium over control (T_4) which recorded significantly higher value of available aluminium. The values were on par with T_3 at 30, 60 and 90 days of incubation. However the aluminium content was found to be decreasing in the period of submergence. At 30 days of incubation the Al content was least for T_2 (144.2 mg kg^{-1}) which was on par with T_1 (154.63 mg kg^{-1}). Same trend was followed during 60 and 90 days. T_2 had 130 mg kg^{-1} available Al on 60 days incubation on par with T_1 (151.07 mg kg^{-1}). On 90 days of incubation T_2 showed the least value of 105.35 mg kg^{-1}on par with T_1 (161.58 mg kg^{-1}).

There was no significant effect by the interaction of treatment and level of submergence on the available Al content throughout the incubation period. T_4 showed highest value of Al for L_1 and L_2, and T_2 gave the lowest value which was on par with T_1, for L_1 and L_2 during the entire period of submergence.

Table 9: Change in available Fe (mg kg^{-1}) of soil with incorporation of different amendments

Treatments	**30 DAS**			**60 DAS**			**90 DAS**		
	L_1	L_2	Mean	L_1	L_2	Mean	L_1	L_2	Mean
T_1	369	325	347	266	294	280	161	160	161
T_2	312	321	316	244	277	260	158	161	159
T_3	456	426	441	463	378	421	294	295	294
T_4	543	529	536	551	581	566	366	390	378
Mean	420	400		381	382		245	251	
Comparison	**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**	
L	12.6	NS		23.58	NS		40.57	NS	
T	17.9	54.19		33.34	100.83		57.38	173.50	
Lx T	25.34	NS		47.16	NS		81.14	NS	

Note: T_1: Lime as per KAU POP, 2011; T_2: Phosphogypsum @ 500 kg ha^{-1} + ½ lime as per KAU POP, 2011; T_3: Magnesium carbonate + ½ lime (as per KAU POP, 2011); T_4: Control; DAS: Days after submergence.

Table 10: Change in Al (mg kg^{-1}) of soil with incorporation of different amendments

Treatments	30 DAS			60 DAS			90 DAS		
	L_1	L_2	Mean	L_1	L_2	Mean	L_1	L_2	Mean
T_1	157.83	151.43	154.63	168.37	133.77	151.07	162.43	160.73	161.58
T_2	145.97	142.47	144.22	132.20	127.84	130.02	103.93	106.76	105.35
T_3	255.30	246.31	250.81	231.60	158.82	195.21	198.93	179.63	189.28
T_4	326.40	298.87	312.63	316.10	314.83	315.46	236.70	225.83	231.26
Mean	221.38	209.77		212.07	183.82		175.50	168.24	
Comparison	**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**		**SEm(±)**	**CD (5%)**	
L	20.07	NS		30.03	NS		18.72	NS	
T	28.38	85.83		42.47	128.42		26.47	80.07	
Lx T	40.14	NS		60.06	NS		37.45	NS	

Note: T_1: Lime as per KAU POP, 2011; T_2: Phosphogypsum @ 500kg/ha + ½ lime as per KAU POP, 2011; T_3: Magnesium carbonate + ½ lime (as per KAU POP, 2011); T_4: Control; DAS: Days after submergence.

4.3 SOLUTION CULTURE EXPERIMENT

A solution culture experiment was carried out using Hoagland's nutrient solution as a base to which different levels of Fe and Al were added. The objective was to study the response of two popular varieties of rice Uma and Prathyasa to four levels of iron and two levels of aluminium. The treatment details are given below:

T_1 - Fe 200 mg L^{-1} and Al 50 mg L^{-1}
T_2 - Fe 400 mg L^{-1} and Al 50 mg L^{-1}
T_3 - Fe 800 mg L^{-1} and Al 50 mg L^{-1}
T_4 - Fe 1200 mg L^{-1} and Al 50 mg L^{-1}
T_5 -Fe 200 mg L^{-1} and Al 100 mg L^{-1}
T_6 - Fe 400 mg L^{-1} and Al 100 mg L^{-1}
T_7 - Fe 800 mg L^{-1} and Al 100 mg L^{-1}
T_8 - Fe 1200 mg L^{-1} and Al 100 mg L^{-1}
T_9 – control - Hoaglanad's nutrient solution.

The result obtained for analysis of various parameters is statistically analyzed and the data are given below.

4.3.1 Percentage increase in plant height

The influence of different treatments was recorded and growth was measured and worked out as percentage increase in height from the initial height. The increase in plant height of solution culture experiment is shown in Table 11. The varieties didn't show any noticeable difference in the increase in plant height. Prathyasa (V_2) (4.94%) showed slightly more plant growth than Uma (V_1) (4.44%).

There was a remarkable effect of treatments on the growth of plant recorded as height percentage. The control (T_9) showed maximum increase (7.69%) in plant height after 14 days in solution culture. Minimum increase in plant height was noticed in T_4 (2.94%) which was on par with T_8 (3.32%) and T_3 (3.86%).

There was no significant difference between the interactions of treatment and variety. In both varieties T_7 showed the highest value. T_4 in V_1 and T_8 in V_2 showed the lowest values of 2.12% and 3.76% respectively.

4.3.2 Percent increase in root length

The relative increase in root length of the rice plants were worked out as percentage increase over initial length in different treatments. The results are given in Table 11. There was no significance by the varieties. V_1 (17.07%) showed more increase in root length than V_2 (16.84%).

The treatments were significantly differing over the root length, recorded as percentage increase. Control showed significantly higher root length (31.57%) than other treatments. T_8 (8.45%) showed the lowest increase in root length which was on par with T_4 (8.73%).

There was no significant difference between the interaction of treatments and variety. The treatment T_9 showed highest value for V_1 (31.46%) and V_2 (31.67%). T_4 (8.70%) in V_1 and T_8 in (8.11%) V_2 showed lowest root length increase.

4.3.3 Root CEC

Root CEC of the rice plant grown in solution culture experiment is given in the Table 11. The varieties did not show any significance in the root CEC of the plant. Variety V_2 (7.9 cmol kg^{-1}) showed slightly higher root CEC than V_1 (7.67 cmol kg^{-1}).

There was notable difference by the treatments on the root CEC of rice plant. The treatment T_4 (44.09 cmol kg^{-1}) showed highest root CEC followed by T_8 (35.87 cmol kg^{-1}). The lowest root CEC was shown by T_9.

There was a remarkable difference with respect to the interaction effect of variety and treatment also. T_4 in V_1 (45.13 cmol kg^{-1}) and V_2 (43.05 cmol kg^{-1}) showed highest root CEC. T_9 showed the lowest value in both varieties.

4.3.4 Root dry weight

The root dry weight of rice plant grown in solution culture is given in Table 12.

The varieties show remarkable difference in root dry weight. Prathyasa (V_2) showed more root dry weight (1.97 mg) than Uma, V_1 (1.52 mg).

The treatments recorded noticeable difference in case of root dry weight. The treatment T_9 showed maximum dry weight (2.19 mg) and T_8 (1.39 mg) showed lowest value. The interaction of variety and treatments were also significantly different T_8 in V_1 (1.15 mg) and T_4 (1.63 mg) on par with T_8 (1.64 mg) in V_2 showed the lowest root dry weight. Both varieties showed highest root dry weight for control T_9.

4.3.5 Iron content in root

During the experiment assessment of iron and Al coated on the root surface was estimated by extracting these elements in 0.1 N HCl. The amount of iron coating in root is given in Table 12. The varieties showed notable difference in iron content. V_2 (2257.11 $\mu g\ g^{-1}$) displayed more iron content than V_1 (2038.89 $\mu g\ g^{-1}$).

The treatments T_4 (4,489.67 $\mu g\ g^{-1}$) showed significantly highest value and control (159.17 $\mu g\ g^{-1}$) showed the lowest value. Interaction of the variety and treatment is also significantly different. T_4 in V_1 (4309.67 $\mu g\ g^{-1}$) and V_2 (4669.67 $\mu g\ g^{-1}$) showed the highest value. The lowest iron concentration was showed by control (T_9) in both varieties.

4.3.6 Aluminium content in root

The amount of aluminium precipitated over root surface is presented in Table 12. The varieties showed significant difference in aluminium content in the root. Variety V_2 (922.81 $\mu g\ g^{-1}$) showed more aluminium content than V_1 (871.39 $\mu g\ g^{-1}$).

The treatment T_8 (1519.48 $\mu g\ g^{-1}$) was significantly higher than other treatments which was on par with T_5 (1507.62 $\mu g\ g^{-1}$). The treatment T_9 (186.00 $\mu g\ g^{-1}$) showed the lowest value. The interaction effect of variety and treatment was also significantly different. T_8 in V_1 (1513.99 $\mu g\ g^{-1}$) and V_2 (1524.98 $\mu g\ g^{-1}$) showed the highest value and the lowest aluminium concentration was showed by (T_9) control in both varieties.

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Table 11: Effect of different solution culture on plant height, root length and root CEC

Treatments	**Increase in plant height (%)**			**Increase in root length (%)**			**Root CEC (cmol kg^{-1})**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	5.24	5.15	5.19	20.86	20.77	20.81	10.10	10.23	10.17
T_2	5.93	5.85	5.88	14.87	15.73	15.30	21.60	21.87	21.73
T_3	3.68	4.04	3.86	13.87	13.80	13.83	24.83	25.70	25.27
T_4	2.12	3.76	2.94	8.70	8.77	8.73	45.13	43.05	44.09
T_5	5.04	5.27	5.16	20.73	20.53	20.63	9.80	9.99	9.89
T_6	3.50	4.55	4.03	18.04	18.27	18.15	29.13	24.45	26.79
T_7	3.86	4.41	4.13	16.27	13.93	15.10	27.00	32.30	29.65
T_8	2.95	3.69	3.32	8.80	8.11	8.45	35.53	36.20	35.87
T_9	7.62	7.76	7.69	31.46	31.67	31.57	7.67	7.90	7.78
Mean	4.44	4.94		17.06	16.84		23.42	23.52	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.23	NS		0.46	NS		0.30	NS	
T	0.48	1.38		0.99	2.836		0.64	1.85	
V x T	0.68	NS		1.39	NS		0.91	2.61	

Note: T_1 - Fe 200 mg L^{-1} and Al 50 mg L^{-1}; T_2 - Fe 400 mg L^{-1} and Al 50 mg L^{-1}; T_3 - Fe 800 mg L^{-1} and Al 50 mg L^{-1}; T_4 - Fe 1200 mg L^{-1} and Al 50 mg L^{-1}; T_5 -Fe 200 mg L^{-1} and Al 100 mg L^{-1}; T_6 - Fe 400 mg L^{-1} and Al 100 mg L^{-1}; T_7 - Fe 800 mg L^{-1} and Al 100 mg L^{-1}; T_8 - Fe 1200 mg L^{-1} and Al 100 mg L^{-1}; T_9 – control - Hoaglanad's nutrient solution

Table 12: Effect of solution culture on root dry weight and iron and Al content of rice root

Treatments	Root dry weight (mg)			Fe (mg kg^{-1})			Al (mg kg^{-1})		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	1.82	2.18	2.00	617.33	646	631.67	508.00	510.7	509.35
T_2	1.55	1.98	1.76	1716.33	1904.33	1810.33	515.33	517.77	516.55
T_3	1.39	1.93	1.66	2665.00	2708.00	2686.50	523.33	524.17	523.75
T_4	1.36	1.63	1.49	4309.67	4669.67	4489.67	499.33	535.00	517.17
T_5	1.71	2.12	1.92	640.00	673.67	656.83	1219.67	1485.00	1352.33
T_6	1.52	2.00	1.71	1803.33	1847.67	1825.50	1379.00	1504.33	1441.67
T_7	1.24	1.77	1.50	2889.33	3241.33	3065.33	1494.90	1520.33	1507.62
T_8	1.15	1.64	1.39	3551.67	4462.33	4007.00	1513.99	1524.98	1519.48
T_9	1.91	2.47	2.19	157.33	161.00	159.17	189.00	183.00	186.00
Mean	1.52	1.97		2038.89	2257.11		871.39	922.81	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.012	0.04		32.99	95.01		17.26	49.71	
T	0.03	0.07		69.98	201.55		36.62	105.45	
V x T	0.04	0.10		98.98	285.04		51.78	NS	

Note: T_1 - Fe 200 mg L^{-1} and Al 50 mg L^{-1}; T_2 - Fe 400 mg L^{-1} and Al 50 mg L^{-1}; T_3 - Fe 800 mg L^{-1} and Al 50 mg L^{-1}; T_4 - Fe 1200 mg L^{-1} and Al 50 mg L^{-1}; T_5 -Fe 200 mg L^{-1} and Al 100 mg L^{-1}; T_6 - Fe 400 mg L^{-1} and Al 100 mg L^{-1}; T_7 - Fe 800 mg L^{-1} and Al 100 mg L^{-1}; T_8 - Fe 1200 mg L^{-1} and Al 100 mg L^{-1}; T_9 – control - Hoaglanad's nutrient solution

4.3.7 Pattern of iron coating

The solution culture experiment was monitored by observing the pattern of Fe and Al deposition on root surface in treatments which provided graded levels of Fe and Al in Hoagland solution.

Iron plaque formation was noticed on the roots of rice plant in solution culture with higher concentration of Fe in culture solution. The cross sections of roots were made and observed under the compound research microscope model Axio lab A-1 (made- Carl zeiss) and analyzed using Zen image analyzer. The thickness of the roots was also measured using the Zen image analyzer by taking the average thickness of iron coating around the cell. It was observed that there was no iron coating around the root cells of control. Treatment containing 1200 mgL^{-1} Fe showed more thickness of iron plaque around the roots in both varieties (Plate. 10). Maximum iron coating (38.32 μm) around the root among the treatments was displayed by solution containing 1200 mgL^{-1} Fe and 100 mgL^{-1} Al (T_8) followed by (37.34 μm) 1200 mgL^{-1} Fe and 50 mgL^{-1}Al (T_4). Minimum thickness (2.17 μm) for iron toxicity was shown by Hoagland's solution containing 200 mgL^{-1} Fe and 50 mgL^{-1} Al followed by 200 mgL^{-1} Fe and 100 mgL^{-1} Al. the details are shown in the Table 13.

Table. 13: Thickness of iron coating in the plant roots of solution culture

Treatments	**Thickness of iron coating (μm)**		
	V_1	V_2	Mean
T_1	2.14	2.19	2.17
T_2	10.37	10.32	10.35
T_3	28.28	28.53	28.41
T_4	33.84	40.84	37.34
T_5	2.32	2.38	2.35
T_6	10.38	10.98	10.68
T_7	28.19	29.14	28.67
T_8	34.28	42.37	38.32
T_9	0	0	0
Mean	16.64	18.52	17.58

4.4 POT CULTURE EXPERIMENT

A pot culture experiment was conducted at College of Agriculture, Padannakkad, to examine the effect of different amelioration strategies for alleviating iron and aluminium toxicity problem in rice grown on acid sulphate soils of 'Kari' lands in Kuttanad. The varieties Uma and Prathyasa were grown on the pots with seven treatments each. The different treatments were:

T_1: Lime @ 600 kg ha^{-1} as per KAU POP, 2011

T_2: Magnesium carbonate @ 50 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} (as per KAU POP, 2011)

T_3: Phosphogypsum @ 500 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} as per KAU POP, 2011

T_4: Lime @ 600 kg ha^{-1} as per KAU POP, 2011 + Potassium silicate 0.25% + 0.25% Boron

T_5: Magnesium carbonate @ 50 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} (as per KAU POP, 2011) + Potassium silicate 0.25% + 0.25% Boron

T_6: Phosphogypsum @ 500 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} as per KAU POP, 2011 + Potassium silicate 0.25% + 0.25% Boron

T_7: Control

The leachate collected in PVC pipe which was inserted in the pot was also monitored for different parameters during different stages of crop. The results of biometric observations of the rice plant and soil analysis data are presented below.

4.4.1 Soil characteristics

4.4.1.1 pH

The effect of treatment application on the pH of the soil at harvest stage of the crop in the pot culture study is given in the Table 14.

The varieties did not show any significant difference among the pH of the soil. The variety V_1 (5.79) comparatively showed more soil pH than V_2 (5.72).

There was significant influence by the application of treatments on increasing the soil pH. The treatment T_4 (6.02) showed higher pH in the soil over other treatments which was on par with T_1 (6.01), T_6 (5.96), T_3 (5.91). The lowest pH in the soil was shown by T_7 (4.87).

There was no significant difference between the interactions. The treatment T_1 (6.01) in V_1 and T_4 (6.05) in V_2 showed higher pH. Treatment T_7 in both varieties showed lowest pH.

4.4.1.2 EC

The effect of application of amendments on electrical conductivity of soil is given in Table 14. The varieties did not show any significance on the EC of soil. Variety V_1 (0.56 dS m^{-1}) showed comparatively higher EC than V_2 (0.54 dS m^{-1}).

The application of different amendments fairly affects the EC. The treatment T_5 (0.59 dS m^{-1}) showed higher EC which was on par with T_2 (0.57 dSm^{-1}), T_6 (0.56 dS m^{-1}), T_7 (0.56 dS m^{-1}), T_3 (0.55 dS m^{-1}). The lowest EC was shown by T_1 (0.48 dS m^{-1}).

The interaction effect of different amendments and variety did not showed any significance. The treatment T_5 in V_1 recorded highest value of EC (0.59 dS m^{-1}) and T_1 showed lowest EC value (0.48 dS m^{-1}). T_5 in V_2 recorded higher EC (0.59 dS m^{-1}) and T_1 gave the lowest value (0.48 dS m^{-1}) similar to V_1.

4.4.1.3 Organic Carbon

The soil organic carbon content at the harvest stage of the crop in the pot culture is given in Table 14. There was no significant effect by the varieties on the soil organic carbon content. V_2 (1.45%) showed comparatively higher organic carbon content, than V_1 (1.44%).

The effect by treatments over the organic carbon content was non-significant. The treatment T_6 showed higher soil organic carbon content in the soil than others and T_7 recorded the lowest soil organic carbon content.

There was no significant effect by different amendments and varieties. The treatment T_6 in V_1 showed the highest amount of organic carbon content and T_2 in V_2 showed the highest value. Both varieties showed the lowest value for treatment T_7.

4.4.1.4 Available Nitrogen

The effect of different amendments on available nitrogen content in soils of the pot culture experiment was done at harvest stage. The data were tabulated and analyzed statistically and presented in Table 15. There was no significant effect by the varieties on available nitrogen content in soil. V_1 (Uma variety) absorbed higher nitrogen and left lower (322.75 kg ha^{-1}) soil available nitrogen as compared to V_2 (Prathyasa variety) (347.18 kg ha^{-1}).

Among treatments control (T_7) recorded lower available soil nitrogen indicating very low biological activity whereas all the treatments were superior to this in available nitrogen content. The treatment T_5 showed higher available N content (371.13 kg ha^{-1}) which was on par with T_1 (368.68 kg ha^{-1}), T_2 (365.18 kg ha^{-1}), T_4 (344.61 kg ha^{-1}) and T_6 (333.98 kg ha^{-1}).

While examining the effect of treatment and variety interaction it was noticed that in both varieties application of amendments registered higher nitrogen values over control. The response of varieties to treatments was almost uniform with no appreciable differences, in general. However T_5 in V_1 (360.61 kg ha^{-1}) and T_1 in V_2 (393.57 kg ha^{-1}) showed superiority. The better values of treatments are indicative of the better biological activities.

