SILICON AVAILABILITY OF TROPICAL SOILS WITH RESPECT TO RICE NUTRITION

By

ARYA LEKSHMI, V.

THESIS

Submitted in partial fulfillment of the

Requirement for the degree of

Doctor of philosophy in Agriculture

Faculty of Agriculture
Kerala Agricultural University

Department of Soil Science and Agricultural Chemistry
COLLEGE OF HORTICULTURE
KERALA AGRICULTURAL UNIVERSITY
THRISSUR 680 656
KERALA, INDIA

2016

DECLARATION

I, hereby declare that this thesis entitled **"Silicon availability of tropical soils with respect to rice nutrition"** is a bona-fide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, fellowship or other similar title, of any other university or society.

28/03/16

Vellanikkara

28-03-2016

ARYA LEKSHMI, V.

(2011-21-117)

CERTIFICATE

Certified that this thesis, entitled **“Silicon availability of tropical soils with respect to rice nutrition”** is a record of research work done independently by **Mrs. Arya Lekshmi, V.** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associate ship to her.

28.3.16

Vellanikkara
28-03-2016

Dr. Jayasree Sankar, S.
Chairman, Advisory Committee

CERTIFICATE

We, the undersigned members of the Advisory Committee of **Mrs. Arya Lekshmi, V. (2011-21-117)**, a candidate for the degree of **Doctor of Philosophy in Agriculture** with major in **Soil Science and Agricultural Chemistry,** agree that the thesis entitled **"Silicon availability of tropical soils with respect to rice nutrition"** may be submitted by Mrs. Arya Lekshmi, V. in partial fulfilment of the requirements for the degree.

28.3.16

Dr. Jayasree Sankar, S.
(Chairman, Advisory Committee)
Professor
Department of Soil Science and
Agricultural Chemistry
College of Horticulture
Vellanikkara

28/3/16

Dr. P.K. Sushama
(Member, Advisory Committee)
Professor and Head
Department of Soil Science and
Agricultural Chemistry
College of Horticulture
Vellanikkara

28/3/16

Dr. P. S. John
(Member, Advisory Committee)
Professor
Department of Agronomy
College of Horticulture
Vellanikkara

28/3/2016

Dr. T. Girija
(Member, Advisory Committee)
Professor
Department of Plant Physiology
College of Horticulture
Vellanikkara

28/3/16

Dr. S. Krishnan
(Member, Advisory Committee)
Associate Professor and Head
Department of Agricultural Statistics
College of Horticulture
Vellanikkara

28/3/16

Dr. Mini Abraham
(Member, Advisory Committee)
Associate Professor and Head
Agronomic Research Station
Chalakudi

28.3.2016

External Examiner

ACKNOWLEDGEMENT

Towards the end of this great voyage in the quest for knowledge and wisdom, which makes the beginning of a new horizon, it gives me an insurmountable task to mention all of them who planted and nurtured the spirit of faith and help in accomplishing this task. I take this opportunity to look back on the path traversed during the course of this endeavour and to remember the guiding faces behind the task with a sense of gratitude.

I recall the words of Henry Adams who said "A teacher effects eternity: he can never tell when his influence stops". It is with immense pleasure that I express my deep sense of gratitude and indebtedness to ***Dr. Jayasree Sankar, S,*** *Professor, Department of Soil Science and Agricultural Chemistry, College of Horticulture, Vellanikkara for her constant inspiration and encouragement, timely help, valuable advice, moral support, constructive criticism and friendly attitude throughout the study period. I admit, it has been great privilege for me to be associated with her during my doctoral degree programme.*

It is with immense pleasure, I express my whole hearted gratitude and never ending indebtedness to ***Dr. P.K. Sushama****, Professor and Head, Department of Soil Science and Agricultural Chemistry and member of my Advisory Committee for her expert guidance, constructive criticisms, valuable suggestions and above all her support and encouragement throughout the course of study.*

I thankfully acknowledge ***Dr. P. S. John****, Professor, Department of Agronomy and member of my Advisory Committee for his esteemed advice, timely help, and valuable suggestions throughout this programme.*

I think it is my privilege to express my heartfelt thanks to ***Dr. T. Girija****, Professor, Department of Plant Physiology and member of my Advisory Committee for her critical evaluation of manuscript, constant encouragement, sincere help and support in times of need especially in the preparation of this thesis.*

I express my gratitude to ***Sri. S. Krishnan****, Associate Professor & Head, Department of Agricultural Statistics and member of my Advisory Committee for his valuable suggestions and help in doing the statistical analysis and interpretation of data.*

I think it is my privilege to express my heartfelt thanks to ***Dr. Mini Abraham,*** *Associate Professor & Head, Agronomic Research Station, Chalakudi and member of my*

Advisory Committee for her critical evaluation of manuscript, constant encouragement, sincere help and support in times of need especially in the preparation of this thesis.

