SILICON AND BORON NUTRITION OF RICE (*Oryza sativa* L.) IN WET LAND SOILS OF NORTHERN KERALA

by

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THESIS

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DECLARATION

I, hereby declare that this thesis entitled **"SILICON AND BORON NUTRITION OF RICE (*Oryza sativa* L.) IN WET LAND SOILS OF NORTHERN KERALA"** 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, associateship, fellowship or other similar title, of any other University or Society.

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CERTIFICATE

Certified that this thesis entitled **"SILICON AND BORON NUTRITION OF RICE (*Oryza sativa* L.) IN WET LAND SOILS OF NORTHERN KERALA"** is a record of research work done independently by Mr. Sainath Nagula (2012-11-186) 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 him.

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LIST OF ABBREVIATIONS

%	-	Percent
@	-	at the rate
^0C	-	Degree Celsius
Al	-	Aluminum
B	-	Boron
Ca	-	Calcium
Cu	-	Copper
CD	-	Critical difference
cm	-	Centimeter
CEC	-	Cation exchange capacity
DAT	-	Days after transplanting
dSm^{-1}	-	deci Siemens per meter
EC	-	Electrical conductivity
et al	-	And others
Fe	-	Iron
FC	-	Field capacity
Fig.	-	Figure
FS	-	Flowering stage
$g\ cc^{-1}$	-	Gram per cubic centimeter
$g\ pot^{-1}$	-	Gram per pot
g	-	Gram
HS	-	Harvesting stage
K	-	Potassium
kg	-	Kilogram
$kg\ ha^{-1}$	-	Kilogram per hectare
l	-	Liter
Mg	-	Magnesium
Mn	-	Manganese
m^2	-	Square meter

mg kg^{-1}	-	Milli gram per kilo gram
MT	-	Maximum tillering stage
N	-	Nitrogen
NS	-	Non significant
P	-	Phosphorous
pH	-	Soil reaction
S	-	Suphur
SAS	-	Statistical analysis software
Si	-	Silicon
t ha^{-1}	-	Tonnes per hectare
Zn	-	Zinc

INTRODUCTION

1. INTRODUCTION

Rice (*Oryza sativa* L.) is the staple food of the people in India. India has the largest acreage under rice of 44 million hectare and a production of about 141 million tonnes with a national productivity of 3.21 t ha^{-1}. The population of our country may stabilize around 1.4 and 1.6 billion by 2025 and 2050, requiring annually 380 and 450 mt of food grains respectively (Yadav *et al.*, 2010). Rice yields are decelerating / stagnating / declining in post green revolution era mainly due to imbalance in fertilizer use, soil degradation, lack of suitable rice genotypes for low moisture adaptability and disease resistance (Prakash, 2010).

Paddy cultivation in Kerala has witnessed a steady decline since the 1980s. The sharp fall in the area under paddy cultivation as well as in the quantity of rice produced in the state has had important implications for Kerala's economic, ecological and social development.

The mid land rice fields of northern Kerala mainly constitute the drainage basins of hills and hillocks. These basins usually accumulate all the leachates washed down from the hills. The soils being lateritic in nature the extent of reduced form of iron accumulating in such soils are high. These soils are acidic, generally having low levels of plant nutrients, low cation exchange capacity, deficient in Ca, Mg, B, Si and having toxic concentration of Fe, Mn and Al. This creates soil stress and the yields of rice crop grown in these soils are reduced, far below the yield potentials.

Laterite soil is the most abundant soil seen in Kerala. They cover about 65% of the total area of the state. They are seen mostly in northern parts of the state in Kozhikode, Kannur, Malappuram and Kasaragod districts. Heavy rainfall and high temperature condition in the state are suitable for the process of laterization. These soils are poor in available N, P and K. They have low cation exchange capacity and high P fixing capacity with low organic matter content.

Crop production in laterite soils has been found to be low due to several constraints. However, there is considerable scope for improving the productivity of these acid soils through proper land management. It is generally agreed that iron plays a key role in the hardening process and in crust formation in the laterite soils of Kerala.

The prevailing form of silicon in soil solution is monosilicic acid (H_4SiO_4). Iron and aluminum oxides of soil have the capacity to adsorb a considerable amount of silicon (Si) on their surfaces. Aluminum oxides are more effective in binding silicon through adsorption mechanism than iron oxides.

Silicon is assimilated by plant roots as monosilicic acid (H_4SiO_4) where it accumulates in leaves and other plant tissue primarily as amorphous silicates or phytolithic opal (Epstein, 1994). Once deposited in this form, Si is immobile and is not redistributed within the plant (Ma *et al.*, 1989; Epstein, 1994). Hydrated, amorphous silica is deposited in cell lumens, cell walls, and intercellular spaces. It also accumulates in external layers below and above the cuticle of leaves. Silicon is present in roots, leaves, and in the inflorescence bracts of cereals, especially in rice, wheat, oats and barley (Epstein, 1999). The uptake of Si by rice and other plants is not well understood, but appears to be influenced by a number of soil and climatic factors. Growth chamber studies comparing the effects of low (4°C) and high (25°C) temperatures on Si assimilation by rice showed that low temperatures substantially suppressed assimilation of Si by rice and corn (*Zea mays*) as did chemical inhibitors of metabolism (Liang *et al.*, 2006). Increasing solution concentrations of Si, however, increased Si uptake even at low temperatures, suggesting that uptake is a combination of both metabolic rate and Si availability. In plants, silicon plays a crucial role in amino acid and protein metabolism.

Rice is a high silicon accumulating plant. Si is a beneficial element for plant growth and is agronomically essential for improving and sustaining rice productivity. Besides rice yield increase, Si has many fold advantages of increasing nutrient availability (N, P, K, Ca, Mg, S, Zn), decreasing nutrient toxicity (Fe, Mn, Al) and minimizing biotic and abiotic stress in plants. Silicon is not much mobile in plants, therefore a continued supply is required for long term sustainable rice production. Hence the application of Si to soil or plant is practically useful in laterite derived paddy soils, not only to increase yield but also to alleviate the iron toxicity problems.

In India, though research on silicon has been initiated earlier, the necessity for silicon fertilization to rice crop has not been widely evaluated as in other countries.

Boron is present in soil solution in several forms but, at soil pH of 5.5-7.5, the most dominant form is the soluble undissociated boric acid (H_3BO_3). Plants take up boron from soil in the form of boric acid. The apparent and latent symptoms of boron deficiency have been recorded on rice grown in acidic soils of laterite zone.

Boron is an important micronutrient required for plants in obtaining quality high yields. It has a primary role in cell wall biosynthesis, fruit and seed setting, regulation of the carbohydrate metabolism, sugar transport, lignification, nucleotide synthesis, respiration, pollen viability and synthesis of amino acids and proteins.

However, it has been observed that in most plant species the boron requirement for reproductive growth is much higher than for vegetative growth (Matoh *et al.*, 1996). This is especially true for gramineaceous plants, which have the lowest boron requirement to maintain normal vegetative growth, but need as much boron as other species at the reproductive stage.

Since the laterite derived paddy soils are deficient in boron, its deficiency symptoms are widespread in rice crop grown in these soils and the yield is depressed. Hence soil/foliar application of boron containing fertilizers are required to increase the rice production in these soils. With this background, the present study on the silicon and boron nutrition of rice to increase the rice yield in laterite derived paddy soils has been proposed with the following objectives.

1. To standardize the dose and method of application of silicon and boron to rice crop in laterite derived paddy soils.
2. To study the effect of silicon and boron on available nutrient status of soil and yield of rice.
3. To study the effect of silicon in alleviating the toxicity of Fe, Mn and Al in laterite derived paddy soils.

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

Rice is life line for almost half of the Earth's population and is the staple food of the people of India. Although rice is grown in 113 countries, about 95 % of the crop is grown and consumed in Asia. In India, rice occupies 23.3 % gross cropped area of the country and contributes 43 % of the total food grain production and 46 % of country's total cereal production. India has largest area under rice crop (about 45 million ha) and ranks second in production next to China.

Nutrients such as silicon and boron are most important for sustainable production of rice. Rice is a silicon (Si) accumulating plant and tends to actively accumulate Si to tissue concentration level of 5 % or higher (Epstein, 1994). Silicon is the only element known that does not damage plants upon excess accumulation. Information on the importance of Si in Indian rice farming system is limited (Prakash, 2002).

Boron is an essential micronutrient for plant growth. Its deficiency symptoms appear when plant faces reduced supplies of boron. Its severe deficiency causes abnormal development of reproductive organs (Huang *et al.*, 2000) and ultimately results in reduction of plant yield (Nabi *et al.*, 2006).

Literature related to the effect of silicon and boron on available nutrient status of soil, nutrient content and uptake in plant, plant growth parameters, yield and yield attributes of rice and its effect on imparting resistance against various biotic and abiotic stresses are elaborated in this chapter.

2.1. SILICON

Silicon (Si) is the second most abundant element in the earth's crust after oxygen, with the chemistry second only in complexity to that of carbon (Bond and McAuliffe, 2003). It's very complex chemistry is of great geochemical significance (Basile *et al.*, 2005).

In the periodic chart, its nearest neighbors are B, C, N, O, P and S. Interestingly all these elements are recognized as "essential elements", while Si is recognized to be the "beneficial element" for some plant species (Gascho, 2001). However, most plants can grow in nutrient solutions lacking silicon (Epstein, 2001). Silicon in the form of silica (silicon dioxide) plays an important role in the natural world, where it serves as an essential element for microorganisms, plants and even higher animals.

Silicon is often a major constituent of plant tissues, although it is not considered as an essential nutrient for terrestrial plants. However, horsetails (class: Equisetaceae) have been conclusively shown to require silicon as an essential nutrient. No other, non-essential element apart from silicon is present in such consistently high amounts in the terrestrial plants. Silicon concentration in the plant tissues sometimes exceeds the concentrations of nitrogen and potassium (Epstein, 1994). Dicots are known to be silicon non-accumulators, with tissue silicon concentration less than 0.5 % (Marschner, 1995), compared to wet grasses, which contain silicon up to 5% or more (Epstein, 1994). However, within a given plant species or cultivar, tissue levels of silicon vary in relation to soil silicon availability (Datnoff *et al.,* 1991).

2.1.1. Sources of silicon

Silicon sources are available as natural resources or industry by-products. Plant residues such as rice (*Oryza sativa* L.) hulls and sugarcane (*Saccharum* spp.) bagasse have a sufficient Si concentration to be used as Si supplement (Ma and Takahashi, 2002). According to the same authors, the supplementation of Si by plant residues enhances plant growth and yield, but the plant demands are higher. Therefore, most commercial applications are from industry by-products with high Si concentrations. The most common commercially used Si sources are calcium silicate slag ($CaSiO_3$), wollastonite (calcium meta-silicate, $CaSiO_3$), sodium silicate ($NaSiO_3$), magnesium silicate ($MgSiO_3$), potassium silicate ($KSiO_3$) and silica gel (soluble SiO_2).

2.1.2. Silicon in plant nutrition

2.1.2.1. Role of silicon in plants

In grasses, silicon is often found in higher amount than any other inorganic constituent (Epstein, 1999). The role of silicon in plants are enhancement of growth and yield, resistance against lodging, enhances photosynthesis, effect on surface properties, resistance against disease causing organisms, resistance to herbivores, resistance to metal toxicity, resistance to salinity stress, reduction of drought stress and protection against temperature extremes (Epstein, 2001).

2.1.2.2. Silicon transport

Mitani *et al.* (2005) indicated that the form of silicon translocated in the xylem sap of rice is monosilicic acid and its high concentration in the xylem is only transiently. The form of silicon in xylem sap was identified by Si-Nuclear Magnetic Resonance Spectroscopy (NMR).

Plant species which employ active uptake of Si, such as rice take up Si faster than water. The Si concentration in rice leaf blades can reach more than 10% Si on a dry weight basis. Si uptake by rice roots is mediated by a proteinaceous transporter. Two transporters (SIT1 and SIT2) are involved in Si transport from the external solution to the xylem in rice roots. SIT1 is responsible for radial transport of Si from the external solution to root cortical cells, while SIT2 regulates the release of Si from cortical cells into the xylem (xylem loading) (Ma *et al.*, 2004). It seems that xylem loading is the most important determinant of a high accumulation of Si in the shoots. Silicic acid is translocated to the shoot via xylem. The form of Si in the xylem has been identified as monomeric silicic acid in rice (Mitani *et al.*, 2005). In the shoot, silicic acid is concentrated through loss of water and is polymerized. The process of Si polymerization converts silicic acid to colloidal silicic acid and finally to silica gel with increasing silicic acid concentration. In rice plants, more than 90% of total Si in the shoot is present in the form of silica gel, while the concentration of colloidal plus monomeric Si is kept below 140-230 mg Si L^{-1} (Ma *et al.*, 2001a).

2.1.2.3. Importance of silicon in rice

Rice is prone to various stresses if the available soil silicon is low for absorption. Production of 5 t ha^{-1} of grain yield of rice is estimated to remove about 230-470 kg ha^{-1} elemental Si from soil, depending upon soil and plant factors. Absorption will be about 108 % more than nitrogen. Adequate supply of silicon to rice from tillering to elongation stage increases the number of grains per panicle and the percentage of ripening (Korndorfer *et al.*, 2001). It is also suggested that the silicon plays a crucial role in preventing or minimizing the lodging incidence in rice, a matter of great importance in terms of agricultural productivity.

Rice requires large amounts of Si for healthy plant growth and development. Under the warm sub humid tropical conditions of India, Si removed by 12 rice cultivars (90-140 days duration) grown on an Inceptisol during the dry season varied from 204 to 611 kg Si ha^{-1} (Nayar *et al.*, 1982).

Silicon depletion has been noticed with intensive cultivation of high yielding varieties in traditional rice growing soils of many countries, if farmers are not replacing the Si removed by rice. However, sustained high rice yields in Japan are most likely due to the widespread application of silicate slag at rates of around 1.5 to 2 t ha^{-1} (Takahashi *et al.*, 1990).

Snyder *et al.* (1986) reported that approximately 30 g Si kg^{-1} of soil (dry weight basis) is needed for optimum production. The soils containing 10 mg L^{-1} or less of acetic acid extractable silicon generally require silicon fertilizer to produce a maximum grain yield and those containing 25 mg L^{-1} of silicon or more generally do not require silicon fertilization (Snyder, 1991).

2.1.2.4. Silicon and biotic stresses

Seebold *et al.* (2000) tested the effects of Si on several components of resistance to blast using susceptible, partially resistant and completely resistant rice cultivars. They reported that regardless of cultivar resistance, incubation period was lengthened and the number of sporulating lesions, lesion size, rate of lesion expansion and number of spores per lesion were significantly reduced by Si application. Similar results were also noticed by Maekawa *et al.* (2001).

Datnoff *et al.* (2005) reported that the occurrence of brown spot, stem rot and sheath brown rot of rice were decreased significantly by the application of higher levels of calcium silicate as a source of Si.

Liang and Abandonon (2005) reported that application of silicon at varied levels helps in significant reduction of damages caused by various insects, pests and diseases. Savant *et al.* (1997) noticed that application of silicon suppresses insect pests such as stem borer, brown plant hopper and rice green leaf hopper.

Two possible hypothesis for Si enhanced resistance to diseases and pests have been proposed by Cherif *et al.* (1994). In the first one, Si deposited on the tissue surface acts as a physical barrier and the other one is that Si functions as a signal to induce the production of phytoalexins. Similar results were also reported by Datnoff *et al.* (2003).

Numerous studies have shown that disease resistance of rice increases in response to Si fertilization in soils (Savant *et al.*, 1997). Silicon has been shown to suppress fungal diseases such as rice blast, brown spot, leaf scald, leaf scald, sheath blight, stem rot, and a complex of fungal and bacterial pathogens that cause grain discoloration (Datnoff *et al.*, 1997; Seebold, 1998).

Relatively large amounts of plant available Si appears to be very important for both robust growth and fungal disease resistance of rice (Datnoff *et al.*, 2001). Although many rice-growing soils initially contain significant quantities of Si, repeated rice cropping can reduce Si levels to the point that Si fertilization becomes beneficial for growth and disease resistance (Savant *el al.*, 1997).

The effect of Si on pre-infection and post-infection physiological plant response has unlimited prospects for blast control at the vegetative phase. The ratio of N/Si plays an important role in the incidence of rice blast, leaf scald and sheath blight (Prabhu *et al.*, 2001).

2.1.2.5. Silicon and abiotic stresses

Rice (*Oryza sativa* L.) is the most effective Si accumulating plant known, and accumulates Si to levels up to 10 % of shoot dry weight (Savant *et al.*, 1997; Epstein, 1999).

Silicon accumulation in rice leaf blades maintains erect leaves resulting in better light interception thus, increasing photosynthetic rates (Ma and Takahashi, 2002). The stimulation of photosynthesis was more intense under water-stress conditions, and was attributed to the decreased transpiration rate caused by Si foliar accumulation (Matoh *et al.*, 1991). Kaufman *et al.* (1972) attempted to explain silicon-enhanced photosynthesis and hypothesized that silica bodies acted as 'windows' that helped the light transmission to mesophyll area. Silicon can play an important role on plant growth and crop production by preventing nutrient imbalances. Ma and Takahashi (2002) suggested Si to equilibrate the negative results of excessive nitrogen fertilization such as disease sensitivity and lodging.

Takahashi (1966) reported that silicon application increases the resistance of rice to radiation stress. The growth recovery of radiation treated plants was much faster with silicon supplied plants compared to that of the plants without Si supply.

Water deficiency leads to the closure of stomata and subsequent decrease in the photosynthetic rate. Silicon can alleviate the water stress by decreasing transpiration by forming silicon cuticle double layer. Silicon deposition can reduce the transpiration rate by 30 percent in rice (Ma *et al.*, 2001a).

Silicon application to rice is effective in alleviating the damage caused by climatic stress such as typhoons, low temperature and insufficient sunshine during summer season (Ma *et al.*, 2001a). Agarie *et al.* (1998) observed that electrolyte leakage caused by high temperature was less pronounced in the leaves grown with Si than in those grown without Si.

2.1.2.6. Silicon and chemical stress

Silicon could alleviate the toxicity of metals in metal-contaminated soils, such as aluminum, manganese, cadmium and zinc (Song *et al.*, 2009). Deposition of Si enhances the strength and rigidity of cell walls and thus increases the resistance of plants to various stresses (Ma *et al.*, 2004).

Application of silicon helps in alleviating the adverse effects caused due to the application of excess N fertilizers (Ohyama, 1985).

Silicon has been shown to ameliorate certain mineral imbalance (Marschner, 1995 and Epstain, 1994). Several studies found that Si reduce or prevent Mn^{2+} and Al^{3+} toxicity (Marschner, 1995).

2.1.2.7. Silicon alleviating Fe toxicity

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).

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).

2.1.2.8. Silicon alleviating Mn toxicity

In rice, Si reduced Mn uptake by promoting the Mn oxidizing power of the roots (Okuda and Takahashi, 1962).

Marschner (1995) reported that when silicon levels in tissue are low, Mn^{2+} tends to be distributed non-homogenously and accumulates to toxic levels in leaves. However sufficient levels of Si seem to prevent the toxic levels of Mn^{2+}.

2.1.2.9. Silicon alleviating Al toxicity

Al toxicity is a major factor limiting crop production in acid soils. Ionic Al inhibits root growth and nutrient uptake (Ma *et al.*, 2001b). Alleviative effect of Si on Al toxicity has been observed in sorghum, barley, maize, rice, and soybean (Cocker *et al.*, 1998). The alleviative effect was more apparent with increasing Si concentration. Concentration of toxic Al^{3+} was found to decrease by the addition of silicic acid. These results suggest that interaction between Si and Al occurs in the solution, presumably by the formation of Al-Si complexes, a non-toxic form. However, other mechanisms for the alleviative effect of Si have also been proposed, including codeposition of Al with Si within the plant, activity in the cytoplasm, effect on enzyme activity and other indirect effects (Cocker *et al.*, 1998).

2.1.3. Forms of silicon and silicon availability in soils

In soil solution, Si occurs mainly as monosilicic acid (H_4SiO_4) and is taken up by plants in this form (Ma and Takahashi, 2002).

Daniela *et al.* (2006) reported that Si compounds in the soils are classified into soil solution and adsorbed Si forms (monosilicic and polysilicic acids), amorphous forms (phytoliths and silica nodules), poorly crystalline and microcrystailine forms (allophane, immogolite and secondary quartz) and crystalline forms (primary silicates: quartz, feldspars & secondary silicates: clay minerals). The dissolution of Si in paddy soils is influenced by soil temperature, soil redox potential, soil pH and Si concentration in soil solution (Sumida, 1992).

Mineral soils develop from rocks or sediments and are mainly composed of primary crystalline silicates such as quartz, feldspars, mica and secondary silicates, especially clay minerals (Conley *et al.,* 2005). More over they contain Si of biogenic origin (Jones, 1969) and pedogenic amorphous silica (Drees *et al.*, 1989). Silicon also occurs in soil as complexes with Fe, Al, heavy metals and organic matter (Farmer *et al.*, 2005).

Silicic acid is also dissolved in soil solution with some part of the silicic acid adsorbed to soil minerals, particularly oxides and hydroxides of iron and aluminium (Dietzel, 2000). Dissolved silicic acid in soil solutions primarily occurs as monomeric or oligomeric silicic acid (Iler, 1979).

The average available Si status of eight different soil types of Kerala as adjudged by four different extractants revealed that Silica extracted by 0.025 M citric acid ranged between 250 to 1500 kg ha^{-1} with an average of 700 kg ha^{-1} (Nair and Aiyer, 1968). Subramanian and Gopalaswamy (1990) reported that the plant available Si status of rice growing soils of Kanyakumari, Madurai and Chinnamannur of Tamilnadu were 29, 70 and 40 ppm, respectively. The plant available soil Si (mean) extracted by N NaOAc (pH 4.0) in soils of Orissa and Andhra Pradesh were 139 and 278 ppm respectively (Nayar *et al.,* 1982). It is apparent from the reviewed literature, that most of the paddy soils studied was deficient in Si (Prakash, 2002).

Depletion of plant available soil silicon in soils where rice is intensively cultivated could be the possible soil related limiting factor contributing to declining rice yields (Singh, 2003).

Silicon content of rice is higher than the "essential elements" like N, P and K (Savant *et al.,* 1997). The definition of essentiality does not hold good for Si as it does not supplement or substitute for any element, or show deficiency symptoms of its own. But it has been grouped under "beneficial element" as it has manifolds of positive effects on general health, growth and productivity of rice, barley, sugarcane etc. (Ma *et al.,* 2001b).

Higher silicon content in soil was associated with the higher rate of silicon application (120 kg ha^{-1}). This might be due to enhanced soil silicon availability with silicon application (Singh *et al.*, 2006).

2.1.4. Effect of silicon on nutrient availability in soil

2.1.4.1. Nitrogen

Application of silicate fertilizers raised the available nitrogen content in soil (Ma and Takahashi, 2002).

Jawahar and Vaiyapuri (2008) reported that application of Si at 120 kg ha^{-1} significantly increased N, P, K, S and Si uptake of rice. The N uptake increased with application of Si @ 120 kg ha^{-1} due to its potential to raise the soil available nitrogen (Ho *et al.*, 1980).

2.1.4.2. Phosphorous

Increasing silicon levels increased phosphorus availability due to decreased retention capacity of soil and increased solubility of phosphorus leading to increased efficiency of phosphotic fertilizer (Subramanian and Gopalswamy, 1990).

2.1.4.3. Potassium

Several studies found that Si increases potassium availability in soil, this may be due to the production of hydrogen ions during reduction of Fe and Al toxicity which would have helped the release of K from the exchange site or from the fixed pool. This may leads to greater availability of K to rice in flooded soils (Patrick and Mikkelsen, 1971; Marschner, 1995).

2.1.4.4. Calcium and magnesium

Islam and Saha (1969) reported that the application of Si along with other nutrients in the culture solution has decreased the potassium uptake of rice plants. This is due to more absorption of Ca and Mg ions promoted by Si application.

2.1.4.5. Iron

Wallace (1992) found that application of Si decreases the uptake of Fe in iron rich acid soil. This is because high concentrations of Si in rice plants could serve to create an alkaline rhizosphere that would decrease the availability of Fe.

The application of silicon to soil would have formed ferrous iron to insoluble ferric iron compounds, thereby decreasing iron concentration in soil as reported by wang *et al.*, 1994.

2.1.4.6. Manganese

The application of silicon fertilizers to soil would have formed insoluble compounds with Mn, thereby reducing Mn toxicity in soil as reported by Wang *et al.*, 1994.

2.1.4.7. Zinc

Silicon has been shown to alleviate the detrimental nutrient imbalance of zinc and phosphorus (Epstain, 1994; Marschner, 1995).