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Table 14: Effect of different amendments on pH, EC and organic carbon content of the soil in pot culture

Treatments	pH			EC (dS m^{-1})			OC (%)		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	6.01	6.00	6.01	0.48	0.48	0.48	1.42	1.48	1.45
T_2	5.74	5.65	5.70	0.56	0.57	0.57	1.43	1.50	1.46
T_3	5.96	5.86	5.91	0.56	0.54	0.55	1.43	1.46	1.45
T_4	6.00	6.05	6.02	0.55	0.54	0.54	1.44	1.47	1.45
T_5	5.940	5.71	5.82	0.58	0.59	0.5	1.43	1.41	1.42
T_6	6.01	5.91	5.96	0.57	0.54	0.55	1.49	1.46	1.48
T_7	4.87	4.88	4.87	0.58	0.53	0.55	1.41	1.41	1.41
Mean	5.79	5.72		0.55	0.54		1.44	1.45	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.03	NS		0.008	NS		0.05	NS	
T	0.05	0.14		0.02	0.04		0.09	NS	
V x T	0.07	NS		0.02	NS		0.13	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control

4.4.1.5. Available Phosphorus

The effect of different amendments on available phosphorus content in soils of the pot culture experiment was done at harvest stage. The data obtained were tabulated and analyzed statistically and presented in Table 15.

The varieties did not have a reflective effect on phosphorus utilization. There was no significant difference between the varieties for the absorption of phosphorus. Comparatively Prathyasa variety V_2 absorbed higher phosphorus and left lower soil available phosphorus than Uma variety V_1.

Among treatments T_7, the control recorded lowest available soil phosphorus for both varieties indicating very low mineralization of the total phosphorous whereas all the other treatments were superior to this in available phosphorus content. The treatment T_6 showed highest value (22.29 kg ha^{-1}) for available phosphorous content which was on par with treatment T_3 (22.26 kg ha^{-1}).

While examining the effect of different amendments and variety interaction, it was noticed that in both varieties with ameliorants registered higher phosphorous values over control. The treatment T_6 in V_1 (22.45 kg ha^{-1}) and V_2 (22.13 kg ha^{-1}) showed superiority. The better values of treatments are indicative of the better utilization of total phosphorous by making them soluble and available in soil.

4.4.1.6 Available Potassium

The effect of different amendments on available potassium content in soils of the pot culture experiment was done at harvest stage. The data obtained were tabulated and analyzed statistically and presented in Table 15.

The varieties did not have a reflective effect on potassium utilization. There was no significant difference between the varieties for the absorption of potassium.

Among treatments T_7, the control recorded lowest available soil potassium for both varieties whereas all the other treatments were superior to this.

There was no significant difference between the interactions. The treatment T_5 showed highest value (176.96 kg ha^{-1}) for available potassium content for variety Uma and T_2 (171.63 kg ha^{-1}) is better for variety Prathyasa.

4.4.1.7 Available Calcium

The results of available Ca content on different amendments were done at harvest stage of crop. The data obtained by statistical analysis of the results are given in the Table 16.

The varieties did not show any significant difference. Similar results were recorded by the two varieties. The variety Prathyasa (V_2) recorded more available Ca in soil compared to Uma variety V_1. The control (T_7) is dominated by all the other treatments in case of both varieties.

The treatments showed significant difference with different amendments with respect to calcium content. The treatment T_6 (779.08 mg kg^{-1}) showed higher amount of available Ca in soil which was on par with treatments T_3 (764.31 mg kg^{-1}), T_1 (711.54 mg kg^{-1}) and T_4 (704.33 mg kg^{-1}).

There was no significant difference among the interaction. Both varieties showed similar trend of result for each treatment. In case of Uma variety (V_1) treatment T_6 gave the highest value 784.83 mg kg^{-1} and Prathyasa variety showed 773.33 mg kg^{-1} for treatment T_6 which was dominated over other treatments. Control (T_7) showed the lowest value in both varieties.

4.4.1.8 Available Magnesium

The data obtained for analyzing the available magnesium from the soil at harvest stage of the crop are statistically analyzed and presented in Table 16. The varieties Uma (V_1) and Prathyasa (V_2) provide analogous results. There was no significant difference between the varieties. All the treatments offer higher amount of available magnesium in soil over control (T_7) for both varieties. V_1 (62.29 mg kg^{-1}) showed comparatively higher magnesium content in soil than V_2 (61.25 mg kg^{-1}).

The treatments showed variation in available Mg values and are significantly different. The treatment T_5 registered higher magnesium content (74.27 mg kg^{-1}) in the soil even after plant uptake which may be because of the magnesium that applied through the treatment. Treatment T_2 (72.51 mg kg^{-1}) and T_3 (67.05 mg kg^{-1}) gave values on par to T_5.

The interaction effect of treatments and varieties did not showed any significant difference. Treatment T_2 in variety Uma (V_1) showed higher value 74.42 mg kg^{-1} and the treatment T_5 in variety Prathyasa (V_2) was dominant over others with 74.30 mg kg^{-1}.

Table 15: Effect of application of different amendments and their combinations on availability of primary nutrients in soil

Treatments	**Available N (kg ha^{-1})**			**Available P (kg ha^{-1})**			**Available K (kg ha^{-1})**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	343.79	393.57	368.68	20.95	19.76	20.35	164.19	166.69	165.44
T_2	357.50	372.83	365.18	18.51	18.17	18.35	176.56	171.63	174.09
T_3	333.21	319.87	326.54	22.37	22.14	22.26	162.96	163.69	163.33
T_4	327.13	362.08	344.61	20.88	20.37	20.63	167.76	168.96	168.36
T_5	360.61	381.64	371.13	17.27	17.22	17.25	176.96	164.29	170.63
T_6	310.46	357.50	333.98	22.45	22.13	22.29	160.96	165.89	163.43
T_7	226.53	242.76	234.65	14.04	14.81	14.43	159.49	159.89	159.66
Mean	322.75	347.18		19.50	19.23		166.98	165.86	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	7.69	NS		0.31	0.91		5.53	NS	
T	14.39	41.90		0.58	1.69		10.34	NS	
V x T	20.35	NS		0.82	NS		14.63	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control

4.4.1.9 Available Sulphur

The results of analysis of available sulphur content in soil at harvesting stage of the pot culture experiment is given in Table 16.

The effect of varieties Uma and Prathyasa did not showed any significant difference. Comparatively the variety (V_1) Uma was recorded higher available sulphur (167.58 mg kg^{-1}) over the variety (V_2) Prathyasa (166.01 mg kg^{-1}).

The treatments have significant effect on available sulphur content. The highest sulphur content was showed by T_7, the control (192.12 mg kg^{-1}). The lowest value of available sulphur was reported by the treatment T_4 (155.79 mg kg^{-1}), which was on par with T_1, T_3, T_6, T_2 and T_5.

The interaction effect of variety and treatment had no significant effect on available S content. The control (T_7) showed highest value in both the varieties. The treatment T_4 exhibited lowest value (158.82 mg kg^{-1}) in variety (V_1) Uma and T_4 showed lowest value (152.71 mg kg^{-1}) in Prathyasa variety (V_2).

4.4.1.10 Available Iron

The effects of different amendments on iron content in the harvest stage of pot culture experiment were statistically analyzed and are given in Table 17.

The effect of treatments showed significant difference for available iron content. Treatment T_7 recorded highest iron content (371.33 mg kg^{-1}) which was on par with treatment T_5 and T_2. The treatment T_6 showed the lowest value of iron content (164.67 mg kg^{-1}) which was on par with treatment T_4 (171.00 mg kg^{-1}) and T_3 (182.67 mg kg^{-1}).

There was no significant difference among the different amendments and varieties interaction was not significantly different. Treatment T_6 in variety V_1 (143.33 mg kg^{-1}) and variety T_4 in V_2 (138.33 mg kg^{-1}) showed the lowest value and the treatment T_7 control registered the higher available iron in both varieties.

Table 16: Effect of different amendments and their combinations on availability of secondary nutrients in soil of pot culture

Treatments	Ca (mg kg^{-1})			Mg (mg kg^{-1})			S (mg kg^{-1})		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	717.92	705.17	711.54	57.72	51.12	54.42	158.82	156.33	157.57
T_2	681.17	635.42	658.29	74.42	70.62	72.51	167.28	173.87	170.57
T_3	776.25	752.37	764.31	65.88	68.22	67.05	160.04	158.40	159.22
T_4	719.08	689.58	704.33	53.07	54.53	53.80	158.88	152.71	155.79
T_5	672.08	677.5	674.79	74.27	74.30	74.28	170.49	171.81	171.15
T_6	784.83	773.33	779.08	64.55	64.30	64.42	163.95	158.37	161.16
T_7	300.02	307.25	303.64	46.18	45.70	45.94	193.65	190.57	192.12
Mean	664.48	648.66		62.29	61.25		167.58	166.01	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	15.56	NS		1.63	NS		3.15	NS	
T	29.11	84.76		3.05	8.89		5.88	17.14	
V x T	41.16	NS		4.32	NS		8.32	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control

4.4.1.11 Exchangeable Aluminium

The analyzed value for Al in soil at the harvest stage of the pot culture experiment is presented in Table 17.

The variety Uma and Prathyasa have similar results and their interaction was not significant. Variety Uma (V_1) showed higher values (145.59 mg kg^{-1}) than variety Prathyasa (V_2) (131.72 mg kg^{-1}).

The treatments had a significant effect on aluminium content in the soil. The treatment T_7 (212.54 mg kg^{-1}) showed significantly higher amount of exchangeable aluminium which was on par with treatment T_5 (167.87 mg kg^{-1}). The lowest value for aluminium content was recorded by treatment T_6 (100.82 mg kg^{-1}) which is on par with T_3 (103.12 mg kg^{-1}), T_1 (107.67 mg kg^{-1}) and T_4 (122.67 mg kg^{-1}).

The interaction of varieties and different amendments did not show any significant difference. The treatment T_7, control showed higher value (220.58 mg kg^{-1}) for Uma variety likewise Prathyasa variety also showed higher value for treatment T_7 (204.50 mg kg^{-1}).

4.4.1.12 Available Manganese

The effects of different amendments on the availability of manganese content in soil at the harvest stage of the pot culture experiment are given in Table 17.

The varieties did not have any significant effect on manganese content. The variety V_2 showed higher amount of available Mn than the variety V_1.

The highest available manganese content was observed in treatment T_7, the control (33.50 mg kg^{-1}) and lowest available Mn was shown by T_6 (23.48 mg kg^{-1}) which was found to be on par with T_4, T_1 and T_3.

There was no significant difference between the effect of varieties and amendments interaction. Control (T_7) showed highest available manganese content in both varieties. T_6 recorded lowest (23.33 mg kg^{-1}) available Mn content in variety V_1 and variety V_2 (23.6 mg kg^{-1}).

4.4.1.13 Available Boron

The results obtained for available boron content in soil after the harvest of the pot culture experiment are presented in Table 18.

The available boron content of soil in both the varieties was same (1.22 mg kg^{-1}).

The treatments had a very significant effect reflected on the availability of boron content. The highest value of boron content was showed by treatment T_6 (1.32 mg kg^{-1}) which was on par with T_3, T_1, T_4 and T_2. Control T_7 (1.06 mg kg^{-1}) showed lowest value of available boron which was on par with T_5.

The interaction effect of amendments and varieties did not showed any significant difference on the availability of boron in soil. The treatment T_3 (1.33 mg kg^{-1}) recorded the highest value in V_1 and the treatment T_6 in V_2 (1.30 mg kg^{-1}) whereas control recorded the lowest value in both varieties.

4.4.1.14 Available Copper

Availability of copper in soil at the harvest stage in pot culture experiment is given in Table 18. The effect of varieties did not show any significance on the availability of copper in soil. Variety Uma (V_1) showed comparatively higher copper content than variety Prathyasa (V_2).

There is significant effect on the availability of copper by the treatments. The treatment T_5 (3.76 mg kg^{-1}) showed highest amount of available copper left in the soil after the plant uptake in all the treatments except control (1.61 mg kg^{-1}) were on par with it.

There was no significant difference among the interaction of different amendments and varieties. The treatment T_3 (3.89 mg kg^{-1}) in Uma variety showed highest amount of available copper and T_5 (3.71 mg kg^{-1}) in Prathyasa variety showed higher amount of available copper.

Table 17: Effect of different amendments and their combinations on iron, aluminium and manganese in soil of pot culture

Treatments	**Available Fe (mg kg^{-1})**			**Exchangeable Al (mg kg^{-1})**			**Available Mn (mg kg^{-1})**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	208.33	241.33	224.83	108.17	107.17	107.67	24.90	25.79	25.34
T_2	333.67	354.00	343.83	188.87	123.00	155.93	27.07	27.10	27.08
T_3	177.33	188.00	182.67	103.93	102.30	103.12	25.23	25.85	25.54
T_4	203.67	138.33	171.00	106.33	139.00	122.67	25.02	25.74	25.38
T_5	319.67	382.00	350.83	193.00	142.73	167.87	26.84	26.00	26.77
T_6	143.33	186.00	164.67	98.27	103.37	100.82	23.33	23.60	23.48
T_7	373.00	369.67	371.33	220.58	204.50	212.54	33.88	33.12	33.50
Mean	251.28	265.62		145.59	131.72		26.61	26.85	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	10.71	NS		8.65	NS		0.37	NS	
T	20.03	58.34		16.17	47.09		0.701	2.04	
V x T	28.33	NS		22.87	NS		0.992	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control

Table 18: Effect of different amendments and their combinations on available boron, copper, zinc and silicon in soil of pot culture

Treatments	B (mg kg^{-1})			Cu (mg kg^{-1})			Zn (mg kg^{-1})			Si (mg kg^{-1})		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	1.28	1.29	1.29	3.44	3.56	3.50	2.61	2.24	2.42	22.89	25.68	24.29
T_2	1.18	1.16	1.17	3.37	3.35	3.37	2.92	2.95	2.94	28.37	30.47	29.42
T_3	1.33	1.30	1.31	3.89	3.57	3.73	3.15	2.54	2.85	28.90	15.96	22.43
T_4	1.29	1.29	1.29	3.56	3.40	3.48	3.32	2.60	2.96	31.00	26.41	28.71
T_5	1.11	1.10	1.10	3.81	3.71	3.76	2.93	2.89	2.91	35.83	27.40	31.62
T_6	1.33	1.30	1.32	3.81	3.70	3.76	3.15	2.53	2.83	30.64	38.09	34.36
T_7	1.04	1.08	1.06	1.63	1.59	1.61	2.26	2.22	2.23	12.81	15.51	14.16
Mean	1.22	1.22		3.61	3.15		2.91	2.57		27.21	25.65	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.03	NS		0.07	NS		0.18	NS		1.17	NS	
T	0.06	0.18		0.14	0.39		0.35	NS		2.19	6.37	
V x T	0.09	NS		0.19	NS		0.49	NS		3.09	9.01	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control

4.3.1.15 Available Zinc

The effects of treatments on the available zinc content in the soil at the harvest stage of the crop in the pot study are given in Table 18.

The variety V_1 and V_2 had no significant effect on the availability of zinc in the soil. The variety (V_1) Uma is comparatively recorded higher available Zn (2.91 mg kg^{-1}) over variety (V_2) Prathyasa (2.57 mg kg^{-1}).

There was no significant effect on the available zinc content by the treatments. The treatment T_4 recorded the highest value (2.96 mg kg^{-1}) of available zinc content. The treatment control (T_7) showed the lowest value (2.23 mg kg^{-1}) of available zinc.

The interaction of different amendments and variety showed no significant effect on the available zinc content. The treatment T_4 in variety V_1 showed highest value of available zinc (3.32 mg kg^{-1}) and the treatment T_2 reported highest value for variety V_2.

4.3.1.16 Available Silicon

The silicon content in the soil at the harvest stage of the rice crop in the pot culture experiment is presented in the Table 18.

The varieties V_1 and V_2 did not show any significant difference. Uma variety (V_1) showed higher value of silicon (27.21 mg kg^{-1}) than Prathyasa variety V_2 (25.65 mg kg^{-1}).

The effect of treatments showed significant difference on the silicon content in soil. Maximum value for available silicon content (34.36 mg kg^{-1}) in soil was recorded by treatment T_6 which was on par with T_5, T_2 and T_4. The control, T_7 recorded lowest value (14.16 mg kg^{-1}) of available silicon.

The interaction of different amendments and varieties showed significant difference. In the variety V_1, treatment T_5 showed highest value (35.83 mg kg^{-1}) of silicon which was on par with T_6, T_4, T_2 and T_3. In the variety V_2 the treatment T_6 showed highest value (38.09 mg kg^{-1}) which was on par with T_2. Both varieties showed the lowest value for control T_7.

4.4.2 Leachate Analysis

A PVC pipe with perforations at the bottom was inserted in to center of the pots in pot culture experiment. Soil solution in the pot entered into the pipe through the holes of the pipe at the bottom was collected and analyzed. The leachate was collected at 30, 60 and harvest stage of the crop. The results of analysis of various parameters in leachate are presented below.

4.4.2.1 pH

The pH of the leachate collected at 30 DAT, 60 DAT and harvest stage of the crop in the pot study are given in Table 19. The effect of varieties did not show any significance towards the pH.

The treatments exhibited an excellent effect towards pH. T_6 showed the highest pH on 30 DAT on par with T_1, T_3, T_4 and T_5. After 60 days of transplanting T_1 (6.67) showed highest pH which was on par with all the other treatments except T_7. At the time of harvest T_6 (6.56) recorded highest pH on par with the remaining treatment except T_7. The control T_7 showed lowest pH throughout the crop period. There was no significant difference among the different amendments and varieties.

4.4.2.2 Calcium

The effect of different amendments on available Ca content in leachate of the pot culture experiment is given in the Table 20. The varieties did not show any significance on the Ca content of leachate. V_2 recorded higher amount of Ca in the leachate than V_1 throughout the crop duration.

There was significant difference among the different treatments. T_3 (29.42 mg L^{-1}) showed maximum amount of Ca in the leachate at 30 DAT on par with T_6, T_1 and T_4. On 60 DAT also T_3 (31.05 mg L^{-1}) showed highest value of Ca on par with T_6 (30.21 mg L^{-1}). At the time of harvest T_3 showed 28.52 mg L^{-1} of Ca on par with T_1, T_6 and T_4. T_7 showed lowest Ca concentration throughout the crop period.

4.4.2.3 Magnesium

The available Mg content in the leachate is given in Table 21. The varieties did not show any significant difference on Mg content.

There was significant difference among the treatments. T_5 showed highest Mg content throughout the crop period. T_7 showed the lowest Mg content at 30 DAT, 60DAT and at harvest. There was no significant difference among the interaction effect of different amendments and varieties.

4.4.2.3 Iron

The effect of different amendments on concentration of available iron in the leachate is given in Table 22. The varieties showed no significant difference on iron content. The variety V_1 showed more iron concentration than V_2 in the leachate.

The treatment T_7 recorded significantly higher iron content over other treatments at 30 DAT, 60 DAT and at harvest. The treatment T_1 (16.75 mg L^{-1}) exhibited lowest iron content at 30 DAT on par with T_3, T_4 and T_6. At 60 DAT treatment T_1 (13.84 mg L^{-1}) gave the lowest iron content. At the time of harvest T_3 (10.89 mg L^{-1} showed lowest iron content on par with all the other treatments except T_7.

4.4.2.4 Aluminium

The available aluminium content of the leachate at 30, 60 and at harvest stage of crop are given in Table 23. The varieties did not show any significant difference on the available aluminium content of the leachate. V_1 showed higher Al content than V_2 at 30 DAT. At 60 DAT and at harvest V_2 showed higher Al content than V_1.

The treatments are significantly different at 30 DAT, 60 DAT and at harvest. T_6 showed the lowest Al content at 30 DAT (71.68 mg L^{-1}), 60 DAT (83.70 mg L^{-1}) and at harvest (81.54 mg L^{-1}). The interaction effect of varieties and treatments did not show any significance.