I wish to express my sincere thanks to ***Dr. Suma Paulose****, Former Professor & Head, Agronomic Research Station. Chalakudi and former member of my Advisory Committee for her inspiring attitude and sincere help during field experiments at ARS, Chalakudi. I express my sincere thanks to* ***Dr. Sreelatha, A. K.****, Assistant Professor, Rice Research Station, Vyttila for her inspiring attitude, constant and sincere help, valuable suggestions and sensiblecriticism during my research work. I am also thankful to my teachers* ***Dr. P. Sureshkumar, Dr. K.M. Durgadevi, Dr. Betty Bastin, Dr. V.I. Beena, Sri. Visveswaran S., Smt. Bindu P.S.and Smt. Rajalekshmi*** *of the Department of Soil Science and Agricultural Chemistry and* ***Dr.Bridgit, T. K.*** *and* ***Dr. Deepa*** *of ARS, Chalakudi for their ever willing help rendered at various phases of my study.*

No words can truly portray my indebtedness to ***Mr. Anilkumar, Mr. George and Mr.Unnikrishnan,*** *farm officers and their labourers of ARS, Chalakudi. I owe my special thanks to* ***Devi chechi, Saradha chechi, Baby chechi, Sujatha chechi, Malathi chechi, Vichithra chechi, Saritha chechi*** *and* ***Prasadettan*** *who were of great help during the hours of need. I express sincere gratitude to* ***Dr. Sindhu****,* ***Arun, Ramana, Surya and Neethu,*** *Teaching assistants of Department of Soil Science and Agricultural Chemistry. I would like to record my sincere thanks to* ***Mr. Sathyan*** *(Former Farm Superindent),* ***Mr.Ananthakrishnan and Mr. Vinod.***

My express gratitude to my seniors ***Divya chechi, Maya chichi and Geetha chechi,*** *and juniors* ***Irene, Chris, Vaisakhi, Shitha, Nithya, Abdu, Rosmy, Anooja, Indhu, Aditya, Rincy, Aneesa, Beena Sridhar, Reshma and Rajkumar.***

Above all, my success would have remained an illusion without the ambitious encouragement, unquantifiable love, continued calm endurance, constant support and affection showered on me throughout the educational endeavour from my beloved parents ***Sri. P. K. Sasidharan Nair*** *&* ***Smt. B. Valsalakumari, Sri. Ramachandran Pillai*** *&* ***Smt. V. Jayakumari,*** *and my brothers.*

I am unable to express my feelings by words to my husband, ***Sandeep J. R.*** *for his affectionate encouragement, patience and sacrifices during the course of the study.*

I am unable to express my feelings by words to my husband, ***Sandeep J. R.*** *for his affectionate encouragement, patience and sacrifices during the course of the study.*

INSPIRE fellowship *funded by* ***Department of Science and Technology*** *is gratefully acknowledged.*

One last word; since it is practically impossible to list all the names who contributed contributions to my work, it seems proper to issue a blanket of thanks for those who helped me directly or indirectly during the course of study.

Finally, I thank God for bestowing me with divine spirit, essential strength and necessary support to find my way towards a glorious career amidst several hurdles and struggles.

.....any omission in this small manuscript does not mean lack of gratitude.

28/03/2016

(ARYA LEKSHMI, V.)

DEDICATED TO

MY FAMILY

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

Introduction

1. INTRODUCTION

The word ‗Silicon' is derived from the Latin word ‗Silex', meaning flint which was proposed by Sir Humphry Davy in 1808. The word was originally used to denote any hard rock. Silicon (Si) is the second most abundant element and is present in nearly all the minerals. It accounts for up to 28.8 per cent of the earth crust by weight. Most of the minerals in igneous rocks are silicates and hence soil is largely composed of silicates. The Si contentof clayey soil is 200 to 350 g kg^{-1} and of sandy soil is 450 to 480 g kg^{-1} (Matichenkov and Calvert, 2002). It is of the current opinion that Si is an inert element and cannot play an important role in the biological and chemical process. However many Si compounds are not inert.

The amounts of silicon in soils depend on parent material, soil type, pedogenicprocess and landscape scale. The concentration of silicon in soil solution ranges between 3 to 17 mg kg^{-1} (Savant *et al*., 1997). This Si is mostly in the form of silicates and aluminosilicates. The main portions of Si rich compounds in soils are represented by quartz and crystalline silicates, which are inert. In many respects, these silicates form the skeleton ofthe soil. The physically and chemically active Si substances in the soil are represented by weakly adsorbed monosilicic acid, polysilicic acid and organosilicon compounds. The solubility of Si minerals is variable and is influenced by temperature, pH, particle size, chemical composition and presence of disrupted layers. Their dissolution kinetics is affected by soil factor such as organic matter, water content, redox potential and sesquioxides. The sesquioxides apparently act as soluble sink or source depending on the pH of the soil. The Si concentration as monosilicic acid (H_4SiO_4) in soil solution is generally 0.1 to 0.6 mM whichis less than that in saturated monosilicic acid solution and is largely due to pH–dependent adsorption of Si by sesquioxides (Epstein, 1994).