2.1.4.8. Aluminium

Wallace (1992) found that increased uptake of Si as an anion could be a potent force in decreasing the availability of Al, providing tolerance under acid soil conditions. Barbosa *et al.* (2012) reported that soils with high levels of toxic Al can cause damage to plants and consequently decrease yield. Silicon can be a good alternative to reduce the toxicity of Al in such soils. Application of Si plays an important role in reducing the toxicity of active Al content in soil (Ma and Takahashi, 2002).

2.1.5. Effect of silicon on content and uptake of nutrients in rice

2.1.5.1. Nitrogen

Singh *et al.* (2006) found that the application of 180 kg ha^{-1} of silicon increased nitrogen levels in the grain and straw of rice. Chanchareonsook *et al.* (2002) reported that application of NPK fertilizer in combination with Si significantly increased total N uptake of rice.

2.1.5.2. Phosphorous

Silicon improves the availability of P by blocking excessive Mn uptake, which can antagonize P uptake (Ma and Takahashi, 1990). Phosphorus contents in grain and straw were significantly increased due to Si application up to 180 kg Si ha^{-1} (Sing *et al.*, 2006).

Ma and Takahashi (1990) observed that there is a high phosphate uptake in rice with silicon application which directly correlates with the increased growth and yield.

2.1.5.3. Potassium

Positive response of higher silicon application towards potassium can be linked to silicification of cell wall. Chanchareonsook *et al.* (2002) reported that application of NPK fertilizer in combination with Si significantly increased total N, P and K uptake of rice.

Takijima *et al.* (1959) noticed an increase in the uptake of potassium by the application of Si. This is due to more absorption of Ca and Mg ions promoted by Si application. Significant improvements in potassium and zinc concentrations were recorded up to 120 kg Si ha^{-1} (Sing *et al.*, 2006).

Padmaja and Verghese (1972) found that percentage of potassium in the grain and straw was maximum in those treatments which included Si. Bridgit (1999) reported that application of Si at 250 kg ha^{-1} limited K removal by the crop within the level of application.

Additions of Si resulted in an increase in uptake of potassium possibly due to the stimulating effect of Si on K uptake which could be due to the activation of H-ATPase in the membranes (Liang, 1999).

2.1.5.4. Calcium and magnesium

Tsuno and Kasahara (1984) concluded that the large amount of Ca in the slag reduced the formation of silica bodies and resulted in an antagonism between Si and Ca. Addition of Si enhances Ca concentration in plant tissue and partially restores the membrane integrity and help in achieving better crop survival (Cachorro *et al.*, 1994).

Silicon application increases the uptake of Mg by rice (Islam and Saha, 1969; Takijima *et al.*, 1970).

2.1.5.5. Sulphur

Silicon application favourably influenced the sulphur uptake showing its synergistic effect with silicon application (Singh *et al.* 2006; Jawahar and Vaiyapuri, 2008).

2.1.5.6. Iron

Application of Si decreases the availability of Fe in flooded rice soils. Silicon enhances the oxidative power of rice roots, resulting in enhanced oxidation of Fe from ferrous iron to insoluble ferric iron (Okuda and Takahashi, 1962; Qiang *et al.*, 2012).

2.1.5.7. Manganese

Okuda and Takahashi (1962) reported that silicon alleviates the Mn toxicity in rice, Si reduced Mn uptake by promoting the Mn oxidizing power of the roots.

Marschner (1995) reported that with low silicon levels in tissue Mn^{2+} tends to be distributed non-homogenously and accumulates at toxic levels in leaves. Sufficient levels of Si prevent the toxic levels of Mn^{2+}.

2.1.5.8. Zinc

Significant improvement in zinc concentration was recorded up to 120 kg Si ha^{-1} (Sing *et al.*, 2006). Application of Si as sodium silicate increased the Zn content of root and shoot of rice as reported by Bridgit (1999).

2.1.5.9. Aluminum

There is a decrease in Al concentration in rice leaves with increased silicon application (Barbosa *et al.*, 2012).

2.1.6. Effect of silicon on plant growth parameters of rice

Ahmad *et al.* (2013) reported that increase in level of applied silicon enhanced the number of productive tillers and total number of tillers m^{-2}. Reduction in kernel sterility due to silicon application might be due to balanced nutrition, optimum metabolic activities or nullification of stresses. Gholami and

Falah (2013) reported that application of Si fertilizers enhanced the plant height, number of tillers per plant and number of productive tillers in rice crop.

Korndorfer and Gascho (1998) observed that both soil and plant parameters were significantly influenced by the Si sources and rates used. Difference in rice growth habit, plant height, drymatter yield and leaf coloration were more favorable in treatments containing calcium silicate, wollastonite and thermo phosphate, when compared to other sources.

Padmaja and Verghese (1966) found that application of sodium silicate as soil amendment in laterite soil increased the tillering, height of plants, depth of penetration of the root system and the proportion of thicker to thinner roots.

Sadanandan and Verghese (1968) reported that application of Si in laterite soil increased the tillering capacity and led to better root development in rice. They also found that application of sodium silicate performed better at the initial stage in increasing the number of tillers, but application of calcium magnesium silicate performed better at the later stages.

Ma *et al.* (1989) reported that the application of Si at various stages of rice increased the plant height and root dry weight. But Si applied at ripening stage has no effect on plant growth attributes.

Yamaguchi and Winslow (1989) found that dry matter production in rice was increased by the application of sodium silicate in highly weathered and leached ultisols of Nigeria. According to Tisdale *et al.* (1993), Si enhances top length, number of stems and fresh and dry weight of rice.

2.1.7. Effect of silicon on yield and yield attributes of rice

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

Gholami and Falah (2013) and Ahmad *et al.* (2013) reported that application of Si fertilizers enhanced the growth parameters, increased yield, yield attributes and quality of rice crop.

Ma *et al.* (1989) reported that when silicon was removed during the reproductive stage, the dry weights of straw and grain decreased by 20 and 50 %. They concluded that the supply of silicon during the reproductive stage is most important for plant growth.

Japanese farmers have increased and sustained average rice yield up to 6 t ha^{-1} (IRRI, 1993). This could be due to adoption of a balanced integrated nutrient management that includes Si fertilization. Yield increase of 10-20 % was common when Si was added and may exceed 30 % or more when leaf blast was severe (Savant *et al.*, 1997).

Research conducted in 16 provinces of China during 1979-1999 showed yield increases from 0 to 400 %, due to silicon application depending on the severity of Si deficiency (Wang *et al.*, 2004).

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, 1995) and the mass of grains (Balastra *et al.*, 1989).

Silicon and boron significantly improved kernel weight, biological yield, protein content and starch content in grain (Ahmad *et al.*, 2013).

2.1.8. Interaction of silicon with other nutrient elements

Silicon was found to have positive interaction with the applied nitrogenous (N), phosphatic (P) and potassic (K) fertilizers.

Idris *et al.* (1975) reported that application of silicon significantly increased the rigidity of rice stalk and this increase was remarkably higher at lower doses of nitrogen. The larger quantities of nitrogen greatly reduced the efficiency of silicon in imparting rigidity to plants.

The rice yields are declining due to the excessive application of nitrogenous fertilizers. But the application of Si has the potential to raise the optimum N rate due to synergistic effect, thus enhancing the productivity of low land rice soils (Ho *et al.*, 1980).

Fertilizing with excessive N tends to make rice leaves droopy, whereas Si keeps them erect. Yoshida (1981) reported a 10 percent increase in the photosynthetic rate due to improved erectness of leaves by proper silicon management and consequently a similar increase in yield.

Nitrogen is essential for plant growth and development, and is often a limiting factor for high productivity. However, when applied in excess it may limit yield because of lodging, especially for cultivars of the traditional and intermediate groups, and promote shading and disease problems. These effects could be minimized by the use of silicon (Ma *et al.*, 2001a).

Silicon and nitrogen interaction was found to be non significant in obtaining higher yield of rice. But increased application of Si and N alone resulted in significant increase in yield attributes (Singh and Singh, 2005; Singh *et al.*, 2006).

Barbosa *et al.* (2012) observed that soils with high levels of toxic Al can cause damage to plants and consequently decrease yield. Silicon is a good alternative to reduce the toxicity of Al in these soils.

The maximum N, P, K, S and Si uptake in rice was noticed with 45 kg S ha^{-1} and 120 kg Si ha^{-1} (Wani *et al.*, 2000).

2.2. BORON

Boron is a nonmetal micronutrient. It is required for rice from start till physiological maturity. Being mobile in soils, it can be leached down the soil profile with excess moisture. The range of B deficiency and toxicity is narrow. Deficiency occurs at <0.5 mg kg^{-1} hot water soluble B while toxicity could occur at >5.0 mg kg^{-1} (Rashid *et al.*, 2004). Critical level of deficiency of B in rice at tillering to panicle initiation is <5 mg kg^{-1} (Dobermann and Fairhurst, 2000). The critical limit of B in third leaf of rice plant is 12 mg kg^{-1} (Debnath and Ghosh, 2012).

2.2.1. Boron in plant nutrition

The boron requirement is much higher for reproductive growth than for vegetative growth in most plant species. Hence the reproductive stage is known as a sensitive period to low B stress (Uraguchi *et al.*, 2011). Boron is associated with a wide range of morphological alterations, tissue differentiation, pollen germination and metabolite transfer which will greatly influence the yield and productivity (Rao *et al.*, 2013). The main functions of B in plant relate to sugar transport, flower production, retention, pollen tube elongation and germination, translocation of carbohydrate and sugars to reproductive organs, all of which improves the spikelet number and fertility that influences the yield and productivity (Ahamad *et al.*, 2009).

Boron is responsible for better pollination, seed setting, low spike sterility and more grain formation in different varieties of rice (Aslam *et al.*, 2002). Boron application at very low rate substantially improved seedling emergence, tillering, chlorophyll, water relations and yield related traits resulting in better yield and grain B contents. Boron application at higher level adversely affected chlorophyll pigments (Rehman *et al.*, 2012).

2.2.2. Boron availability in soil

Boron uptake correlated well with the concentration of H_3BO_3 in soil solution. Leaf boron increased in a linear fashion as the concentration of the nutrient in soil solution increased (Tariq *et al.*, 2005). Gupta (1979) reported that the deficient levels of boron are associated with plant disorders and or reductions in the yield of crops. Available B is derived from decomposition of organic matter and release from clay minerals. The H_3BO_3 form of B is highly mobile in the soil (Dunn *et al.*, 2005). Soil application of boron leads to fixation and unavailability (Rao *et al.*, 2013). Boron is immobile in plant. Deficiency symptoms of B in rice begin with a whitish discoloration and twisting of new leaves. Severe deficiency symptoms in rice include thinner stems, shorter and fewer tillers, death of growing point and failure to produce viable seeds (Dunn *et al.*, 2005).

Young soils and marine sediments are generally rich in B. Boron may also get accumulated in alkaline soils even to levels which are toxic to plants. Highly weathered soils in humid areas are often absolutely low in B and crops on these soils may suffer from B deficiency (Ellis *et al.*, 1982). On such sites B can be easily leached out of the root zone. The soluble B in soils is mainly present in the form of boric acid $B(OH)_3$ or as $B(OH)_4$. The later anion is formed under alkaline pH conditions.

The anion is adsorbed by Al/Fe oxides and clay minerals and the adsorption is strong with higher soil pH (Goldberg and Forster, 1991). It is for this reason that B deficiency in crop frequently occurs on clay soils high in pH. On sandy soils a substantial portion of B is bound as ester to soil organic matter (Goldberg and Glaubig, 1986).

Boron deficiency can occur in highly weathered red acid soils, sandy rice soils, and soils derived from igneous rocks. Rice plants were unable to produce panicles if affected by B deficiency at the panicle formation stage (Doberman and Fairhurst, 2000).

In soils, B is considered to be the most mobile and often deficient element compared to other trace elements. The availability of soil B depends on soil texture, pH, liming, organic matter content, soil moisture and relationship with certain cations and anions in soils (Tisdale *et al.,* 1985).

Rice, when grown on a wide range of soil types such as calcareous, clayey laterite, acid, *etc.* with varying soil pH levels, boron availability, uptake and mobilization become limiting leading to reduced productivity and poor rice yields (Rao *et al.*, 2013).

B is generally applied through broadcasting and mixing into the soil prior to sowing or before transplanting the crop (Yermiyahu *et al.,* 2001; Singh *et al.*, 2005). Band placement of B can lead to B toxicity in plants when it is applied in excess, or if it is placed too close to seedlings or shoots. Therefore, B should neither be placed in contact with seed or seedlings, nor should excessive doses be used because of potential toxicity problems. Regular use of higher doses of B can lead to its toxicity in crop plants. Optimum doses of B for light textured entisols ranged between 0.5 and 1.0 kg B ha^{-1} (Singh, 2006). Also Dangarwala (2001) reported that optimum requirement of B for wheat and rice were found to be between 0.75 and 1.5 kg B ha^{-1}.

2.2.3. Effect of boron on nutrients availability in soil

2.2.3.1. Macronutrients

Barman *et al.* (2014) observed that application of boron (20 mg kg^{-1}) and lime (1/3 LR) significantly increased N, P, K, Ca, Mg, S and Zn content in soil while the availability of Cu, Fe and Mn in soil was reduced due to application of boron and lime.

2.2.3.2. Micronutrients

Santra *et al.* (1989) conducted an experiment to study the influence of applied boron on the changes of DTPA-extractable Fe, Mn, Cu and Zn in lowland rice soil. Extractable Fe and Mn decreased with the application of boron while Cu and Zn increased.

2.2.4. Effect of boron on content and uptake of nutrients in rice

Two principal methods of applying B are soil application and foliar spraying. Soil applications of B are made through broadcasting or in bands. Touchton and Boswell (1975) reported that band or foliar applied B in corn resulted in greater B uptake in plants than B applied by broadcast. Early foliar application results in greater absorption of B than when applied at later stages of growth (Gupta and Cutcliffe, 1972; 1975).

Mortvedt *et al.* (1991) stated that early-morning foliar applications of nutrients may result in increased absorption, as the relative humidity is high, the stomata are open, and photosynthesis is taking place. B up to 0.25 mg kg^{-1} increased dry matter yield and nutrient uptake in rice (Rakshit *et al.*, 2002).

Increase in B application levels increased the B concentration in shoots of rice (Debnath and Ghosh, 2012).

2.2.4.1. Macronutrients

Application of boron increases the N and K uptake in rice (Rakshit *et al.*, 2002). In plants N, K, Ca, Mg and S concentration significantly increased with application of boron (20 mg kg^{-1}) and lime (1/3 LR) (Barman *et al.*, 2014).

Application of boron had no effect on NPK concentration and uptake in straw and grain (Ghatak *et al.*, 2006). Yu and Bell (2002) reported that the application of boron at tillering significantly increased Ca and Mo in new leaves while it decreased Cu, Fe, K and S content. They also observed that boron application at flowering increased K concentration and decreased Ca concentration in rice plant.

Kabir *et al.* (2007) stated that application of B at 2 kg ha^{-1} produced highest straw and grain yield and maximum uptake of N, P and K nutrients by rice plants.

2.2.4.2. Micronutrients

Barman *et al.* (2014) reported that application of boron (20 mg kg^{-1}) and lime (1/3 LR) reduced Cu, Fe and Mn concentration in rice plant.

Bhutto *et al.* (2013) concluded that application of Zn and B at the doze 10 and 2 kg ha^{-1} to rice in addition to recommended doses of N and P improved the nutritional contents within grains. Barman *et al.* (2014) reported a positive relationship between Zn concentration in the plant and application of boron (20 mg kg^{-1}) and lime (1/3 LR).

2.2.5. Effect of boron on plant growth parameter of rice

Debnath *et al.* (2009) reported that the application of 1.5 kg B ha^{-1} increased the plant height, number of tillers, dry weight and spikelet sterility. Several studies conducted reported that application of boron to rice reduced panicle sterility and enhanced the yield (Jana *et al.*, 2005, Rashid *et al.*, 2006 and Hussain *et al.*, 2012).

Rice receiving soil applied boron produced significantly greater yields than rice with foliar applied B (Dunn *et al.*, 2005). Since the soil applied treatments were made at planting as compared to foliar treatments at early tiller stage, soil applied B may have helped early vegetative growth and promoted tillering.

Foliar application of boron increased photosynthetic rate and grain filling rate and decreased respiration rate in rice (Yu *et al.*, 2002).

The effects of B spray on plant growth parameters were much greater for hybrid than the conventional rice cultivar. At maturity, the single grain weight and grain yield were significantly increased. Boron spray in combination with Zn and other nutrient management at the late stage of rice growth increases grain yield and improves grain Zn content in rice cultivars (Aslam *et al.*, 2002; Yu *et al.*, 2002).

Shafiq and Maqssod (2010) reported that application of boron at different levels increased panicle weight, 1000 grain weight and yield. Ahmad and Irshad (2011) observed that application of boron @ 1 kg ha^{-1} significantly increased number of tillers $plant^{-1}$, plant height, panicle length, number of grain per panicle, 1000 grain weight and paddy yield.

2.2.6. Effect of boron on yield and yield attributes of rice

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).

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 (Rao *et al.*, 2013).

Hussain *et al.* (2012) reported that soil applied boron (1.5 kg ha^{-1}) and foliar applied (1.5 % B) at different stages substantially improved the rice growth and yield. However, soil application was better in improving the number of grains per panicle, 1000-grain weight, grain yield and harvest index.

In rice, positive crop responses to B application were initially observed by Chaudhry *et al.* (1977) in cvs. Basmati-370 and IR-6 grown in major rice growing areas of Punjab with a mean paddy yield increase of 14 %. Yield increases with B was because of reduced panicle sterility (on lower portion of the ear) and increased productive tillers per hill. Post-harvest grain shedding also reduced with improved B nutrition. Optimum B dose for effective management of B deficiency in rice is 0.75 kg ha^{-1} (Rashid *et al.*, 2004).

On an average of five years (1998-2002), B application @ 1 kg ha^{-1} produced the highest paddy yield of 4285 kg ha^{-1}, which was significantly higher than NPK + Zn, NPK and control (Rashid *et al.* 2004). Similar results were reported by Ali *et al.* (1996) and Rashid *et al.* (2002).

Garg *et al.* (1979) reported that under sand cultures for rice plant, up to 2.5 mg L^{-1} of boron content in nutrient solution can increase the yield of rice grain by improving the pollen vitality of rice flower, but inhibitory effects appeared beyond 5 mg L^{-1} of boron content. Lewis (1980) reported that for pollen tube growth, high B levels in the stigma and style are required. The viability of pollen grains is also severely inhibited by B deficiency.

In Pakistan, the soil B contents are reported to be a key determinant in rice yields, and B is supplied as fertilizers to maintain sufficient yields. B deficiency also delays flowering in rice (Rashid *et al.*, 2000).

Singh *et al.* (2005) reported that percent response of boron over NPK controls in rice is 16.6 %. Red lateritic soils (Alfisols) are highly deficient in boron, so application of 0.5-2.0 kg B ha^{-1} increased the rice yield by 460-1500 kg ha^{-1} (12.5-37.2 %) over controls (Sakal, 2001). Response of rice for B was greater in rabi than in kharif (Datta *et al.*, 1992). The results of 19 field trials in deltaic alluvial soils in Assam revealed that application of 2 kg B ha^{-1} to rice increased the grain yield significantly by 180-460 kg ha^{-1} (25.2-39 %) and that of the following wheat crop by 230-320 kg ha^{-1} (23.1-35.8%) (Sakal *et al.*, 2002).

Frequency of B application depends upon doses of B applied and the nature of the crop. Regular application of more than 2 kg B ha^{-1} caused adverse effects on the growth and yield of crops (Singh *et al.*, 2005).

Boron fertilization in soil deficient situations not only enhances yield of crops but, the quality of grains is also improved. This implies, apart from causing yield reductions; inadequate B supply to plants may also deteriorate the quality of the crop produce and hence, will lower the price of grain produced from B deficient situations (Rashid *et al.*, 2004).

Senescence of flag leaf was greatly delayed by foliar application of B as well as also reflected in significant increase of photosynthetic rate, grain filling rate and decrease of respiration rates (Yu *et al.*, 2002).

As fertilizer boron dosage for correcting the deficiency is very small (0.75kg B ha^{-1}) and crop yield increases with B applications are appreciable, its use is highly cost-effective. 16 % yield increase of paddy over control was observed with the 1 kg ha^{-1} level of boron (Hussain and Yasin, 2004).

Rashid *et al.* (2002) reported an increase of 5 to 26 % in rice yield with B application. Ali *et al.* (1996) reported an increase in paddy grain yield due to B application to the tune of 34.6 % and 19 % at 2.0 kg B ha^{-1} on Miranpur and Satgara soils, respectively.

In addition to its adverse effect on grain set, B deficiency also depressed grain filling and weight of individual grains in rice. The variation in grain weight was closely associated with grain set and number of spikelets. Grain set was closely related to pollen viability, and both were increased with increasing anther B concentration at >20 mg B kg^{-1} (Lordkaew *et al.*, 2013).

Khan *et al.* (2006) reported that highest yield was obtained with application of 2 kg B ha^{-1} to rice crop. The number of spikes, number of spikes per plant, spike length, plant height and 1000 grain weight of paddy were significantly increased. The application of boron significantly increased the boron content of leaves of rice crop (Khan *et al.*, 2006).

Mehmood *et al.* (2009) reported that highest grain and straw yield was obtained by application 1.5 kg B ha^{-1} in saline and saline sodic soils.

2.2.7. Interaction of boron with other nutrient elements

Hussain and Yasin (2004) reported that application of Zn (5 kg ha^{-1}) + B (2 kg ha^{-1}) in rice-wheat system increased the yield by 10 %.

Bhutto *et al.* (2013) observed that application of Zn and B at the dose 10 and 2 kg ha^{-1} in addition to recommended doses of N and P to rice crop imparts better nutritional contents within grains (Bhutto *et al.*, 2013).

Santra *et al.* (1989) observed an antagonistic effect of boron with Fe and Mn and synergistic effect with Cu and Zn in relation to their changes in the soils.

The interactive effect of silicon at 1.5 % and boron at 1 % has significantly improved kernels weight, biological yield, protein content and starch content in rice (Ahmad *et al.*, 2013).

MATERIALS AND METHODS

3. MATERIALS AND METHODS

An investigation was carried out at College of Agriculture, Padannakkad to study the silicon and boron nutrition of rice (*Oryza sativa* L.) in wet land soils of northern Kerala.

The whole investigation was carried out as two experiments, a pot culture experiment at College of Agriculture, Padannakkad and a field experiment in farmer's field at Karivellur.

The investigations include:

- Collection of soil samples and analysis of physical and chemical properties.
- Standardizing the dose and method of application of silicon and boron fertilizers to rice crop.
- Pot culture experiment and field experiment to evaluate the effect of Si and B on available nutrient status of soil and yield of rice.
- Evaluation of the effect of silicon in alleviating the toxicity of Fe, Mn and Al.

The experiment details with special reference to the materials used and methods adopted are discussed in this chapter.

3.1. COLLECTION OF SOIL SAMPLES

Soil samples for initial analysis were collected from the prepared field of field experiment and from the field where soil was collected for pot culture experiment. Soil sample were drown from surface 15 cm from 10 different places of the field, pooled, reduced to required quantity and air dried. The air dried soil samples were ground and passed through 2 mm sieve and stored in air tight containers.

The samples were analyzed for bulk density, particle density, porosity, texture, pH, EC, cation exchange capacity, organic carbon, available nutrients such as N, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn, Al, Si and B following standard procedures given in Table 1. The soil analysis data is presented in Table 2.

Table 1. Analytical methods followed in soil analysis

S. No.	Parameter	Method	Reference
1	Bulk density	Undisturbed core sample	Black *et al.* (1965)
2	Particle density	Pycnometer method	Black *et al.* (1965)
3	Porosity	-	Black *et al.* (1965)
4	Textural analysis	International pipette method	Robinson (1922)
5	Electrical conductivity	Conductivity meter	Jackson (1958)
6	pH	pH meter	Jackson (1958)
7	Organic carbon	Chromic acid wet digestion method	Walkley and Black (1934)
8	Available N	Alkaline Permanganate method	Subbaiah and Asija(1956)
9	Available P	Bray extraction and photoelectric colorimetry	Jackson (1958)
10	Available K	Flame photometry	Pratt (1965)
11	Available Ca	Atomic absorption spectroscopy	Jackson (1958)
12	Available Mg	Atomic absorption spectroscopy	Jackson (1958)
13	Available S	Photoelectric colorimetry	Massoumi and Cornfield (1963)
14	Available Fe	Atomic absorption spectroscopy	Sims and Johnson (1991)
15	Available Cu	Atomic absorption spectroscopy	Emmel *et al.* (1977)
16	Available Mn	Atomic absorption spectroscopy	Sims and Johnson (1991)
17	Available Zn	Atomic absorption spectroscopy	Emmel *et al.* (1977)

Table 1. Continued...