Table 19: Effect different amendments and their combinations on pH of leachate in pot culture

Treatments	30 DAT			60 DAT			At harvest		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	5.55	5.50	5.53	6.56	6.78	6.67	6.48	6.47	6.48
T_2	5.29	5.25	5.27	6.40	6.37	6.38	6.48	6.30	6.39
T_3	5.52	5.48	5.50	6.73	6.57	6.63	6.45	6.36	6.41
T_4	5.49	5.57	5.53	6.63	6.64	6.63	6.42	6.39	6.41
T_5	5.58	5.46	5.52	6.44	6.40	6.42	6.40	6.30	6.35
T_6	5.55	5.59	5.57	6.71	6.57	6.63	6.60	6.53	6.56
T_7	5.11	5.15	5.13	5.56	5.45	5.50	5.80	5.81	5.81
Mean	5.44	5.43		6.43	6.39		6.38	6.31	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.02	NS		0.07	NS		0.05	NS	
T	0.03	0.09		0.14	0.407		0.10	0.30	
V x T	0.04	NS		0.19	NS		0.15	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control; DAT: days after transplanting

Table 20: Effect of different amendments and their combinations on (Ca mg L^{-1}) content of leachate in pot culture

Treatments	**30 DAT**			**60 DAT**			**At harvest**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	21.83	21.73	21.77	23.61	24.19	23.90	22.57	21.66	22.12
T_2	15.02	15.99	15.51	17.49	19.49	18.49	15.71	18.32	17.02
T_3	29.37	29.45	29.42	31.84	30.27	31.05	29.31	27.74	28.52
T_4	21.97	20.87	21.42	24.07	23.33	23.70	21.53	21.41	21.47
T_5	15.60	16.23	15.91	18.07	20.97	19.52	15.53	19.00	17.27
T_6	28.88	28.90	28.89	31.08	29.33	30.21	28.55	26.80	27.67
T_7	9.19	9.15	9.17	11.66	11.62	11.64	9.13	9.08	9.11
Mean	20.27	20.33		22.55	22.75		20.33	20.57	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	1.55	NS		1.31	NS		1.27	NS	
T	2.89	8.44		2.45	7.15		2.38	6.93	
V x T	4.10	NS		3.47	NS		3.37	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control; DAT: days after transplanting; DAT: days after transplanting

Table 21: Effect of different amendments and their combinations on Mg (mg L^{-1}) content of leachate in pot culture

Treatments	**30 DAT**			**60 DAT**			**At harvest**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	8.42	10.06	9.24	8.65	8.63		9.20	9.17	9.18
T_2	21.68	21.86	21.77	26.34	23.64	24.99	26.39	23.52	24.95
T_3	8.43	19.32	13.88	10.60	10.00	10.30	13.80	13.60	13.70
T_4	15.03	10.13	12.58	9.40	9.60	9.50	9.13	10.38	9.76
T_5	21.83	23.89	22.86	27.13	24.86	25.99	25.58	26.67	26.13
T_6	9.86	19.56	14.72	8.53	8.63	8.58	13.66	12.12	12.89
T_7	8.99	7.85	8.42	7.92	7.47	7.69	7.82	7.46	7.64
Mean	13.46	16.09		14.08	13.26		15.08	14.70	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	1.26	NS		0.56	NS		0.64	NS	
T	2.36	6.88		1.04	3.04		1.19	3.47	
V x T	3.34	NS		1.47	NS		1.68	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control; DAT: days after transplanting

Table 22: Effect of different amendments and their combinations on Fe (mg L^{-1}) content of leachate in pot culture

Treatments	**30 DAT**			**60 DAT**			**At harvest**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	16.83	16.67	16.75	13.84	13.67	13.75	11.68	11.75	11.71
T_2	25.66	25.60	25.63	22.67	22.60	22.63	13.32	12.97	13.15
T_3	20.00	15.87	17.93	17.00	17.17	17.08	10.77	11.01	10.89
T_4	15.82	19.53	17.67	17.48	16.53	17.01	12.53	11.70	12.12
T_5	26.73	26.33	26.53	23.73	23.33	23.53	12.71	12.67	12.69
T_6	20.05	20.27	20.15	17.05	17.27	17.16	10.96	11.23	11.09
T_7	32.71	32.59	32.65	29.71	29.59	29.65	16.18	16.21	16.19
Mean	22.54	22.41		20.21	20.02		12.59	12.51	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.68	NS		0.46	NS		0.59	NS	
T	1.27	3.69		0.87	2.52		1.11	3.21	
V x T	1.79	NS		1.23	NS		1.56	NS	

Note:

T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control; DAT: days after transplanting; DAT: days after transplanting

Table 23. Effect of application of amendments and their combinations on Al (mg L^{-1}) content of leachate in pot culture

Treatments	**30 DAT**			**60 DAT**			**At harvest**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	99.5	92.70	96.10	103.83	120.80	112.32	101.42	118.38	109.9
T_2	105.10	108.44	106.77	109.43	112.77	111.11	107.03	110.36	108.68
T_3	81.00	85.27	83.13	86.80	89.60	88.20	84.73	93.95	89.34
T_4	107.10	102.03	104.57	111.43	106.37	108.90	109.02	102.93	105.97
T_5	134.00	100.77	117.38	110.16	105.11	107.64	108.37	102.69	105.53
T_6	71.97	71.40	71.68	76.30	91.11	83.70	74.38	88.69	81.54
T_7	182.69	182.10	182.39	187.02	188.00	187.51	184.61	180.33	182.46
Mean	111.62	106.10		112.14	116.25		109.93	113.91	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	11.79	NS		5.67	NS		4.19	NS	
T	22.06	64.25		10.62	30.91		7.84	22.83	
V x T	31.20	NS		15.01	NS		11.09	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control; DAT: days after transplanting

4.4.3 Biometric observations

4.4.3.1 Plant height

The plant height of rice grown in pot culture experiment at 30, 60 and at harvest stage of the crop are given in Table 24. The varieties showed a noticeable difference in plant height throughout the crop period. The variety V_2 Prathyasa showed significantly higher plant height than variety Uma (V_2) in the experiment.

The treatments also showed remarkable effect on the plant height. At 30 days after transplanting the treatments did not show any significant difference. The treatment T_4 recorded highest plant height (91.21 cm) and T_3 displayed the lowest plant height (89.25 cm). The treatments were significantly different at 60 days after transplanting. T_6 showed largest value for plant height (102.25 cm) which was on par with all the other treatments except T_7 control which showed the lowest value. The treatment T_4 (112.42 cm) recorded significantly higher value on par with T_6 and T_5 at the time of harvest.

The interaction effect of different amendments and varieties showed non-significant in relation to plant height. The treatment T_4 (83.33 cm) in V_1 and T_7 in V_2 (100.58 cm) shows highest value in 30days after transplanting. After 60 days of transplanting T_6 (95.85 cm) and T_1 (108.83 cm) in V_1 and V_2 recorded highest values respectively. At the time of harvest T_6 (105.33 cm) and T_4 (119.83 cm) displayed highest value for plant height.

4.4.3.2 Number of tillers

The effect of different treatments on the number of tillers at 30 days, 60 days and at harvest of the rice plant grown in the pot culture experiment are given in the Table 25. There was no significant difference between the two varieties with respect to number of tillers at 30, 60 and harvest stage of the crop. The variety V_2 is dominant over V_1 in the whole crop period.

The number of tillers was significantly influenced by the treatments at 30, 60 and harvest stage. At 30 days after transplanting the treatments T_2 and T_6 showed highest number of tillers (21.58) which was on par with all the other treatments

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except control T_7 which recorded the lowest value (18.50). After 60 days of transplanting the treatment T_6 shows maximum number of tillers (23.8) in the plant which was on par with T_4 (22.58) and T_5 (22.83). At the harvest stage of the crop T_6 (26.67) showed highest number of tillers which was on par with T_4 (25.83), T_1 (25.75), T_3 (25.08) and T_5 (24.92). T_7 showed the lowest number of tillers (21.83).

There was no significant difference among different amendments and variety interaction. The treatment T_1 in V_1 (21.83) and T_6 in V_2 (22.00) showed highest no. of tillers at 30 days. At 60 days after transplanting the treatment T_6 in V_1 and V_2 recorded 23.8 tillers. After 90 days of transplanting also T_6 showed higher value in both V_1 (26.5) and V_2 (26.8).

4.4.3.3 Grain yield (g/pot)

The effect of different ameliorants on the grain yield of rice crop grown in the pot study is given in the Table 26. The varieties did not have any significant increase in the grain yield of the crop. V_2 (68.13 g/pot) gave higher grain yield than V_1 (67.75 g/pot).

There was significant difference among the treatments. The treatment T_4 (76.52 g/pot) showed highest yield among different amendment application on par with T_1 (74.17 g/pot) and T_6 (73.28 g/pot). T_7 (54.65 g/pot) recorded the lowest yield. The interaction of different amendments and varieties did not show any significance.

4.3.3.4 Straw yield

Straw yield obtained from the pot culture experiment are given in the Table 26. There was no significant interaction by the varieties on the straw yield. V_1 (68.91 g/pot) showed more yield than V_2 (67.71 g/pot).

The different amendments did not influence the straw yield significantly. T_4 (70.83 g/pot) showed highest straw yield and T_6 (65.50 g/pot) showed lowest straw yield.

The interaction of different amendment and variety showed significant interaction. The treatment T_3 (71.33 g/pot) in V_1 and T_4 (71.33 g/pot) in V_2 showed highest straw yield. T_6 and T_5 in V_1 and V_2 respectively showed the lowest value.

4.3.3.5 Chaffiness percentage

The effects of treatments on chaffiness of grains are given in Table 26. The effect of varieties, treatments, interaction of treatments and varieties did not showed any significance. Variety V_2 showed higher chaffiness than V_1.

Treatment T_3 (11.97%) showed the least amount of chaffiness and T_7 (14.30%) showed the highest amount of chaffiness. T_3 (11.67 %) in V_1 and T_1 (11. 67 %) in V_2 showed the lowest chaffiness percent.

4.4.3.6 Germination percentage

The effect of treatments on germination percentage of grains from the pot culture experiment is presented in Table 27. The varieties did not show any significant effect on the germination percentage of grains.

The treatments showed significant effect with respect to the germination percentage. The treatment T_1 (96.00%) showed highest germination percentage which was on par with T_3, T_4, T_6 and T_5. The control T_7 recorded minimum germination percentage. There was no significant effect by the interaction of variety and treatments.

4.4.3.7 Number of grains per panicle

The influence of treatments on number of grains per panicle is given in the Table 27. The varieties did not show any significance on the number of grains. V_2 (157.54) showed more number of grains than V_1 (156.43).

The treatments show significant results on number of grains. Phosphogypsum @ 500kg/ha + ½ lime as per KAU POP, 2011 + Potassium silicate 0.25% + 0.25% Boron (T_6) recorded maximum number of grains (160.67) which is on par with T_5, T_4 and T_3. Control showed the least number of grains per panicle (150.67)

The interaction of different amendment and variety also did not have any significant interaction. The treatment T_6 in V_1 and V_2 showed the highest number of grains per panicle. T_7 showed the lowest value in both varieties.

4.4.3.8 Root CEC

The effects of treatments on root cation exchange capacity of rice plants in the pot culture experiment is given in table 27. The varieties did not show any significance on the root cation exchange capacity.

Application of amendments showed significant effect on the root cation exchange capacity. The treatment T_6 (32.03 cmol kg^{-1}) showed highest root CEC and control T_2 recorded lowest root CEC (25.03 cmol kg^{-1}). There was no significant effect by the interaction of variety and treatments.

4.4.3.9 Test weight

The influence of treatments on test weight of grains from the pot culture experiment are given in Table 27. The varieties did not show any significance on the test weight of grains.

The treatments had profound effect on the test weight of grains. The treatment T_6 (26.17 g) showed maximum test weight which was on par with T_1, T_3, T_4 and T_5. The control T_7 recorded lowest value for test weight. There was no significant effect by the interaction of variety and treatments.

Table 24: Effect of different amendments and their combinations on plant height (cm)

Treatments	**30 DAT**			**60 DAT**			**At harvest**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	81.08	100.17	90.62	92.42	108.833	100.63	102.25	113.83	108.04
T_2	81.133	100.75	90.94	91.05	105.833	98.44	101.20	110.58	105.89
T_3	79.58	98.91	89.25	92.33	107.25	99.79	101.22	114.83	108.03
T_4	83.33	99.08	91.21	94.17	107.683	100.93	105.00	119.83	112.42
T_5	79.55	99.95	89.75	91.87	104.7	98.25	103.83	115.17	109.50
T_6	79.23	100.41	89.81	95.85	108.667	102.25	105.33	116.83	111.083
T_7	80.30	100.58	90.44	90.17	101.083	95.62	99.83	108.83	104.33
Mean	80.60	99.98		92.54	106.29		102.67	114.27	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.38	1.11		0.49	1.45		0.66	1.92	
T	0.71	NS		0.93	2.72		1.23	3.58	
V x T	1.01	NS		1.32	NS		1.74	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control; DAT: days after transplanting

Table 25: Effect of different amendments and their combinations on no. of tillers of plant

Treatments	30 DAT			60 DAT			At harvest		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	21.83	20.00	20.92	22.67	22.33	22.50	25.83	25.67	25.75
T_2	21.50	21.67	21.58	21.67	22.50	22.08	24.00	24.50	24.25
T_3	19.83	21.00	20.42	21.33	22.00	21.67	25.17	25.00	25.08
T_4	18.83	20.33	19.58	22.17	23.00	22.58	25.67	26.00	25.83
T_5	20.83	21.83	21.33	21.83	22.83	22.33	24.33	25.50	24.92
T_6	21.17	22.00	21.58	23.83	23.83	23.83	26.50	26.83	26.67
T_7	18.50	18.50	18.50	19.83	19.17	19.50	22.00	21.67	21.83
Mean	20.35	20.76		21.91	22.24		24.78	25.03	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.38	NS		0.26	NS		0.23	NS	
T	0.71	2.08		0.50	1.46		0.43	1.25	
V x T	1.01	NS		0.71	NS		0.61	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control; DAT: days after transplanting

Table 26. Effect of different amendments and their combinations on grain yield (g/pot), straw yield (g/pot) and chaffiness percentage

Treatments	Grain yield (g/plant)			Straw yield (g)			Chaffiness (%)		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	73.77	74.57	74.17	70.67	69.33	70.00	12.67	11.67	12.17
T_2	60.47	63.00	61.73	66.00	69.33	67.67	13.00	13.90	13.45
T_3	72.63	71.03	71.83	71.33	66.67	69.00	11.67	12.27	11.97
T_4	75.89	77.17	76.52	70.33	71.33	70.83	12.33	12.50	12.42
T_5	62.50	64.20	63.35	74.00	62.67	68.33	13.33	13.13	13.23
T_6	73.86	72.69	73.28	60.67	70.33	65.50	12.87	12.67	12.77
T_7	55.10	54.20	54.65	69.33	64.33	66.83	14.33	14.27	14.30
Mean	67.75	68.13		68.91	67.71		12.89	12.91	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.58	NS		0.88	NS		0.42	NS	
T	1.08	3.16		1.65	NS		0.79	NS	
V x T	1.53	NS		2.34	6.81		1.12	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control; DAT: days after transplanting

Table 27. Effect of different amendments and their combinations on number of grains per panicle, root CEC, test weight, germination percentage

Treatments	No. of grains per panicle			Root CEC (cmol kg^{-1})			Test weight (g)			Germination percentage		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	157.00	156.33	156.67	27.43	29.06	28.25	24.33	25.67	25.00	96.33	95.67	96.00
T_2	155.00	153.67	154.33	25.16	24.89	25.03	23.33	25.00	24.17	94.33	93.33	93.83
T_3	157.33	157.00	157.17	28.80	27.36	28.08	26.00	25.67	25.83	95.33	95.33	95.33
T_4	158.00	161.13	159.57	28.56	29.46	29.01	25.00	25.00	25.00	94.67	95.00	94.83
T_5	158.67	161.00	159.83	23.03	24.26	23.65	25.00	24.67	24.83	94.33	94.33	94.33
T_6	159.33	162.00	160.67	31.96	32.10	32.03	25.67	26.67	26.17	95.33	95.67	95.50
T_7	149.67	151.67	150.67	25.80	26.03	25.91	21.33	21.67	21.50	90.67	91.00	90.83
Mean	156.43	157.54		27.25	27.59		24.38	24.91		94.43	94.33	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.69	NS		0.29	NS		0.28	NS		0.36	NS	
T	1.29	3.76		0.55	1.628		0.52	1.52		0.67	1.95	
V x T	1.82	NS		0.79	NS		0.74	NS		0.95	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control; DAT: days after transplanting

4.4.4 Nutrient content in plant

4.4.4.1 Nitrogen

The concentration of nitrogen in the plant at harvest stage of crop is given in Table 28. The varieties Uma and Prathyasa did not showed any significance on the concentration of nitrogen in plant. The variety (V_2) Prathyasa showed higher nitrogen content (5.35%) in the plant than the variety Uma (V_1) (5.32%).

There was no significant difference among the treatments. The treatment T_2 (5.76%) displayed highest nitrogen content in plant and the treatment T_7 (4.98%) recorded the lowest nitrogen content in plant.

The interaction of different amendments and varieties did not showed any significant effect on the nitrogen content in the plant. The treatment T_2 in variety V_1 recorded highest value (5.61%) and the variety V_2 also recorded highest value (5.92%) for treatment T_2.

4.4.4.2 Phosphorus

The percentage of phosphorus content in plant at the harvest stage of the crop in the pot culture experiment is given in Table 28.

The varieties exhibit a reflective effect on the phosphorus content in plant. The variety V_1 registered significantly higher value (0.16%) of phosphorus than V_2 (0.14%) in the rice plant.

The treatments also give a profound effect on the phosphorus content. The treatment T_6 show significantly higher amount of phosphorus in plant (0.22%) followed by T_4 (0.16%). The lowest concentration of phosphorus was recorded by T_7 control (0.11%).

The interaction of treatment and variety showed statistically significant effect on the concentration of phosphorus in plant. The treatment T_6 (0.26%) in V_1 indicate higher phosphorus followed by T_4 (0.21%) and in case of V_2 also T_6 confirm highest phosphorus content (0.17%) on par with T_3. While the control (T_7) recorded lowest phosphorus content in both varieties.

4.4.4.3 Potassium

The effect of treatments on the concentration of potassium in the rice plant at the harvest stage of crop in the pot culture experiment is given in Table 28. The effect of varieties was found to be significant on the potassium content in the plant. V_1 showed slightly higher amount of potassium (2.24%) than V_2 (2.17%).

The treatment T_2 give significantly higher content of potassium (2.30 %) in plant whereas control T_7 recorded lowest (2.08 %) content of potassium in the plant. The interaction effect of treatments and varieties was also showed significant difference. The treatment T_2 (2.42%) in V_1 and T_6 (2.22%) in V_2 recorded highest potassium concentration.

4.4.4.4 Calcium

The calcium content in the rice plant at harvest of the pot culture experiment is given in Table 29. There was no significant difference among the varieties.

Application of amendments had a prominent effect in the Ca nutrient content. The treatment T_3 contain significantly more concentration of Ca (1.82%) in plant which is on par with T_6, T_4, T_1 and T_2. The control T_7 showed lowest concentration of calcium.

There was no significant differences among the interactions. The treatment T_3 in V_1 contain more Ca (1.82%) in the plant while T_6 in V_2 showed higher concentration (1.82%) of Ca. The control showed lowest concentration of Ca in plant in both varieties.