Silicon is not considered as an essential element for higher plants, but it has been proved to be beneficial for the healthy growth and development of many plant speciesparticularly graminaceous plants such as rice, sugarcane and some cyperaceous plants. The beneficial effects of Si are particularly distinct in plants exposed to abiotic and biotic stress. An awareness of Si deficiency in soil is now recognized as a limiting factor for crop production; particularly in soils that are seemed to be low or limiting in plant available Si. Silicon is taken up by the roots in the form of monosilicic acid (H_4SiO_4), an uncharged monomeric molecule when the solution pH is below 9. Plants differ greatly in their ability to accumulate Si, ranging from 0.1 to 10 per cent Si. The difference in Si accumulation between species has been attributed to difference in the Si uptake ability of roots (Epstein, 1999).

In warm subhumid and humid tropical ecoregions, a high degree of weathering,mainly as desilication, has resulted in the development of soils rich in iron and aluminum oxides and low in nutrient bases and Si. This could be one of the reasons for low available Si in major rice growing tracts of Kerala. Nayar *et al*. (1982) revealed that the available Si extracted by different extracts in soils of Kerala ranged from 8 to 435 mg kg^{-1}. As a result of Si leaching, the soluble Si content of tropical soils, such as Ultisols and Oxisols, is generally5 to 10 times less than in most temperate soils (Friesen *et al.,* 1994).

Rice (*Oryza sativa L.*) is the most staple food of Kerala. The productivity of rice is comparatively low in tropical soils of Kerala. As a Si accumulator, rice benefits from Si nutrition. The application of Si enhances growth and yield of rice. Savant *et al*. (1997) reported that Si depletion can occur in traditional rice soils from continuous monoculture of high yielding cultivars with intensive cultivation practices, especially if farmers are not replacing the Si removed by rice. Consequently, there is a definitive need for proper management of Si to increase yield and sustain crop production appears to be necessary in temperate and tropical countries.

Recycling of Si through plant residue to the soil is of great importance in rice farming. Biocycling of Si through plant materials and back into soil is comparatively rapid and thus may exert a dominant control on the biogeochemical cycling of Si within soil. The return of rice residues to soil may provide a low cost affordable means of Si fertilization that is feasibleto farmers. Rice husk is the major waste generated by rice mills. It is well known that rice plant accumulate large amount of Si in its husk. In certain regions of India, rice husk is mainly used as a cheap source of energy. The product of combustion is the partially burnt ricehusk, which is not only a waste material but also an environmental pollutant. Hence the composting of rice husk is the most acceptable solution for economical disposal of rice husk. Use of rice husk compost as organic manure, might play a vital role not only in improvingsoil properties but also for improving the plant nutrition. The incorporation of rice straw into soil after harvest of rice crop may be regarded as a low cost measure to increase the available Si pool, to decrease the depletion of Si which could lead to accumulation of Si in above ground tissues. The effectiveness of different sources of Si is mainly depend on pools and adsorption of Si, supplying power and plant available Si content of soils.

In this background the present study was conducted with the following objectives in view

1. To categorize rice growing soils of Kerala according to plant available silicon.
2. To monitor release of silicon from different rice growing soils added with various silicon sources under different water regimes.
3. To evaluate the efficacy of different sources of silicon including rice straw in wet land rice.

Review of literature

2.REVIEW OF LITERATURE

2.1 Importance of silicon in lithosphere

Silicon (Si) is the second most abundant element of the Earth‘s crust with a mean content of 28.8 per cent (wt) (Wedepohl, 1995) and it occurs in a large range of minerals at the earth surface, ranging from 0.5 to 47 per cent (wt) in the pedosphere (McKeague and Cline, 1963a). As the ultimate source, chemical weathering of silicate minerals liberates dissolved Si (DSi) as monosilicic acid (H_4SiO_4). DSi contributes to soil formation through biogeochemical reactions such as neoformation of secondary minerals, adsorption onto Fe and Al hydroxides or oxides and uptake by plants and biogenic silica (BSi) would be returnedtopsoil and carried from the lithosphere to the hydrosphere (Sommer *et al*., 2006).