S. No.	Parameter	Method	Reference
18	Exchangeable Al	Atomic absorption spectroscopy	Willis (1965)
19	Available Si	Photolectric colorimetry	Korndorfer *et al.* (2001)
20	Available B	Photoelectric colorimetry	Gupta (1967)

Table 2. Physico-chemical properties of the soil

S.No.	Parameter	Pot culture experiment	Field experiment
I	Physical Properties		
1	Bulk Density (g cc^{-1})	1.23	1.35
2	Particle Density (g cc^{-1})	2.64	2.53
3	Pore space (%)	53.5	46.7
II	Mechanical Composition		
1	Sand (%)	50	76
2	Silt (%)	5.5	5.5
3	Clay (%)	44.5	18.5
4	Texture	Sandy Clay	Sandy Loam
III	Chemical Parameters		
1	pH	4.7	4.7
2	Electrical Conductivity (dsm^{-1})	0.16	0.12
3	Cation Exchange Capacity (meq/100g)	7.5	7.25
4	Organic carbon (%)	0.036	0.033
5	Organic matter (%)	0.062	0.056
6	Available Nitrogen (kg ha^{-1})	200.88	220.88
7	Available Phosphorus (kg ha^{-1})	15.68	61.6

Table 2. Continued...

S.No.	Parameter	Pot culture experiment	Field experiment
8	Available Potassium (kg ha^{-1})	152.32	58.56
9	Available Calcium (mg kg^{-1})	1114	261.75
10	Available Magnesium (mg kg^{-1})	45	17.97
11	Available Sulphur (mg kg^{-1})	25	13.25
12	Available Iron (mg kg-^{1})	78.2	144.2
13	Available Manganese (mg kg^{-1})	31.5	21.85
14	Exchangeable Aluminum (mg kg^{-1})	320	135.5
15	Available Zinc (mg kg^{-1})	3.73	2.65
16	Available Copper (mg kg^{-1})	2.98	1.26
17	Available Boron (mg kg^{-1})	0.17	0.16
18	Available Silicon (mg kg^{-1})	24	20.5

3.2. POT CULTURE EXPERIMENT

A pot culture experiment was conducted at College of Agriculture, Padannakkad to standardize the dose and method of application of silicon and boron to rice crop in laterite derived paddy soils, its effect on available nutrient status of soil and yield, and to study the effect of silicon in alleviating the toxicity of Fe, Mn and Al in laterite derived paddy soils.

3.2.1. Experimental details

The details of the experiment are presented below:

Number of treatments: 9

T_1 - Control- No Si and B.

T_2 - Calcium silicate @ 4 g kg^{-1} soil

T_3 - Potassium silicate @ 0.5% spray 3 rounds

T_4 - Borax @ 0.5 g kg^{-1} soil

T_5 - Borax 0.5% foliar spray 3 rounds

T_6 - Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil

T_7 - Calcium silicate @ 4 g kg^{-1} soil + borax 0.5% spray 3 rounds

T_8 - Potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds

T_9 - Potassium silicate @ 0.5% spray 3 rounds + borax @ 0.5g kg^{-1} soil

Replications - 3

Design: CRD

Variety: Aishwarya

Composition of silicon and boron sources used are detailed below:

Calcium silicate - 19 % Si, 20.2 % Ca.

Potassium silicate - 45 % Si, 17 % K.

Borax - 11 % B.

The layout of the pot culture experiment is shown in Fig.1.

3.2.2. Soil

Soil for pot culture experiment was collected from the paddy fields where field experiment was laid out rice growing area at Karivellur. 10 kg of soil was taken and filled in each pot for conducting pot culture experiment. The experimental soil was sandy clay with pH 4.7 belonging to the taxonomical order Inceptisol.

3.2.3. Transplanting

After the application of lime, pots were maintained at water level of 1.5 cm during transplanting and there after increased gradually to about 5 cm until maximum tillering stage. 4-5 seedlings were transplanted in each pot at a depth of 3-4 cm.

Fig.1 Layout of the pot culture experiment

T_1R_2	T_5R_1	T_7R_3
T_7R_2	T_8R_1	T_8R_2
T_2R_2	T_5R_2	T_5R_3
T_2R_3	T_8R_3	T_6R_2
T_3R_2	T_9R_3	T_9R_1
T_4R_2	T_2R_1	T_9R_2
T_3R_1	T_4R_1	T_6R_3
T_3R_3	T_1R_3	T_7R_1
T_4R_3	T_9R_1	T_1R_1

3.2.4. Fertilizer application

Fertilizers were applied as per package of practices recommendations (POP) of KAU (2011). Full dose of P and half the dose of N and K were applied as basal. Remaining N and K were applied at panicle initiation stage. The other cultural practices were adopted as per POP, KAU, 2011.

3.2.5. Collection of plant samples for analysis

The fully matured green leaves were collected from mature plants by cutting 10 cm above the soil surface. To minimize soil contamination, leaves and straw were washed in 0.2 % detergent, and thoroughly rinsed with DI water (Wallace *et al.*, 1980) prior to oven-drying (70°C; 24 h). Dried tissue samples were ground and passed through a 20-mesh screen. Ground samples were re-dried for 48 h (70°C) and placed in snap-cap vials, then stored in desiccators until use.

3.2.6. Analysis of plant samples

Plant samples were collected at harvest stage and analyzed for different macro and micro nutrients *viz.,* N, P, K, Ca, Mg, Fe, Cu, Mn, Zn, Si and B by standard procedures given in Table 3.

3.2.7. Chemical analysis of soil sample

Soil samples from each treatment was collected from surface 15 cm in plastic bags, excess water drained, air dried, ground, sieved with 2 mm sieve and stored in air tight container in laboratory until analysis. Soil samples were drawn at maximum tillering, flowering and harvest stages and analyzed for Si and B. Soil sample collected at harvesting stage was analyzed for available nutrients such as N, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn and Al by standard procedures which have been shown in Table 1.

Table 3. Analytical methods followed for plant analysis

S. No.	Parameter	Method	Reference
1	Total N	Modified kjeldhal method	Jackson (1958)
2	Total P	Vanodo molybdate yellow colour method	Piper (1966)
3	Total K	Flame photometry	Jackson (1958)
4	Total Ca and Mg	Atomic Absorption Spectroscopy	Issac and Kerber (1971)
5	Total S	Turbidimetric method	Bhargava and Raghupathi (1995)
5	Total Fe and Mn	Atomic Absorption Spectroscopy	Piper (1966)
6	Total Cu and Zn	Atomic Absorption Spectroscopy	Emmel *et al.* (1977)
7	Total B	Azomethen-H colorimetric method	Bingaham (1982)
8	Total Si	Blue silicomolybdous acid method	Ma *et al.* (2002)

3.2.8. Biometric observations

The following biometric observations were made in the pot culture experiment.

3.2.8.1. Plant growth parameters

3.2.8.1.1. Plant height

Plant height was measured from the base of the stem to the tip of the youngest leaf using a meter scale and expressed in cm. Plant height was noted at 30, 60, 90 days after transplanting (DAT) and harvest stages.

3.2.8.1.2. Number of tillers

The number of tillers per hill at 30, 60, 90 DAT and harvest stages were counted and recorded.

3.2.8.1.3. Number of Productive tillers

The number of productive tillers per plant was recorded at harvest stage.

3.2.8.2. Yield and yield attributes

3.2.4.8.1. Panicle weight

Panicle weight per plant was recorded at harvest stage and expressed in grams.

3.2.4.8.2. Thousand grain weight

One thousand grains were counted from the produce of each pot and their weight was recorded and expressed in grams.

3.2.4.8.3. Grain and straw yield

The crop harvested from each pot was threshed separately and grain and straw weight was recorded and expressed as grain and straw yield in grams.

3.3. FIELD EXPERIMENT

A field experiment was conducted in farmer field at Karivellur to standardize the dose and method of application of silicon and boron to rice crop in laterite derived paddy soils and to study its effect on available nutrient status of soil, yield and alleviation of the toxicity of Fe, Mn and Al.

3.3.1. Location

The field experiment was laid out in farmers filed at Karivellur. It is geographically located at12.1°N latitude, 5.2°E longitude and at an altitude of 16 m above mean sea level, having a humid tropical climate.

3.3.2. Soil

The soil of experimental site was sandy loam belonging to the taxonomical order Inceptisol.

3.3.3. Land preparation

The experimental area was ploughed well and plots of 4 m x 2 m were prepared by constructing bunds of 30 cm width and height. Irrigation and drainage channels were provided between each plot.

3.3.4. Transplanting

After the application of lime on the surface of soil, it was irrigated and water level maintained at 1.5 cm during transplanting and thereafter increased gradually to about 5 cm until maximum tillering stage. 18 days old seedlings were transplanted at 3-4 cm depth at a spacing of 20 cm x 15 cm.

3.3.5. Fertilizer application

Fertilizers were applied as per package of practices recommendations (POP) of KAU (2011). Full dose of P and half the dose of N and K were applied as basal. Remaining N and K were applied at panicle initiation stage. The other cultural practices were followed as per POP of KAU (2011).

3.3.6. Experimental details

The experimental plot was divided into three blocks of nine plots each and treatments were applied. The treatments details are presented below.

Number of Treatments- 9

T_1 - Control- No Si and B.

T_2 - Calcium silicate @ 100 kg Si ha^{-1}

T_3 - Potassium silicate @ 0.5% spray 3 rounds

T_4 - Borax @ 10 kg ha^{-1}

T_5 - Borax 0.5 % foliar spray 3 rounds

T_6 - Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1}

T_7 - Calcium silicate @ 100 kg Si ha^{-1} + borax 0.5% spray 3 rounds

T_8 - Potassium silicate @ 0.5% spray 3 rounds + borax 0.5% spray 3 rounds

T_9 - Potassium silicate @ 0.5% spray 3 rounds + borax 10 kg ha^{-1}

Replications - 3

Design: RBD

Plot size: 4 m x 2 m

Variety: Aishwarya

Composition of silicon and boron sources used are detailed below:

Calcium silicate - 19 % Si, 20.2 % Ca.

Potassium silicate - 45 % Si, 17 % K.

Borax - 11 % B.

The layout of the field experiment is shown in Fig. 2.

Fig. 2 Layout of the field experiment

T_9R_1	T_7R_1	T_1R_1
T_8R_1	T_6R_2	T_4R_3
T_3R_1	T_1R_2	T_8R_3
T_7R_1	T_9R_2	T_5R_3
T_1R_1	T_4R_2	T_3R_3
T_2R_1	T_8R_2	T_7R_3
T_6R_1	T_3R_2	T_6R_3
T_5R_1	T_5R_2	T_9R_3
T_4R_1	T_2R_2	T_2R_3
BLOCK I	**BLOCK II**	**BLOCK III**

Plate 1. View of pot culture experiment at COA, Padannakkad

Plate 2. View of field experiment at Karivellur

3.3.7. Collection and analysis of plant samples

The fully matured green leaves were collected from mature plants by cutting 10 cm above the soil surface. To minimize soil contamination, leaves and straw were washed in 0.2 % detergent, and thoroughly rinsed with DI water (Wallace *et. al.*, 1980) prior to oven-drying (70°C; 24 h). Dried tissue samples were ground, passed through a 20-mesh screen. Ground samples were re-dried for 48 h (70°C) and placed in snap-cap vials, then stored in desiccators until use.

Plant samples were collected at harvest stage and analyzed for different macro and micro nutrients *viz.,* N, P, K, Ca, Mg, Fe, Cu, Mn, Zn, Si and B by standard procedures given in Table 3.

3.3.8. Chemical analysis of soil sample

Soil samples from each treatment plot was collected from surface 15 cm in plastic bags, excess water drained, air dried, ground, sieved with 2 mm sieve and stored in air tight container in laboratory until analysis.Soil samples drawn at maximum tillering, flowering and harvest stages were analyzed for Si and B. soil sample collected at harvesting stage was analyzed for available nutrients such as N, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn and Al by standard procedures which have been shown in Table 1.

3.3.9. Biometric observations

The following observations were made in the field experiment.

3.3.9.1. Plant growth parameters

3.3.9.1.1 Plant height

Plant height was measured from the base of the stem to the tip of the youngest leaf using a meter scale and expressed in cm. Plant height noted at 30,

3.3.7. Collection and analysis of plant samples

The fully matured green leaves were collected from mature plants by cutting 10 cm above the soil surface. To minimize soil contamination, leaves and straw were washed in 0.2 % detergent, and thoroughly rinsed with DI water (Wallace *et. al.*, 1980) prior to oven-drying (70°C; 24 h). Dried tissue samples were ground, passed through a 20-mesh screen. Ground samples were re-dried for 48 h (70°C) and placed in snap-cap vials, then stored in desiccators until use.

Plant samples were collected at harvest stage and analyzed for different macro and micro nutrients *viz.*, N, P, K, Ca, Mg, Fe, Cu, Mn, Zn, Si and B by standard procedures given in Table 3.

3.3.8. Chemical analysis of soil sample

Soil samples from each treatment plot was collected from surface 15 cm in plastic bags, excess water drained, air dried, ground, sieved with 2 mm sieve and stored in air tight container in laboratory until analysis.Soil samples drawn at maximum tillering, flowering and harvest stages were analyzed for Si and B. soil sample collected at harvesting stage was analyzed for available nutrients such as N, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn and Al by standard procedures which have been shown in Table 1.

3.3.9. Biometric observations

The following observations were made in the field experiment.

3.3.9.1. Plant growth parameters

3.3.9.1.1 Plant height

Plant height was measured from the base of the stem to the tip of the youngest leaf using a meter scale and expressed in cm. Plant height noted at 30, 60, 90 DAT and harvest stages from 10 plants in each treatment and average was worked out.

3.3.9.1.2. Number of tillers

The number of tillers per plant at 30, 60, 90 DAT and harvest stages were counted from 10 plants in each treatment and average was worked out.

3.3.9.1.3. Number of productive tillers

The number of productive tillers per plant was recorded at harvest stage from 10 plants in each treatment and average was worked out.

3.3.9.2. Yield and yield attributes

3.3.9.2.1. Panicle weight

Panicle weight per plant was recorded at harvest stage from 10 plants in each treatments and average was worked out and expressed in gram.

3.3.9.2.2. Thousand grain weight

One thousand grains were counted from the produce of each plot and their weight was recorded and expressed in grams.

3.3.9.2.3. Grain and straw yield

The crop harvested from each treatment plot was threshed separately and grain and straw weight was recorded and the grain and straw yield were computed and expressed in t ha^{-1}.

3.4. DETERMINATION OF SILICON IN SOIL AND PLANT SAMPLES

3.4.1. Determination of silicon in soil sample

3.4.1.1. Extraction of silicon in soils

5g soil was weighed in plastic centrifuge tube, and 12.5 ml of 0.5 M Acetic acid (1:2.5 ratio) was added (Korndorfer *et al.*, 1999). After shaking continuously for a period of one hour, it was centrifuged at 3000 rpm for 3 minutes and then filtered. Silicon in the extract was determined by adopting the procedure of Korndorfer *et al.* (2001).

3.4.1.2. Estimation of silicon in soils

Silicon in the extract was determined by transferring 0.25 ml of filtrate into plastic centrifuge tube followed by the addition of 10.5 ml of distilled water, 0.25 ml of 1:1 HCl and 0.5 ml of 10 % ammonium molybdate solution (pH 7-8). After 5 minutes 0.5 ml of 20 % tartaric acid solution was added, and after another 2 minutes 0.5 ml reducing agent ANSA (Amino Naphthol Sulphonic Acid) was added and color was developed. Absorbance was measured at 630 nm using UV visible spectrometer after 5 minutes. Simultaneously silicon standards (0.2, 0.4, 0.8 and 1.2 mgL^{-1}) were prepared, color was developed and measured using UV visible spectrometer (Korndorfer *et al.*, 2001).

3.4.2. Determination of silicon in plant sample

3.4.2.1. Plant sample digestion

Powdered leaves and straw samples were dried in an oven at 70^0C for 2 days prior to analysis. The sample (0.5 g) was digested in a mixture of 3ml each of HNO_3 (62 %) and H_2O_2 (30 %) and 2 ml of HF (46 %) using microwave digester (milestone MLS 1200) with following steps: 250 watts for 5 minutes, 500 watts 5 minutes and venting for 5 minutes. Then the digested samples were diluted to 50 ml with 4 % boric acid (Ma *et al.*, 2003).

3.4.2.2. Estimation of silicon in digested plant samples

Silicon concentration in the digested solution was determined as described below.

Digested 0.5 ml aliquot was transferred to plastic centrifuge tube. To this 3.75 ml of 0.2N HCl, 0.5 ml of 10 % ammonium molybdate solution, 0.5ml of 20 % tartaric acid solution and 0.5 ml reducing agent ANSA (Amino Naphthol Sulphonic Acid) were added and the volume was make up to 12.5 ml with distilled water. After 1 hour the absorbance was measured at 600 nm using UV visible spectrometer.

Simultaneously silicon standards (0, 0.2, 0.4, 0.8 and 1.2 ppm) were prepared in the same matrix and measured using UV visible spectrometer.

3.5. DETERMINATION OF BORON IN SOIL AND PLANT SAMPLES

3.5.1. Extraction and estimation of boron in soils

Crop response to boron was assayed by hot water extraction method as followed by Gupta (1967).

20 g of sieved air dried soil sample was weighed in a 250 ml boron free conical flask, 40 ml distilled water and 0.5 g of activated charcoal added and boiled on hot plate for 5 minutes. The contents was filtered immediately through Whatman no.42 filter paper and cooled to room temperature. 1 ml aliquot was transferred to 10 ml polypropylene tubes, 2 ml of buffer and 2 ml of azomethine-H reagent mix added and the absorbance was read at 420 nm after 30 minutes on a spectrometer.

Similarly standard B concentrations (0.1, 0.2, 0.4, 0.6, 0.8 and 1 ppm) were read using the same procedure.

3.5.2. Determination boron in plant sample

3.5.2.1. Ashing and extraction of the plant sample

Boron in plant sample was determined by dry ashing method followed by Gain and Mitchel (1979).

0.5 g air dried plant sample was weighed in a glazed paper, 0.1 g calcium oxide powder added, mixed well and transferred to porcelain crucible and placed in a muffle furnace. The temperature of the furnace was raised slowly to a maximum of 550°C and the contents ignited completely, cooled with water and covered with watch glass. 3 ml of dilute HCl (1:1) was added and heated on a water bath for 20 minutes. Finally the contents were transferred to 25 ml volumetric flask and volume was made up.

3.5.2.2. Estimation of boron in the plant digests

1ml of made up digest was transferred in to polypropylene tubes and 2 ml of buffer and 2 ml of azomethine-H reagent mix was added and the absorbance was measured after 30 minutes at 420 nm on a spectrometer (Binghum, 1982).

Similarly standard B concentrations (0.1, 0.2, 0.4, 0.6, 0.8 and 1 ppm) were measured using same procedure.

3.6. STATISTICAL ANALYSIS

The data obtained from pot culture and field experiments was subjected to statistical analysis using statistical analysis software (SAS) (Hatcher, 2003). The data after statistical analysis were used for comparison and interpretation of the results.

RESULTS

4. RESULTS

The results generated from the pot culture experiment and field experiments are presented in this chapter.

4.1. POT CULTURE EXPERIMENT

A pot culture experiment was conducted at College of Agriculture, Padannakkad, to standardize the dose and method of application of silicon and boron to rice crop in laterite derived paddy soils, its effect on available nutrient status of soil and yield, and to study the effect of silicon in alleviating the toxicity of Fe, Mn and Al in laterite derived paddy soils.

4.1.1. Available nutrient status of soil

4.1.1.1. Nitrogen

The results of available N content in soil are presented in Table 4. The available nitrogen content in soil ranged from 241.7 kg ha^{-1} (T_8) to 230.7 kg ha^{-1} (T_1). There was no significant difference between the treatments with respect to available nitrogen content in soil.

4.1.1.2. Phosphorous

The analytical data on available P content in soil is presented in Table 4. Application of calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (T_6) recorded the highest available phosphorous content in soil (33.84 kg ha^{-1}) which was significantly higher than T_4 (25.61 kg ha^{-1}), T_5 (24.92 kg ha^{-1}) and T_1 (19.38 kg ha^{-1}) and on par with other treatments.

4.1.1.3. Potassium

The results with respect to available K in soil are presented in Table 4. Highest available K in soil of 270.1 kg ha^{-1} was observed in T_8 (potassium silicate

@ 0.5% spray + borax 0.5% spray 3 rounds) which was on par with T_9 (266.0 kg ha^{-1}), T_3 (254.1 kg ha^{-1}) and these were significantly higher than other treatments.

Table 4. Effect of silicon and boron on availability of primary nutrients in soil

Treatments	Primary nutrients (kg ha^{-1})		
	N	P	K
Control- No Si and B (**T_1**)	230.7	19.38	202.8
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	241.0	31.60	223.0
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	232.6	28.17	254.1
Borax @ 0.5 g kg^{-1} soil (**T_4**)	236.0	25.61	215.0
Borax 0.5 % foliar spray 3 rounds (**T_5**)	235.3	24.92	217.4
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	240.4	33.84	220.4
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	239.3	29.09	231.7
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	241.7	31.84	270.1
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	238.3	28.00	266.0
CD (5 %)	NS	7.29	24.7

4.1.1.4. Calcium

The analytical results of available Ca content in soil with respect to various treatments are presented in Table 5. The highest available Ca content in soil was obtained in T_6 (1516 mg kg^{-1}) which was on par with T_7 (1489 mg kg^{-1}) and T_2 (1481 mg kg^{-1}) and significantly higher than all other treatments. This was followed by T_8 (1347 mg kg^{-1}) which was on par with the remaining treatments except control (1230 mg kg^{-1}).

4.1.1.5. Magnesium

Table 5 shows results of available Mg content in soil. The available magnesium content in soil ranged from 53.41 mg kg^{-1} (T_6) to 49.58 mg kg^{-1} (T_1).

There was no significant difference between the treatments with respect to available magnesium content in soil.

4.1.1.6. Sulphur

The results of available S content in soil are presented in Table 5. The available sulphur content in soil ranged from 31.66 mg kg^{-1} (T_8) to 28.83 mg kg^{-1} (T_1). There was no significant difference between the treatments with respect to available sulphur content in soil.

Table 5. Effect of silicon and boron on availability of secondary nutrients in soil

Treatments	Secondary nutrients (mg kg^{-1})		
	Ca	Mg	S
Control- No Si and B (**T_1**)	1230	49.58	28.83
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	1481	51.91	30.66
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	1315	51.98	29.58
Borax @ 0.5 g kg^{-1} soil (**T_4**)	1285	50.17	29.45
Borax 0.5 % foliar spray 3 rounds (**T_5**)	1291	50.25	29.12
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	1516	53.41	30.41
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	1489	52.58	30.08
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	1347	52.52	31.66
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	1313	51.41	30.25
CD (5 %)	76	NS	NS

4.1.1.7. Zinc and copper

The analytical results of available Zn and Cu with respect to various treatments are presented in Table 6. The available zinc content in soil ranged from 4.18 mg kg^{-1} (T_8) to 3.91 mg kg^{-1} (T_1). There was no significant difference between the treatments with respect to available zinc in soil.

The available copper content in soil ranged from 3.83 mg kg^{-1} (T_3) to 3.60 mg kg^{-1} (T_1). There was no significant difference between the treatments with respect to available copper content in soil.

Table 6. Effect of silicon and boron on availability of zinc and copper in soil

Treatments	Micronutrients (mg kg^{-1})	
	Zn	Cu
Control- No Si and B (**T_1**)	3.91	3.60
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	4.14	3.81
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	4.08	3.83
Borax @ 0.5 g kg^{-1} soil (**T_4**)	4.01	3.70
Borax 0.5 % foliar spray 3 rounds (**T_5**)	4.00	3.68
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg $^{-1}$ soil (**T_6**)	4.09	3.79
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	4.04	3.76
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	4.18	3.79
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	4.12	3.75
CD (5 %)	NS	NS

4.1.2. Effect of silicon and boron on content of Fe, Mn and Al in soil

4.1.2.1. Iron

The iron content of soil was estimated for various treatments and the results are shown in Table 7. There was a significant decline in available iron content in soil with the treatments in comparison to control (181.0 mg kg^{-1}). Lowest value were obtained in T_8 (120.0 mg kg^{-1}) which was on par with T_6 (121.0 mg kg^{-1}), T_7 (122.3 mg kg^{-1}), T_2 (135.0 mg kg^{-1}) and T_9 (136.3 mg kg^{-1}).

4.1.2.2. Manganese

The Mn content in soil as influenced by various treatments is presented in Table 7. All the treatments resulted in a significant reduction in available Mn content in soil when compared to control (38.20 mg kg^{-1}). (T_6) recorded lowest Mn content of 25.60 mg kg^{-1} which was on par with T_8 (25.70 mg kg^{-1}), T_3 (26.53) and T_2 (25.96 mg kg^{-1}). This was followed by T_7 (27.90 mg kg^{-1}) which was on par with T_9 (28.76 mg kg^{-1}).