4.4.4.5 Magnesium

The effect of different amendments on magnesium content in the plant is given in the Table 29. The varieties did not showed any significant difference on the uptake of magnesium by the plant. Variety V_1 (0.21%) contains more concentration of magnesium than V_2 (0.20%).

The treatment T_2 (0.34%) express significantly higher amount of magnesium in plant, which is on par with T_5 (0.32%). T_3 (0.19%) showed the next highest concentration of manganese on par with T_6 (0.18%). Control (T_7) gives the lowest concentration (0.11%) of magnesium in plants which is on par with T_1 (0.15%) and T_4 (0.16%).

There was no significant difference by the treatment and variety interaction. Treatment T_2 in V_1 (0.35%) and V_2 (0.33%) recorded highest quantity of magnesium on plant.

4.4.4.6 Sulphur

The effect of treatments on the uptake of sulphur by the plants is given in the Table 29. There was no noticeable difference by the varieties on the concentration of sulphur in plant. Variety V_1 (0.30%) contain more concentration of sulphur in the plant than V_2 (0.29%).

There was significant influence by the treatments on the uptake of sulphur. The treatment T_6 (0.34%) contain more concentration of sulphur than other treatments. It was on par with T_3 (0.34%) and T_7 (0.33%). The lowest concentration of sulphur was shown by T_1 (0.24%) which was on par with T_4 (0.24%).

There is no significant effect by the treatment and variety interaction. The treatment T_3 in V_1 showed the highest concentration of sulphur whereas T_4 (0.22%) showed the least concentration of sulphur. In case of V_2 the highest sulphur uptake was displayed by T_7 (0.33%) and T_1 (0.24%).

Table 28: Effect of different amendments and their combinations on primary nutrients in plant

Treatments	**Plant N (%)**			**Plant P (%)**			**Plant K (%)**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	5.06	5.53	5.29	0.17	0.14	0.15	2.15	2.18	2.17
T_2	5.61	5.92	5.76	0.13	0.10	0.12	2.43	2.17	2.30
T_3	5.56	5.15	5.35	0.13	0.17	0.15	2.13	2.15	2.14
T_4	5.28	5.26	5.27	0.21	0.12	0.16	2.12	2.14	2.13
T_5	5.37	5.15	5.26	0.12	0.15	0.14	2.42	2.12	2.27
T_6	5.40	5.38	5.39	0.26	0.17	0.22	2.19	2.22	2.21
T_7	4.92	5.04	4.98	0.12	0.11	0.11	2.16	2.00	2.08
Mean	5.32	5.35		0.16	0.14		2.24	2.17	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.09	NS		0.002	0.005		0.001	0.002	
T	0.18	NS		0.003	0.009		0.001	0.004	
V x T	0.26	NS		0.005	0.013		0.002	0.006	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control

Table 29: Effect of different amendments and their combinations on secondary nutrients in plant

Treatments	**Plant Ca (%)**			**Plant Mg (%)**			**Plant S (%)**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	1.72	1.69	1.70	0.16	0.15	0.15	0.24	0.24	0.24
T_2	1.48	1.59	1.54	0.35	0.33	0.34	0.31	0.31	0.31
T_3	1.82	1.81	1.82	0.21	0.17	0.19	0.35	0.33	0.34
T_4	1.70	1.72	1.71	0.16	0.16	0.16	0.22	0.26	0.24
T_5	1.48	1.38	1.43	0.31	0.33	0.32	0.34	0.28	0.31
T_6	1.78	1.82	1.80	0.18	0.18	0.18	0.34	0.32	0.34
T_7	1.30	1.31	1.30	0.11	0.11	0.11	0.34	0.33	0.33
Mean	1.61	1.62		0.21	0.20		0.30	0.29	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.06	NS		0.006	NS		0.01	NS	
T	0.12	0.35		0.010	0.05		0.02	0.06	
V x T	0.17	NS		0.015	NS		0.03	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control

4.4.4.7 Iron

The iron content in the rice plant grown in the pot study at harvest stage is presented in the Table 30. The varieties Uma (V_1) and Prathyasa (V_2) did not have any significant effect on the iron content in the plant. V_2 (225.29 mg kg^{-1}) absorb higher quantity of iron than V_1 (215.71 mg kg^{-1}).

The treatments had a significant effect on the content of iron by the plants. The treatment T_7 showed the highest amount of iron in the plant. The treatment T_1 (159.92 mg kg^{-1}) showed the least amount of iron content in plant which is on par with T_4 (165.58 mg kg^{-1}).

The interaction effect of different amendments and varieties also showed significance on the content of iron. The treatment T_7 in V_1 (363.85 mg kg^{-1}) and V_2 (420.18 mg kg^{-1}) showed dominance in iron content. The treatment T_1 in V_1 (159.32 mg kg^{-1}) showed the lowest value of iron uptake which is on par with T_4 (165.45 mg kg^{-1}). In variety, V_2 also the treatment T_1 (160.52 mg kg^{-1}) showed the lowest value of iron which is on par with T_4 (165.72 mg kg^{-1}).

4.4.4.8. Aluminium

The effect of different treatments on content of aluminium in the plant is given in the Table 30. The varieties had a reflective effect on the content of aluminium. Variety V_2 (326.52 mg kg^{-1}) recorded significantly higher aluminium content than V_1 (301.94 mg kg^{-1}).

The treatments have a remarkable effect on the content of aluminium. The lowest amount of aluminium content was showed by T_6 (291.37 mg kg^{-1}) which was on par with T_1 (293.28 mg kg^{1}) and T_4 (296.68 mg kg^{-1}). Aluminium content was higher in the treatment T_7 (374.32 mg kg^{-1}) control.

There was notable difference in treatment and variety interaction. The treatment T_6 in V_1 (282.40 mg kg^{-1}) and V_2 (300.33 mg kg^{-1}) showed lowest value of aluminium content in plant which was on par with T_3 and T_1 in both V_1 and V_2.

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4.4.4.9 Manganese

The influence of treatments on manganese content by the plant is presented in Table 30. The varieties did not show any significant effect on the content of manganese. Variety V_1 (111 mg kg^{-1}) contains more amount of manganese in the plant than V_2 (109.97 mg kg^{-1}).

The effect of treatments had a significant result on the content of manganese by the plant. The treatment T_7 showed highest concentration (168.35 mg kg^{-1}) of manganese content in plant. Lowest manganese content was shown by T_4 (76.48 mg kg^{-1}) which was on par with T_1 (81.57 mg kg^{-1}).

There is notable difference for variety x treatment interaction. The treatment T_4 showed significantly lower value of manganese (79.27 mg kg^{-1}) in the variety V_1 which is on par with T_1 (82.63 mg kg^{-1}). The treatment T_4 showed the lowest value (73.70 mg kg^{-1}) also in V_2 which is on par with T_6 (75.83mg kg^{-1}), T_3 (78.57 mg kg^{-1}) and T_1 (80.51 mg kg^{-1}).

4.3.3.9 Copper

The effect of different amendments on content of copper by the rice plant is given in Table 31. There was a significant effect by the varieties on the content of copper. The variety Prathyasa (V_2) recorded more copper (31.75 mg kg^{-1}) compared to Uma (V_1) (21.60 mg kg^{-1}).

The treatment T_2 (36.13 mg kg^{-1}) recorded significantly higher concentration of copper which is statistically on par to treatments T_3 (35.60 mg kg^{-1}) and T_6 (34.81 mg kg^{-1}). The lowest concentration of copper was showed by control T_7 (24.40 mg kg^{-1}) on par with T_1 (26.40 mg kg^{-1}) and T_4 (27.34 mg kg^{-1}).

There was no significant difference among the interaction of variety and treatment. The treatment T_2 in V_1 (36.17 mg kg^{-1}) showed highest amount of copper similarly T_5 in V_2 also showed higher value (37.50 mg kg^{-1}). T_1 in V_1 and control (T_7) in V_2 showed the lowest value in both varieties.

Table 30: Effect of different amendments and their combinations on Fe, Al and Mn in plant

Treatments	Plant Fe (mg kg^{-1})			Plant Al (mg kg^{-1})			Plant Mn (mg kg^{-1})		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	159.32	160.52	159.92	284.23	302.33	293.28	82.63	80.51	81.57
T_2	219.25	225.84	222.55	302.05	319.67	310.86	130.53	141.33	135.93
T_3	190.05	192.52	191.28	286.87	319.67	303.27	93.23	78.57	85.90
T_4	165.45	165.72	165.58	295.37	298.00	296.68	79.27	73.70	76.48
T_5	219.65	193.05	206.35	296.37	363.33	329.85	136.97	146.93	141.95
T_6	192.38	219.27	205.83	282.40	300.33	291.37	91.43	75.83	83.63
T_7	363.85	420.18	392.02	366.30	382.33	374.32	163.73	172.97	168.35
Mean	215.71	225.29		301.94	326.52		111.11	109.97	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	3.47	NS		1.32	3.85		1.07	NS	
T	6.49	18.89		2.47	7.21		2.00	5.83	
V x T	9.18	26.72		3.50	10.20		2.83	8.25	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control

Table 31: Effect of different amendments and their combinations on Cu, Zn, B and Si in plant

Treatments	**Plant Cu (mg kg^{-1})**			**Plant Zn (mg kg^{-1})**			**Plant B (mg kg^{-1})**			**Plant Si (%)**		
	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean	V_1	V_2	Mean
T_1	24.30	28.50	26.40	24.55	21.41	22.98	46.99	48.13	47.56	1.88	1.85	1.87
T_2	36.17	36.09	36.13	26.62	25.48	26.05	46.40	48.19	47.30	1.85	1.85	1.85
T_3	35.53	35.67	35.60	19.58	19.52	19.55	46.80	48.36	47.58	1.81	1.86	1.83
T_4	24.20	30.40	27.34	24.83	25.34	25.09	49.65	50.43	50.04	3.37	3.36	3.36
T_5	32.13	37.50	34.81	23.31	42.82	33.06	50.46	52.73	51.60	3.18	3.04	3.11
T_6	28.48	31.56	30.02	24.07	22.50	23.28	51.81	52.38	52.10	3.32	3.02	3.17
T_7	26.40	22.40	24.40	18.58	17.56	18.07	43.27	44.98	44.12	1.80	1.83	1.82
Mean	29.60	31.75		23.08	24.95		47.91	49.31		2.46	2.40	
Comparison	SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)		SEm(±)	CD (5%)	
V	0.63	1.82		0.65	NS		0.23	0.65		0.03	NS	
T	1.17	3.41		1.22	3.54		0.42	1.22		0.06	0.19	
V x T	1.66	NS		1.72	5.00		0.59	NS		0.09	NS	

Note: T_1: lime; T_2: magnesium carbonate + ½ lime T_3: phosphogypsum @ 500 kg ha^{-1} + ½ lime; T_4: lime + potassium silicate 0.25% + 0.25% boron; T_5: magnesium carbonate + ½ lime + potassium silicate 0.25% + 0.25% boron; T_6: phosphogypsum @ 500 kg ha^{-1} + ½ lime + potassium silicate 0.25% + 0.25% boron; T_7: control

4.3.3.11 Zinc

The influence of different amendments application on zinc content is given in Table 31. There is no significant effect by the varieties on the concentration of zinc in the plants. The variety V_2 (24.95 mg kg^{-1}) showed more concentration of zinc in the plant than the variety V_1 (23.08 mg kg^{-1}).

The zinc content in plant showed appreciable differences among the treatments. The treatment T_5 (33.06 mg kg^{-1}) recorded significantly higher concentration of Zn in the plant which was followed by T_2 (26.05 mg kg^{-1}) on par with T_4 (25.09 mg kg^{-1}), T_6 (23.28 mg kg^{-1}) and T_1 (22.98 mg kg^{-1}). The lowest value for Zn is shown by control, T_7 (18.07 mg kg^{-1}).

There was substantial difference in the interaction of different amendments and variety. The treatment T_2 showed significantly higher amount of zinc (26.62 mg kg^{-1}) in the variety V_1 which was on par to all the other treatment except T_7 and T_3. In the variety V_2 the treatment T_5 exhibited highest concentration (42.82 mg kg^{-1}) of zinc in the plant. T_7 showed the least value in both varieties.

4.3.2.12 Boron

The result of boron content in rice plant at harvest stage of pot culture experiment is given in Table 31. The varieties had a significant effect on boron content. The variety V_2 (49.31 mg kg^{-1}) recorded more quantity of boron than the variety V_1 (47.91 mg kg^{-1}).

The treatments showed a superior and significant effect on the concentration of boron in plant. The treatment T_6 contain significantly higher amount of boron (52.1 mg kg^{-1}) which is on par with T_5 (51.60 mg kg^{-1}). Control (T_7) showed the lowest concentration of boron (44.12 mg kg^{-1}).

There was no significant interaction between treatment and variety. The treatment T_6 (51.81 mg kg^{-1}) in V_1 showed higher content of boron and T_7 (43.27 mg

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kg^{-1}) showed the lowest boron content. In the variety V_2 the treatment T_5 (52.73 mg kg^{-1}) showed the highest uptake and T_7 (44.98 mg kg^{-1}) showed the lowest.

4.3.2.13 Silicon

The data on the content of silicon by the plant at harvest stage of the pot culture experiment are given in the Table 31. The varieties did not reflect any significant change in the content of silicon. The variety V_1 (2.46%) showed higher content of silicon over the variety V_2 (2.40%).

There is a notable difference by the treatments on the concentration of silicon in plant. Treatment T_4 (3.36 %) contains significantly higher amount of silicon which is on par with T_6 (3.17 %). The control T_7 (1.82%) showed the lowest silicon content in plant which was on par with T_3 (1.83%), T_2 (1.85%) and T_1 (1.87%).

The treatment and variety did not have significant interaction. The treatment T_4 (3.37%) in V_1 showed higher content of boron and T_7 with lower content (1.81%). Similarly, T_4 in V_2 also showed highest boron content (3.36%) and T_7, the lowest (1.83%).

4.4 Correlation analysis

4.4.1 Incubation experiment

Correlation analysis of soil pH, available Ca, Fe and Al was carried out and the results are presented in Table 32. There was positive correlation between pH and Ca whereas it showed negative correlation with Fe and Al. The Ca was also found to be negatively correlated with Fe and Al. There was positive correlation between Fe and Al.

Table 32: Correlation of pH, Ca, Fe, Al status in soil of incubation

Parameters	pH	Ca	Fe	Al
pH	1			
Ca	0.97**	1		
Fe	-0.88**	-0.91**	1	
Al	-0.92**	-0.94**	0.89**	1

4.4.2 Solution culture experiment

The correlation between iron content in rice roots and percentage increase in root length was analyzed and the results are given in Table 33. The results revealed highly negative correlation between iron content in root and root length.

Table 33: Correlation of Fe content in root and percentage increase in root length in solution culture

Parameters	Root length	Fe content
Root length	1	
Fe content	-0.90^{**}	1

4.4.3 Pot culture experiment

Correlation analysis was done for various parameters and the results are given in Table 34. The results of correlation analysis showed that there were significant correlation between yield, pH, available P, Ca, Fe, Al, plant Ca and Fe. The rice yield from the pot culture experiment was found to be positively correlated with pH, available P, Ca and plant Ca content whereas negatively correlated with 0.1 N HCl extractable Fe and Al. The pH was positively correlated with available P and Ca while Fe and Al content in soil Fe content in plant was found to be negatively correlated. The available Ca in soil was negatively correlated with Fe and Al in the soil and plant Fe concentration whereas positively correlated with Ca content in plant. The available Fe in soil was found to be positively correlated to extractable Al in soil and plant Fe concentration and was negatively correlated to plant Ca content. The Al content was found to be positively correlated with plant Fe concentration and was negatively correlated with plant Ca content. The plant Ca content showed negative correlation to plant Fe content.

Table 34: Correlation of yield, pH, available P, Ca, Fe, Al, plant Ca, Fe and Al in pot culture experiment

Parameters	Yield	pH	P	Ca	Fe	Al	Plant Ca	Plant Fe	Plant Al
Yield	1.00								
pH	0.86^{**}	1.00							
P	0.89^{**}	0.83^{**}	1.00						
Ca	0.81^{**}	0.96^{**}	0.89^{**}	1.00					
Fe	-0.90^{**}	-0.71^{**}	-0.90^{**}	-0.68^{**}	1.00				
Al	-0.87^{**}	-0.75^{**}	-0.89^{**}	-0.81^{**}	0.75^{**}	1.00			
Plant Ca	0.89^{**}	0.79^{**}	0.97^{**}	0.82^{**}	-0.92^{**}	-0.89^{**}	1.00		
Plant Fe	-0.84^{**}	-0.96^{**}	-0.77^{**}	-0.92^{**}	0.62^{*}	0.76^{**}	-0.72^{**}	1.00	
Plant Al	-0.28	-0.42	-0.38	-0.39	0.36	0.14	-0.33	0.37	1