2.2 Silicon status in soil

Monger and Kelly (2002) reported that Si ranged from more than 46.5 per cent in igneous rock (ortho-quartzite), 23 per cent in basic rocks (basalt) and to trace amounts in carbonaceous rocks (limestones and carbonatites). In derived soils, Si ranged from 46.0 per cent in silcretes to 7.9 per cent in petrocalcic horizons, and even lower in some highly weathered Oxisols such as bauxites or ferricretes. Soils mainly contained Si as silica minerals, primary silicates and secondary silicates, especially phyllosilicates. Epstein (1999) reported that silicon was an important component and occurs mainly in the molecular form ofuncharged monomeric silicic acid (H_4SiO_4) in soil solution. The concentrations of monosilicic acid in soil solution ranged from 0.1 to 0.6 mM. Silicon hardly forms complexes with dissolved organic matter, but can combine with Al along the whole soil solution to form colloidal Al-Si polymers

Dietzel (2002) reported that Si fluxes in soils and terrestrial biogeosystems were mainly mediated through water. Silicic acid (H_4SiO_4) is the main component of soil solutions,mostly as monomeric silicic acid. Monomeric silicic acid could be transformed into polymeric silicic acid under strongly alkaline conditions, which was composed of two ormore Si atoms and might occur in different forms. Dissolution experiments with various minerals at pH 3.0 showed that solutions contain both monomeric and polymeric species, but polymeric Si decomposing into monomeric Si over time. Polymerization had also beenobserved at Fe oxide surfaces which were confined to acidic solutions at pH < 6. Under soil conditions, Al seemed to stabilize polymeric silicic acids against depolymerization. Silicic acid formed complex bonds with organic compounds of soil solutions. The concentration of Si in soil solution depended on the solubility of primary and secondary Si compounds in soils. Solubility was a function of temperature, particle size, chemical composition and the presence of disrupted surface layers.

2.2.1 World Scenario

The available Si concentrations in the soils of southern and south eastern regions of China were lower than those in northern and western China due to strong desilicification and weathering. Most light-textured paddy soils were Si deficient, with the available Si concentration below 80 mg SiO_2 kg^{-1}. Clayey soils in this region generally had moderate Si supply capacity with an average extractable Si of 120 mg SiO_2 kg^{-1}. High available Si concentrations (greater than 200 mg SiO_2 kg^{-1}) could be found in paddy soils developed from alluvium originated from large rivers and lakes, basalt, shale and other Si-rich parent materials. In paddy soils with a long history of rice cultivation in northern and north eastern regions of China, concentrations of available Si in soils varied greatly (Wang *et al*., 2001). Berthelsen *et al*., (2003) reported that three different Australian soils *viz*. Hydrosol, Tennosol and Ferrosol varied in their levels of plant available silicon in the order Hydrosol > Tennesol >Ferrosol. Husnain *et al*. (2008) observed that soils in West Java derived from volcanic ash and tuff volcanic in upper topographical position and alluvial in lower topographical position were low compared to Central Java where volcanic ash and tuff volcanic were distributed from upper to lower topographical position.

An investigation of soil silicon in alluvial soils of the Nile valley and transitional belts of the desert plateaus in Middle Egypt showed that the amounts of water-soluble Si ranged between 0.05 and 2.34 mg SiO_2 100 g^{-1} soil. Fine textured soils showed the highest values of soluble and amorphous Si. It increased from the desert plateaus toward the Nile stream. As a percentage of total Si fractions, amorphous Si constituted 0.07 to 7.55 per cent. Total Si as SiO_2 percent varied greatly from one site to another and ranged between 40.18 and 90 per cent. The highest values were obtained from the coarse-textured soils which are located in/or near both Eastern and Western plateaus, while the lowest values were obtained from the alluvial soils of medium to heavy texture grades (Morsy, 2008). Lalljee (2008) reported that the available Si in Mauritius soils showed wide variation between the different soil types, ranging from 10 to 90 mg kg^{-1}. The pH was positively and strongly correlated with available Si. Similarly the soil Si was also positively correlated with the textural index of the soil, as well as several soil parameters. Fassil (2009) studied Si distribution in the soils of the northern highlands of Ethiopia and revealed that Si contents ranged from 79.8 to 166.3 g Si kg^{-1}. The highest concentration of Si was found in Wukro where the sand content was 50 per cent whereas the lowest level was obtained from soils of Adigudom where the clay content exceeded 60 per cent. The concentrations of dissolved and biogenic silica (DSi and BSi) in two salt marshes of the Wadden Sea coast under different management conditions were measured by Muller *et al.* (2013). Ungrazed sites had significantly higher seepage water DSi concentrations than sites which were grazed by sheep. BSi concentrations were lower and more variable.

The silica content in lateritic soils of south western Nigeria derived from Gneiss, Quartz-schist and Granite were from 39.50 to 56.32, 46.98 to 96.97 and 37.99 to 70.90 per cent respectively (Adebisi *et al.*, 2013). Klotzbucher *et al.* (2014) reported that the plant available Si (acetate extraction) concentrations in top soils of paddy fields differed between Philippine (141 – 322 mg Si kg^{-1}) and Vietnam (20 – 51 mg Si kg^{-1}) regions. This might be due to the differences in geo/pedologic conditions between these countries. Large plant available Si concentrations in the Philippines were due to recent rock formation by active volcanism, hence by a large Si input due to mineral weathering in recent geologic history. Land use pattern can also affect Si in top soils. Si concentrations in Philippine regions were significantly larger for paddy field than other land use pattern. In some of the Vietnamese paddy field, Si concentrations were below critical values due to removal of rice straw from the fields. This might cause decreasing Si concentrations in soils.