4.1.2.3. Aluminium

The results with respect to Al content in soil is shown in Table 7. The treatments were capable of reducing Al levels in soil. The exchangeable Al content of soil was significantly reduced in all treatments when compared to control (340.6 mg kg^{-1}). Application of calcium silicate @ 4 g kg^{-1} soil (T_2) resulted in lowest exchangeable Al content of 227.6 mg kg^{-1} which was on par with T_8 (235.3 mg kg^{-1}), T_3 (248.0 mg kg^{-1}), T_6 (248.3 mg kg^{-1}) and T_7 (260.0 mg kg^{-1}).

Table 7. Effect of silicon and boron on content of Fe, Mn and Al in soil

Treatments	Micronutrients (mg kg^{-1})		
	Fe	Mn	Al
Control- No Si and B (T_1)	181.0	38.20	340.6
Calcium silicate @ 4 g kg^{-1} soil (T_2)	135.0	25.96	227.6
Potassium silicate @0.5% spray 3 rounds(T_3)	139.6	26.53	248.0
Borax @ 0.5g kg^{-1} soil (T_4)	178.3	36.26	290.3
Borax 0.5 % foliar spray 3 rounds (T_5)	170.0	35.76	304.0
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (T_6)	121.0	25.60	248.3
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5% spray 3 rounds (T_7)	122.3	27.90	260.0
Potassium silicate @ 0.5 % spray + borax 0.5% spray 3 rounds (T_8)	120.0	25.70	235.3
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (T_9)	136.3	28.76	264.6
CD (5 %)	17.3	1.16	36.1

Table 8. Effect of silicon and boron on silicon content in soil at different stages of rice

Treatments	Silicon (mg kg^{-1})		
	Maximum tillering stage	Flowering stage	Harvesting stage
Control- No Si and B (**T_1**)	25.00	25.25	23.91
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	26.08	44.58	37.66
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	27.50	35.25	32.83
Borax @ 0.5 g kg^{-1} soil (**T_4**)	26.08	27.08	25.66
Borax 0.5 % foliar spray 3 rounds (**T_5**)	26.41	27.83	26.16
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	27.50	43.75	38.50
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	26.25	43.00	36.25
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	26.08	32.08	27.83
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	25.91	33.33	29.91
CD (5 %)	NS	5.03	5.82

4.1.3. Silicon content in soil at different stages

The results of Si content in soil at different stages are presented in Table 8. The treatments could not show any significant effect on silicon content at maximum tillering stage. The silicon content in soil increased from maximum tillering stage to flowering stage.

At flowering stage highest available silicon content in soil of 44.58 mg kg^{-1} was recorded with the application of calcium silicate @ 4g kg^{-1} soil (T_2) which was on par with T_6 (43.75 mg kg^{-1}), T_7 (43.00 mg kg^{-1}) and significantly higher than the other treatments.

The silicon content in soil decreased from flowering stage to harvesting stage. At harvesting stage highest silicon content of 38.50 mg kg^{-1} was noticed in

T_6 (calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil) which was on par with T_2 (37.66 mg kg^{-1}), T_7 (36.25 mg kg^{-1}), T_3 (32.83 mg kg^{-1}) and significantly higher than T_9 (29.91 mg kg^{-1}), T_8 (27.83 mg kg^{-1}), T_5 (26.16 mg kg^{-1}) and T_4 (25.66 mg kg^{-1}). Control recorded lowest value of 23.91 mg kg^{-1}.

Table 9. Effect of silicon and boron on boron content in soil at different stages of rice

Treatments	Boron (mg kg^{-1})		
	Maximum tillering stage	Flowering stage	Harvesting stage
Control- No Si and B (**T_1**)	0.220	0.230	0.207
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	0.230	0.287	0.250
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	0.237	0.270	0.260
Borax @ 0.5 g kg^{-1} soil (**T_4**)	0.237	0.553	0.320
Borax 0.5 % foliar spray 3 rounds (**T_5**)	0.237	0.347	0.307
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	0.267	0.587	0.327
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	0.240	0.357	0.287
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	0.233	0.287	0.260
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	0.230	0.467	0.213
CD (5 %)	NS	0.046	0.079

4.1.4. Boron content in soil at different stages

The analyzed data on boron content in soil as influence by various treatments is given in Table 9. The treatments did not show any significant effect on boron content at maximum tillering stage. The available boron content of soil increased from maximum tillering stage to flowering stage. T_6 gave the highest value of 0.587 mg kg^{-1} which was on par with T_4 (0.557 mg kg^{-1}) and significantly higher than all other treatments. From the flowering stage to harvesting stage there was a decrease in available boron content in all the treatments.

Highest available boron content at harvesting stage was obtained in T_6 (0.327 mg kg^{-1}) which was on par with T_4 (0.320 mg kg^{-1}), T_5 (0.307 mg kg^{-1}), T_7 (0.287 mg kg^{-1}), T_3 (0.260 mg kg^{-1}), T_8 (0.260 mg kg^{-1}) and T_2 (0.250 mg kg^{-1}) and significantly more than T_9 (0.213 mg kg^{-1}) and T_1 (0.207 mg kg^{-1}).

Table. 10. Effect of silicon and boron on the nitrogen content in straw, grain and total uptake of by plant

Treatments	N content (%)		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	0.98	0.56	0.62
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	1.40	1.20	1.61
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	1.37	1.21	1.49
Borax @ 0.5 g kg^{-1} soil (**T_4**)	1.35	1.00	1.34
Borax 0.5 % foliar spray 3 rounds (**T_5**)	1.35	1.03	1.36
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	1.43	1.26	1.95
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	1.40	1.23	1.71
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	1.59	1.33	2.32
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	1.43	1.19	1.55
CD (5 %)	0.15	0.26	0.22

4.1.5. Nutrient content in straw, grain and total uptake

4.1.5.1. Nitrogen

The experimental results with respect to nitrogen content and uptake are presented in Table 10. The N content in straw varied from 1.59 % in T_8 (potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds) to 0.98 % in control. T_8 gave significantly higher value than all other treatments.

Highest N content in grain was also recorded for the same treatment T_8 with 1.33 % which was on par with T_6 (1.26 %), T_7 (1.23 %), T_3 (1.21 %), T_2 (1.20 %), T_9 (1.19 %) and these values were significantly higher than control as well as other treatments.

The total uptake of N was maximum in T_8 (2.32 g pot^{-1}) which was significantly more than all other treatments. This was followed by T_6 (1.95g pot^{-1}) which was significantly higher than remaining treatments.

Table. 11. Effect of silicon and boron on the phosphorous content in straw, grain and total uptake by plant

Treatments	P content (%)		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	0.085	0.083	0.066
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	0.123	0.133	0.156
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	0.122	0.130	0.143
Borax @ 0.5 g kg^{-1} soil (**T_4**)	0.114	0.114	0.128
Borax 0.5 % foliar spray 3 rounds (**T_5**)	0.120	0.119	0.136
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	0.132	0.140	0.194
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	0.123	0.138	0.168
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	0.140	0.153	0.229
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	0.127	0.133	0.152
CD (5 %)	0.013	0.012	0.013

4.1.5.2. Phosphorous

The P content in straw was significantly influenced by the treatments, results are presented in Table 11. The highest values for straw was 0.140 % in T_8 which was on par with T_6 (0.132 %), T_9 (0.127 %) and significantly more than all other treatments. With respect to grain T_8 (0.153 %) was significantly superior to all other treatments. This was followed by T_6 (0.140 %) which was on par with T_7 (0.138 %), T_2 (0.133 %), T_9 (0.133 %) and T_3 (0.130 %).

The total uptake of P also followed the same trend with T_8 recording the maximum uptake of 0.229 g pot^{-1} which was significantly more than all other treatments. Among the remaining treatments T_6 (0.194 g pot^{-1}) gave maximum P uptake which was significantly higher than the rest of the treatments.

Table. 12. Effect of silicon and boron on the potassium content in straw, grain and total uptake by plant

Treatments	K content (%)		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	3.20	0.19	1.47
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	4.80	0.39	3.53
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	5.13	0.40	3.47
Borax @ 0.5 g kg^{-1} soil (**T_4**)	4.50	0.27	2.97
Borax 0.5 % foliar spray 3 rounds (**T_5**)	4.60	0.33	3.12
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	5.06	0.40	4.35
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	4.70	0.34	3.63
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	5.16	0.45	4.90
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	5.16	0.44	3.65
CD (5 %)	0.06	0.04	0.07

4.1.5.3. Potassium

The results of K content in straw, grain and total uptake per pot are presented in Table 12. The K content in straw was maximum in T_8 and T_9 with 5.16 % which was on par with T_3 (5.13 %) and significantly higher than other treatments. All the treatments were superior to control.

Highest K content in grain was recorded with the application of potassium silicate @ 0.5 % spray + borax 0.5% spray 3 rounds (T_8) with 0.45 % which was on par with T_9 (0.44 %) and significantly higher than all other treatments. This was followed by T_3 (0.40 %) and T_6 (0.40 %) were superior to the remaining treatments.

The total K uptake range from 1.47 g pot^{-1} (T_1) to 4.90 g pot^{-1} (T_8). T_8 (potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds) registered significantly higher K uptake than all other treatments. This was followed by T_6 (4.35 g pot^{-1}) which was superior to the remaining treatments.

4.1.5.4. Calcium

Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8) significantly increased calcium content in straw (2147 mg kg^{-1}) compared to all other treatments except T_9 (2138 mg kg^{-1}) and T_5 (2131 mg kg^{-1}) which gave on par values, as shown in Table 13.

The calcium content in grain was influenced by the treatments. T_8 and T_3 recorded highest Ca content (692.3 mg kg^{-1}) which were significantly higher than all other treatments. Control recorded lowest value of 686.6 mg kg^{-1} (Table 13).

Highest total uptake of calcium was recorded in T_8 (potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds) with 19.11 g pot^{-1} which was significantly higher than all other treatments (Table 13).

Table. 13. Effect of silicon and boron on the calcium content in straw, grain and total uptake by plant

Treatments	Ca content (mg kg^{-1})		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (T_1)	1916	686.6	8.48
Calcium silicate @ 4 g kg^{-1} soil (T_2)	1948	689.0	13.53
Potassium silicate @ 0.5 % spray 3 rounds (T_3)	2070	692.3	13.38
Borax @ 0.5 g kg^{-1} soil (T_4)	2039	690.6	12.92
Borax 0.5 % foliar spray 3 rounds (T_5)	2131	690.0	13.74
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (T_6)	1943	688.0	15.78
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (T_7)	1964	688.6	14.41
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8)	2147	692.3	19.11
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (T_9)	2138	691.0	14.20
CD (5 %)	77	1.0	0.59

Table. 14. Effect of silicon and boron on the magnesium content in straw, grain and total uptake by plant

Treatments	Mg content (mg kg^{-1})		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (T_1)	403.0	402.0	1.79
Calcium silicate @ 4 g kg^{-1} soil (T_2)	427.6	422.3	2.98
Potassium silicate @ 0.5 % spray 3 rounds (T_3)	431.6	423.0	2.80
Borax @ 0.5 g kg^{-1} soil (T_4)	425.6	418.0	2.71
Borax 0.5 % foliar spray 3 rounds (T_5)	429.6	417.0	2.78
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (T_6)	433.0	427.0	3.53
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (T_7)	432.3	426.6	3.18
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8)	442.3	428.0	3.95
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (T_9)	427.0	420.0	2.85
CD (5 %)	8.0	1.6	0.08

4.1.5.5. Magnesium

The results of Mg content of straw and grain as well as total uptake is presented in Table 14. The highest content of magnesium in straw was noticed in T_8 with 442.3 mg kg^{-1} which was significantly higher than all other treatments. T_8 followed by T_6 (433.0 mg kg^{-1}) which was on par with remaining all other treatments except control (403.0 mg kg^{-1}).

Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8) recorded highest magnesium content in grain with 428.0 mg kg^{-1} which was on par with T_6 (427.0 mg kg^{-1}), T_7 (426.6 mg kg^{-1}) and significantly different from all other treatments, the sequential ranking being $T_3 > T_2 > T_9 > T_4 > T_5 > T_1$. Control (402 mg kg^{-1}) recorded lowest value.

Similar trend was obtained with respect to total Mg uptake by plant where T_8 (3.95 g pot^{-1}) showed significantly higher uptake than all other treatments, followed by T_6 (3.53 g pot^{-1}) which was superior to the remaining treatments.

4.1.5.6. Sulphur

There was a significant influence of treatments on S content in straw as shown in Table 15. The highest S content was recorded in T_8 (2316 mg kg^{-1}) which was significantly higher than all other treatments. The remaining treatments followed the order $T_6 > T_7 > T_9 > T_3 > T_2 > T_4 = T_5 > T_1$. Among these T_6, T_7 and T_9 were on par.

Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8) recorded highest sulphur content in grain (566.6 mg kg^{-1}) which was on par with T_6 (565.0 mg kg^{-1}), T_3 (563.6 mg kg^{-1}), T_7 (564.0 mg kg^{-1}) and T_9 (563.6 mg kg^{-1}). All the other treatments gave significantly lower value with control recording the lowest value of 550.0 mg kg^{-1} (Table 15).

The total uptake of sulphur was highest in T_8 (potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds) with 20.60 g pot^{-1} which was significantly higher than all other treatments. All the treatments were superior to control (9.29 g pot^{-1}).

Table. 15. Effect of silicon and boron on the sulphur content in straw, grain and total uptake by plant

Treatments	S content (mg kg^{-1})		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (T_1)	2100	550.0	9.29
Calcium silicate @ 4 g kg^{-1} soil (T_2)	2190	562.3	15.20
Potassium silicate @ 0.5 % spray 3 rounds (T_3)	2200	563.6	14.22
Borax @ 0.5 g kg^{-1} soil (T_4)	2133	555.0	13.51
Borax 0.5 % foliar spray 3 rounds (T_5)	2133	554.0	13.74
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (T_6)	2250	565.0	18.25
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5% spray 3 rounds (T_7)	2233	564.0	16.37
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8)	2316	566.6	20.60
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (T_9)	2216	563.6	14.71
CD (5 %)	46	3.2	0.37

4.1.5.7. Iron

There was a reduction in Fe content of straw in all treatments when compared to control (431.6 mg kg^{-1}). As shown in Table 16, the application of calcimm silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (T_6) recorded lowest value (333.3 mg kg^{-1}) which was on par with T_8 (336.0 mg kg^{-1}) and T_7 (339.3 mg kg^{-1}). The sequential ranking of other treatments were $T_9 < T_2 < T_3 < T_4 < T_5 < T_1$.

The iron content in grain was also significantly influenced by the treatments. Lowest value was associated with T_6 (119.6 mg kg^{-1}) which was on par with T_8 (124.0 mg kg^{-1}), T_3 (127.6 mg kg^{-1}) and T_2 (128.3 mg kg^{-1}).

The uptake of Fe was significantly higher in T_8 (2.99 g pot^{-1}) compared to all other treatments. The lowest value was recorded for control (1.90 g pot^{-1}).

Table. 16. Effect of silicon and boron on the iron content in straw, grain and total uptake by plant

Treatments	Fe content (mg kg^{-1})		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	431.6	216.0	1.90
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	390.0	128.3	2.70
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	396.0	127.6	2.56
Borax @ 0.5 g kg^{-1} soil (**T_4**)	422.6	194.3	2.68
Borax 0.5 % foliar spray 3 rounds (**T_5**)	424.6	215.3	2.74
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	333.3	119.6	2.70
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	339.3	148.3	2.49
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	336.0	124.0	2.99
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	342.0	157.3	2.27
CD (5 %)	8.4	25.1	0.07

4.1.5.8. Manganese

There was a reduction in Mn content in straw by treatments (Table 17). T_7 recorded lowest Mn content of 227.3 mg kg^{-1} which was on par with T_8 (237.4 mg kg^{-1}). The sequential ranking of remaining treatments were $T_6 < T_9 < T_3 < T_2 < T_5 < T_4 < T_1$.

Application of potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds (T_8) recorded lowest Mn content in grain (123.8 mg kg^{-1}) which was on par with T_6 (125.6 mg kg^{-1}), T_7 (126.0 mg kg^{-1}), T_9 (129.3 mg kg^{-1}), T_3 (131.3 mg kg^{-1}), T_2 (131.6 mg kg^{-1}), T_5 (132.6 mg kg^{-1}) and significantly superior to remaining treatments (Table 17).

The uptake of Mn was significantly higher in T_6 (2.38 g pot^{-1}) when compared to all other treatments except T_2 (2.27 g pot^{-1}) and T_4 (2.27 g pot^{-1}) which were on par. This was followed by T_8 (2.11 g pot^{-1}) which was on par with T_5 (2.10 g pot^{-1}), T_3 (2.03 g pot^{-1}) and T_9 (2.03 g pot^{-1}). The lowest value was recorded for control (1.61 g pot^{-1}).

Table. 17. Effect of silicon and boron on the manganese content in straw, grain and total uptake by plant

Treatments	Mn content (mg kg^{-1})		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (T_1)	365.0	139.3	1.61
Calcium silicate @ 4 g kg^{-1} soil (T_2)	326.6	131.6	2.27
Potassium silicate @ 0.5 % spray 3 rounds (T_3)	314.6	131.3	2.03
Borax @ 0.5 g kg^{-1} soil (T_4)	359.2	135.9	2.27
Borax 0.5 % foliar spray 3 rounds (T_5)	326.6	132.6	2.10
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (T_6)	293.3	125.6	2.38
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (T_7)	227.3	126.0	1.67
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8)	237.4	123.8	2.11
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (T_9)	306.6	129.3	2.03
CD (5 %)	14.3	10.6	0.11

4.1.5.9. Zinc

The treatments significantly influenced the Zn content in straw, grain and uptake by plant as shown in Table 18. Highest Zn content in straw was recorded in T_9 (57.46 mg kg^{-1}) which was on par with T_2 (54.86 mg kg^{-1}) and T_8 (54.20 mg kg^{-1}). With respect to grain, the highest Zn content was obtained in T_6 (29.13 mg kg^{-1}) which was significantly higher than all other treatments. This was followed by T_3 (26.66mg kg^{-1}) which was on par with T_2 (25.20mg kg^{-1}), T_8 (25.20mg kg^{-1}) and T_9 (24.80 mg kg^{-1}). Control recorded lowest value of 18.40 mg kg^{-1}.

The total uptake of zinc was significantly higher in T_8 (0.48 g pot^{-1}) when compared to other treatments. Among the other treatments T_6 (0.39 g pot^{-1}), T_7 (0.38 g pot^{-1}), T_9 (0.38 g pot^{-1}) and T_2 (0.38 g pot^{-1}) gave on par results which was significantly higher than the remaining treatments.

Table. 18. Effect of silicon and boron on the zinc content in straw, grain and total uptake by plant

Treatments	Zn content (mg kg^{-1})		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	43.40	18.40	0.19
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	54.86	25.20	0.38
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	50.33	26.66	0.32
Borax @ 0.5 g kg^{-1} soil (**T_4**)	48.26	21.26	0.30
Borax 0.5 % foliar spray 3 rounds (**T_5**)	49.13	22.80	0.31
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	49.13	29.13	0.39
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	51.86	24.20	0.38
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	54.20	25.20	0.48
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	57.46	24.80	0.38
CD (5 %)	4.17	1.95	0.02

4.1.5.10. Copper

Results of copper content and uptake are presented in Table 19. The content of copper in straw was influenced by the treatments. Although T_8 (potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds) recorded highest content (80.60 mg kg^{-1}) it was on par with T_6 (79.36 mg kg^{-1}), T_2 (78.70 mg kg^{-1}), T_9 (77.36 mg kg^{-1}), T_3 (75.70 mg kg^{-1}) and T_7 (72.86 mg kg^{-1}).

Application of potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds (T_8) recorded highest copper content in grain with 27.19 mg kg^{-1} which was significantly higher than T_5 (20.28 mg kg^{-1}), T_4 (19.83 mg kg^{-1}) and T_1 (17.62 mg kg^{-1}) but on par with other treatments.

Highest total uptake of copper was recorded in T_8 (potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds) with 0.78 g pot^{-1} which was significantly higher than all other treatments. The other treatments followed the order $T_2 > T_7 > T_9 > T_3 > T_5 > T_4 > T_1$.

Table. 19. Effect of silicon and boron on the copper content in straw, grain and total uptake by plant

Treatments	Cu content (mg kg^{-1})		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	32.40	17.62	0.12
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	78.70	27.02	0.55
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	75.70	25.11	0.49
Borax @ 0.5 g kg^{-1} soil (**T_4**)	34.56	19.83	0.22
Borax 0.5 % foliar spray 3 rounds (**T_5**)	40.06	20.28	0.25
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	79.36	24.33	0.64
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	72.86	25.22	0.53
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	80.60	27.19	0.78
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	77.36	25.53	0.51
CD (5 %)	9.40	3.51	0.06

4.1.5.11. Silicon

The Si content in straw is illustrated in Table 20. It varied from 5.35 % in T_8 to 2.80 % in control. T_8 gave significant higher value than all other treatments except T_3 (5.20 %), T_2 (5.18 %) and T_9 (5.18 %) which were on par. This was followed by T_7 (4.13 %) which was on par with T_6 (4.05 %) and significantly higher than the remaining treatments.

Highest Si content in grain of 3.68 % was recorded with the application of potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds (T_8) which was on par with T_2 (3.61 %), T_9 (3.25 %) and T_3 (3.20 %) and significantly higher than the other treatments. All the treatments except T_5 (1.45 %) and T_4 (1.36 %) were significantly superior to control (Table 20).

The total uptake of Si was maximum in T_8 (7.26 g pot^{-1}) which was significantly more than all other treatments. This followed by T_2 (5.51 g pot^{-1}) which was on par with T_9 (5.09 g pot^{-1}), T_6 (5.07 g pot^{-1}) and T_3 (4.93 g pot^{-1}).

Table. 20. Effect of silicon and boron on the silicon content in straw, grain and total uptake by plant

Treatments	Si content (%)		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	2.80	1.23	1.65
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	5.18	3.61	5.51
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	5.20	3.20	4.93
Borax @ 0.5 g kg^{-1} soil (**T_4**)	3.20	1.36	2.68
Borax 0.5 % foliar spray 3 rounds (**T_5**)	3.11	1.45	2.72
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	4.05	2.88	5.07
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	4.13	2.53	4.45
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	5.35	3.68	7.26
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	5.18	3.25	5.09
CD (5 %)	0.63	0.61	0.62

Table. 21. Effect of silicon and boron on the boron content in straw, grain and total uptake by plant

Treatments	B content (mg kg^{-1})		Total uptake (g pot^{-1})
	Straw	Grain	
Control- No Si and B (T_1)	2.60	1.50	0.012
Calcium silicate @ 4 g kg^{-1} soil (T_2)	3.80	3.26	0.027
Potassium silicate @ 0.5 % spray 3 rounds (T_3)	3.80	3.40	0.025
Borax @ 0.5 g kg^{-1} soil (T_4)	5.58	4.50	0.036
Borax 0.5 % foliar spray 3 rounds (T_5)	5.30	4.70	0.034
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (T_6)	5.25	4.46	0.043
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5% spray 3 rounds (T_7)	5.36	4.40	0.040
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8)	5.25	4.23	0.047
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (T_9)	5.31	4.36	0.035
CD (5 %)	1.16	0.63	0.009

4.1.5.12. Boron

The results of B content in straw and grain as well as total uptake is presented in Table 21. Application of borax @ 0.5 g kg^{-1} soil (T_4) significantly increased boron content in straw (5.58 mg kg^{-1}) compared to all other treatments except T_7 (5.36 mg kg^{-1}), T_9 (5.31 mg kg^{-1}), T_5 (5.30 mg kg^{-1}), T_6 (5.25 mg kg^{-1}) and T_8 (5.25 mg kg^{-1}) which gave on par values. All the treatments were superior to control (2.60 mg kg^{-1}).

Highest boron content in grain of 4.70 mg kg^{-1} was recorded with the application of borax 0.5 % spray 3 rounds (T_5) which was on par with T_4 (4.50 mg kg^{-1}), T_6 (4.46 mg kg^{-1}), T_7 (4.40 mg kg^{-1}), T_9 (4.36 mg kg^{-1}) and T_8 (4.23 mg kg^{-1}). Control (T_1) recorded lowest value of 1.50 mg kg^{-1}.

Highest total uptake of boron was recorded in T_8 (potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds) with 0.047 g pot^{-1} which was on par with T_6 (0.043 g pot^{-1}), T_7 (0.040 g pot^{-1}) and significantly higher than all other treatments. All the treatments except T_2 (0.027 g pot^{-1}) and T_3 (0.025 g pot^{-1}) were significantly superior to control (0.012 g pot^{-1}).