** Significant at 1% level of significance

* Significant at 5% level of significance

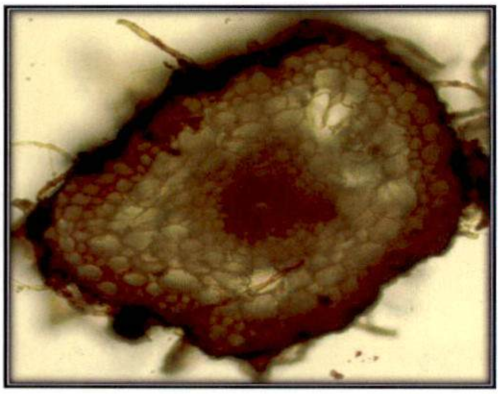

Plate 8a: 1200 mg L^{-1} Fe and 100 mg L^{-1} Al

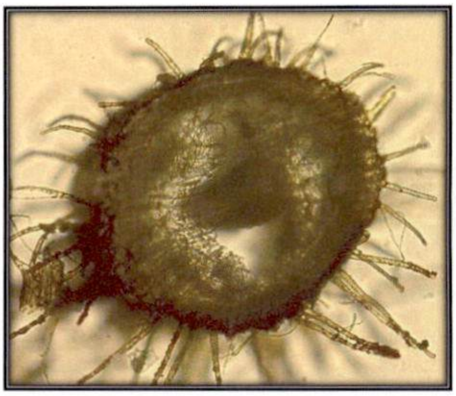

Plate 8b: 800 mg L^{-1} Fe and 100 mg L^{-1} Al

Plate 8c: Control

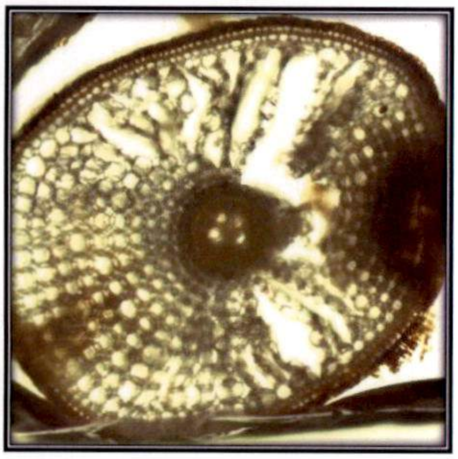

Plate 8d: 400 mg L^{-1} Fe and 100 mg L^{-1} Al
Al

Plate 8e: 200 mg L^{-1} Fe and 100 mg L^{-1}

Plate 8: Cross Sections of rice roots showing iron plaque (100x) - Uma

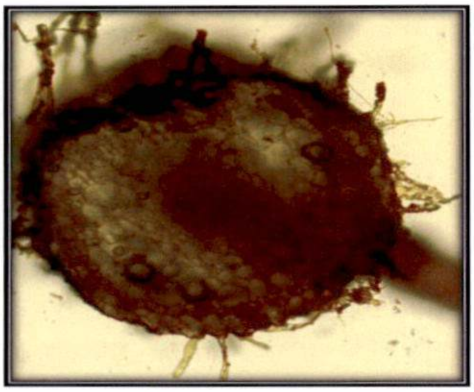

Plate 9a: 1200 mg L^{-1} Fe and 100 mg L^{-1} Al

Plate 9b: 800 mg L^{-1} Fe and 100 mg L^{-1} Al

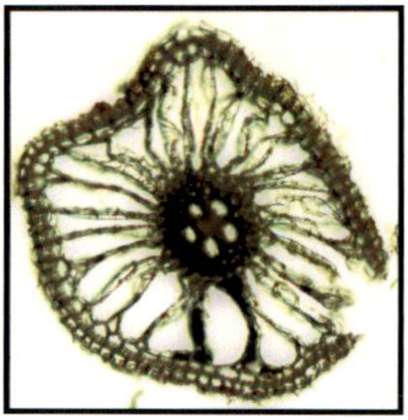

Plate 9c: Control

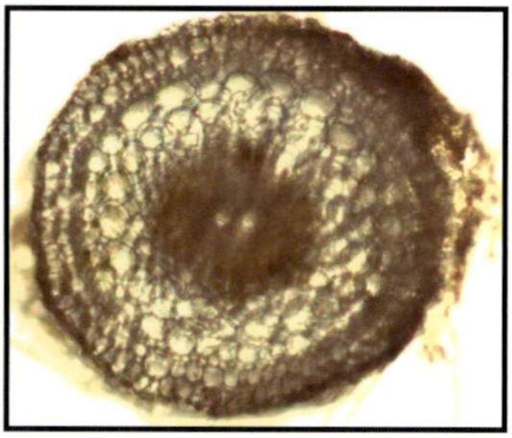

Plate 9d: 400 mg L^{-1} Fe and 100 mg L^{-1} Al

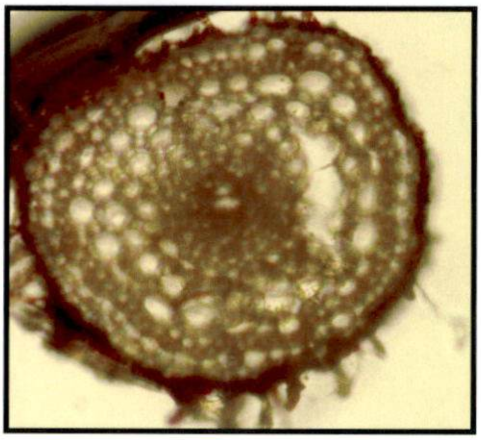

Plate 9e: 200 mg L^{-1} Fe and 100 mg L^{-1} Al

Plate 9: Cross Sections of rice roots showing iron plaque (100x) - Prathyasa

Plate 10a: Best treatments of Uma variety in pot culture experiment

Plate 10b: Best treatments of Prathyasa variety in pot culture experiment

Plate 10: Best treatments of the varieties in pot culture experiment

$T_2 V_1$ $T_5 V_1$ Control Prathyasa Control Uma $T_2 V_2$ $T_5 V_2$

Plate 11: Iron plaque formation on rice roots in pot culture experiment

Discussion

5. DISCUSSION

The Discussion of the results on investigation carried out at College of Agriculture, Padannakkad to assess the iron and aluminium toxicity problem in rice grown on acid sulphate soils of 'Kari' lands in Kuttanad, to evaluate the performance of two popular rice varieties to variable levels of iron and aluminium concentrations and to examine suitable amelioration strategies are presented in this chapter. The entire investigation was carried out in three parts. This include collection of soil sample from the 'Kari' lands of Kuttanad and analysis of their various physical and chemical properties, solution culture experiment to study the response of two popular varieties of rice to different levels of iron and aluminium and pot culture experiment. As a preparatory study an incubation experiment was carried out to know the release pattern of iron and aluminium under varying levels of pattern.

5.1. Incubation experiment

In the incubation experiment the soils collected from 'Kari' of Kuttanad lands and brought to College of Agriculture, Padannakkad were treated with different ameliorants, maintained at two level of submergence (5cm and 10cm) and analyzed at 30, 60 and 90 days. The results of the incubation study showed that the treatments had significant effect on soil pH, available calcium, magnesium, iron and aluminium throughout the submergence period.

Soil pH was found to be increasing during the course of incubation study. The level of submergence at 5 cm and 10 cm and the interaction between treatments and levels of submergence were non-significant whereas application of different amendments showed significance. At 30 days after incubation application of lime T_1 (@ 500 kg ha^{-1}) showed maximum increase in pH. This may be due to the ability of lime to neutralize the pH. After 60 and 90 days phosphogypsum @ 500 kg ha^{-1} + ½ lime (as per KAU POP) showed increase in pH which might be attributed to the higher amount of Ca present in the treatment receiving combination of

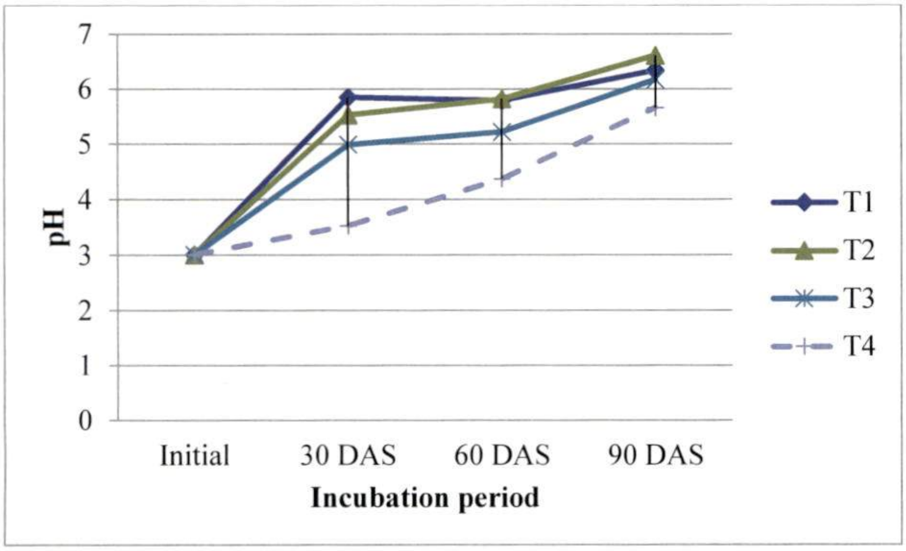

Fig 2: pH as influenced by treatments in the incubation experiment

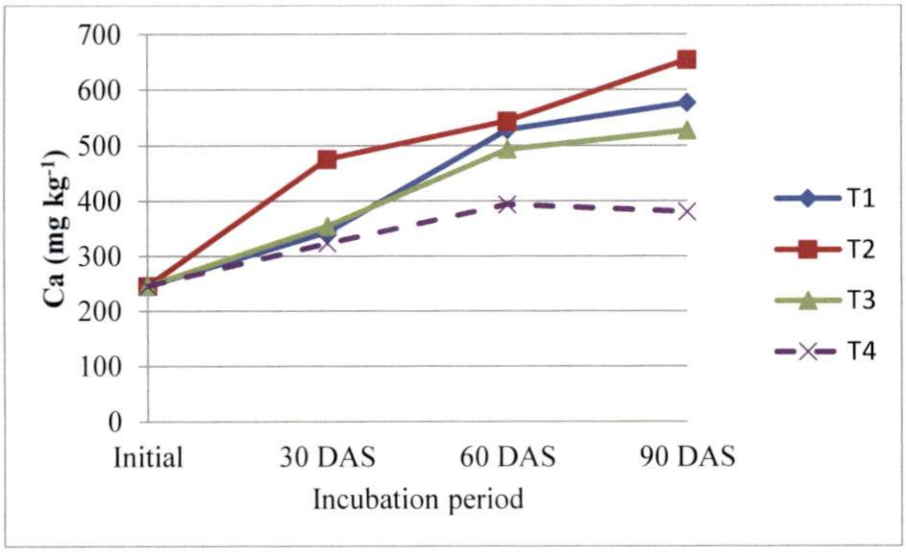

Fig 3: Ca as influenced by treatments in the incubation experiment

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phosphogypsum and lime. Both phosphogypsum and lime are highly effective amendments in reducing the soil acidity on submerged condition. Similar results of lime and phosphogypsum in increasing the soil pH were reported by Lee *et al.*, 2006; Suswanto *et al.*, 2007; Shamshuddin *et al.*, 2015.

The available Ca was found to increase during the period of incubation. The treatments showed significant effect throughout the incubation period. The levels of submergence and interaction between levels of submergence and treatments were non-significant with respect to availability of Ca. Application of phosphogypsum + ½ lime (T_2) showed significantly superior available Ca after 30, 60 and 90 days of incubation. It may be because of the higher availability of Ca applied through phosphogypsum and enhanced pH due to lime. Moreover calcium present in phosphogypsum is readily soluble form and thereby enhancing its availability in soil (Deepa, 2008; Lee *et al*, 2007; Azman *et al.*, 2013).

The treatments were highly significant with respect to availability of Mg whereas the levels of submergence and interaction between levels of submergence and treatments were found to be non-significant. The application of magnesium carbonate + ½ lime (T_3) was recorded as the superior treatment with regard to available Mg. This may be because of the availability of Mg through the treatment. Suswanto *et al.*, (2007), Shamshuddin *et al.*, (2015) and Castro *et al.*, (2016) also reported that application of ground magnesium limestone containing Mg increased the availability of magnesium.

Iron and aluminium concentration in the soil showed a decreasing trend throughout the incubation period. The treatments showed significant effect in reducing the toxic levels of iron and aluminium content in the soil from 536 mg kg^{-1} to 161 mg kg^{-1}. The levels of submergence (5 and 10 cm) and interaction between the levels of submergence and treatments showed non-significance for iron and aluminium content. Since the pH of the soil increased significantly with the application of amendments and submergence the concentration of iron and aluminium

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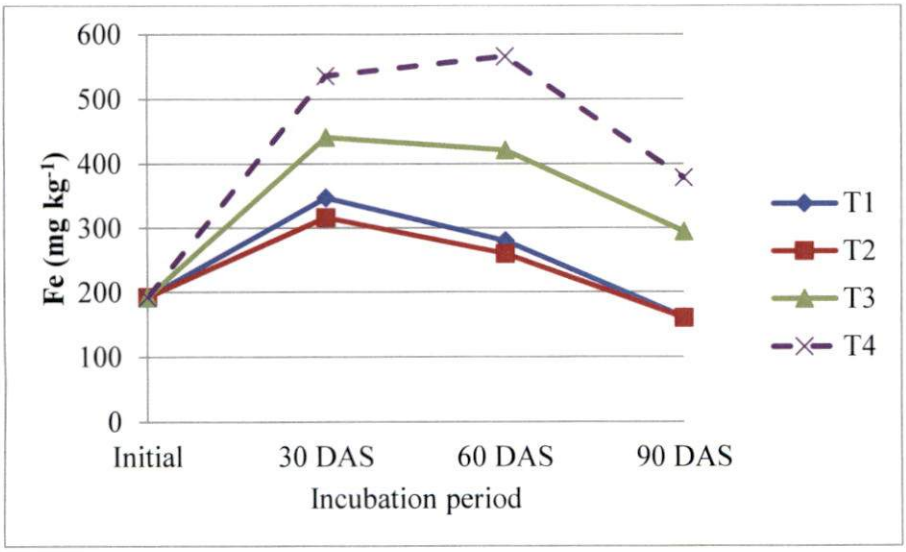

Fig 4: Fe as influenced by treatments in the incubation experiment

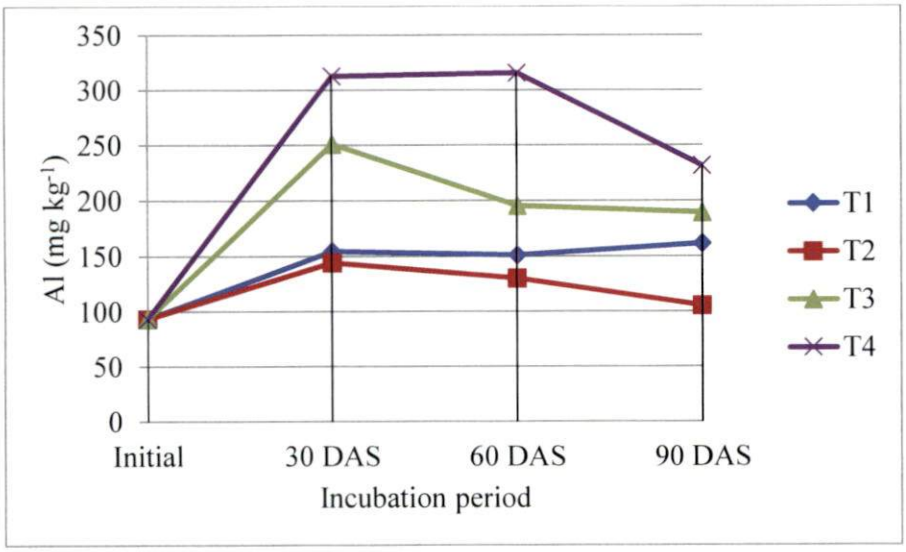

Fig 5: Al as influenced by treatments in the incubation experiment

showed remarkable reduction. This is in conformity with the antagonistic interaction of these ions. Tran and Vo (2004) reported that Fe may be reduced in flooded condition from Fe^{3+} to Fe^{2+} but flooding will cause increase in the soil pH which results in concomitant reduction of soluble Fe. The present study also showed that flooding causes increase in pH from the initial value which may result in reduction of Fe content here the soil reduction results in conversion of Fe^{3+} to soluble Fe^{2+} forms but the enhanced pH reduce the flux. Ponnamperuma and Nhung (1965) also reported that activities of water soluble Al^{3+} and Fe^{2+} decreases for each unit increase in pH. Application of lime alone and combination of lime and phosphogypsum showed superior effect in reducing their toxic concentration in soil. Increase in Ca and Mg added through amendments also favours the reduction of toxic Fe and Al. Azman *et al.*, (2014) also reported that after the application of lime Fe and Al concentration will decline whereas Ca and Mg will increase. Phosphogypsum is a very good source of Ca amendment (Mrabet *et al.*, 2003) it also alleviate the aluminium toxicity and increases plant growth (Alva and Sumner, 1989).

5.2. Solution culture experiment

The solution culture experiment was conducted using Hoagland's nutrient solution supplemented with different concentrations of Fe and Al. Fourteen days old rice plant (Uma and Prathyasa variety) were maintained in the treatment solutions for a period of 7 days and different observations were recorded and analyzed for various parameters. Nutrient solution was changed in two days interval.

5.2.1. Effect of toxic Fe and Al on plant growth characters

The growth of rice plant was observed after maintaining them in the treatment solution for 7 days. The relative increase in percentage of the growth parameters (plant height and root length) were recorded and analysed statistically.

The effect of treatments on percentage increase in plant height was found to be significant. Minimum increase in plant height was displayed by rice plant maintained in Hoagland's solution containing 1200 mg L^{-1} Fe and 50mg L^{-1} Al followed by the treatment solution containing 1200 mg L^{-1} Fe and 100 mg L^{-1} Al.

This may be due to the action of the toxic iron and aluminium in the rice roots which would hinder the uptake of nutrients thus resulting in poor plant growth. Snowden and Wheeler, (1995); Sharma and Dubey, (2007); Kang *et al.*, (2011) and Wang *et al.*, 2013 reported similar results. The effect of varieties and interaction of varieties and treatments were found to be non-significant.

The effect of different concentration of Fe and Al on percentage increase in root length was found to be significant. Minimum increase in root length among the treatments was showed by 1200 mg L^{-1} Fe and 100 mg L^{-1} Al which might be due to the increased Fe and Al content in the root zone. Sharma and Dubey, (2007) reported that as Al concentration increases, plant growth mainly root growth reduced accordingly. High Al concentration in the root zone would reduce the root growth. Kang *et al.*, (2011) and Wang *et al.*, 2012 also reported similar results.

The root dry weight of plants showed significant effect with respect to treatments. Hoagland's solution containing 1200 mg L^{-1} Fe and 100 mg L^{-1} Al showed maximum reduction in root dry weight. This may be due to the effect of high concentration of Fe and Al in the solution which inhibits the root growth. Sharma and Dubey, (2007); Kang *et al.*, (2011) and Wang *et al.*, 2012 reported that high concentration of Al reduces the root growth. The varieties and interaction of treatment and variety also showed significance with respect to root dry weight of the plant. Prathyasa variety showed higher root dry weight than Uma variety which may be due to the varietal character of Prathyasa which puts in more vegetative growth as compared to the Uma variety. The study also showed that the roots of treated rice plant were able to withstand the Fe and Al toxicity even after the other plant parts dried off.

The root CEC of plants showed significant effect with respect to treatments. The highest root CEC was recorded in the Hoagland's solution containing 1200 mg L^{-1} Fe and 100 mg L^{-1} Al. This may be due to the presence of higher concentration of Fe^{2+} and Al^{3+} ions around the root surface. Alia *et al.*, (2015) also showed similar results in a solution culture experiment where in the root CEC increased with increase in Fe and Al concentration.

5.2.2. Effect of toxic concentration of Fe and Al on its content in rice roots

The concentration of iron in roots of rice plant was found to be significant with respect to treatments. Hoagland's solution containing 1200 mg L^{-1} Fe and 50 mgl^{-1} Al showed maximum concentration of iron in the root surface. This may be due to the formation of iron plaque on the root surface. In microscopic examination thick iron coating was visible in the solution containing 1200 mg L^{-1} of Fe in both varieties (Plate 7). Liu *et al*., (2004); Chen *et al.,* (2006) reported that increase in Fe concentration will increase the iron content in root. The varieties and interaction of treatments and varieties showed significance. Prathyasa showed higher iron content in the plant root surface than Uma variety. This may be due to the root exclusion principle enabling the rice plant to with stand toxic levels of iron and aluminium, more prominent in Prathyasa variety. Prathyasa variety exhibits more iron toxicity symptoms on the plant but shows high recovery and thereby did not reflect any adverse effect on the yield.

The aluminium content in the roots of rice plant showed significant effect with respect to treatments. The solution containing 1200 mg L^{-1} Fe and 100 mg L^{-1} Al showed highest aluminium concentration. Sharma and Dubey, (2007); Kang *et al.,* (2011) and Wang *et al.,* (2012) reported similar results. The varieties also showed significance with Prathyasa variety containing more concentration of Al in the root surface than Uma variety.