Li *et al.* (1999) reported that available Si in soil was generally extracted using sodium acetate buffer solution in China. Si content within the range of 95 - 110 mg SiO_2 of extractable Si as a critical index to evaluate whether a soil was deficient in Si. Matichenkov & Calvert (2002) reported that 210 - 224 million tonnes of plant available Si was removed from arable soils globally on an annual basis, assuming 70 - 800 kg ha^{-1} of plant available silica is removed with the harvesting of crops. Rodrigues *et al*., (2003) conducted a study to compare a Florida based acetic acid extraction protocol with the sodium acetate buffermethod used in Japan and Korea, and the 0.01M calcium chloride method used in Australia,to extract Si from soil samples collected from 31 countries. The sodium acetate buffer extracted the greatest amounts of Si (0 to 509 mg kg^{-1}), followed by acetic acid (1 to 239 mg L^{-1}) and calcium chloride (3 to 109 mg kg^{-1}). Acetic acid and sodium acetate buffer Si values were well correlated ($r^2 = 0.77$) with availability of Si. Results with calcium chloride were less well correlated with acetic acid ($r^2 = 0.73$) and were poorly related to sodium acetate buffer ($r^2 = 0.57$).

Heinai and Saigusa (2006) reported that the phosphate buffer method was the most easily adjusted method for estimation of silicon availability in nursery bed soils, and silicon fertilizers should be applied when silicon availability in non-volcanic nursery bed soils went below 200 mg kg^{-1}. Gontijo (2000) observed that soil Si values decreased with increased content of sand in the soil. He further found that a soil having high percentage of sand showed low available Si contents due to their poor capacity to supply Si to plants. According to Keller *et al*. (2012), the biogeochemical cycling of Si was generally not impacted by atmospheric input or fertilization. It was significantly altered by agriculture through the depletion of the phytolith pool. The exportation of straw could lead to the depletion of thesoil phytoliths pool in 10 years. In order to maintain the current levels of Si in crops, the contribution of other soil silicates such as clay minerals to the phyto available silica pool may become a key parameter, when straw was exported. As grazing management potentially altered vegetation and sedimentation dynamics in salt marshes, it could have an indirect impact on silica cycling in grass dominated ecosystem.

2.2.2 Indian Scenario

A study conducted by Lotse *et al*. (1975) in Indian soils revealed that the silicacontent of red soil were lower than black soils and decreased with increasing depth of soil. Nayar *et al.* (1977) reported that the available Si extracted by NaOAc ranged from 8 to 278 mg kg^{-1} in soils of Orissa. Nayar *et al*. (1982) revealed that the available Si extracted by different extracts in soils of Kerala ranged from 8 to 435 mg kg^{-1}. Subramanian and Gopalaswamy (1991) reported that the soils of Coimbatore (Tamilnadu) contained 29 to 80 mg kg^{-1} available Si. Nair and Aiyer (1968) reported the well water from Kerala contained less Si (2.4 - 3.2 ppm) than irrigation water from dam (5.6 ppm). Narayanaswamy and Prakash (2009 & 2010) categorized plant available silicon in rice soils of South India using eleven extractants. The extractable silicon (Si) using selected extractants irrespective of the soils used for the study was in the order of 0.005 M sulfuric acid (H_2SO_4) > 0.1 M citric acid
> 1 N sodium acetate (NaOAc) 2 > N NaOAc-1 > 0.5 M acetic acid-3 > 0.5 M acetic acid-2 > 0.5 M acetic acid-1> 0.01 M calcium chloride ($CaCl_2$) > 0.5 M ammonium acetate (NH_4OAc) > distilled water-4 > distilled water - 1.The critical levels for plant available Si in the soil

ranged from 14 mg kg^{-1} (distilled water) to 207 mg kg^{-1} (0.005 M H_2SO_4). The NaOAc-1 and 0.5M acetic acid-2 were considered as the most suitable extractants for extracting plant available soil Si in rice soils.

2.3 Silicon availability in soil

Silicon concentration in aqueous extract of soils generally ranged from 1 to 80 ppm. The range of 1 – 2 ppm appeared to be most common for tropical upland Oxisols and Ultisols (Jones and Handreck, 1967). The solubility of soil Si was variable and influenced by temperature, pH, texture, chemical composition and weathering. Their dissolution kinetics was affected by soil factors such as organic matter, water content, redox potential and sesquioxides (Savant *et al*., 1997). According to Berthelsen *et al* (2003), the solubility of Siin the soil is affected by a number of dynamic processes occurring in the soil including the particle size of the Si fertilizer, the soil pH, organic complexes, presence of Al, Fe and phosphate ions, temperature, exchangeable/dissolution reactions and soil moisture. The concentration of Si in soil solution depended on the solubility of primary and secondary Si compounds in soils. Solubility is a function of temperature, particle size, chemical composition and the presence of disrupted surface layers.