4.1.6. Plant growth parameters

4.1.6.1. Plant height

The results of the 9 treatments with respect to plant height are shown in Table 22. The application of potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds (T_8) recorded maximum plant height of 131.6 cm which was on par with T_6 (120.0 cm) and T_4 (115.0 cm) and significantly higher than all other treatments. This was followed by T_2 (110.0 cm) which was on par with all the remaining treatments and significantly superior to control (91.6 cm).

4.1.6.2. Number of tillers $plant^{-1}$

The results with respect to number of tiller $plant^{-1}$ are given in Table 22. The treatment T_8 recorded maximum number of tillers $plant^{-1}$ (25.00) which was on par with T_6 (23.00), T_7 (20.33) and T_2 (20.00). Treatments T_5 (19.66), T_3 (18.00), T_4 (17.33) and T_9 (17.33) were on par with control (15.33).

4.1.6.3. Productive tillers $plant^{-1}$

The highest number of productive tillers $plant^{-1}$ of 23.33 was observed in T_8 (potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds) which was significantly higher than T_3, T_9, T_4 and T_1 which recorded 17.00, 17.00, 16.33 and 14.66 productive tillers $plant^{-1}$ respectively (Table 22).

Table 22. Effect of silicon and boron on plant growth parameters of rice

Treatments	Plant height (cm)	Number of tillers/plant	Productive tillers/plant
Control- No Si and B (**T_1**)	91.6	15.33	14.66
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	110.0	20.00	18.33
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	107.3	18.00	17.00
Borax @ 0.5 g kg^{-1} soil (**T_4**)	115.0	17.33	16.33
Borax 0.5 % foliar spray 3 rounds (**T_5**)	105.0	19.66	20.33
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	120.0	23.00	21.33
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	101.6	20.33	19.33
Potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (**T_8**)	131.6	25.00	23.33
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	106.6	17.33	17.00
CD (5 %)	18.6	5.03	5.09

4.1.7. Yield and yield attributes

4.1.7.1. Panicle weight plant^{-1}

The panicle weight plant^{-1} was observed and the results are presented in Table 23. T_8 recorded maximum panicle weight plant^{-1} of 70 g which was on par with T_6 (64 g) and significantly higher than all other treatments. This was followed by T_7 (58 g) and T_2 (55 g) which were on par among remaining treatments and significantly superior to control (44 g).

4.1.7.2. Thousand grain weight

The result of the treatments with respect to thousand grain weight (g) is given in Table 23. The highest thousand grain weight of 27.16 g was obtained in the treatment T_8 (potassium silicate @ 0.5% spray + borax 0.5 % spray 3 rounds) which was significantly more than all other treatments. Among the remaining treatments, T_6 (26.03 g) was on par with T_4 (25.80 g), T_3 (25.70 g), T_2 (25.53 g), T_5 (25.10 g) and superior to T_9 (24.86 g), T_7 (24.80 g) and control (23.00 g).

Table 23. Effect of silicon and boron on yield and yield attributes of rice

Treatments	Panicle weight plant^{-1} (g)	Thousand grain weight (g)	Grain yield (g pot^{-1})	straw yield (g pot^{-1})
Control- No Si and B (**T_1**)	44.00	23.00	33.96	44.15
Calcium silicate @ 4 g kg^{-1} soil (**T_2**)	55.00	25.53	53.30	69.29
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	51.00	25.70	49.63	64.52
Borax @ 0.5 g kg^{-1} soil (**T_4**)	49.00	25.80	48.63	63.22
Borax 0.5 % foliar spray 3 rounds (**T_5**)	50.33	25.10	50.96	66.25
Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil (**T_6**)	64.00	26.03	62.30	80.99
Calcium silicate @ 4 g kg^{-1} soil + borax 0.5 % spray 3 rounds (**T_7**)	58.00	24.80	56.30	73.19
Potassium silicate @ 0.5 % spray + Borax 0.5 % spray 3 rounds (**T_8**)	70.00	27.16	68.30	88.79
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 0.5 g kg^{-1} soil (**T_9**)	51.00	24.86	49.46	64.30
CD (5 %)	6.45	1.01	0.88	1.15

4.1.7.3. Grain and straw yield (g pot^{-1})

Table 23 shows the results of grain and straw yield. Rice grain yield ranged from 33.96 g in control to 68.30 g in T_8. All the other treatments gave significantly higher yield than control. T_8 was significantly superior to all other treatments in terms of grain yield. This was followed by T_6 (62.30 g) which was significantly higher from the remaining treatments.

The highest straw yield was recorded in T_8 (88.79 g) which was significantly higher than all other treatments. This was followed by T_6 (80.99 g) which was significantly higher than remaining treatments. Control recorded the lowest straw yield of 44.15 g

4.2. FIELD EXPERIMENT

A field experiment was conducted in farmer field at Karivellur, to standardize the dose and method of application of silicon and boron to rice crop in laterite derived paddy soils, its effect on available nutrient status of soil and yield, and to study the effect of silicon and boron on alleviating of the toxicity of Fe, Mn and Al in laterite derived paddy soil.

4.2.1. Available nutrient status of soil

4.2.1.1. Nitrogen

The results of available N content in soil are presented in Table 24. The available nitrogen content in soil ranged from 296.6 kg ha^{-1} (T_8) to 287.6 kg ha^{-1} (T_1). There was no significant difference between the treatments with respect to available nitrogen content in soil.

4.2.1.2. Phosphorus

The analytical data on available P content in soil is presented in Table 24. Application of calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (T_6) recorded the highest available phosphorous content in soil (102.02 kg ha^{-1}) which was on par with T_7 (99.25 kg ha^{-1}), T_8 (96.42 kg ha^{-1}), T_2 (95.14 kg ha^{-1}), T_3 (94.82 kg ha^{-1}) and significantly higher than T_9 (90.64 kg ha^{-1}), T_5 (85.65 kg ha^{-1}), T_4 (83.97 kg ha^{-1}) and T_1 (76.08 kg ha^{-1}).

4.2.1.3. Potassium

The results with respect to available K in soil are presented in Table 24. The highest available K in soil of 106.45 kg ha^{-1} was obtained in T_8 (potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds) which was on par with T_3 (99.76 kg ha^{-1}), T_9 (98.58 kg ha^{-1}), T_2 (97.33 kg ha^{-1}), T_7 (95.94 mg kg^{-1}) and T_6 (93.36 kg ha^{-1}). Control recorded lowest value of 63.62 kg ha^{-1}.

Table 24. Effect of silicon and boron on availability of primary nutrients in soil

Treatments	Primary nutrients (kg ha^{-1})		
	N	P	K
Control- No Si and B (**T_1**)	287.6	76.08	63.62
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	294.6	95.14	97.33
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	290.4	94.82	99.76
Borax @ 10 kg ha^{-1} (**T_4**)	289.3	83.97	72.77
Borax 0.5 % foliar spray 3 rounds (**T_5**)	291.6	85.65	68.18
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	292.8	102.02	93.36
Calcium silicate @ 100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	292.0	99.25	95.94
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5 % spray 3 rounds (**T_8**)	296.6	96.42	106.45
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	291.0	90.64	98.58
CD (5 %)	NS	7.89	10.65

4.2.1.4. Calcium

The analytical results of available Ca content in soil in respective to various treatments were estimated and the results are presented in Table 25. The highest available Ca content in soil was obtained in T_6 (499.1 mg kg^{-1}) which was on par with T_2 (491.2 mg kg^{-1}), T_7 (484.5 mg kg^{-1}), T_5 (452.0mg kg^{-1}), T_8 (451.2mg kg^{-1}), T_9 (388 mg kg^{-1}) and significantly higher than all other treatments. Control recorded lowest value of 328.1 mg kg^{-1}.

4.2.1.5. Magnesium

Table 25 shows results of available Mg content in soil. The available magnesium content in soil ranged from 20.17 mg kg^{-1} (T_6) to 18.30 mg kg^{-1} (T_1). There was no significant difference between the treatments with respect to available magnesium content in soil.

4.2.1.6. Sulphur

The results of available S content in soil are presented in Table 25. The available sulphur content in soil ranged from 15.77 mg kg^{-1} (T_8) to 14.02 mg kg^{-1} (T_1). There was no significant difference between the treatments with respect to available sulphur content in soil.

Table 25. Effect of silicon and boron on availability of secondary nutrients in soil

Treatments	Secondary nutrients (mg kg^{-1})		
	Ca	Mg	S
Control- No Si and B (**T_1**)	328.1	18.30	14.02
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	491.2	19.03	15.33
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	350.6	18.55	14.58
Borax @ 10 kg ha^{-1} (**T_4**)	336.4	18.48	14.25
Borax 0.5 % foliar spray 3 rounds (**T_5**)	452.0	18.45	14.62
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	499.1	20.17	15.43
Calcium silicate @ 100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (T_7)	484.5	18.51	15.47
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5 % spray 3 rounds (**T_8**)	451.2	18.84	15.77
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	388.7	18.20	14.06
CD (5 %)	111.2	NS	NS

4.2.1.7. Zinc and copper

The analytical results of available Zn and Cu with respect to various treatments are presented in Table 26. The available zinc content in soil ranged from 3.09 mg kg^{-1} (T_8) to 2.89 mg kg^{-1} (T_1). There was no significant difference between the treatments with respect to available zinc in soil.

The available copper content in soil ranged from 1.37 mg kg^{-1} (T_2 and T_6) to 1.32 mg kg^{-1} (T_1). There was no significance different between the treatments with respect to available copper content in soil.

Table 26. Effect of silicon and boron on availability of zinc and copper

Treatments	Micronutrients (mg kg^{-1})	
	Zn	Cu
Control- No Si and B (**T_1**)	2.89	1.32
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	2.95	1.37
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	2.90	1.35
Borax @ 10 kg ha^{-1} (**T_4**)	2.90	1.34
Borax 0.5 % foliar spray 3 rounds (**T_5**)	2.97	1.33
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	3.07	1.37
Calcium silicate @ 100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	2.99	1.35
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5 % spray 3 rounds (**T_8**)	3.09	1.36
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	3.05	1.35
CD (5 %)	NS	NS

4.2.2. Effect of silicon and boron on content of Fe, Mn and Al in soil

4.2.2.1. Iron

The iron content of soil was estimated for various treatments and the results are shown in Table 27. There was a significant decline in iron content in soil with the treatments compared to control (186.8 mg kg^{-1}). Lowest value were obtained in T_8 (167.5mg kg^{-1}) which was on par with T_6 (172.5mg kg^{-1}), T_3 (174.1mg kg^{-1}), T_7 (174.1 mg kg^{-1}), T_2 (177.5 mg kg^{-1}) and T_9 (177.8 mg kg^{-1}). T_4 (181.6 mg kg^{-1}) and T_5 (181.6 mg kg^{-1}) were on par with control.

4.2.2.2. Manganese

The Mn content in soil as influenced by various treatments is presented in Table 27. All the treatments resulted in a significant reduction in available Mn content in soil in comparison to control (25.76 mg kg^{-1}). (T_6) recorded lowest Mn content of (13.03 mg kg^{-1}) which was on par with T_7 (14.10 mg kg^{-1}), T_8 (14.46 mg kg^{-1}), T_2 (14.76 mg kg^{-1}), T_9 (14.86 mg kg^{-1}) and significantly lower than T_5 (24.53 mg kg^{-1}), T_4 (23.73 mg kg^{-1}) and T_3 (22.70 mg kg^{-1}).

4.2.2.3. Aluminium

The results with respect to Al content in soil is shown in Table 27. The effect of treatments on exchangeable Al content of soil was significant in all the treatments except T_4 (164.3 mg kg^{-1}) and T_5 (163.3 mg kg^{-1}) compared to control. Application of calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (T_6) resulted in lowest exchangeable Al content of 141.0 mg kg^{-1} followed by T_8 (144.3 mg kg^{-1}), T_2 (145.0 mg kg^{-1}) and T_7 (145.3 mg kg^{-1}) which were on par.

Table 27. Effect of silicon and boron on content of Fe, Mn and Al in soil

Treatments	Micronutrients (mg kg^{-1})		
	Fe	Mn	Al
Control- No Si and B (**T_1**)	186.8	25.76	166.0
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	177.5	14.76	145.0
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	174.1	22.70	147.6
Borax @ 10 kg ha^{-1} (**T_4**)	181.6	23.73	164.3
Borax 0.5 % foliar spray 3 rounds (**T_5**)	181.6	24.53	163.3
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	172.5	13.03	141.0
Calcium silicate @ 100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	174.1	14.10	145.3
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5 % spray 3 rounds (**T_8**)	167.5	14.46	144.3
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	177.8	14.86	146.3
CD (5 %)	10.3	9.12	4.6

Table 28. Effect of silicon and boron on silicon content in soil at different stages of rice

Treatments	Silicon (mg kg^{-1})		
	Maximum tillering stage	Flowering stage	Harvesting stage
Control- No Si and B (**T_1**)	17.83	17.58	16.66
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	21.66	27.58	24.00
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	23.75	26.25	23.91
Borax @ 10 kg ha^{-1} (**T_4**)	21.66	21.33	19.58
Borax 0.5 % foliar spray 3 rounds (**T_5**)	20.41	19.58	18.33
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	22.50	31.00	27.08
Calcium silicate @ 100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	23.33	29.75	25.00
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds (**T_8**)	23.41	24.16	23.00
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	22.58	23.00	21.16
CD (5 %)	NS	5.19	5.09

4.2.3. Silicon content in soil at different stages

The results of Si content in soil at different stages are presented in Table 28. The treatments could not show any significant effect on silicon content at maximum tillering stage.

At flowering stage application of calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (T_6) recorded highest available silicon content in soil (31.0 mg kg^{-1}) which was on par with T_7 (29.75 mg kg^{-1}), T_2 (27.58 mg kg^{-1}) and T_3 (26.25 mg kg^{-1}). This was followed by T_8 (24.16 mg kg^{-1}) which was on par with T_9 (23.00 mg kg^{-1}), T_4 (21.33 mg kg^{-1}) and T_5 (19.58 mg kg^{-1}). Control recorded lowest value of 17.58 mg kg^{-1}.

At harvesting stage highest silicon content of 27.08 mg kg^{-1} was noticed in T_6 which was on par with T_7 (25.0 mg kg^{-1}), T_2 (24.0 mg kg^{-1}), T_3 (23.91 mg kg^{-1}) and T_8 (23.0 mg kg^{-1}). T_4 (19.58 mg kg^{-1}) and T_5 (18.33 mg kg^{-1}) were on par with control (16.66 mg kg^{-1}).

Table 29. Effect of silicon and boron on boron content in soil at different stages of rice

Treatments	Boron (mg kg^{-1})		
	Maximum tillering stage	Flowering stage	Harvesting stage
Control- No Si and B (**T_1**)	0.207	0.207	0.193
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	0.233	0.267	0.240
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	0.220	0.247	0.220
Borax @ 10 kg ha^{-1} (**T_4**)	0.247	0.547	0.307
Borax 0.5 % foliar spray 3 rounds (**T_5**)	0.227	0.300	0.250
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (T_6)	0.227	0.503	0.280
Calcium silicate @ 100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	0.240	0.250	0.227
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds (**T_8**)	0.227	0.263	0.240
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	0.220	0.480	0.250
CD (5 %)	NS	0.029	0.022

4.2.4. Boron content in soil at different stages

The analyzed data on boron content in soil as influenced by various treatments is given in Table 29. The treatments could not show any significant effect on boron content at maximum tillering stage.

The available boron content of soil increased from maximum tillering stage to flowering stage. At flowering stage, T_4 gave the highest value of 0.547 mg kg^{-1}

which was significantly higher than all other treatments and control (T_1) recorded lowest value of 0.207 mg kg^{-1}.

Highest available boron content at harvesting stage was obtained in T_4 (0.307 mg kg^{-1}) which was significantly higher than all treatments. This was followed by T_5 (0.250 mg kg^{-1}) and T_9 (0.250 mg kg^{-1}) which were superior to the remaining treatments. T_8 (0.240 mg kg^{-1}), T_2 (0.240 mg kg^{-1}), T_7 (0.227 mg kg^{-1}) and T_3 (0.220 mg kg^{-1}) were on par but significantly higher than control (0.193 mg kg^{-1}) and then declined at harvesting stage.

Table. 30. Effect of silicon and boron on the nitrogen content in straw, grain and total uptake of by plant

Treatments	N content (%)		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	1.19	0.41	69.4
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	1.43	1.27	146.9
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	1.44	1.34	147.0
Borax @ 10 kg ha^{-1} (**T_4**)	1.41	1.12	123.9
Borax 0.5 % foliar spray 3 rounds (T_5)	1.40	1.02	120.8
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (T_6)	1.68	1.46	180.2
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (T_7)	1.68	1.32	153.3
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds (**T_8**)	1.70	1.30	175.8
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 Kg ha^{-1} (**T_9**)	1.68	1.18	151.9
CD (5 %)	0.03	0.07	6.8

4.2.5. Nutrient content in straw, grain and total uptake

4.2.5.1. Nitrogen

The experimental results with respect to nitrogen content and uptake are presented in Table 30. The N content in straw varied from 1.70 % in T_8 to 1.19 %

in control. T_8 gave significantly higher values than all other treatments except T_6 (1.68 %), T_7 (1.68 %) and T_9 (1.68 %) which were on par.

Application of calcium silicate @ 100 kg Si ha^{-1} + borax @10 kg ha^{-1} (T_6) recorded highest N content in grain with 1.46 % which was significantly higher than all other treatments. Among the remaining treatments T_3 (1.34 %) was on par with T_7 (1.32 %), T_8 (1.30 %), T_2 (1.27 %) and significantly higher than T_4 (1.12 %), T_5 (1.02 %) and control (0.41 %).

The total uptake of nitrogen was maximum in T_6 (180.2 kg ha^{-1}) which was on par with T_8 (175.8 kg ha^{-1}) and significantly more than all other treatments. This was followed by T_7 (153.3) which was on par with T_9 (151.9 kg ha^{-1}), T_3 (147.0 kg ha^{-1}) and T_2 (146.9kg ha^{-1}). T_4 (123.9 kg ha^{-1}) and T_5 (120.8 kg ha^{-1}) were superior to control (69.4 kg ha^{-1}) but on par among themselves.

Table. 31. Effect of silicon and boron on the phosphorous content in straw, grain and total uptake by plant

Treatments	P content (%)		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	0.083	0.089	10.62
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	0.125	0.132	21.53
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	0.125	0.130	21.13
Borax @ 10 kg ha^{-1} (**T_4**)	0.118	0.107	18.02
Borax 0.5 % foliar spray 3 rounds (**T_5**)	0.122	0.108	18.53
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	0.128	0.141	23.59
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	0.127	0.133	20.78
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds (**T_8**)	0.235	0.127	37.11
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	0.138	0.124	22.19
CD (5 %)	0.038	0.011	5.53

4.2.5.2. Phosphorous

The P content in straw was significantly influenced by the treatments, results are presented in Table 31. The highest value for straw was 0.235 % in T_8 which was significantly higher than all other treatments, with respect to grain T_6 (0.141 %) gave the highest value which was on par with T_7 (0.133 %), T_2 (0.132%), T_3 (0.130%) and significantly superior to all other treatments.

The total uptake of P also followed the same trend with T_8 recording the maximum uptake of 37.11 kg ha^{-1} which was significantly more than all other treatments (Table 33). All the treatments were superior to control (10.62 kg ha^{-1}).

Table. 32. Effect of silicon and boron on the potassium content in straw, grain and total uptake by plant

Treatments	K content (%)		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	2.80	0.16	138.1
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	3.45	0.36	229.9
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	3.20	0.30	211.3
Borax @ 10 kg ha^{-1} (**T_4**)	3.06	0.26	193.2
Borax 0.5 % foliar spray 3 rounds (**T_5**)	2.93	0.26	186.5
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	3.50	0.37	248.1
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	3.20	0.37	216.0
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5 % spray 3 rounds (**T_8**)	3.60	0.46	258.7
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	3.40	0.40	228.0
CD (5 %)	0.08	0.04	13.0

4.2.5.3. Potassium

The results of K content in straw, grain and total uptake per pot are presented in Table 32. The potassium content in straw was maximum in T_8 with

3.60 % which was significantly higher than all other treatments. This was followed by T_6 (3.50 %) which was on par with T_2 (3.45 %) and superior to the remaining treatments. Control recorded lowest value of 2.80 %.

A similar trend was observed in the K concentration of grain also with highest content of 0.46 % in T_8 which was significantly more than all other treatments. Control (T_1) recording lowest value of 0.16 %.

The total K uptake ranged from 138.1 kg ha^{-1} (T_1) to 258.7 kg ha^{-1} (T_8). T_8 registered significantly higher uptake of K than all other treatments except T_6 (248.1 kg ha^{-1}) which was on par. This was followed by T_2 (229.9 kg ha^{-1}) which was on par with T_9 (228.0 kg ha^{-1}) and significantly higher than the remaining treatments.

Table. 33. Effect of silicon and boron on the calcium content in straw, grain and total uptake by plant

Treatments	Ca content (mg kg^{-1})		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	2025	670.0	11.66
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	2063	677.6	15.87
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	2236	683.3	16.78
Borax @ 10 kg ha^{-1} (**T_4**)	2218	680.3	15.69
Borax 0.5 % foliar spray 3 rounds (**T_5**)	2261	680.6	16.06
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	2033	674.3	16.58
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	2040	675.6	15.31
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds (**T_8**)	2345	684.0	18.72
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	2285	681.0	16.96
CD (5 %)	63	2.8	1.04

4.2.5.4. Calcium

The results of Ca content and total uptake are presented in Table 33. Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8) significantly increased calcium content in straw (2345 mg kg^{-1}) compared to all other treatments except T_9 (2285 mg kg^{-1}) which gave on par value. Among the remaining treatments T_5 (2261 mg kg^{-1}), T_3 (2236 mg kg^{-1}) and T_4 (2218 mg kg^{-1}) were on par and superior to T_2 (2063 mg kg^{-1}), T_7 (2040 mg kg^{-1}), T_6 (2033 mg kg^{-1}) and control (2025 mg kg^{-1}).

The calcium content in grain was influenced by the treatments. Although T_8 recorded highest content (684.0 mg kg^{-1}) it was on par with T_3 (683.3 mg kg^{-1}) and significantly higher than all other treatments. Control recorded lowest value of 670.0 mg kg^{-1}.

Highest total uptake of calcium was recorded in T_8 (18.72 kg ha^{-1}) which was significantly more than all other treatments. All the treatments were superior to control (11.66 kg ha^{-1}) with respect to calcium uptake.

4.2.5.5. Magnesium

The results of Mg content of straw and grain as well as total uptake is presented in Table 34. The highest content of magnesium in straw was noticed in T_8 with 636.0 mg kg^{-1} which was on par with T_9 (626.3 mg kg^{-1}) and significantly higher than all other treatments. Control recorded lowest value of 555.0 mg kg^{-1}.

Application of calcium silicate @ 100 kg ha^{-1} soil + borax @ 10 kg ha^{-1} (T_8) recorded highest magnesium content in grain (423.0 mg kg^{-1}) which was on par with T_6 (422.6 mg kg^{-1}), T_7 (421.3 mg kg^{-1}), T_9 (420.0 mg kg^{-1}) and significantly higher than all other treatments. T_3 (417.0 mg kg^{-1}), T_4 (416.3 mg kg^{-1}) and T_5 (416.0 mg kg^{-1}) were on par with control (414.3 mg kg^{-1}).

Highest total uptake of magnesium was recorded in T_8 with 6.25 kg ha^{-1} which was on par with T_6 (5.98 kg ha^{-1}) and significantly higher than all other treatments. This was followed by T_2 (5.65 kg ha^{-1}) which was on par with T_9 (5.58 kg ha^{-1}) and T_3 (5.38 kg ha^{-1}).

Table. 34. Effect of silicon and boron on the magnesium content in straw, grain and total uptake by plant

Treatments	Mg content (mg kg^{-1})		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	555.0	414.3	3.90
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	603.0	418.3	5.65
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	582.0	417.0	5.38
Borax @ 10 kg ha^{-1} (**T_4**)	563.0	416.3	4.83
Borax 0.5 % foliar spray 3 rounds (**T_5**)	564.0	416.0	4.87
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	603.3	422.6	5.98
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	587.0	421.3	5.21
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5 % spray 3 rounds (**T_8**)	636.0	423.0	6.25
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	626.3	420.0	5.58
CD (5 %)	30.7	3.5	0.31

4.2.5.6. Sulphur

There was a significant influence of treatments on S content in straw as shown in Table 35. There was a significant influence of treatments on S content in straw. T_8 (2433 mg kg^{-1}) recorded the highest S content which was significantly higher than all other treatments and the sequential ranking of other treatments were $T_6 > T_9 > T_3 = T_7 > T_2 > T_5 > T_4 < T_1$.