The patterns of iron coating on the roots were also observed. Formation of iron plaque on the root surface was found to be visible in the solution containing 1200 mgl^{-1} of Fe in both varieties (Plate 7). The cross sections of roots were taken and observed under the compound research microscope (model- Axio lab A-1) and analysed using Zen image analyzer. The thickness of the roots was also measured using the Zen image analyser by taking the average thickness of iron coating around

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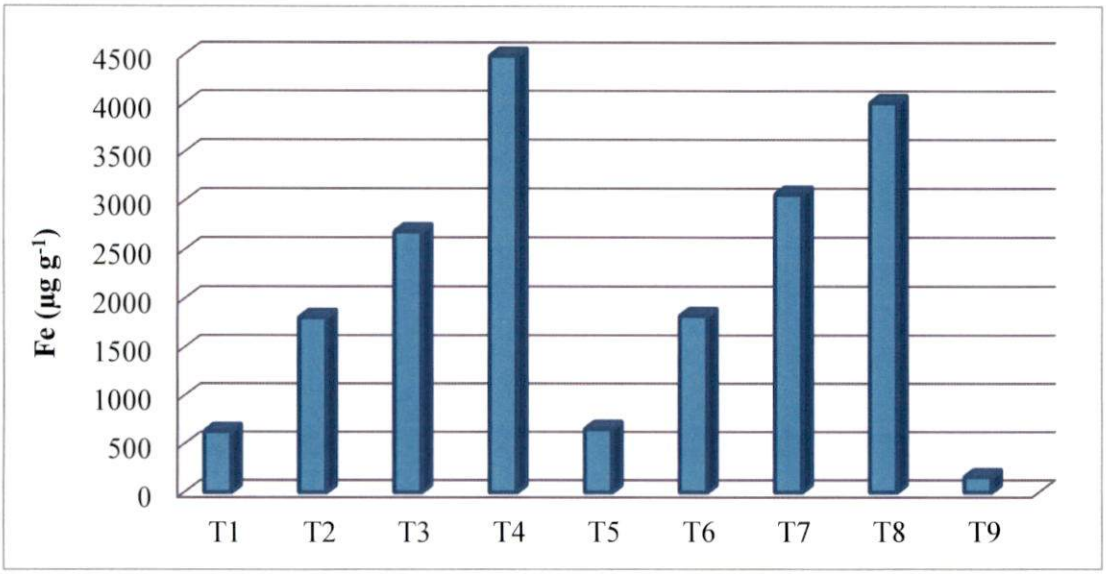

Fig 6: Fe content in the roots of plants in solution culture

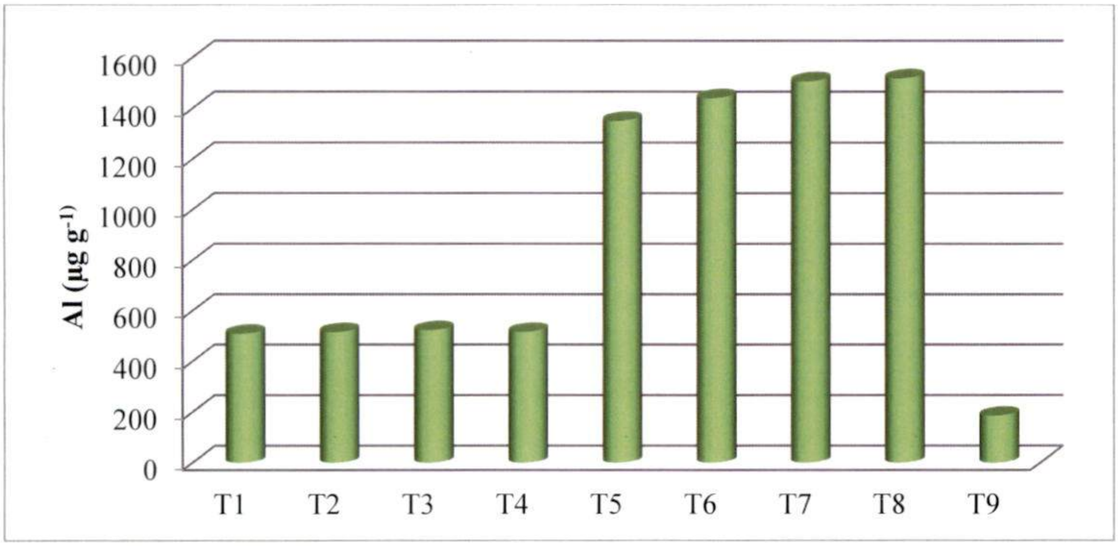

Fig 7: Al content in the roots of plants in solution culture

the cell. It was observed that there was no iron coating around the root cells of control. Maximum iron coating around the roots among the treatments was displayed by solution containing 1200 mg L^{-1} Fe and 100 mg L^{-1} Al. This may be due to the higher concentration of Fe in the solution which was precipitated and deposited as Fe plaque on the root surface. Hansel *et al.*, (2001) also reported that iron (Fe^{3+}) forms precipitates on root surfaces, which is predominantly of ferrihydrite and goethite.

5.3. Pot culture experiment

5.3.1. Effect of different amendments on biometric characters

The treatment application and varieties exhibit significant effect on height of the rice plant grown in pot culture. After 30 days of transplanting there was significant difference in the plant height of Uma and Prathyasa varieties. This may be due to the difference in morphology of the variety Prathyasa is a short duration variety and it showed higher plant height than Uma which is a medium duration variety. The treatments were non-significant at 30 DAT, however application of lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed higher plant growth. The treatments were significant at 60 DAT and at harvest. Application of lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed higher plant growth during the course of experiment and control exhibited lowest plant height. This may be due to the action of lime in alleviating the Fe, Al toxicity of soil and improving the plant growth. The interaction of treatment and variety was found to be non-significant. Similar results were also reported by Suswanto *et al.*, (2007); Elisa *et al.*, (2016) and Soltani *et al.*, (2016).

The different amendments showed significant effect on number of tillers of the rice plant grown in pot culture. The treatments were significant at 30 DAT, application of lime + foliar spray of 0.25% boron and 0.25% potassium silicate and phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed more number of tillers. At 60 DAT and at harvest application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed more number of tillers. Control showed minimum number of tillers throughout the experiment. This may be due to the action of lime and phosphogypsum in alleviating the Fe, Al toxicity of soil and improving the plant growth and also availability of more Ca and Mg from the treatment application. Similar results were also reported by Chang and Thomas (1963); Isabelo and Jack., (1993); Crusciol *et al*., (2016); Suswanto *et al.*, (2007); Elisa *et al.*, (2016); Soltani *et al.*, (2016).

The grain yield of the plant was found to be significant. Application of lime + foliar spray of 0.25 % boron and 0.25% potassium silicate recorded highest grain yield per plant and control showed lowest yield. This may be due to the ameliorating effect of lime on reduced Fe, Al toxicity, increased Ca content and also enhancing the soil conditions for better plant growth. Similar results were also reported by Ponnamperuma and Nhung (1965); Chang and Thomas (1963); Martin *et al*., (1988); Isabelo *et al*., (1993); Suswanto *et al.*, (2007); Elisa *et al.*, (2016); Soltani *et al.*, (2016); Crusciol *et al*., (2016) The varieties and interaction of treatment and variety was found to be non-significant.

Number of grains per panicle was found to be significant with respect to treatments and non-significant with respect to the varieties and interaction of treatments and varieties. Maximum number of grains per panicle was given by phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate and minimum value was showed by control. This may be due the action of phosphogypsum and lime in alleviating Fe and Al toxicity and enhancing the uptake of available nutrients their by improving the quality of grains. Lee *et al*., (2007) also reported that application of phosphogypsum enhances the grain quality and yield of rice.

The straw yield per plant was found to be non-significant on treatment and varieties. The treatment application of lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded highest straw yield. This may be due to the enhanced plant growth by the action of lime and Si and B nutrition to rice. The interaction of treatments and varieties was found to be significant.

Highest chaffiness percentage was showed by control and the lowest by phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate. This may be due to the absence of amendments to alleviate the toxicity problem in control. Phosphogypsum and lime was found to be very much effective for alleviating Fe and Al toxicity and they also assist in excellent plant growth which may reduce the chaffiness of grains.

The root CEC was significant with respect to the application of amendments. The treatment T_6 (Phosphogypsum @ 500 kg ha^{-1} + ½ lime+ foliar spray of 0.25% boron and 0.25% potassium silicate) showed maximum root CEC. The application of higher amount of Ca significantly increased the root CEC of plants (Bolan *et al.*, 1992). Repeated application of phosphogypsum reduced the exchangeable aluminium (Alva *et al.*, 1990) and increased cation exchange capacity of acid soil (Alva *et al.*, 1991). Ram (1980) reported that the uptake of nutrients such as P, K, Fe and Mn was positively linked with the root CEC in most of the paddy and wheat varieties.

The test weight of grains was found to be significant. Among the treatments, the treatment T_6 (Phosphogypsum @ 500 kg ha^{-1} + ½ lime+ foliar spray of 0.25 % boron and 0.25% potassium silicate) exhibited a significantly higher weight for one thousand grains. The higher thousand grain weight recorded with the application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate might be due to its beneficial effect on yield attributes. The beneficial effect of phosphogypsum may also be due to the presence of Ca, P, S, F, K, Mg etc. Phosphogypsum is positively correlated to higher yield in rice as reported by Liu *et al.* (2004).

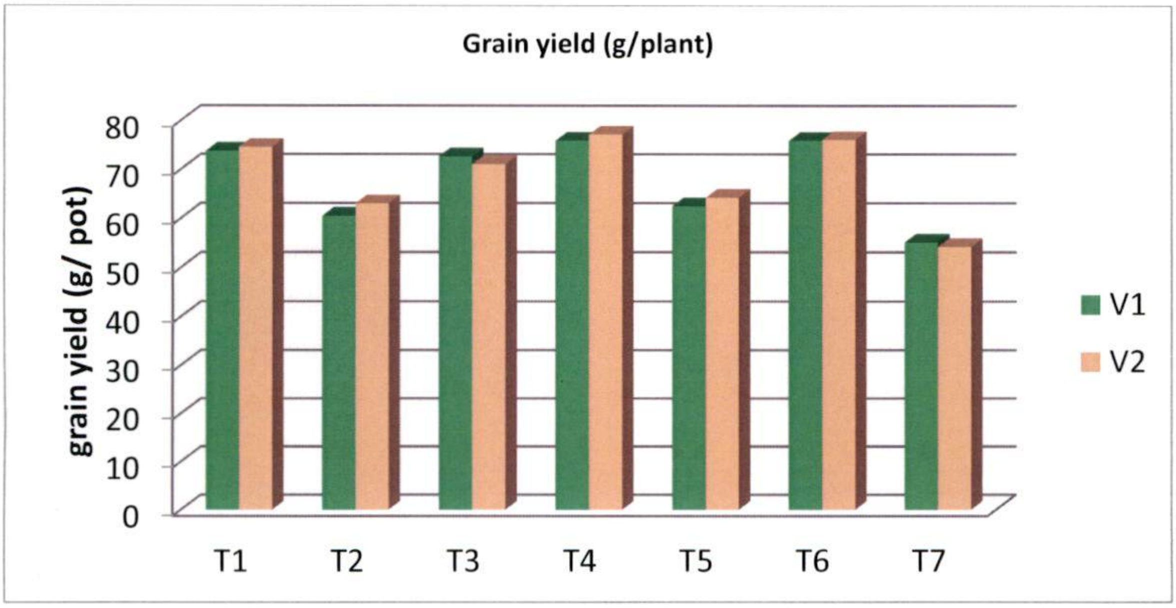

Fig. 8: Grain yield as influenced by treatments and varieties in the pot culture

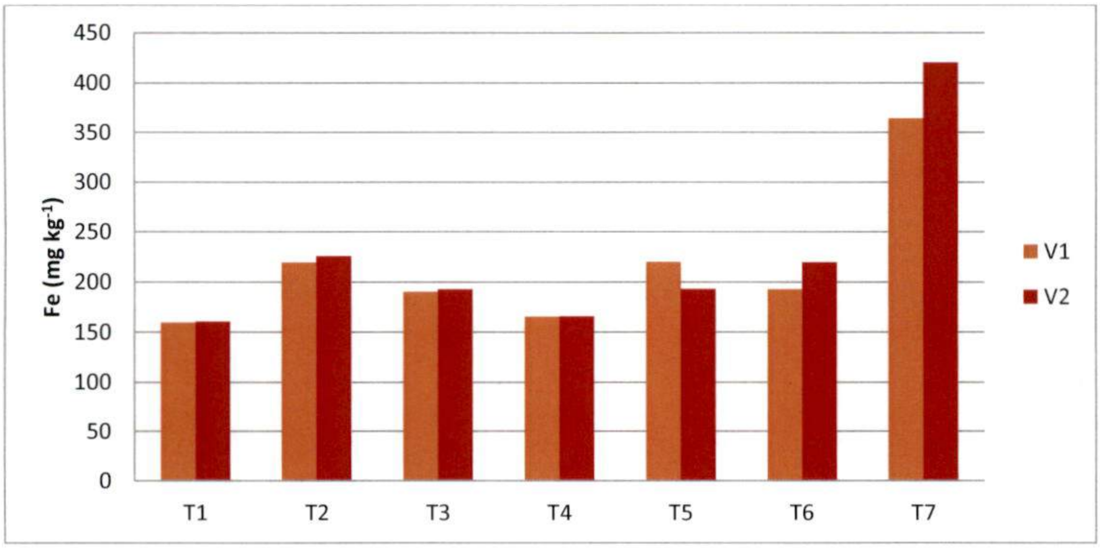

Fig. 9: Plant iron content as influenced by treatments and varieties in the pot culture

5.3.2. Effect of different amendments on nutrient content in plant

The nitrogen content in plant showed non-significance with respect to treatment, variety, interaction between treatment and variety. All the treatments showed superiority over control. Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate reported higher nitrogen content in the plant than other treatments. This may be due to the action of Ca in phosphogypsum. Fenn *et al*., (1995) reported that Ca increased the absorption of NH^{4+}, consequently leading to the increased tillering, and thus produce higher grain yields. Ca increases the use of N efficiency in the plant tissue by greater metabolite deposition in seeds and it may increases photosynthesis also. Rasouli *et al.,* (2013) also reported similar results.

The treatments, varieties and interaction between variety and treatment were found to be significant in case of P content in plants. The highest p content in plant was recorded by phosphogypsum + ½ lime + foliar spray of 0.25 % boron and 0.25 % potassium silicate and control showed the lowest value of plant phosphorus content. This may be due to the availability of phosphorus from the applied phosphophogysum. Ayadi *et al*., (2015) reported that application of phosphogypsum increased the inorganic phosphorus content and P uptake by plants. The variety Uma showed significantly higher P in plant compared to Prathyasa variety.

The treatments, varieties and interaction between variety and treatment showed significant effect in K content in plants. The highest K concentration in plant was recorded by phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate and control showed the lowest value of plant K content. This may be due to the uptake of potassium by plants from the foliar application of potassium silicate, effect of phosphogypsum and lime in improving the soil conditions. This results might be also due to the production of hydrogen ions during reduction of Fe and Al toxicity that caused the release of K from the exchange sites or from the fixed pool to the soil solution. Similar results were reported by Patrick and Mikkelsen

(1971). The variety Uma showed significantly higher K in plant compared to Prathyasa variety

Application of amendments showed significant effect in uptake of Ca by the rice plants. The treatment application of phosphogypsum + ½ lime recorded highest Ca content in plants. The treatment with no amendment application, control showed lowest concentration of Ca in plants. This may be due to the high concentration of Ca available from lime and phosphogypsum. Mc-Cray *et al.,* (1991); Mrabet *et al.*, (2003); Astolfi and Zuchi, (2013) also reported similar results.

Application of amendments showed significant effect in content of Mg by the rice plants. The treatment application of magnesium carbonate + ½ lime recorded highest Mg content in plants. The treatment with no amendment application, control showed lowest concentration of Mg in plants. This may be due to the high concentration of Mg available from magnesium carbonate. Mann, (1930) also reported similar results. Varieties and interaction between variety and treatment were non-significant in case of Mg uptake.

Application of amendments showed significant effect in uptake of S by the rice plants. Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate reported highest S content in plants. The control showed lowest concentration of S in plants. This may be due to the high concentration of S available from phosphogypsum (Alcordo and Rechcigl, 1993). Varieties and interaction between variety and treatment were non-significant in case of S uptake.

The effect of treatments on concentration of iron in plants was found to be significant. The varieties did not show any significance with uptake of iron. There was significant effect by the variety and treatment interaction. The treatment application of lime showed lowest concentration of iron in plants. This may be due to the action of Ca in lime and the increase in pH. Similar results were reported by

Mann, (1930); Ponnamperuma and Nhung (1965); Tran and Vo (2004); Saha, *et al.*, (2008) and Azman *et al.*, (2014). Control showed the highest uptake of Fe by plants.

The treatments, variety and interaction of treatment and variety showed significance on the concentration of aluminium in plants. Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed lowest uptake of Al by plants. Control showed the highest uptake of Al compared to the treatment application. This may be due to the effect of phosphogypsum in alleviating Al toxicity since it decreases acidity in soil and contain soluble Ca which reduces the uptake of Al by plants. Similar results were recorded by (Alva and Sumner,1989); Martin *et al.*, (1988); Isabelo *et al.*, (1993); Mrabet *et al.*, (2003); Crusciol *et al.*, (2016). The variety Prathyasa contained more Al concentration in plant than Uma variety. This may be due to the morphological character of Prathyasa which showed more toxicity symptoms than Uma but will not reflect it on yield parameters.

The manganese content in plant was significant with respect to the amendments applied. Highest Mn content in plant was reported by control and the lowest Mn content in plant was recorded by application of lime + foliar spray of 0.25 % boron and 0.25 % potassium silicate. This might be due to the activity of lime in soil which decreases the Mn content in soil thereby reduces the Mn content Saha *et al.*, (2008). The varieties did not show any significant effect on Mn content. The interaction between treatment and varieties are found to be significant.

The treatments and varieties are significant in case of uptake of copper by plants. The application of magnesium carbonate + ½ lime showed highest Cu uptake whereas control showed lowest Cu content by plants. This may be due to the action of Ca and Mg supplied through the treatment. Even though application of lime has negative effect on Cu (Williams *et al.*, 2007) improvement of physical conditions of soil and enhancement of plant growth might be act as the reason for high Cu content compared to other treatments. There was no significant effect on the interaction of variety and treatment on Cu content by the plant.

The application of amendments showed significant effect on the content of Zn. Treatment with magnesium carbonate + ½ lime + foliar spray of 0.25 % boron and 0.25% potassium silicate showed highest content of Zn while control showed the lowest content. This may be due to the increase in Ca and Mg content in soil which provide very good physical and chemical condition in soil thus favored the content of elements by plants. Similar results were reported by Williams *et al.*, (2007). The varieties were non-significant with respect to Zn content whereas treatment and variety interaction found to be significant.

The application of treatments exhibited significant effect on the content of B. Treatment with phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed highest uptake of B whereas control showed the lowest content. Boron nutrition of rice can be achieved efficiently by the application of borax as foliar spray. The results obtained may be due to foliar content of B by plant (Gupta and Cutcliffe, 1978 and Rakshit *et al.*, 2002) and also the effect of phosphogypsum which made the B in soil more available. The varieties and interaction effect of variety and treatment also showed significance.

The silicon content in rice plant showed significant increase by the application of treatments lime + foliar spray of 0.25% boron and 0.25% potassium silicate. This treatment recorded highest Si content in plants while control recorded the lowest Si concentration in plants. This may be due to the action of phosphogypsum and lime that improves the soil conditions and fertility. Application of silicon as foliar spray naturally increases the Si concentration in plant (Sing *et al.*, 2006).

5.3.3. Effect of different amendments on soil characteristics

The effect of application of different amendments on soil nutrient status were studied and found that pH, EC, available N, P, Ca, Mg, S, B, Fe, Cu, Mn, Al and Si were found to be significant with treatment application while OC, available K and Zn status in soil were found to be non- significant.

The application of amendments had profound effect on pH of the soil. Application of lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed highest value of pH at the time of harvest. Control showed the lowest value of pH. Lime has the capacity to increase soil pH. Moreover the calcium present in lime also helps in reducing the soil acidity. Application of lime to the soil surface is the most efficient practice to reduce soil acidity and thereby increase soil pH (Crusciol *et al.*, 2016). Application of lime alone and lime + phosphogypsum also recorded high pH values following lime + foliar spray of 0.25% boron and 0.25% potassium silicate. The effect of lime + phosphogypsum to increase the soil pH is also reported by (Crusciol *et al.*, 2016). There was no significant effect with respect to two different varieties Uma and Prathyasa on soil pH. The interaction effect of treatment and variety also found to be non-significant. This may be because of the action of amendments in soil was uniform which was not affected by the varieties.