Matichenkov *et al*. (2000) reported that it was possible to distinguish three main directions of Si migration and transformation in the soil; leaching of soluble Si-rich compounds without transformation, adsorption of monosilicilic acid by plant roots with consequent transformation of monosilicic acid into amorphous silica, and transformation of soluble forms of Si into the soil without movement from the soil profile. The pool of Si leached depended on the amount of atmospheric precipitates and velocity of weathering. Polysilicilic acids were more leachable than monosilicic acid due to the peculiar chemical structure of these substances (Matichenkov *et al*., 1996). Monosilicic acid had a positive charged anion which was adsorbed very well by the soil particles, while the non-compensatedelectrical charge of polysilicic acid could be self - neutralized by the high flexibility of polysilicic acid molecule (Iler, 1979).

2.3.1 Factors affecting silicon dissolution in soil

pH

Khalid *et al*. (1978) reported that soil acidification arised in areas of high rainfall and temperature undergoing significant weathering and in turn leaching of Si. Acidifying a particular soil sample increased soluble Si concentration, presumably because H^+ ions competed with silicic acid hydroxyl unit for hydrogen bond sites at sesquioxide surface, displacing some silicic acid molecules into soil solution. Neutral pH soils, in fact often had more available Si than acid soils. This was because neutral pH soils were usually less weathered than acid soils and richer in easily weatherable clays that could release Si into soil solution. Neutral soils also tend to be lower in sesquioxide content. Thus, highly weathered tropical acidic soils had less than 1 ppm soluble Si, while neutral black clay Vertisols and young alluvial bottom soils might had 13 – 35 ppm Si (Fox *et al.*, 1969). The investigation onspatial and temporal variability of dissolved reactive silica (DSi) and salinity in Tairua Harbour (Coromandel, New Zealand) revealed that DSi concentration had very high linear correlation with salinity indicated that physical dilution being the only process having any effect on the distribution of DSi in both estuarine and coastal waters (Bell, 1994). The solubility and availability of silicon could be influenced by soil reaction. A pot experiment with a clayey textured Rhodic Acrustox revealed that the materials increased soil pH as the applied rates increased, except silicic acid. Soluble silicon extracted by 0.5 mol L^{-1} acetic acid also increased with applied rates (de Camargo, 2007). He & Li (1996) found that Si concentration was positively correlated with soil pH. The available Si concentrations for the soils with pH < 6, pH 6 to 6.5 and pH > 7 were < 100, 166.9, and 229.8 - 580 mg SiO_2 kg^{-1}, respectively. Depending on soil pH, paddy soils were categorized into three categories of Si supplying capacity as high, medium and low.

Particle size

There was a good correlation between grain size of soil and silica content in soil samples. Grinding quartz particles to a size below 5 microns in diameter increases Si solubility from 6 ppm to 120 ppm or more. Apart from grain size of soil, a second factor influencing the silica distribution in soil was bed rock geology. This principle could be used for developing more effective Si fertilizers (Datnoff *et al.*, 1992).

Texture

Plants growing in soils with high percentages of sand had low Si concentrations. Although sand was largely composed of Si dioxide, this material provides very little soluble or plant-available Si. Sandy soils also usually had good drainage, which prevented Si accumulation. Thus, it is not unusual for crops grown on sandy soils to benefit from applications of soluble Si (Heckman, 2013). Soluble silicon was evaluated in clayey, loamy and sandy soils treated with lime (0, 2, 4 & 6 Mg ha^{-1}) and silicic acid (0 to 400 mg kg^{-1}). Si contents were higher in clayey than in loamy and sandy soils and B horizon had more silicon than A horizon in latosols (de Camargo *et al*., 2007).

Weathering

Weathering of soil was an ageing process characterized by the breakdown of young clays into simpler forms with the concomitant release of soluble Si, a process known as desilication. Substitution of other atoms such as Mg, Al, Ca, Na, K, etc into silica lattice weakens silicate minerals, making them weather more easily (McKeague and Cline, 1963b). Terrestrial plants and their associated microbiota directly affected silicate mineral weathering in several ways: affecting the temperature of the soil, protecting soil against erosion, generating of chelating ligands, modifying pH through production of CO_2 and organic acids (mainly when pH is below 4 – 5), modifying element concentrations in soil solution by root uptake and return by litter and altering the physical properties of a soil, particularly the exposed surface areas of minerals and the residence time of water (Moulton *et al*., 2000). As less tightly bound Si was removed, only the more weathering resistant mineral structures remained. Thus the type of clay found in a particular soil indicated degree of weathering. Thesoils which were rich in more weathered gibbsite clay were likely to be low in soluble Si content. Since extreme weathering was a characteristic of Ultisols and Oxisols which represent upland rice soils of world, Si deficiency might be widespread in upland rice (Juoand Sanchez, 1986). According to Derry *et al.* (2005), most of the Si resided within primary and secondary minerals and is slowly released to soil solution through chemical weathering. Weathering reaction and leaching often occurring over geological time scale tend to remove Si from soil. Thus strongly weathered soils in humid climates (Ultisols/Acrisols and particularly Oxisols/Ferrasols) tend to be Si-depleted. In strongly weathered soils, release of Si from decompositing plant materials (phytolith dossolution) was a critical source of Si to terrestrial and wet land plants.