Application of potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds (T_8) recorded highest sulphur content in grain (564.0 mg kg^{-1}) which was on par with T_6 (563.6 mg kg^{-1}) and significantly higher than all other treatments. Control (T_1) recorded lowest value of 557.0 mg kg^{-1} (Table 35).

Similar trend was obtained with respect to total S uptake by plant where T_8 with 18.71 kg ha^{-1} was on par with T_6 (18.46 kg ha^{-1}) and significantly higher than all other treatments (Table 35).

Table. 35. Effect of silicon and boron on the sulphur content in straw, grain and total uptake by plant

Treatments	S content (mg kg^{-1})		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B **(T_1)**	1833	557.0	10.41
Calcium silicate @100 kg Si ha^{-1} **(T_2)**	2083	562.0	15.46
Potassium silicate @ 0.5% spray 3 rounds **(T_3)**	2333	561.0	16.87
Borax @ 10 kg ha^{-1} **(T_4)**	1860	559.0	13.12
Borax 0.5 % foliar spray 3 rounds **(T_5)**	1933	558.0	13.64
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} **(T_6)**	2400	563.6	18.46
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds **(T_7)**	2333	563.0	16.77
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds **(T_8)**	2433	564.0	18.71
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} **(T_9)**	2350	561.3	16.88
CD (5 %)	58	0.7	1.08

4.2.5.7. Iron

There was a reduction in Fe content of straw in all treatments in comparison to control (460.0 mg kg^{-1}). As shown in Table 36, the application of potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds (T_8) recorded lowest Fe content (346.0 mg kg^{-1}) which was on par with T_6 (350.0 mg kg^{-1}) and T_7 (352.0 mg kg^{-1}). The sequential ranking of other treatments were $T_1 > T_4 > T_5 > T_2 > T_3 > T_9$. With respect to grain, lowest iron content was recorded in T_8 (137.3mg kg^{-1}) which was significantly lower than all other treatments except T_6 (139.0 mg kg^{-1}) and T_7 (145.3 mg kg^{-1}) which were on par.

The highest total manganese uptake was associated with T_5 (2.99 kg ha^{-1}) which was on par with T_4 (2.96 kg ha^{-1}) and T_6 (2.84 kg ha^{-1}). All other treatments were superior to control (2.44 kg ha^{-1}).

Table. 37. Effect of silicon and boron on the manganese content in straw, grain and total uptake by plant

Treatments	Mn content (mg kg^{-1})		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	421.6	146.0	2.44
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	350.6	135.6	2.79
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	348.0	134.0	2.72
Borax @ 10 kg ha^{-1} (**T_4**)	410.0	143.2	2.96
Borax 0.5 % foliar spray 3 rounds (**T_5**)	412.0	144.0	2.99
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	337.0	131.3	2.84
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (T_7)	340.0	134.6	2.63
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds (T_8)	327.0	128.3	2.77
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (T_9)	335.0	133.2	2.62
CD (5 %)	2.8	0.8	0.15

4.2.5.9. Zinc

The treatments significantly influenced the content of Zn in straw, grain and uptake of Zn by plant as shown in Table 38. T_9 (52.73 mg kg^{-1}) registered the highest Zn content in straw which was on par with T_2 (52.07 mg kg^{-1}) and T_8 (47.86 mg kg^{-1}). With respect to grain the highest value for Zn content was associated with T_6 (28.33 mg kg^{-1}) which was significantly higher than all other treatments but on par with T_8 (27.86 mg kg^{-1}).

The total uptake of zinc was significantly higher in T_8 (0.45 kg ha^{-1}) compared to other treatments expect T_9 (0.42 kg ha^{-1}) and T_2 (0.43 kg ha^{-1}) which were on par. Control registered the lowest Zn uptake of 0.19 kg ha^{-1} which was significantly lower than all other treatments.

Table. 38. Effect of silicon and boron on the zinc content in straw, grain and total uptake by plant

Treatments	Zn content (mg kg^{-1})		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B (T_1)	29.26	17.93	0.19
Calcium silicate @100 kg Si ha^{-1} (T_2)	52.06	25.40	0.43
Potassium silicate @ 0.5 % spray 3 rounds (T_3)	31.86	23.86	0.30
Borax @ 10 kg ha^{-1} (T_4)	32.80	22.80	0.27
Borax 0.5 % foliar spray 3 rounds (T_5)	35.06	21.73	0.28
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (T_6)	38.33	28.33	0.38
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (T_7)	38.26	24.93	0.33
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds (T_8)	47.86	27.86	0.45
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (T_9)	52.73	24.06	0.42
CD (5 %)	7.74	2.73	0.05

4.2.5.10. Copper

Results of copper content and uptake are presented in Table 39. The content of copper in straw was influenced by the treatments. Although T_8 recorded highest Ca content (74.95 mg kg^{-1}) which was on par with T_3 (72.86 mg kg^{-1}). All other treatments gave significantly lower values with control recording the lowest value of 60.20 mg kg^{-1}.

Application of potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds (T_8) recorded highest copper content in grain with 75.76 mg kg^{-1} which was significantly higher than T_2 (66.56 mg kg^{-1}), T_9 (66.26 mg kg^{-1}), T_7 (46.06 mg kg^{-1}), T_3 (37.36 mg kg^{-1}), T_4 (33.76 mg kg^{-1}), T_5 (34.96 mg kg^{-1}) and T_1 (30.70 mg kg^{-1}) but on par with T_6 (75.66 mg kg^{-1}).

Highest total uptake of copper was recorded in T_8 (potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds) with 0.49 kg ha^{-1} which was significantly higher than all other treatments except T_6 (0.46 kg ha^{-1}). The other treatments followed the order $T_3 > T_9 > T_7 > T_2 > T_5 = T_4 > T_1$.

Table. 39. Effect of silicon and boron on the copper content in straw, grain and total uptake by plant

Treatments	Cu content (mg kg^{-1})		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	60.20	30.70	0.37
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	65.86	66.56	0.41
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	72.86	37.36	0.45
Borax @ 10 kg ha^{-1} (**T_4**)	62.38	33.76	0.38
Borax 0.5 % foliar spray 3 rounds (**T_5**)	63.16	34.96	0.38
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	70.36	75.66	0.46
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	65.33	46.06	0.41
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds (**T_8**)	74.95	75.76	0.49
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	71.47	66.26	0.44
CD (5 %)	3.30	3.33	0.03

4.2.5.11. Silicon

The Si content in straw is illustrated in Table 40. There was an increase in Si content of straw in all the treatments in comparison to control (2.00 %). T_3 (4.95 %) recorded the highest Si content which was significantly more than all other treatments. The next best treatment was T_2 (4.16 %) which was significantly higher than the remaining treatments.

Among the remaining treatments T_8 (4.28 mg kg^{-1}), T_9 (4.13 mg kg^{-1}), T_6 (4.06 mg kg^{-1}) and T_7 (4.00 mg kg^{-1}) were on par.

Highest boron content in grain of 4.33 mg kg^{-1} was recorded with the application of borax 0.5% spray 3 rounds (T_5) which was on par with T_4 (4.23 mg kg^{-1}), T_7 (3.96 mg kg^{-1}) and T_9 (3.86 mg kg^{-1}). Control (T_1) recorded lowest value of 1.96 mg kg^{-1}.

Highest total uptake of boron was recorded in T_8 (potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds) with 0.047 kg ha^{-1} which was on par with T_4 (0.044 kg ha^{-1}), T_6 (0.044 kg ha^{-1}) and T_5 (0.042 kg ha^{-1}). This was followed by T_9 (0.041 kg ha^{-1}) which was on par with T_7 (0.039 kg ha^{-1}) and superior to T_2 (0.032 kg ha^{-1}), T_3 (0.032 kg ha^{-1}) and control (0.018 kg ha^{-1}).

Table. 41. Effect of silicon and boron on the boron content in straw, grain and total uptake by plant

Treatments	B content (mg kg^{-1})		Total uptake (kg ha^{-1})
	Straw	Grain	
Control- No Si and B (**T_1**)	2.50	1.96	0.018
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	3.06	2.80	0.032
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	3.18	2.86	0.032
Borax @ 10 kg ha^{-1} (**T_4**)	4.86	4.23	0.044
Borax 0.5 % foliar spray 3 rounds (**T_5**)	4.50	4.33	0.042
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	4.06	3.70	0.044
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	4.00	3.96	0.039
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5% spray 3 rounds (**T_8**)	4.28	3.76	0.047
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	4.13	3.86	0.041
CD (5 %)	0.52	0.51	0.005

4.2.6. Plant growth parameters

4.2.6.1. Plant height

The results of the 9 treatments with respect to plant height are shown in Table 42. The application of potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds (T_8) recorded maximum plant height of 90.00 cm which was followed by T_6 (87.00 cm) which was on par with T_4 (85.73 cm), T_9 (85.33 cm), T_2 (84.66 cm) and significantly higher than all other treatments. T_1 (control) registered the lowest plant height of 74.66 cm.

4.2.6.2. Number of tillers plant^{-1}

The results with respect to number of tiller plant^{-1} are given in Table 42. The treatment T_8 recorded maximum number of tillers1plant^{-1} (18.66) which was on par with T_6 (17.00) and significantly higher than all other treatments. This was followed by T_3 (16.33) which was on par with T_2 (15.33) and significantly superior to control (11.66).

4.2.6.3. Productive tillers plant^{-1}

The highest number of productive tiller plant^{-1} of 17.33 was recorded in T_8 which was on par with T_6 (16.00), T_2 (15.33) and T_9 (15.00) and significantly higher than T_3, T_5, T_7, T_4 and T_1 which recorded 14.66, 14.66, 14.33, 14.00 and 12.00 productive tillers plant^{-1} respectively (Table 42).

4.2.7. Yield and yield attributes

4.2.7.1. Panicle weight plant^{-1}

The panicle weight plant^{-1} was observed and the results are presented in Table 43. T_8 recorded maximum panicle weight plant^{-1} of 45.06 g which was on par with T_6 (41.60 g), T_2 (39.86 g) and T_9 (39.00 g) and significantly higher than all other treatments. This was followed by T_3 (38.13 g) and T_5 (38.13 g) which was on par with T_4 (36.40 g) and significantly superior to control (31.20 g)

Table 42. Effect of silicon and boron on plant growth parameters of rice

Treatments	Plant height (cm)	Number of tillers/plant	Productive tillers/plant
Control- No Si and B (**T_1**)	74.66	11.66	12.00
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	84.66	15.33	15.33
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	80.66	16.33	14.66
Borax @ 10 kg ha^{-1} (**T_4**)	85.73	14.00	14.00
Borax 0.5 % foliar spray 3 rounds (**T_5**)	83.33	14.00	14.66
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	87.00	17.00	16.00
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	82.33	14.00	14.33
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5 % spray 3 rounds (**T_8**)	90.00	18.66	17.33
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	85.33	14.33	15.00
CD (5 %)	2.71	1.78	2.34

4.2.7.2. Thousand grain weight

The result of the treatments with respect to thousand grain weight (g) is given in Table 43. The highest thousand grain weight of 30.70 g was obtained in the treatment T_8 which was significantly more than all other treatments. All the treatments were superior to control (20.96 g).

4.2.7.3. Grain and straw yield (t ha^{-1})

Table 43 shows the results of grain and straw yield. There was a significant influence of treatments on grain yield. Increased from 3.05 t ha^{-1} in control to 4.95 t ha^{-1} in T_8 (potassium silicate @ 0.5% spray + borax 0.5% spray 3 rounds). T_8 was superior to all other treatments in terms of grain yield. This was followed by T_6 (4.76 t ha^{-1}) which was significantly higher than the remaining treatments.

The highest straw yield was recorded in T_6 (calcium silicate @100kg Si ha^{-1} + borax @10 kg ha^{-1}) with 6.57 t ha^{-1} which was on par with T_8 (6.54 t ha^{-1}), T_7

(6.33 t ha^{-1}), T_9 (6.22 t ha^{-1}), T_3 (6.20 t ha^{-1}), T_2 (6.17 t ha^{-1}) and significantly higher than T_4, T_5 and T_1 which recorded 6.00, 6.04 and 4.75 t ha^{-1} respectively.

Table 43. Effect of silicon and boron on yield and yield attributes of rice

Treatments	Panicle weight plant^{-1} (g)	Thousand grain weight (g)	Grain yield (t ha^{-1})	straw yield (t ha^{-1})
Control- No Si and B (T_1)	31.20	20.96	3.05	4.75
Calcium silicate @ 100 kg Si ha^{-1} (T_2)	39.86	30.20	4.61	6.17
Potassium silicate @ 0.5% spray 3 rounds (T_3)	38.13	29.30	4.25	6.20
Borax @ 10 kg ha^{-1} (T_4)	36.40	29.90	3.50	6.00
Borax 0.5 % foliar spray 3 rounds (T_5)	38.13	29.53	3.52	6.04
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (T_6)	41.60	30.30	4.76	6.57
Calcium silicate @100 kg Si ha^{-1} + borax 0.5% spray 3 rounds (T_7)	37.26	29.63	3.54	6.33
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5 % spray 3 rounds (T_8)	45.06	30.70	4.95	6.54
Potassium silicate @ 0.5% spray 3 rounds + borax @ 10 kg ha^{-1} (T_9)	39.00	29.86	4.00	6.22
CD (5 %)	6.08	1.57	0.09	0.41

DISCUSSION

5. DISCUSSION

The results generated from the study on silicon and boron nutrition of rice in wet land soils of northern Kerala are discussed hereunder.

5.1. EFFECT OF SILICON AND BORON ON AVAILABLE NUTRIENT STATUS OF SOIL

5.1.1. Nitrogen

The treatments could not show any significant effect on available N in soil in the case of both pot and field experiments. Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds showed highest available N. In spite of the enhanced removal of N for increased dry matter production, there was an increase in alkaline $KMnO_4$- N content of the soil in the case of application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds. This may be due to the positive effect of Si and B on N availability since in the present study, appreciable increase in available B and Si content of soil was evidenced for the application of potassium silicate and borax as foliar spray. Similar results have been made by Ho *et al.* (1980) and Barman *et al.* (2014).

5.1.2. Phosphorous

In the pot culture experiment the available P content in soil was significantly higher in the case of application of calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil. However it was an on par with the foliar application potassium silicate @ 0.5 % spray + borax 0.5 % sprays 3 rounds. This might be due to the fact that the anion monosilicic acid $[Si(OH)_3]^-$ can replace the phosphate anion $[HPO_4]^{2-}$ from aluminum and iron phosphates there by increasing the solubility of phosphorus. In the case of field experiment, application of calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} showed similar results. Similar results have been reported by Subramanian and Gopalswamy (1990); Matinchav *et al.* (2000).

5.1.3. Potassium

The available potassium content in soil was influenced by the treatments in both pot and field experiments. Potassium silicate @ 0.5 % spray + borax 0.5 % sprays 3 rounds was superior to other treatments. This may be due to the production of hydrogen ions during reduction of Fe and Al toxicity which would have helped in 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).

5.1.4. Calcium

In the case of pot culture experiment the highest available Ca content in soil was obtained from the application of calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil while in the field experiment, application of calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} was superior. Similar results were reported by many workers (Islam and Saha, 1969 and Barman *et al.*, 2014).

5.1.5. Mg, S, Zn and Cu

Availability of Mg, S, Zn and Cu were not significantly influenced by the treatments in the case of both pot and field experiments. However application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds gave the highest values for available S and Zn in both the experiments showing a positive but non significant influence of silicon and boron on the availability of S and Zn.

5.2. EFFECT OF SILICON AND BORON ON CONTENT OF IRON, MANGANESE AND ALUMINIUM IN SOIL

5.2.1. Iron

The results obtained from the present investigation (pot and field experiments) revealed a significant reduction in HCl extractable iron content in soil for the application of silicon both as soil and foliar application (Fig.3, 4).

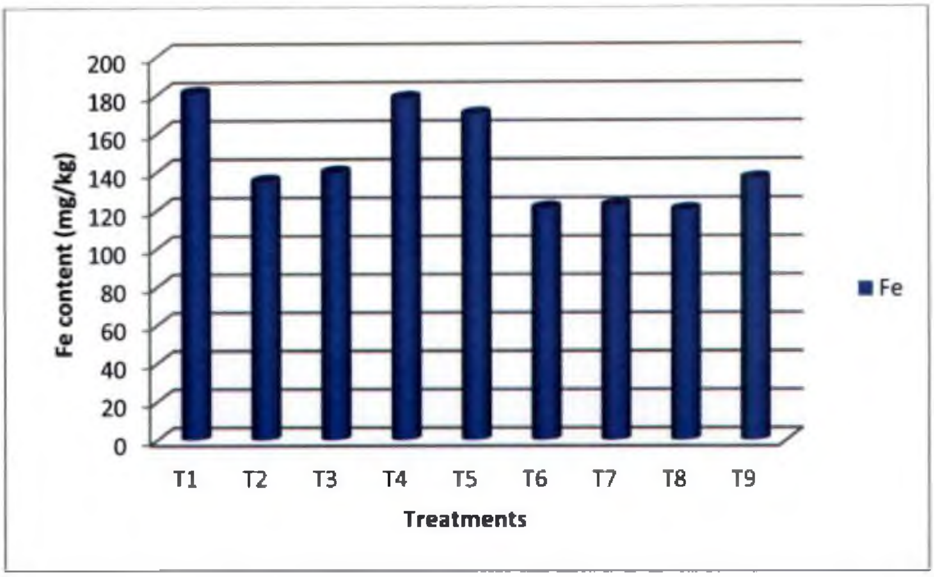

Fig.3. Effect of silicon and boron on alleviating toxicity of Fe (mg kg^{-1}) in soil in pot culture experiment

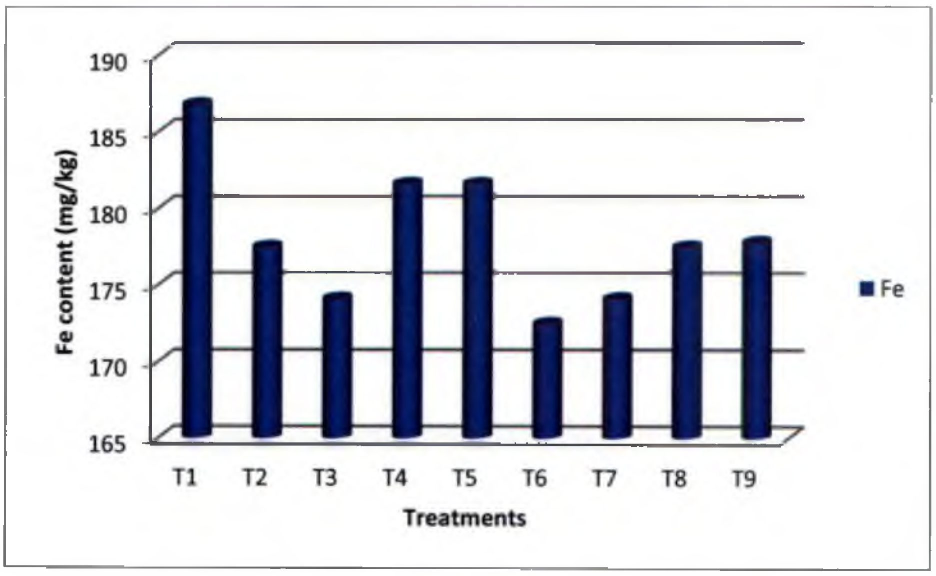

Fig.4. Effect of silicon and boron on alleviating toxicity of Fe (mg kg^{-1}) in soil in field experiment

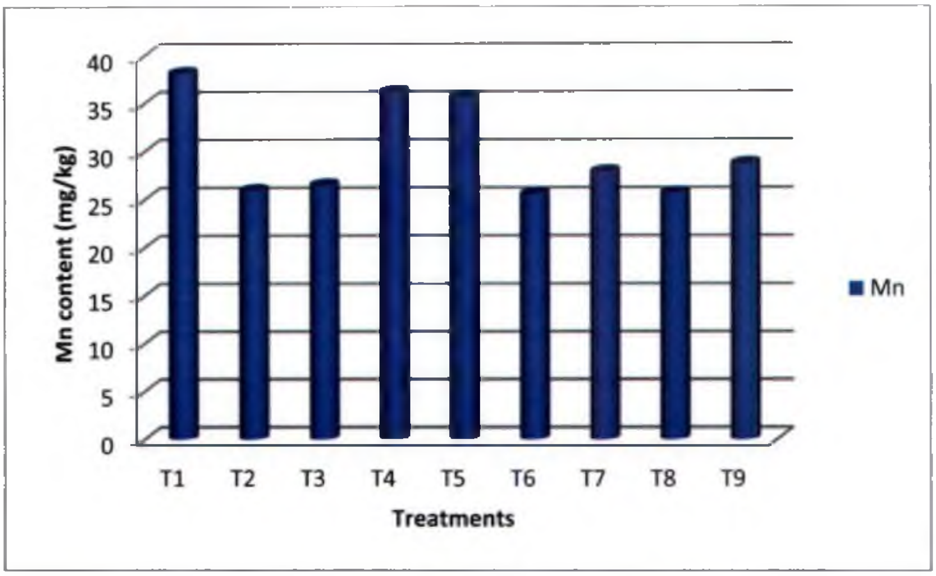

Fig.5. Effect of silicon and boron on alleviating toxicity of Mn (mg kg^{-1}) in soil in pot culture experiment

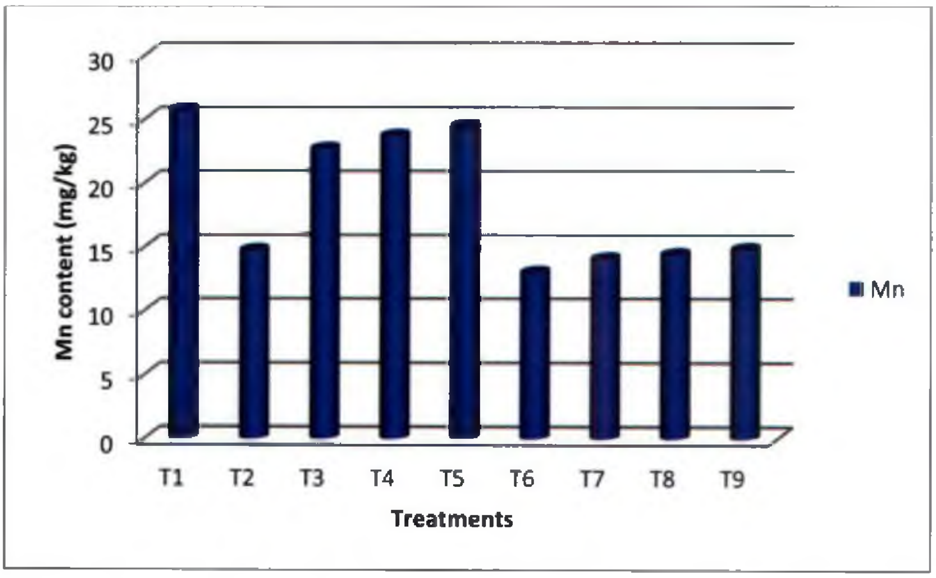

Fig.6. Effect of silicon and boron on alleviating toxicity of Mn (mg kg^{-1}) in soil in field experiment

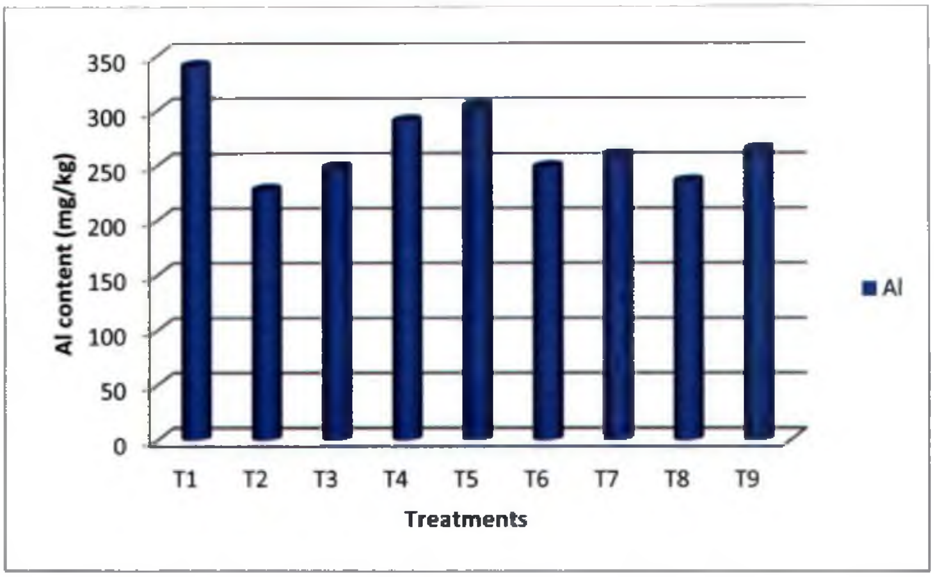

Fig.7. Effect of silicon and boron on alleviating toxicity of Al (mg kg^{-1}) in soil in pot culture experiment

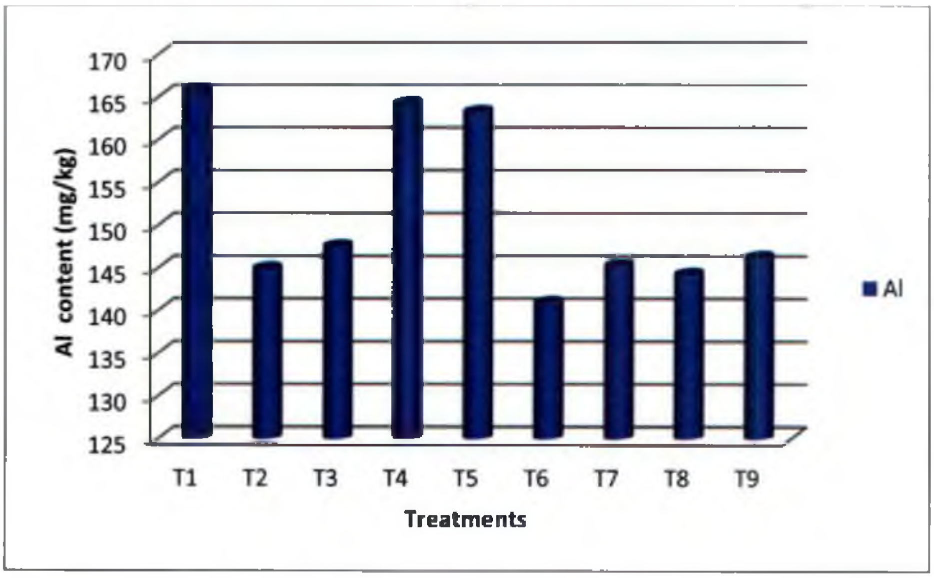

Fig.8. Effect of silicon and boron on alleviating toxicity of Al (mg kg^{-1}) in soil in field experiment

Foliar application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds (T_8) was superior to other treatments in reducing iron toxicity in both the experiments. But this did not affect the iron nutrition of rice as indicated by the absence of any significant decrease in total iron uptake by rice. Instead the uptake of iron in grain and straw were enhanced. Hence it can be concluded that the treatment could reduce iron toxicity in the soil.