The electrical conductivity of soil showed significant changes with respect to the application of different amendments. The lowest EC was showed by lime application. This may be due to the decrease in soluble salts in the soil. The highest value of EC was showed by control. This might be due to the effect of amendments in reducing the soluble salt content in soil by making them insoluble by forming other compounds. Lipman *et al.* (1926) stated that the electrical conductivity of soil solution was controlled by pH, sum of concentration of cation and anions and the carbon content.

The organic carbon content in the soil was found to be non-significant with respect to treatments, varieties and there was no effect on interaction between treatment and variety also. Even though the effect was non-significant the highest value for organic carbon was recorded by phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate and all the other treatments also recorded higher organic carbon content than control. The inherent level of organic carbon status of 'Kari' lands is high.

Available nitrogen in soil was influenced by application of amendments. The highest available nitrogen content was given by magnesium carbonate + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate and the lowest available nitrogen content was showed by control. This may be due to the action of both Ca and Mg which improve the soil physical and chemical conditions and also enhances microbiological activity in soil and facilitates more nitrogen fixation also. Similar results were showed by Castro *et al.,* (2016). The varieties showed non-significant effect for available nitrogen content. Uma variety recorded lowest nitrogen content than Prathyasa which may be due to the higher nitrogen uptake of Uma variety.

The treatments showed significant effect on the available phosphorus content in soil. Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded highest P content in soil. Control recorded lowest available phosphorus in soil. This may be because of the action of phosphogypsum which is also a good source of phosphorus in the soil. Ayadi *et al.*, 2014 reported that application of phosphogypsum increases the inorganic phosphorus content in soil. Kordlaghari and Rowell (2005) also reported similar results. The varieties and phosphorus content in soil showed significant relation. Uma variety reported higher phosphorus content in the soil than Prathyasa. This may be due to the higher P uptake by the Prathyasa variety than Uma variety which left lower available phosphorus in the soil. The interaction between treatments and varieties were also found to be non-significant.

The available potassium content in soil was found to be non-significant with respect to treatment application, varieties and interaction of treatments and varieties. However, all the treatments showed superiority over control. The application of magnesium carbonate + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed higher potassium content in the soil which may be due to the effect of magnesium and calcium present in the amendments along with the boosting effect of foliar spray. Kunishi (1982); Marykutty (1986) also reported that liming improves the soil physical condition and Ca and Mg in soil also improves the concentration of potassium availability Rasouli *et al.,* (2012).

The available Ca content in soil was found to be significant with respect to treatment application. Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate in soil significantly increases the available Ca content higher than other treatments. This indicates the capacity of phosphogypsum and lime to increase the Ca content in soil. Sancho *et al.*, (2009); Crusciol *et al.,* (2016) reported that phosphogypsum and lime increases the Ca concentration of soil and also improves the soil fertility. The varieties and interaction of varieties and treatments were found to be non-significant with respect to available Ca content in soil.

The treatments show significant effect for available Mg content in soil. Application of magnesium carbonate + ½ lime + foliar spray of 0.25 % boron and 0.25 % potassium silicate showed highest amount of magnesium in soil. This may be due to the availability of magnesium through the magnesium carbonate which is a good source of magnesium. Delmez *et al.*, (1996) reported that the application of magnesium carbonate will increases the available magnesium content in the soil. There was no significant effect shown by varieties and interaction of varieties and treatments on available Mg content in soil.

The available sulphur content in soil significantly increased with the application of different amendments but it did not showed any significance on the effect of varieties and interaction of varieties and treatments. Application of lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed the lowest value of available sulphur. The highest value of available sulphur was showed by control. Since the study was conducted using acid sulphate soil, treatment (T_7) control reported highest sulphur with the absence of ameliorative measures. Haynes and

Naidu, (1991) and Astrom *et al.*, 2007 reported that liming decreases the sulphur content of the acid sulphate soils.

There was a significant reduction in iron content in soil caused by the application of different amendments. Minimum iron content was recorded by phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate application. Maximum Fe concentration was recorded by control. Application of amendments as phosphogypsum + ½ lime, lime alone, lime and foliar spray also recorded lower iron content in soil. Application of phosphogypsum reduces Fe content in soil Quintero *et al.*, 2014. Chang and Thomas (1963) also showed that the amount of Fe and Al released into the soil solution decreased with application of gypsum. Ponnamperuma and Nhung (1965) reported that lime ($CaCO_3$) decreases the iron content of the soil. Benckiser *et al.*, (1984) suggested that calcium and magnesium plays a crucial role in alleviating iron toxicity in rice. The ameliorating effect of mined gypsum or phosphogypsum is due to the supply of calcium and also due to the enhanced mobility of gypsum (Hoveland, 2000). There were no significant effect shown by the varieties and interaction of varieties and treatments observed for the iron content in soil.

Aluminium content in soil was significantly reduced by application of amendments. The lowest Al content was noted with the application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate application. Highest Al concentration in soil was recorded in control treatment. Calcium in phosphogypsum is more soluble and it plays a prominent role in alleviating Al toxicity (Alva and Sumner, 1989). Similar results were recorded by Ponnamperuma and Nhung (1965); Chang and Thomas (1963); Isabelo *et al.*, (1993); Crusciol *et al.*, (2016). There were no significant impact by the varieties and interaction of varieties and treatments on the Al content in soil.

The available manganese status in soil varied significantly with the application of treatments. The highest manganese content in soil was recorded in

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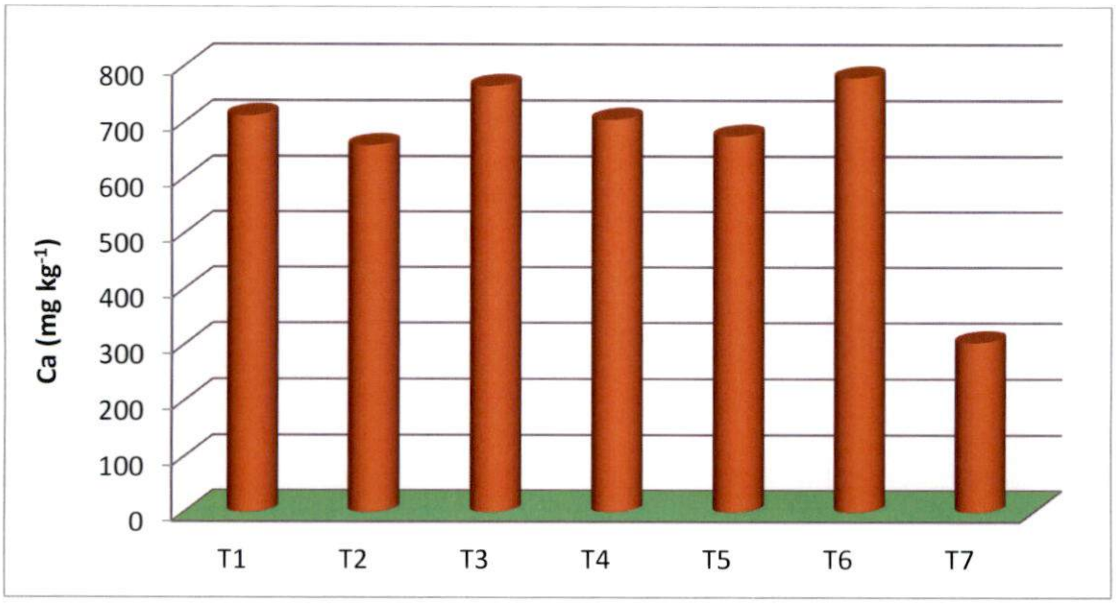

Fig. 10: Available Ca as influenced by treatments in pot culture experiment

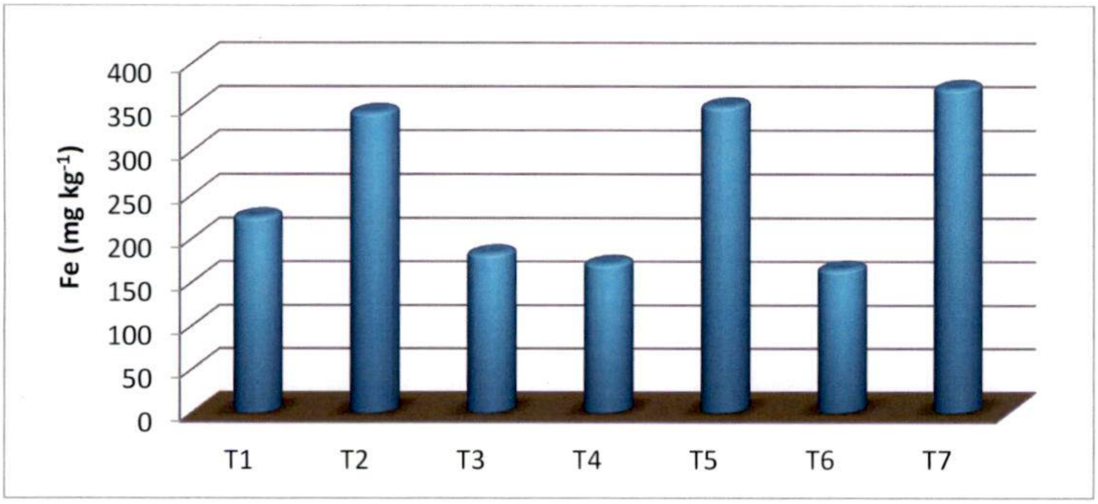

Fig. 11: Available Fe as influenced by treatments in pot culture experiment

control. The application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded lowest concentration of Mn in soil. Similar results were reported by Alcordo and Rechcigl, (1993); Saha *et al.*, (2008); Rasouli *et al.*, (2013); Quintero *et al.*, (2014).

The available boron content in soil showed significant effect with the application of treatments. Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded highest boron content. The lowest boron content was recorded by control. There was no significant effect by the varieties and interaction of varieties and treatments. Quintero *et al.*, (2014) reported that application of phosphogypsum increased the concentration of boron.

The treatments showed significant effect on copper content in soil. The highest amount of copper was recorded in the treatment magnesium carbonate + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate. The lowest concentration of Cu in soil was recorded in control treatment. The varieties and interaction of varieties and treatments was found to be non-significant.

The treatments, the varieties and interaction of varieties and treatments were non-significant with respect to available zinc content in soil. Even though it was non-significant, all the treatments showed superiority over control. Highest zinc content in soil was recorded in the treatment lime + foliar spray of 0.25 % boron and 0.25 % potassium silicate.

Application of amendments showed significant effect for the silicon content in soil. The highest value of silicon in soil was recorded by phosphogypsum + ½ lime + foliar spray of 0.25 % boron and 0.25 % potassium silicate and the lowest concentration of Si in soil was recorded in control.

5.3.4. Effect of different amendments on nutrient status of leachate

The leachate collected from the PVC pipe with perforations at the bottom which was inserted into the pots were analyzed for various soil properties at 30, 60

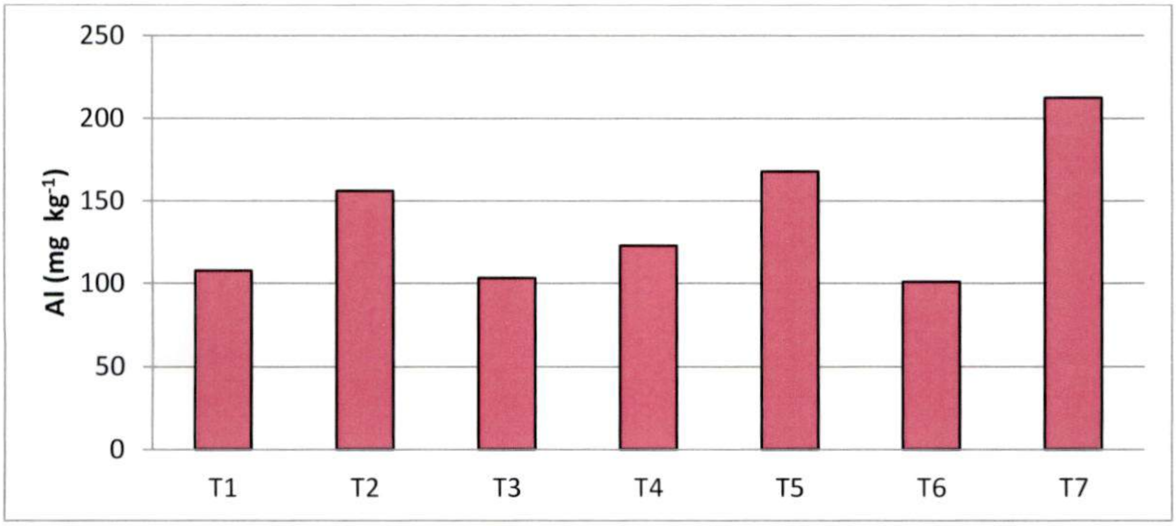

Fig. 12: Al as influenced by treatments in pot culture experiment

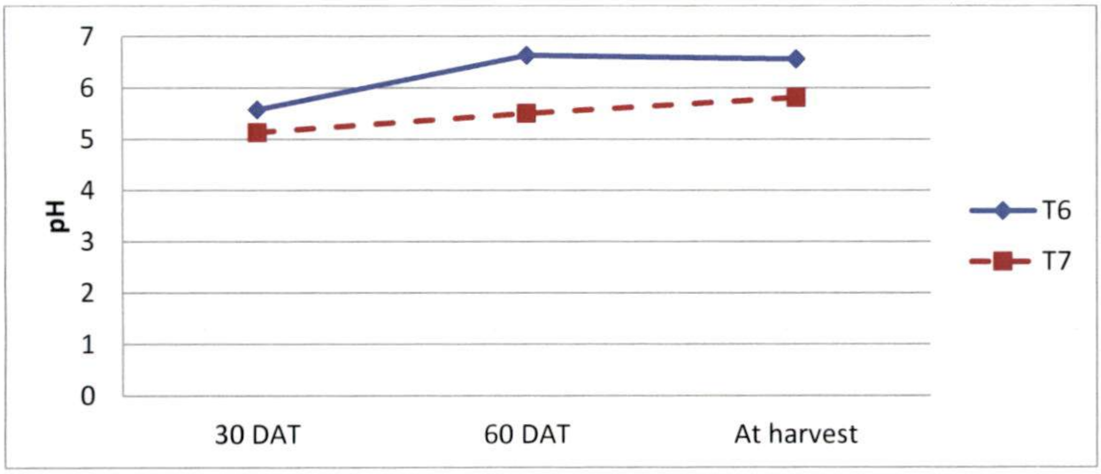

Fig. 13: pH of the leachate as influenced by selected treatments

days after transplanting and at harvest. The analysis of pH, Ca, Mg, Fe and Al was found to be significant with the application of different amendments.

The pH of the leachate was found to be significant at 30, 60 days after transplanting and at harvest with lime and combination of lime and phosphogypsum showing highest values. At 30 days after transplanting application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed the highest value of pH than other treatments. Application of lime alone recorded the higher value at 60 days after transplanting and at harvest again phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed highest pH among different amendments. The lowest value was reported by control throughout the experiment. This may be due to the presence of Ca in the soil solution by the application of amendments which reduces the activity of Al^{3+} and H^+ ions and their by increased soil pH in the soil solution. Similar results were reported by Lee *et al.*, 2007; Shamshuddin *et al.*, 2015 and Crusciol *et al.*, 2016.

The Ca content in leachate was significant with respect to treatments at 30, 60 days after transplanting and at harvest with superiority by phosphogypsum + ½ lime application than other treatments. Control showed lowest Ca content in the leachate throughout the experiment. This may be due to the soluble Ca present in the phosphogypsum. Application of phosphogypsum increases the exchangeable Ca present in soil solution (Crusciol *et al.*, 2016).

The magnesium content in leachate showed significance with application of different amendments. At 30, 60 days after transplanting and at harvest magnesium carbonate + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded highest content of Mg in leachate. This might be due to the release of Mg in to the solution when magnesium carbonate was used as amendment.

The iron and aluminium content in leachate showed significant effect with respect to treatment application. At 30 days after transplanting application of lime showed lowest concentration of Fe in leachate. At 60 days after transplanting and at

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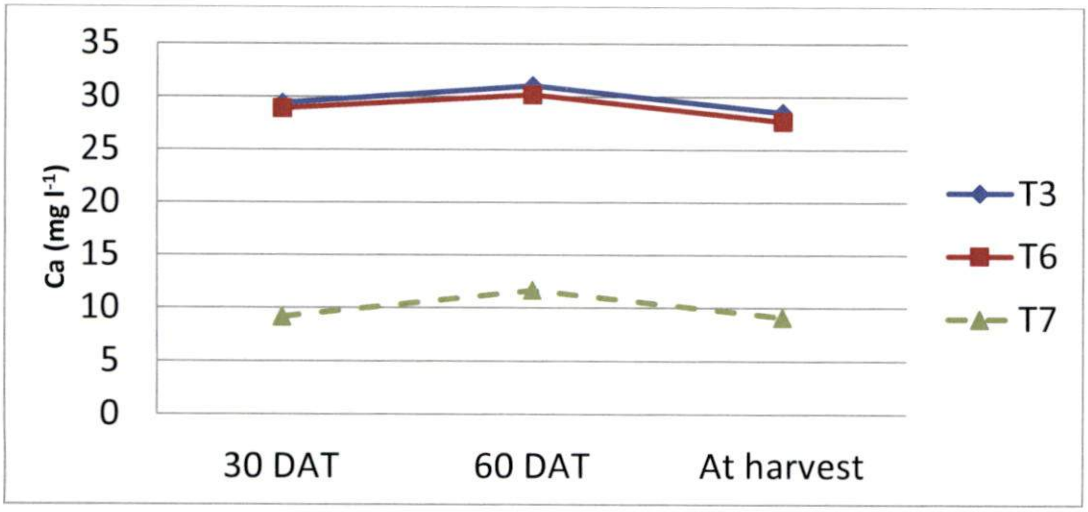

Fig. 14: Ca content of the leachate as influenced by selected treatments

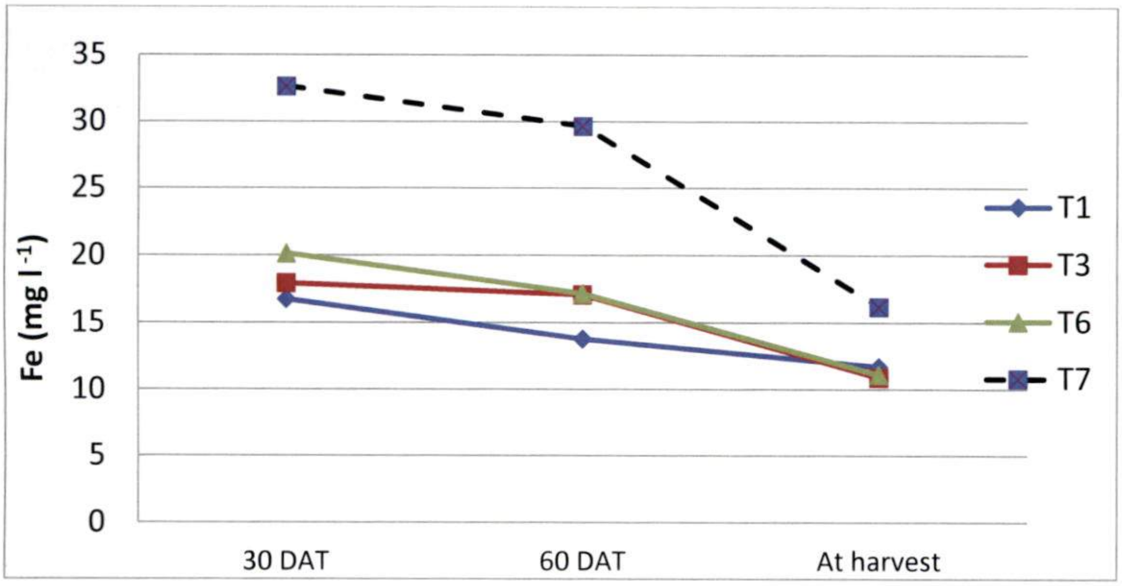

Fig. 15: Fe content of the leachate as influenced by selected treatments

harvest phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded lowest amount of iron. This may be due to the effect of lime and phosphogypsum in reducing the iron content in solution and in soil Ponnamperuma and Nhung (1965). Control showed highest concentration of iron in leachate at 30, 60 days after transplanting and at harvest.