Chemical composition of soil

Silica units in quartz were closely packed and stable, and contribute little Si to soil solution (3 ppm). These sandy soils with 100 per cent silica, apparently referred as –siliceous‖, were very low in available Si. Jones and Hendrick (1967) found that the presence of aluminium and iron oxides in the soil had been shown to decrease the amount of soluble Si in soil solution. High concentration of silicic acid (120 – 140 ppm) in soil solution could lead to colloidal silica.

Water source

McKeague and Cline (1963b) reported that when sufficient water was added to just saturate the soil samples, soluble Si concentration rose rapidly and then leveled off, such that five minute after wetting the soil. Si concentration reached 50 per cent of that achieved in ten days. This suggested that Si rapidly re-entered into the soil solution upon rewetting of dry soil. Flooding raises the soil pH to around 7.0, but also increases soluble Si. This attributed tothe reducing conditions created by flooding, which deactivate the aluminium and iron oxides that adsorb Si. This could also be caused by CO_2 and organic acid which build up in flooded rice fields. Acids released Si from adsorption sites. Following the initial rise in Si concentration after flooding, a slow decline on concentration of Si over a period of months could result in values lower than original aerobic level (de Datta, 1981). Soil reduction due to flooding increased the soil solution Fe^{2+} concentration which in turn increased concentration of [Si $(OH)_4$] and $H_2PO_4^-$. Soil drying at any stage adversely affected these changes (Patra and Neue, 2010). In flooded soils, Si generally increased after submergence. This increase was probably due to the release of adsorbed and occluded Si from oxyhydroxides of Fe andAl as well as to the effect of the increased pH resulting from submergence. Decompositing rice straw with its high silica content might also contribute to the increased Si content of the soil solution of flooded soils (Fageria *et al.,* 2011). Drying a soil reduced the total amount of soluble Si, presumably but enhancing adsorption as the solution becomes more concentrated.

Vegetation and Organic matter

Organic compounds such as low molecular weight organic acids contributed to the weathering of soil minerals through acidification and complexation and identified complexes of organic compounds and silica in soil solution. Cornelis *et al.* (2011) reported that the Si concentration decreased from the humus layer to 15 cm depth and then slightly increased until a depth of 75 cm. In the humus layer, the Si concentration consisted mainly of phytolith sand differed significantly between tree species (expressed as mg SiO_2 g^{-1}). Tree speciescould impact the readily soluble Si content in the top soil, through different rates of Si uptake and phytolith restitution by the vegetation. Fifty six years of experiments showed that the continuous application of rice straw compost and silica fertilizer had revealed a significant impact on increasing OM and available silica contents in surface and subsurface soils (Kim *et al*., 2010). The biocycling of Si through plant material (phytoliths) and back into soil is comparatively rapid, and thus might exert a dominant control on the biogeochemical cycling of Si within soils and near-surface sediments in some environments. Si cycling was poorly resolved in cultivated systems, such as rice cropping. Monitoring of seasonal trends of Si in pore-water, plants, and soil over a two-year period in a California rice cropping system where straw was incorporated into the soil during the fallow season. There was a clear seasonaltrend of high pore-water Si concentrations during the winter fallow that approached predicted equilibrium with amorphous Si, followed by low concentrations during the growing season within the top 20 cm of the profile (Seyfferth, 2013). Silicon was not a major component of soil organic matter. Therefore in soils composed almost entirely of humus and organic matter (muck soils or Histosols), certain crops grown on these soils might benefit from Si application. Similarly, the widespread use of soilless mixes in greenhouse production resultedin very little Si being supplied from the growth medium. Plants growing in these greenhouse production systems frequently showed benefit from Si fertilization (Heckman, 2013). According to Houben *et al*. (2013), biochar from Miscanthus could be considered as apotential source of bio-available Si for the culture of such crop as Si-accumulator plants growing in highly weathered tropical soils with low content in carbon, nutrients and bio- available Si. Various organic compounds might increase or decrease silica solubility.