Application of silicon improves the air passages in the leaves and stem of the plant and permits the passages of air for the leaves to the stem and finally to the roots. This enhances the oxidative power of rice roots and results in enhanced oxidation of iron from ferrous iron to ferric iron which reduces the toxicity of iron in soil. Similar results have been reported by Wallace (1992).

5.2.2. Manganese

The available Mn content of soil was significantly reduced by the application of silicon as both soil and foliar sprays. In the case of pot experiment, application of calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil was superior (Fig. 5) and in the field experiment application of calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} performed best (Fig.6).

The effect of application of calcium silicate in alleviating Mn toxicity in rice may be due to the influence of silicon in improving the oxidizing power of the rice roots. Similar results were reported by Wang *et al.* (1994). However the reduced Mn content in soil did not reflect on the uptake of Mn by rice as evidenced by higher total uptake of Mn. The enhanced Mn uptake in treatments may be due to the decreased toxicity of Mn resulted from the soil application of calcium silicate and borax.

5.2.3. Aluminium

The available Al of soil was significantly reduced by the treatments in both the experiments. In the case of pot experiment, application of calcium silicate @ 4 g kg^{-1} soil (Fig. 7) and in the field experiment application of calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} was superior in reducing the toxicity of Al in soil (Fig.8). The silicon applied to soil would have formed complexes with Al which would have reduced the concentration of Al in the soil. Similar results were reported by Wallace (1992).

5.3. SILICON AND BORON CONTENTS OF SOIL AT DIFFERENT STAGES OF RICE

5.3.1. Silicon

The silicon availability naturally showed a concomittant increase with application of silicon as soil and foliar spray. In both the pot and field experiments, soil application of calcium silicate was superior to foliar application of potassium silicate. The silicon availability increased from maximum tillering stage to flowering stage and then decreased at harvesting stage. This decrease may be due to increased absorption of silicon by the plant at vegetative and reproductive stages. In the pot culture experiment at flowering stage significantly higher available silicon was observed in the treatment receiving calcium silicate @ 4 g kg^{-1} soil while at the harvesting stage calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil was superior (Fig. 9). The results from field experiment revealed that the treatment receiving calcium silicate @ 100 kg Si ha^{-1} + borax @ 10kg ha^{-1} was superior at both flowering and harvesting stages (Fig. 10). The silicon applied as soil application of calcium silicate would have prevailed in soil as monosilicic acid (H_4SiO_4) and enhanced soil silicon availability. These findings are in agreement with those reported by Sing *et al.* (2006).

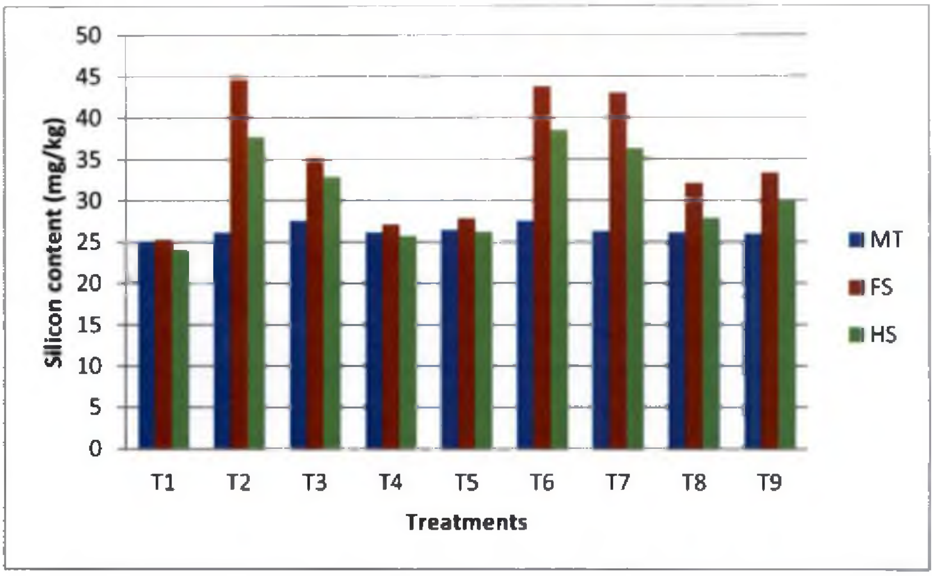

Fig.9. Silicon content (mg kg^{-1}) of soil at different stages in pot culture experiment

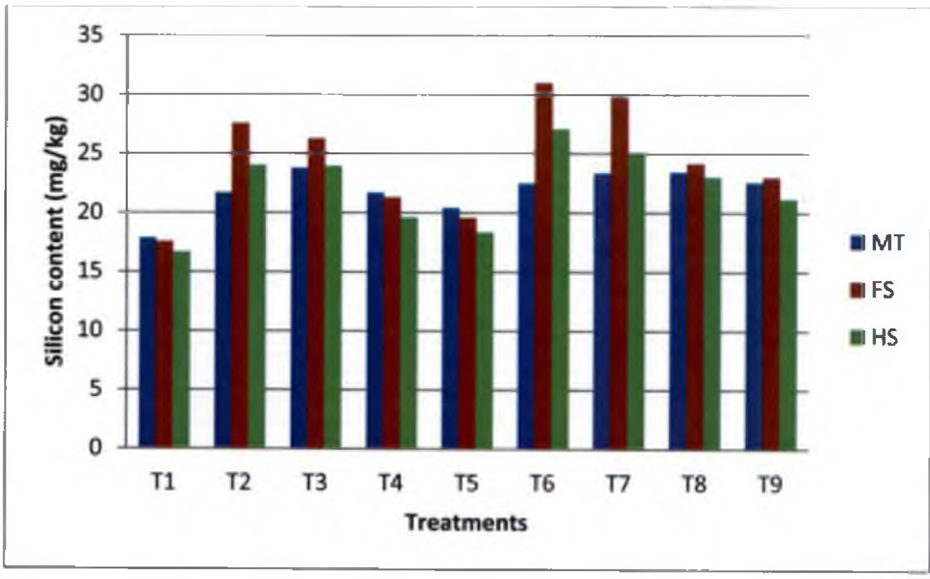

Fig.10. Silicon content (mg kg^{-1}) of soil at different stages in field experiment

*MT-Maximum tillering stage *FS-Flowering stage *HS-Harvesting stage

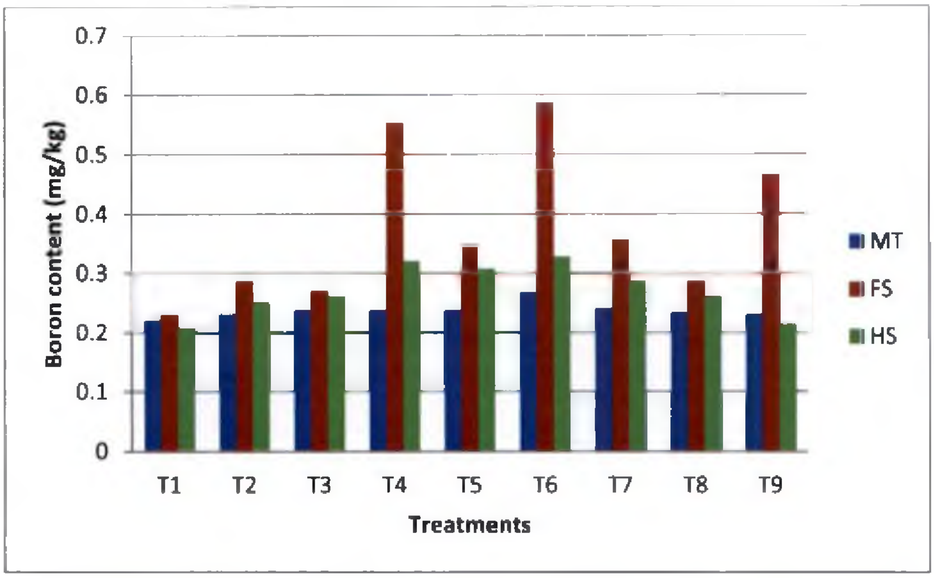

Fig.11. Boron content (mg kg^{-1}) of soil at different stages in pot culture experiment

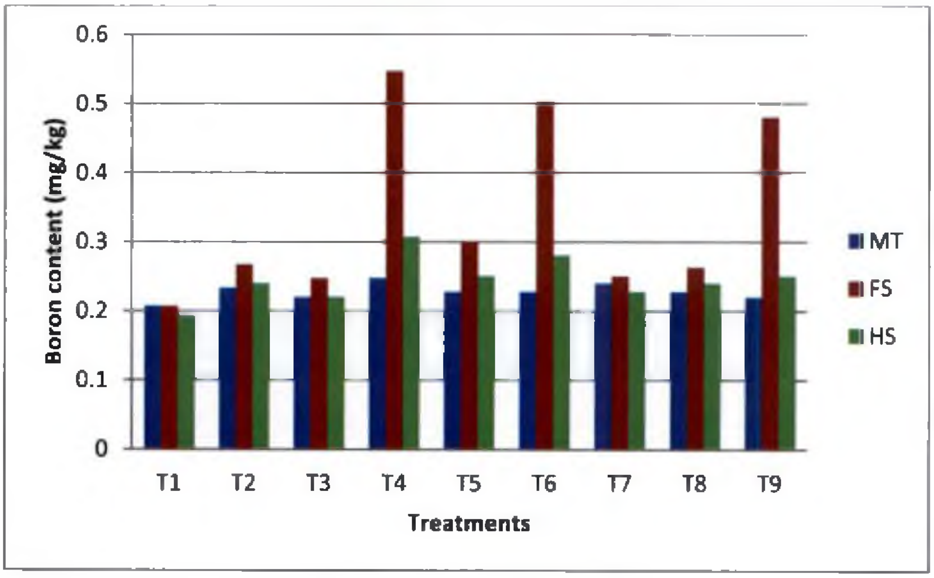

Fig.12. Boron content (mg kg^{-1}) of soil at different stages in field experiment

*MT-Maximum tillering stage *FS-Flowering stage *HS-Harvesting stage

5.3.2. Boron

As expected the availability of boron in soil also showed concomittant increase with application of boron to soil and plant. Soil application of borax was superior to foliar application in both pot and field experiments. These was an increases in boron availability from maximum tillering stage to flowering stage and there after a decline was observed at harvest stage which can be attributed to increased uptake of boron by the plant. The perusal of results obtained for available boron in soil at different stages of crop revealed that the treatments did not influence boron availability at maximum tillering stage in both the experiments. In the pot culture experiment soil application of calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil was superior at both flowering and harvesting stages (Fig. 11) while soil application of borax @ 10 kg ha^{-1} was superior in the field experiment (Fig. 12). The boron applied to soil would have dissociated to soluble boric acid form which would have increased the boron availability in soil and reached just sufficiency level in the treatments mentioned above as compared to the critical limit of 0.5 mg kg^{-1} fixed for Kerala soils. While for the other treatments though it was increased to a statistically significant level, the actual concentration was below the sufficiency level only. The total uptake of boron is also conspicuously high for the above treatments. Therefore after meeting the requirement of the crop, the added boron might have helped to increase the boron status of the soil from the deficiency to sufficiency level for these treatments. These finding are in line with those reported by Dunn *et al.* (2005).

5.4. EFFECT OF SILICON AND BORON ON MACRONUTRIENT CONTENTS IN RICE STRAW, GRAIN AND TOTAL UPTAKE

5.4.1. Nitrogen

Both the content and uptake of N in straw and grain was conspicuously higher for the treatments receiving foliar and soil application of silicon and boron in both the pot and field experiment. Among the treatments in the case of pot experiment foliar application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was superior with respect to content in straw, grain and total uptake. With respect to field experiment, potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds again performed better with respect to N content in straw. However with respect to N content in grain and total uptake of N, calcium silicate @ 100 kg Si ha^{-1} + borax @ 10kg ha^{-1} was superior. The alkaline $KMnO_4$-N content of soil was also high for the above treatments. This might have naturally resulted in enhanced absorption of N by the crop ultimately leading to higher N content and uptake. Similar results have also been reported by Sing *et al.* (2006) and Barman *et al.* (2014).

5.4.2. Phosphorous

The P nutrition of rice in terms of concentration and uptake of P showed a positive influence of soil and foliar application of silicon and boron. Foliar application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds produced significantly higher content of P in straw, grain and total uptake of P in both pot and field experiments. The available P in the soil was also high in the above treatments owing to the phosphate anions released from Fe and Al phosphate by monosilicic acid anions produced by the treatments. This would have resulted in better absorption of P by plant which has reflected in better content and uptake of P. Similar results were reported by Ma and Takahashi (1990).

5.4.3. Potassium

The content of K in grain, straw and total uptake of K in rice crop showed an upward trend for the application of silicon and boron as soil and foliar application in both the pot and field experiments. Foliar application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was significantly superior in both the experiments with respect to content in straw, grain and total uptake. It should be noted that the available K in the soil was also high in the treatment receiving potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds due to the release of K from the exchange sites to the soil solution by the hydrogen ions produced during the oxidation of Fe and Al compounds. This increased K concentration in soil would have contributed to greater K absorption by plant which has reflected in higher content in straw, grain and total uptake. Liang (1999) reported similar results.

5.4.4. Calcium

There was a significant influence of soil and foliar application of silicon and boron to rice on content of Ca in straw, grain and total uptake of Ca in plant. In both pot and field experiments, application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was superior in terms of content and uptake. It is to be noted that the above treatments was superior with respect to most of the available nutrients. This would have produced better root system for the crop which would have resulted in enhanced absorption of all nutrients including Ca. This has reflected in the higher content of Ca in straw, grain and total uptake of Ca. Similar results reported by Cachorro *et al.* (1994)

5.4.5. Magnesium and Sulphur

The results from the present investigation revealed a significant increase in content and uptake of Mg and S in response to soil and foliar application of silicon and boron. Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was superior in both pot and field experiments. Considering that the available Mg and S content of the soil was not influenced by the treatments, it should be persumed that the greater dry matter produced (root and shoot) would have improved the absorption of all the nutrients including Mg and S from the soil which would have translocated into increased content and uptake of Mg and S. Similar results were reported by Jawahar and Vaiyapuri (2008).

5.4.6. Iron

The content of iron in straw, grain and uptake of iron were significantly influenced by silicon and boron application. The iron content in straw and grain were found to decrease with treatments receiving silicon while its uptake in plant alone was significantly increased. Application of calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil resulted in significantly lower content of iron in both straw and grain in pot culture experiment while the treatment receiving potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds recorded significantly lower content of Fe in both straw and grain in the case of field experiment. The HCl extractable iron in the soil was also low for the above treatments due to the favourable effect of silicon in improving the oxidation power of rice roots thereby reducing iron toxicity in the soil. This might have naturally resulted in reduced absorption of iron and this coupled with the dilution effect attributed to high dry matter production would have contributed to the reduced content of iron in straw and grain. However the total uptake of iron by the plant in the pot culture experiment was significantly higher in the treatment receiving potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds. This can be attributed to the higher dry matter production associated with this treatment. In the case of field experiment, the treatment receiving borax @ 10 kg ha^{-1} and borax 0.5 % spray 3 rounds produced significantly higher total uptake of iron compared to the other treatments. Similar results on the effect of silicon on iron nutrition were reported by Okuda and Takahashi, 1962; Qiang *et al.*, 2012.

5.4.7. Manganese

The Mn nutrition of rice evaluated in terms of concentration in straw, grain and total uptake in plant was influenced by the soil and foliar application of silicon and boron. There was a significant reduction in the Mn content in grain and straw in the case of treatments receiving silicon in the form of soil and foliar applications. The application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds resulted in significantly lower content of Mn in grain and straw in both pot and field experiments. This may be due to dilution effect. The increased dry matter production in straw and grain might have resulted in decreased content of Mn. Similar results were reported by Okuda and Takahashi (1962) and Marschner (1995).

There was significantly higher uptake of Mn associated with the treatment receiving calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil in pot culture experiment and the application of calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} in the field experiment. The available Mn content of soil is the lowest in these treatments which would have helped in reducing Mn toxicity in rice. This would have resulted in better adsorption of all nutrients including Mn by the plant which has reflected in the higher uptake of Mn by the plant.

5.4.8. Zinc and Copper

The results obtained from the present investigation revealed a significant increase in Zn and Cu content in straw, grain and total uptake of Zn and Cu in plant. Application of potassium silicate @ 0.5 % spray + borax @ 0.5 g Kg^{-1} soil was superior in terms of content while the treatment receiving potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was superior in terms of uptake. The HCl extractable Zn and Cu content in soil was not influenced by treatments. This coupled with the better biomass (root and shoot) associated with the above treatments would have contributed to the higher content and uptake of Zn and Cu in the plant. These also corroborates with the findings of Bridgit (1999) and Bhutto *et al.* (2013).

5.5. SILICON AND BORON CONTENT IN RICE STRAW, GRAIN AND TOTAL UPTAKE

5.5.1. Silicon

The silicon nutrition of rice evaluated in terms of concentration and uptake was naturally influenced by silicon fertilization as calcium silicate (soil application) and potassium silicate (foliar spray). With respect to content and uptake of silicon, in the pot culture experiment application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was significantly superior to other treatments (Fig. 13) while in the field experiment potassium silicate @ 0.5 % spray was superior (Fig. 14). In any case of foliar application of potassium silicate @ 0.5% proved to be superior to soil application of calcium silicate. However it should be noted that with respect to available silicon in soil, soil application of calcium silicate was superior to foliar application of potassium silicate. Hence it can be persumed that the foliar application of potassium silicate (0.5 %) would have resulted in better absorption and translocation of silicon compared to soil application of calcium silicate which would has reflected in the significantly higher content and uptake of Si in plant. There finding are in line with those reported by Singh *et al.* (2006).

5.6.2. Boron

Boron nutrition of rice of course as one could expect showed a promising improvement for the application of borax both as soil treatment and as foliar spray. The treatments that received boron alone as soil application (borax 0.5 g kg^{-1} soil and borax 10 kg ha^{-1}) and foliar spray (borax 0.5 % spray 3 rounds) showed significant increase in boron content in straw and grain respectively in both pot and field experiments. Besides the well pronounced increase for content of boron in grain and straw, an upheaval trend for total uptake of boron was also seen. Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was superior in terms of uptake (Fig. 15, 16). This is because the available boron content of soil also was increased from sub optimal level to the sufficiency level for the addition of borax as soil and foliar spray. Similar results were reported by Gupta and Cutcliffe (1978) and Rakshit *et al.* (2002).