The Al content in leachate was significantly reduced by application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate throughout the experiment. The lowest value was recorded by control. This may be due to the soluble Ca in phosphogypsum which can increase the soil pH and their by reduced the soil acidity and also Al content in soil and solution. The release of Al in to the solution also affected by the action of phosphogypsum. Application of phosphogypsum reduces the toxic levels of soluble Al in soil solution.

5.4 CORRELATION ANALYSIS

5.4.1 Incubation experiment

There was positive correlation between pH and Ca whereas, negative correlation was observed with Fe and Al. The Ca was also found to be negatively correlated with Fe and Al. There was positive correlation between Fe and Al. Ponnamperuma and Nhung (1965) also reported that activities of water soluble Al^{3+} and Fe^{2+} decreases for each unit increase in pH. Application of Ca sources reduced the toxic concentration of Fe and Al in soil. Increase in Ca added through amendments favours the reduction of toxic Fe and Al. Azman *et al*., (2014) also reported that after the application of lime Fe and Al concentration will decline whereas Ca will increase.

5.4.2 Solution culture experiment

There was highly negative correlation between root length and iron content concentration in roots. Sharma and Dubey (2007) reported that, as the concentration of Fe and Al increases, root growth reduces accordingly.

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5.4.3 Pot culture experiment

There were significant correlation between yield, pH, available P, Ca, Fe, Al, plant Ca and Fe. Application of lime (Ca sources) increases the pH and also decreases the Fe and Al concentrations (Crusciol *et al.*, 2016). Ponnamperuma and Nhung (1965) reported that lime ($CaCO_3$) decreases the iron content of the soil. Benckiser *et al.*, (1984) suggested that calcium and magnesium plays a crucial role in alleviating iron toxicity in rice.

Summary

6. SUMMARY

The salient findings of the present study on "Flux and dynamics of iron and aluminium in wetlands of Kuttanad and its management for rice (*Oryza sativa* L.)" are summarized in this chapter.

An investigation was carried out at College of Agriculture, Padannakkad during 2015- 17 to study the toxicity problems of iron and aluminium in wet land rice grown on acid sulphate soils of 'Kari' lands in Kuttanad. The study was undertaken to evaluate the performance of two popular rice varieties to variable levels of iron and aluminium concentrations at different stages and to examine suitable amelioration strategies. The experiment was carried out in three parts, which included collection and analysis of soil sample from Kuttanad, an incubation experiment as a preparatory study, solution culture and pot culture experiments.

Soil samples were collected from the 'Kari' lands of Kuttanad which is included in the ambalappuzha acid sulphate soil series in Karuvatta region of Kuttanad. The samples were drawn to a depth of 0 to 25 cm from the surface of a rice field and brought to College of Agriculture, Padanakkad. The soil collected was used for analyzing various physical and chemical properties, conducting incubation study and pot culture experiment.

The incubation study was conducted using two levels of submergence (5 cm and 10 cm) and four treatments in factorial CRD. The treatments used were T_1: Lime @ 600 kg ha^{-1} as per KAU POP, 2011; T_2: phosphogypsum @ 500 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} as per KAU POP, 2011; T_3: magnesium carbonate @ 50 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} (as per KAU POP, 2011); T_4: control. The soil samples were analyzed at 30, 60 and 90 days after the submergence.

The results of incubation study showed that the treatments were significantly different for pH, Ca, Mg, Fe and Al. After 30 days of submergence application of lime (T_1) showed highest increase in pH. After 60and 90 days of submergence, phosphogypsum @ 500 kg ha^{-1} + ½ lime as per KAU POP (T_2) showed the highest increase in pH from control which reported the lowest pH throughout the submergence period. There was no significant difference with respect to the level of submergence and the interaction of level of submergence and treatments. The Ca content in soil was found to be increased after submergence period. Application of phosphogypsum @ 500 $kgha^{-1}$ + ½ lime (as per KAU POP) showed significantly higher amount of calcium after 30, 60 and 90 days of submergence. Magnesium content was also found to be increased after the submergence. The application of treatment containing magnesium carbonate + ½ lime (as per KAU POP) was the most superior treatment with available Mg content. The iron and aluminium content in the soil decreased after the incubation experiment with the application of treatments. Application of lime + phosphogypsum showed superior effect in reducing their concentration in soil. Control showed the highest value for Fe and Al.

The solution culture experiment was carried out using Hoagland's nutrient solution as a base with the addition of different levels of Fe and Al. The objective was to study the response of two popular varieties of rice Uma and Prathyasa. The experiment was conducted in factorial-completely randomized design. The treatments were combinations of iron at 200, 400, 800 and 1200 mg L^{-1} and Al at 50 and 100 mg L^{-1} with a control in Hoaglanad's nutrient solution.

The results of solution culture showed significant effect with respect to amendments. The percentage increase in plant height was found to be significant. Maximum increase in plant height was showed by control, Hoagland's solution. Minimum increase in plant height was displayed by rice plant in Hoagland's solution containing 1200 mg L^{-1} Fe and 50 mg L^{-1} Al (T_4) followed by this 1200 mg L^{-1} Fe and 100 mg L^{-1} Al (T_8). The control was found to be superior over other treatments in root length increase and root dry weight also. Minimum increase in root length and root dry weight among the treatments was showed by 1200 mg L^{-1} Fe and 50 mg L^{-1} Al.

The higher concentration of Fe and Al increased their content in the root surface. Control showed the lowest concentration of iron and aluminium around the root surface. Hoagland's solution containing 1200 mg L^{-1} Fe and 50 mg L^{-1} Al showed maximum concentration of iron in the root surface while 1200 mg L^{-1} Fe and 100 mg L^{-1} Al recorded maximum Al content. Significantly lowest Fe and Al content was found in control. Maximum iron coating around the root among the treatments was displayed by solution containing 1200 mg L^{-1} Fe and 100 mg L^{-1} Al. The control did not showed the Fe coating in root.

The pot culture experiment was carried out in College of Agriculture, Padanakkad using the soil collected from 'Kari' lands of Kuttanad. The experiment was conducted with seven treatments comprising different amendments along with two varieties Uma and Prathyasa. The treatments were designed based on the recommendations of KAU POP.2011.The treatment combinations were: Lime (T_1); Magnesium carbonate + ½ lime The treatment (T_2); Phosphogypsum @ 500kg ha^{-1} + ½ lime (T_3); Lime + Potassium silicate 0.25% + 0.25% Boron (T_4); Magnesium carbonate + ½ lime + Potassium silicate 0.25% + 0.25% Boron (T_5); Phosphogypsum @ 500 kg ha^{-1} + ½ lime + Potassium silicate 0.25% + 0.25% Boron (T_6) and control (T_7).

The result of pot culture experiment showed that pH, EC, N, P, Ca, Mg, S, B, Fe, Cu, Mn, Al and Si were found to be significant with treatment application while OC, Zn and K content in soil were found to be non- significant. Application of lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed highest value of pH at the time of harvest while control showed the lowest value of pH.

The highest available nitrogen content was given by magnesium carbonate + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate and the lowest available nitrogen content was recorded in control. Application of phosphogypsum +

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½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded highest increase in P content in soil. The application of magnesium carbonate + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed significant increase in potassium content of the soil.

Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate in soil significantly increases the available Ca content higher than other treatments. The treatment application of magnesium carbonate + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed highest amount of magnesium in soil.

The highest value of available sulphur was recorded in control. Application of lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed the lowest value of available sulphur. Minimum iron and aluminium content was recorded by phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate application. Maximum Fe concentration was recorded in control.

The highest manganese content in soil was showed by control. The application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded lowest concentration of Mn in soil. The highest boron and Si content were showed by the application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate. The highest amount of copper was showed by magnesium carbonate + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate.

The results of analysis of leachate also showed significant effect with the application of treatments. The pH of the leachate was found to be significant at 30, 60 days after transplanting and at harvest. At 30 days after transplanting application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed the highest value of pH than other treatments. Application of lime alone recorded the higher value at 60 days after transplanting and at harvest again phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed highest pH among different amendments.

The Ca content in leachate is significant with respect to treatments at 30, 60 days after transplanting and at harvest with superiority by phosphogypsum + ½ lime application than other treatments. At 30, 60 days after transplanting and at harvest magnesium carbonate + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded highest content of Mg in leachate. Control showed lowest pH, Ca and Mg content in the leachate throughout the experiment.

The application of treatments significantly reduced the Fe and Al content in leachate. Control showed highest concentration of iron and aluminium in leachate at 30, 60 days after transplanting and at harvest. At 30 days after transplanting application of lime showed lowest concentration of Fe in leachate. At 60 days after transplanting and at harvest phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded lowest amount of iron. The Al content in leachate was also significantly reduced by application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate throughout the experiment.

The application of amendments showed significant improvement in biometric characters, yield and yield attributes. Lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed higher plant growth, grain yield per plant. Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed more number of tillers, maximum number of grains per panicle.

The straw yield per plant and chaffiness percentage were found to be non-significant, application of lime + foliar spray of 0.25% boron and 0.25% potassium silicate recorded highest straw yield. Highest chaffiness percentage was showed by control and the lowest by phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate.

The application of treatments showed significant effect on the nutrient content in plant. Even though the N content in plant was found to be non-significant all the treatments showed superiority over control. Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate reported higher nitrogen content in the plant than other treatments.

The treatments, varieties and interaction between variety and treatment were found to be significant in case of P and K content in plants. The highest p and K content in plant was recorded by phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate and control showed the lowest value of plant phosphorus and potassium content.

Application of amendments showed significant effect in uptake of Ca, Mg and S by the rice plants. The treatment application of phosphogypsum + ½ lime recorded highest Ca and S content in plants and the application of magnesium carbonate + ½ lime recorded highest Mg content in plants. The treatment with no amendment application, control showed lowest concentration of Ca, S and Mg in plants.

The effect of treatments on concentration of iron in plants was found to be significant with the reduction in Fe content. The varieties did not show any significance with uptake of iron. There was significant effect by the variety and treatment interaction. The treatment application of lime showed lowest concentration of iron in plants.

Application of treatments significantly decreased the concentration of aluminium in plants. Application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed lowest uptake of Al by plants while control showed the highest uptake. The variety Prathyasa contained more Al concentration in plant than Uma variety.

The manganese content in plant was significant with respect to the amendments applied. Highest Mn content in plant was reported by control and the lowest Mn content in plant was recorded by application of lime + foliar spray of

0.25% boron and 0.25% potassium silicate. The application of amendments reduced the Mn uptake.

The application of treatments increased the uptake of Cu, Zn, B and Si. The application of magnesium carbonate + ½ lime showed highest Cu and Zn uptake whereas control showed lowest uptake of all these elements by plants. Treatment with phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate showed highest B uptake. The silicon content in rice plant showed significance by the application of treatments, lime + foliar spray of 0.25% boron and 0.25% potassium silicate reported highest Si content in plants.

The positive effects of the amendment application and foliar spray of boron and silicon in the reduction of Fe and Al content in soil and plant, increased pH and uptake of nutrients indicate the need of their application to rice grown on acid sulphate soil. The incubation and pot study shown that application of phosphogypsum + ½ lime + foliar spray of 0.25% boron and 0.25% potassium silicate significantly improved the available nutrient content of the soil, content and uptake of nutrient by the plant and yield and yield attributes of rice. It was also effective in reducing the toxicity of Fe, Al and Mn in the soil. This effect can be further evaluated by conducting field study and also can be evaluated on other crops grown in acid sulphate soil.

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FLUX AND DYNAMICS OF IRON AND ALUMINIUM IN WETLANDS OF KUTTANAD AND ITS MANAGEMENT FOR RICE

(*Oryza sativa* L.)

by

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ABSTRACT

The investigation entitled "Flux and dynamics of iron and aluminium in wetlands of Kuttanad and its management for rice (*Oryza sativa* L.)" was carried out at College of Agriculture, Padannakkad during 2015-2017. The objective of the study was to evaluate the performance of two popular rice varieties *viz.* Uma and Prathyasa to varying levels of iron and aluminium concentrations at different growth stages and to examine suitable amelioration strategies. The entire experiment was conducted in three parts, which included collection and analysis of soil sample from Kuttanad, solution culture with graded levels of Fe and Al and a pot culture experiment using the Kuttanad soil. As a preparatory to pot culture study, an incubation experiment was also conducted using the bulk soil collected from Kuttanad so that nutrient release pattern under submergence could be obtained.

Soil samples at GPS coordinates (latitude: 9°:18':56''.99, longitude: 76°:24':30''.68) were collected from the 'Kari' lands of Kuttanad and brought to College of Agriculture, Padannakkad and analysed for various physical and chemical properties. It was observed that the soil has extremely low pH, very low available P and toxic levels of Fe and Al. This soil was used for incubation study and pot culture experiment.

The incubation study was conducted with four treatments at two levels of submergence (5 cm and 10 cm) in factorial CRD. The treatments were designed based on the recommendations of KAU POP 2011 *viz.* lime @ 600 kg ha^{-1} (T_1); phosphogypsum + ½ lime @ 300 kg ha^{-1} (T_2); magnesium carbonate @ 50 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} (T_3) and control (T_4).

During the submergence period among the various parameters monitored, a steady increase was observed for pH, Ca and Mg of the soil. Application of phosphogypsum + ½ lime showed the highest increase in soil pH and available

calcium content and was highly effective in lowering the toxic concentration of Fe and Al in the acid sulphate soils of Kuttanad.

The solution culture experiment was carried out using Hoagland's nutrient solution as nutrient medium in which four levels of Fe (200, 400, 800 and 1200 mg L^{-1}) and two levels of Al (50 and 100 mg L^{-1}) were added in factorial combination and experiment was designed in CRD. The treatment with 1200 mg L^{-1} Fe and 100 mg L^{-1} Al suppressed the plant height, root length, root dry weight and recorded maximum concentration of Fe and Al in the root and displayed thick iron coating (iron plaque) around the root as observed in the root sections.

The third part of the investigation, pot culture experiment was conducted with seven treatments as amendments and two varieties Uma and Prathyasa in factorial CRD. The leachate was collected and analysed by placing a perforated pipe at the centre of the pot. The treatments were designed based on the recommendations of KAU POP 2011. The treatment combinations were: lime @ 600 kg ha^{-1} (T_1); magnesium carbonate @ 50 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} (T_2); phosphogypsum + ½ lime @ 300 kg ha^{-1} (T_3); lime @ 600 kg ha^{-1} + potassium silicate 0.25% + 0.25% boron (T_4); magnesium carbonate @ 50 kg ha^{-1} + ½ lime @ 300 kg ha^{-1} + potassium silicate 0.25% + 0.25% Boron (T_5); phosphogypsum + ½ lime @ 300 kg ha^{-1} + potassium silicate 0.25% + 0.25% boron (T_6) and control (T_7).

The application of amendments significantly improved the biometric characters. The treatment T_4 showed higher plant height and grain yield per pot whereas T_6 showed more number of tillers and maximum number of grains per panicle.

The treatment T_6 considerably reduced the Fe, Al and Mn content in soil and leachate, which also recorded significantly higher of P, Ca, B and Si content in soil and leachate. The treatment T_6 also recorded highest plant nutrient concentrations of N, P, K, Ca, S and B while significantly reduced the concentration of Fe and Al whereas the treatment T_4 reduced the Mn content, increased the Si content and maximum increase in value of soil pH. The highest soil available N, K and Mg was recorded in treatment T_5 which also showed highest plant content of Mg, Zn and Cu.

The acid sulphate soils of Kuttanad region are having constraints of extreme acidic soil pH and pronounced toxicity of Fe and Al. This can be ameliorated using amendments and can be made more productive. The results of the investigation clearly indicate that application of phosphogypsum along with lime and foliar application of B and Si enhances the grain and straw yield of rice. This treatment also enhanced the available nutrient status of soil and plant nutrient content. It was very effective in alleviating toxicity of Fe and Al.

Appendices

APPENDIX I

MONTHLY WEATHER DATA DURING THE CROP PERIOD

Period	Maximum temperature (^{0}C)	Minimum temperature (^{0}C)	Rainfall (mm)	Relative humidity (%)	Evaporation (mm)
June 2016	32.62	23.94	126.10	78.03	3.29
July 2016	30.76	22.75	532.60	85.03	1.97
August 2016	29.96	23.42	902.00	88.08	2.43
September 2016	30.35	23.41	17.62	87.24	2.94
October 2016	31.21	23.44	12.51	87.91	3.48
November 2016	31.35	23.62	265.70	84.57	3.15
December 2016	31.39	23.05	106.80	81.75	2.95

APPENDIX -II

CORRELATION ANALYSIS OF POT CULTURE EXPERIMENT

Parameters	Yield	pH	P	Ca	Fe	Al	B	Si	Plant P	Plant K	Plant Ca	Plant S	Plant Fe	Plant Al	Plant B	Plant Si
Yield	1															
pH	0.86**	1														
P	0.89**	0.83**	1													
Ca	0.81**	0.96**	0.89**	1												
Fe	-0.90**	-0.71**	-0.90**	-0.68**	1											
Al	-0.87**	-0.75**	-0.89**	-0.81**	0.75**	1										
B	0.92**	0.79**	0.97**	0.80**	-0.94**	-0.88**	1									
Si	0.41	0.66**	0.44	0.67**	-0.27	-0.37	0.34	1								
Plant P	0.56*	0.45	0.61*	0.50	-0.59*	-0.58*	0.58*	0.23	1							
Plant K	-0.15	0.27	-0.04	0.22	0.14	0.31	-0.11	0.45	-0.13	1						
Plant Ca	0.89**	0.79**	0.97**	0.82**	-0.92**	-0.89**	0.97**	0.40	0.51*	-0.10	1					
Plant S	-0.51	-0.40	-0.18	-0.24	0.20	0.35	-0.28	-0.08	-0.16	0.09	-0.17	1				
Plant Fe	-0.84**	-0.96**	-0.77**	-0.92**	0.62*	0.76**	-0.72**	-0.54	-0.41	-0.16	-0.72**	0.51	1.00			
Plant Al	-0.28	-0.42	-0.38	-0.39	0.36	0.14	-0.34	-0.32	-0.43	-0.41	-0.32	-0.03	0.37	1		
Plant B	0.53*	0.66*	0.49	0.68**	-0.38	-0.51	0.37	0.72**	0.48	0.09	0.41	-0.18	-0.59*	0.05	1	
Plant Si	0.41	0.44	0.26	0.37	-0.35	-0.19	0.20	0.60*	0.48	0.09	0.19	-0.20	-0.36	-0.12	0.81**	1

** Significant at 1% level of significance

* Significant at 5% level of significance