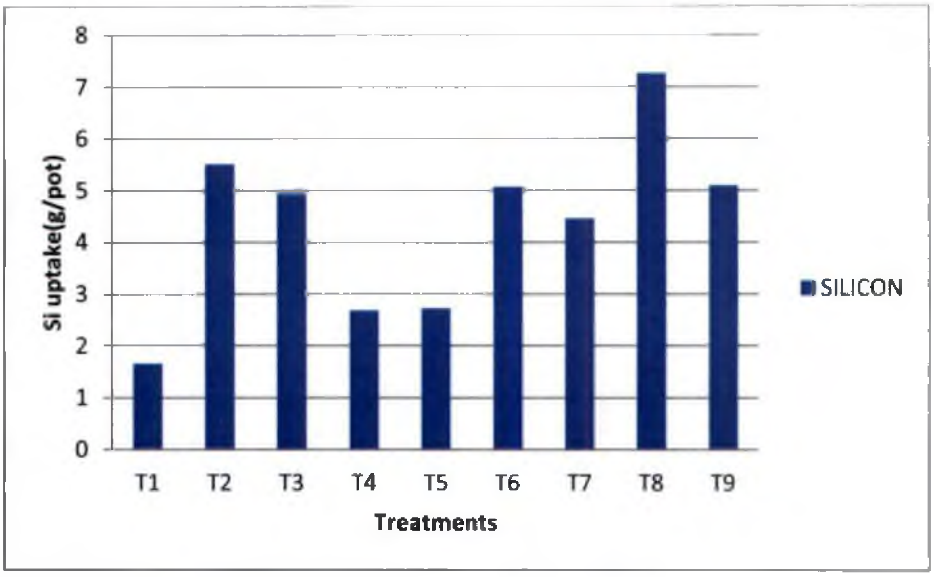

Fig.13. Silicon total uptake (g pot^{-1}) by plant in pot culture experiment

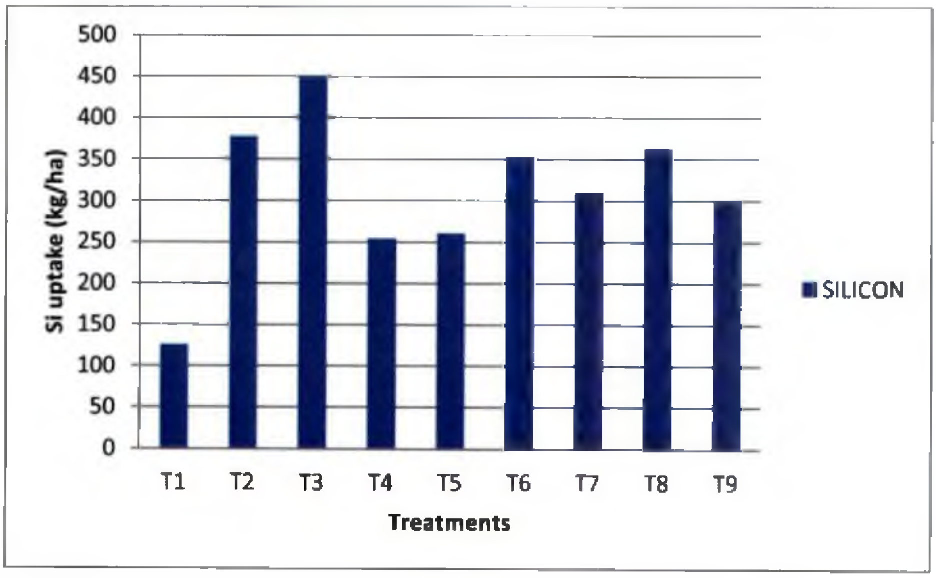

Fig.14. Silicon total uptake (kg ha^{-1}) by plant in field experiment

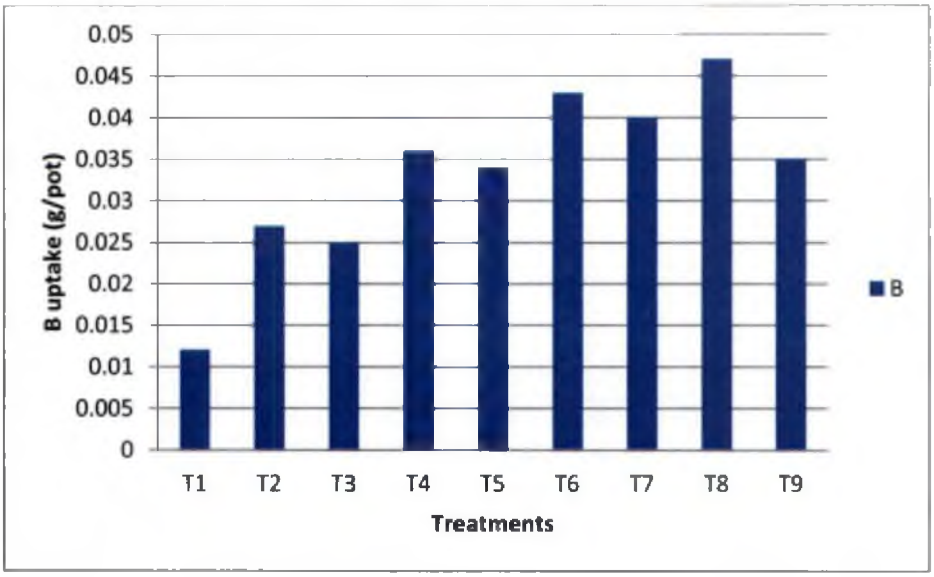

Fig.15. Boron total uptake (g pot^{-1}) by plant in pot culture experiment

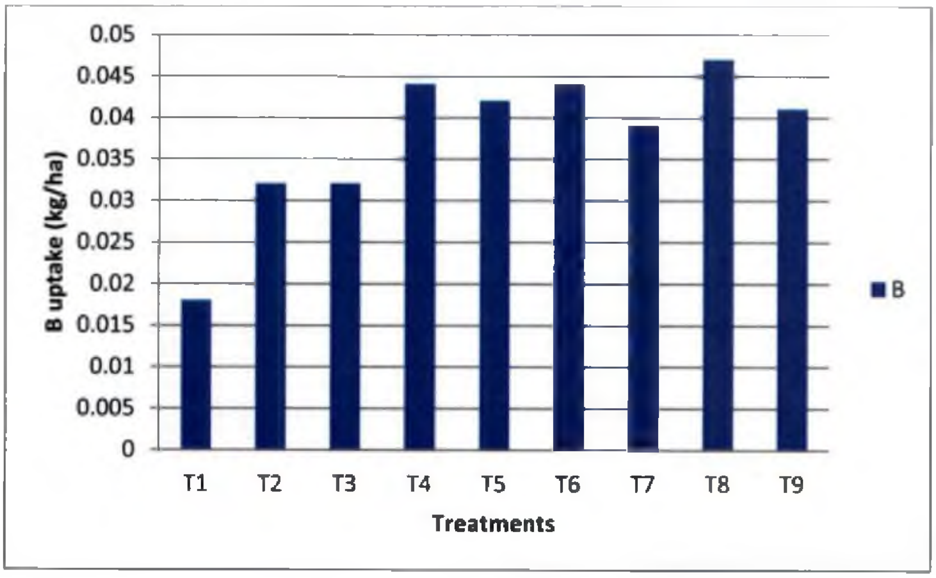

Fig.16. Boron total uptake (kg ha^{-1}) by plant in field experiment

5.6. EFFECT OF SILICON AND BORON ON PLANT GROWTH PARAMETERS OF RICE

Silicon and boron fertilization through soil and foliar application of fertilizers has accomplished significant variation in plant growth parameters like plant height (Fig. 17, 18), number of tillers plant^{-1} (Fig. 19, 20) and productive tillers plant^{-1}. In both pot and field experiments, the treatment receiving potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was superior. This can be attributed to the significant increase in available silicon and boron in this treatment and positive influence on the availability and uptake of other macro and micro nutrients except Fe and Mn. Similar reports were made by Debnath *et al.* (2009), Gholami and Falah (2013) and Ahmad *et al.* (2013).

5.7. EFFECT OF SILICON AND BORON ON YIELD AND YIELD ATTRIBUTES OF RICE

The yield attributes (panicle weight plant^{-1} and thousand grain weight), grain yield and straw yield of rice were significantly influenced by the application of silicon and boron as soil application and foliar spray in both pot and field experiments. Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was significantly superior with respect to yield attributes, grain and straw yield for pot experiment and yield attributes and grain yield for field experiment. In the case of straw yield in the field experiment, the treatment receiving calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} was superior. The tune of increase in grain yield in the superior treatment (potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds) was 34.34 g pot^{-1} and 1.90 t ha^{-1} in pot and field experiments respectively (Fig. 21, 22). The positive trend of results for yield obtained for silicon and boron fertilization in quit reasonable because of the following.

- A significant increase noticed in available silicon and boron for the treatments.

- Positive influence of silicon and boron on plant growth parameter likes plant height, number of tillers plant^{-1} and productive tillers plant^{-1}.
- Significant influence of silicon and boron on yield attributes like panicle weight plant^{-1} and thousand grain weight.
- The prevalence of substantial synergistic effect of silicon and boron on availability, absorption and translocation of N, K and S. Similar results have also been reported by Ahmad and Irshad (2011) and Rao *et al.* (2013).

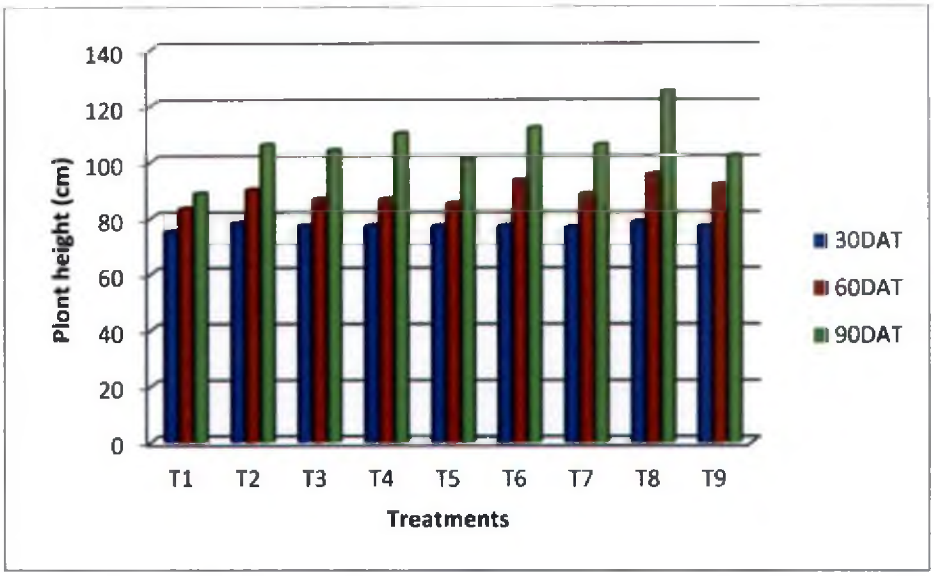

Fig.17. Effect of silicon and boron on plant height (cm) at different stages in pot culture experiment

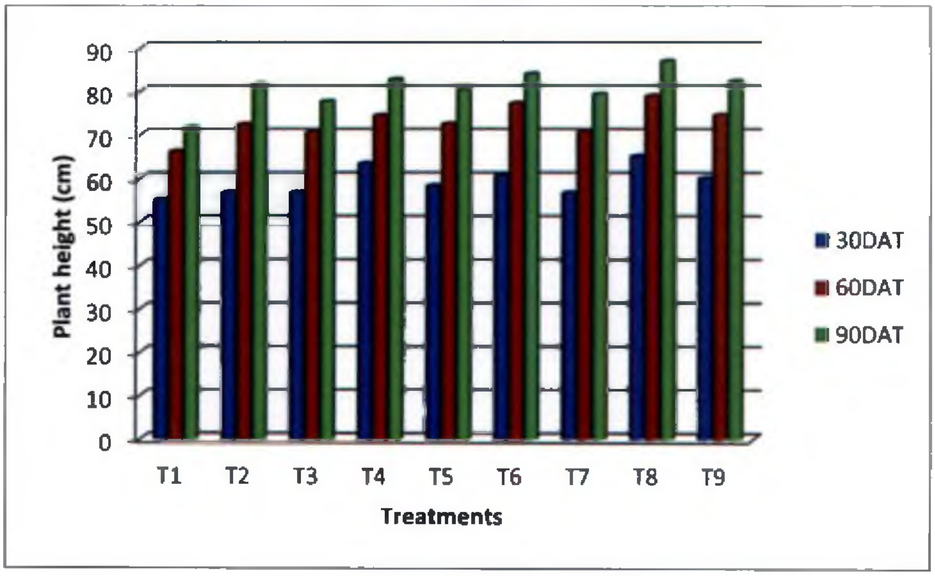

Fig.18. Effect of silicon and boron on plant height (cm) at different stages in field experiment

*DAT- Days after transplanting

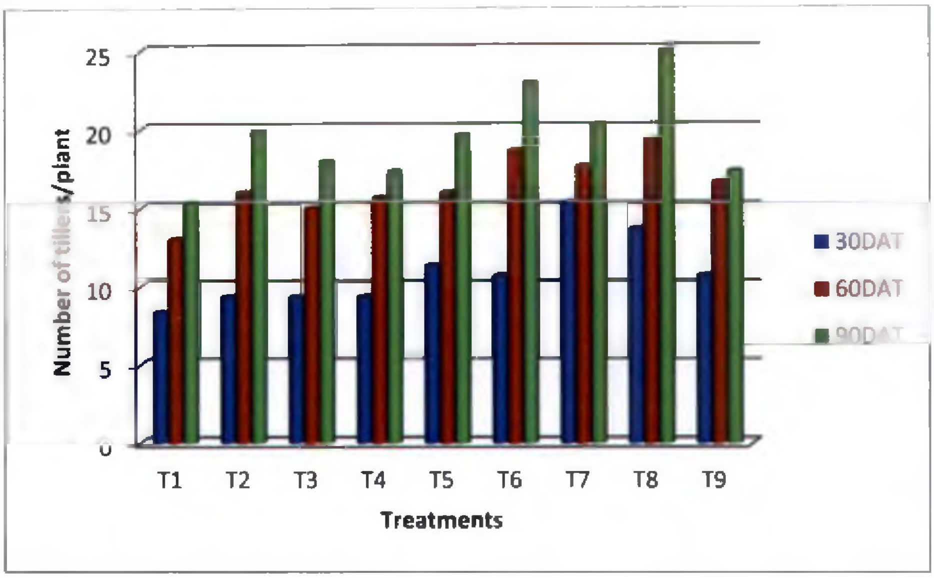

Fig.19. Effect of silicon and boron on number of tillers plant^{-1} at different stages in pot culture experiment

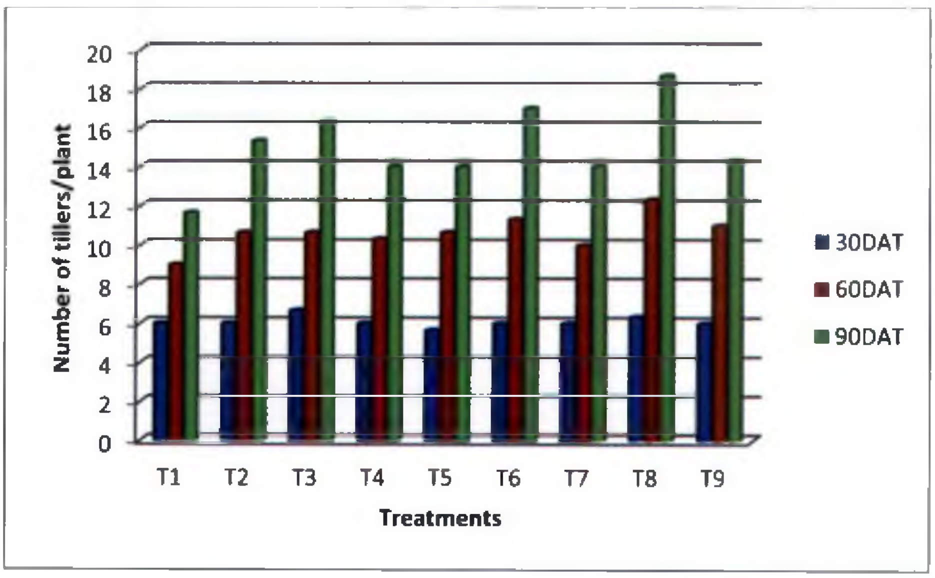

Fig.20. Effect of silicon and boron on number of tillers plant^{-1} at different stages in field experiment

*DAT- Days after transplanting

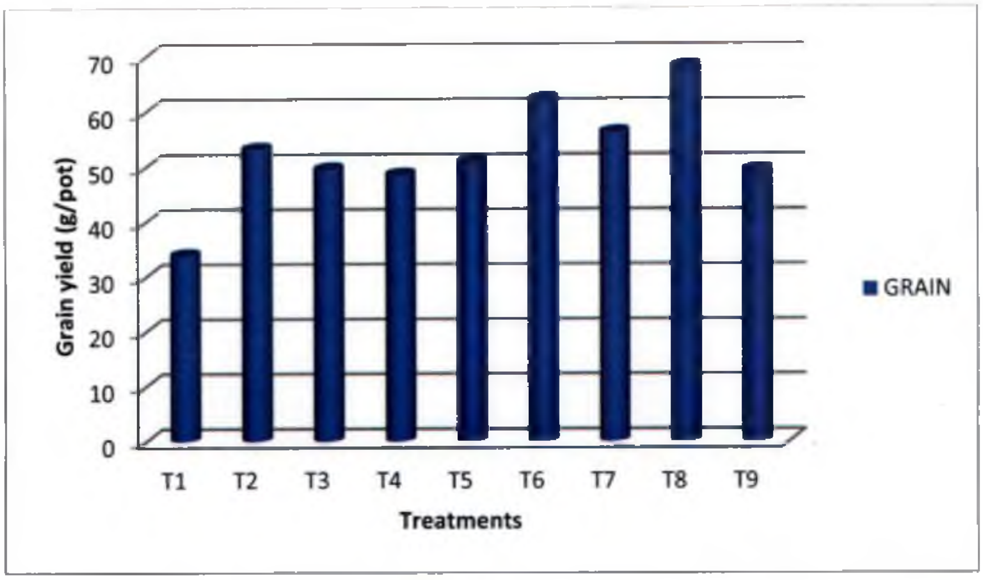

Fig.21. Effect of silicon and boron on grain yield (g pot^{-1}) in pot culture experiment

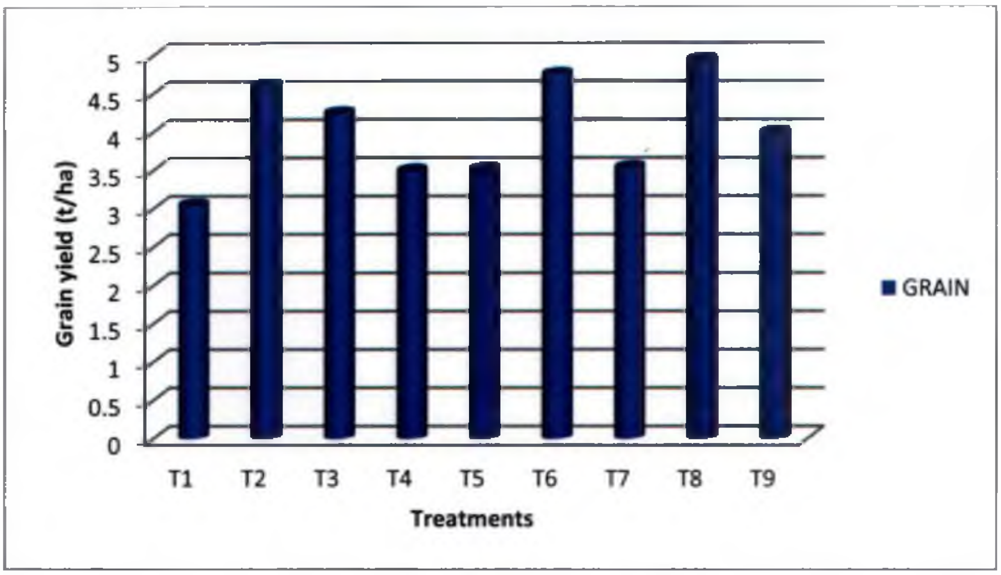

Fig.22. Effect of silicon and boron on grain yield (t ha^{-1}) in field experiment

SUMMARY

6. SUMMARY

The salient findings emanated from the pot culture and field experiments conducted to study "Silicon and boron nutrition of rice *(Oryza sativa* L.) in wet land soils of northern Kerala" are summarised in this chapter.

A pot culture experiment and a field experiment were conducted to standardize the dose and method of application of silicon and boron to rice crop in paddy soils, to evaluate its effect on available nutrient status and yield and to study the effect of silicon in alleviating the toxicity of Fe, Mn and Al in laterite derived paddy soils.

The sources of silicon tried were potassium silicate and calcium silicate and the source for boron was borax. Method of application evaluated were soil application and foliar spray.

In the pot culture experiment borax was applied to soil at 0.5 g kg^{-1} soil and as foliar spray (0.5 % 3 rounds). Silicon was applied as calcium silicate 4 g kg^{-1} soil and potassium silicate as 0.5 % spray 3 rounds.

In the case of field experiment, borax treatments were soil application at 10 kg ha^{-1} and foliar spray 0.5 % 3 rounds while silicon was applied as calcium silicate 100 kg ha^{-1} and potassium silicate 0.5 % foliar spray 3 rounds. Various combinations of the above treatments were tried using CRD design for pot culture experiment and RBD design for field experiment with rice variety Aishwarya as test crop. From the results of the present investigation the following conclusions were derived.

- There was no significant influence of treatments on available N content of soil in both pot and field experiments.
- The treatments calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil and calcium silicate @ 100 kg ha^{-1} + borax @ 10 kg ha^{-1} produced

significantly higher available P in the soil compared to other treatments in the case of pot and field experiments respectively.

- Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was superior to other treatments with respect to available K in soil for both pot and field experiments.
- Soil application of calcium silicate and borax resulted in highest available Ca in soil in both pot and field experiments.
- There was no influence of application of silicon and boron on availability of Mg, S, Zn and Cu in soil.
- The HCl extractable iron of soil was decreased due to the application of silicon. Foliar application of potassium silicate @ 0.5 % spray + borax 0.5% spray 3 rounds was superior in reducing iron toxicity of soil compared to other treatments.
- The available Mn and Al in soil were also significantly reduced by the treatments. Application of calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5g kg^{-1} soil and calcium silicate @ 100 kg ha^{-1} + borax @ 10 kg ha^{-1} were superior in pot and field experiments respectively.
- Soil application of calcium silicate was superior to foliar application of potassium silicate with respect to available Si content in soil.
- With respect to available boron status of soil, soil application of borax was superior to foliar application in both pot and filed experiments. Soil application calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil was superior at both flowering and harvesting stages in pot culture experiment while soil application of borax @ 10 kg ha^{-1} was superior in the field experiment.
- The increased alkaline $KMnO_4$-N content of soil associated with the treatments have also reflected in the content of N in straw, grain and total uptake of N by plant.
- Foliar application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds produced significantly higher content of P and K in straw, grain and total uptake of P and K in both pot and field experiments.

- The results revealed a significant increase in content in straw, grain and total uptake of Ca, Mg and S in response to soil and foliar application of silicon and boron with potassium silicate @ 0.5% spray + borax 0.5 % spray 3 rounds being superior in both pot and field experiments.
- The iron in straw and grain were found to significantly decrease with the application of silicon in response to the decrease in iron toxicity associated with silicon application. Calcium silicate @ 4 g kg^{-1} soil + borax @ 0.5 g kg^{-1} soil and potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds resulted in lowest content of iron in straw and grain in pot and field experiments respectively.
- There was a significant reduction in the Mn content in straw and grain in the case of treatments receiving silicon. The treatment potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds resulted in significantly lower content of Mn in straw and grain in both pot and field experiments.
- Foliar application of potassium silicate @ 0.5 % spray proved to the superior to soil application of calcium silicate with respect to silicon nutrition of rice in terms of content and uptake of silicon.
- Foliar application of borax 0.5 % spray in combination with potassium silicate @ 0.5 % spray 3 rounds significantly improved the boron content in straw, grain and total uptake of boron when compared to soil application of borax.
- The plant growth parameters of rice like plant height, number of tiller $plant^{-1}$ and productive tiller $plant^{-1}$ were significantly higher in the treatment receiving potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds in both pot and field experiments.
- Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was significantly superior with respect to yield attributes, grain and straw yield for pot culture experiment and yield attributes and grain yield in field experiment.
- The investigation carried out under pot as well as field conditions in low land rice ecosystem in laterite derived paddy soils of northern Kerala has

shown that the application of potassium silicate @ 0.5 % spray + borax 0.5% spray 3 rounds at 15 days interval significantly improved the available nutrient status of 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, Mn and Al in the soil.

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SILICON AND BORON NUTRITION OF RICE (*Oryza sativa* L.) IN WET LAND SOILS OF NORTHERN KERALA

by

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ABSTRACT

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ABSTRACT

The experiment entitled "Silicon and boron nutrition of rice (*Oryza sativa* L.) in wet land soils of northern Kerala" was carried out to standardize the dose and method of application of silicon and boron to rice crop in paddy soils, to evaluate its effect on available nutrient status and yield and to study the effect of silicon in alleviating the toxicity of Fe, Mn and Al in laterite derived paddy soils.

The treatments were a combination of boron source as borax (soil and foliar application) and silicon sources as calcium silicate (soil application) and potassium silicate (foliar application). Two experiments, a pot culture and a field experiment were conducted with rice variety Aishwarya as the test crop.

Application of silicon and boron fertilizers improved the availability of silicon and boron in soil. Soil application of calcium silicate along with borax was superior in maintaining the available silicon and boron status of soil than foliar application of potassium silicate and borax.

The study revealed that the application of silicon and boron as soil and foliar application had a synergistic effect on the availability of N, P, K, Ca, Mg, S, Zn and Cu in the soil.

Application of silicon as foliar application of potassium silicate 0.5 % along with borax 0.5 % spray was effective in reducing iron toxicity in the soil while the use of calcium silicate 100 kg Si ha^{-1} and borax 10 kg ha^{-1} proved to be more effective in reducing manganese and aluminium toxicity in the soil.

The content and uptake of N, P, K, Ca, Mg, and S in rice were significantly improved by the application of potassium silicate 0.5 % foliar spray along with borax 0.5 % spray 3 rounds.

Foliar application of silicon and boron as potassium silicate 0.5 % spray and borax 0.5 % spray was more efficient on improving the content and uptake of silicon and boron compared to soil application of calcium silicate and borax.

Application of potassium silicate @ 0.5 % spray + borax 0.5 % spray 3 rounds was significantly superior with respect to yield and yield attributes of rice.

In a nutshell, both the pot and field experiments clearly indicated that application of Si and B significantly improves the available nutrient status of soil, nutrient uptake, grain and straw yield of rice. Foliar application of potassium silicate and borax (0.5 % each) 3 rounds at 15 days interval significantly improved the available nutrient status of soil, yield and yield attributes of rice. It was also effective on alleviating toxicity of Fe, Mn and Al in laterite derived paddy soils.

APPENDICES

APPENDIX-I

Composition of silicon and boron sources used

S.No.	Name	Chemical formula	Content
1	Calcium silicate	$CaSi0_3$	14-19% Si, 20.2% Ca
2	Potassium silicate	K_2SiO_3	45% Si, 17% K
3	Borax	$Na_2B_4O_7$ $10H_2O$	11% B

APPENDIX-II

Economic of cultivation of rice per ha (field experiment)

Treatments	Gross return	Cost of cultivation	Net return	B:C ratio
Control- No Si and B (**T_1**)	61420.8	43750.0	17670.8	1.40
Calcium silicate @100 kg Si ha^{-1} (**T_2**)	90837.5	48512.5	42325.0	1.87
Potassium silicate @ 0.5 % spray 3 rounds (**T_3**)	84729.1	47787.5	36941.6	1.77
Borax @ 10 kg ha^{-1} (**T_4**)	71500.0	44900.0	26600.0	1.59
Borax 0.5 % foliar spray 3 rounds (**T_5**)	72079.1	45900.0	26179.1	1.57
Calcium silicate @ 100 kg Si ha^{-1} + borax @ 10 kg ha^{-1} (**T_6**)	94183.3	49662.5	44520.8	1.89
Calcium silicate @100 kg Si ha^{-1} + borax 0.5 % spray 3 rounds (**T_7**)	72945.8	50662.5	22283.3	1.43
Potassium silicate @ 0.5 % spray 3 rounds + borax 0.5 % spray 3 rounds (**T_8**)	97375.0	46087.5	51287.5	2.11
Potassium silicate @ 0.5 % spray 3 rounds + borax @ 10 kg ha^{-1} (**T_9**)	80458.3	48937.5	31520.8	1.64