Bocharnikova and Matichenkov (2012) evaluated Si cycle in the various soil-plant systems via the determination of mobile Si forms in the soil and of the total content of in unmowed meadow, mowed meadow, birch-aspen forest, spruce wood and agricultural land soil-plant systems of Moscow. The concentration of monosilicic acid in the upper soil horizon depended on the type of plant association and on the total content of adsorbed Si. Theremoval of plant remains from the ecosystems resulted in decreased monosilicilic acid concentration in the upper soil horizon. The ecosystems which utilize annual plant remains increased the content of monosilicilic acid of the surface soil horizon. The concentration of monosilicic acid in the upper soil layer could be used as indicator of the stability of plant association. The unmowed meadow and the birch-aspen forest were characterized as ecosystems with accumulative type of Si cycle. The agricultural land, the mowed meadowand spruce wood all had alluvial type of Si cycle.

Parent material

He and Li (1996) reported that concentrations of soil available Si depended mainly on the parent material. Concentrations of available Si were high in soils developed from limestone and red-purplish carbonated shale; medium from alluvium and lacustrine deposits, and quaternary red clay; and low from granitic gneiss and sandy shale.

2.4 Si fractions in soil

According to Danilova *et al*. (2010), a large variety of silicon fractions might occur in soils. Soil particles could adsorb dissolved silicic acid from the soil solution. Silica could also be included in sesquioxides or bound to organic matter. Amorphous silica existed in the form of biogenic (e.g. phytoliths) and minerogenic opal (e.g. silica cutans). Moreover, Si in the form of dissolved silicic acid was retained in the soil solution. Finally, many primary and secondary crystalline silicates (e.g. quartz, feldspar, micas and clay minerals) were generally found in soils. The main fractions of Si in soil were mobile, adsorbed, organic, occluded, amorphous and residual. In forest ecosystems, the silicon (Si) mass balance at the watershed scale can be strongly influenced by readily soluble Si components, such as dissolved Si, adsorbed Si, amorphous silica (biogenic and pedogenic opal) and short-range ordered aluminosilicates. Silicon from minerogenic amorphous silica and organically bound silicon made up the highest proportion of extractable silicon in the soils analyzed in this study. However it comprised only up to 1 - 2 per cent of total Si. The majority of silicon in the investigated soils was in secondary and primary silicates.

Alexandre *et al*. (1997) estimated that Si released from bio-opal was two to three times as great as that from silicate weathering. This implicated a high turnover of this fraction. Biogenic and pedogenic processes controlled silica cycling in grasslands growing ona soil chronosequence and dominated by strong seasonal variabilities of a Mediterranean climate. Shallow pore water Si exhibited only moderate seasonal fluctuations reflectingstrong buffering from labile biogenic Si, dominated by phytoliths and by secondary pedogenic silicates. Water-extractable Si was closely associated with Al, indicating seasonal precipitation and dissolution of a highly labile 1:1 hydroxyaluminosilicate (HAS), probably allophane, which transformed in deeper soil into fine grained, poorly crystalline kaolinite. A study conducted by Sauer and Burghardt (2006) in four soil profiles (two in France and twoin Germany) of young soils developed in blast furnace slag, slag sand and ash revealed that dissolved silicic acid and amorphous silica occurred in these soils. In the blast furnace slag, the formation of amorphous silica seemed to be enhanced by decreasing pH and increasing

Mg content. In the slag sand, Mg also appeared to promote the formation of amorphous silica. In addition, there was a weaker correlation between rising $CaCO_3$ content and an increasing amount of amorphous silica. Longer periods of water saturation of the soil enhance the development of zeolites and inhibited the formation of amorphous silica.

In Typical Argiudolls, under different vegetation of the Pampean Plain, Argentina. 90.7 – 94.4 per cent of the phytolith content constituted the labile pool and 9.3 – 5.6 per cent the stable pool. In the arboreal plots, SiO_2 content in soil solution was higher (406 – 1,106 μmol L^{-1}) and decreases with depth, while in the grass plot, SiO_2 content was lesser (421 – 777 μmol L^{-1}) and increases with depth; probably because of differences in the nutritional requirements and root design between vegetal species (Borrelli *et al*., 2010). Tallberg *et al*. (2010) reported that the biogenic Si content in the different parts of the watershed varied, and biogenic Si produced by diatom algae in the aquatic part of the watershed appeared to bemore important than the transformation of dissolved Si into phytoliths by terrestrial plants in the soil of southern Finland. Although tree species had taken up to 43.5 kg Si ha^{-1} yr^{-1}, which constituted a large amount of biogenic Si restituted on topsoil (Cornelis *et al*., 2010), dissolution of phytoliths did not seem to control the dissolved Si composition of the forest floor leachates, even at high dissolution rates for phytoliths (Fraysse *et al*., 2009). Indeed, the amorphous Si stock, including biogenic Si, in organic horizon is low relative to crystallizedSi stock.

Shallow plant roots extracted greater proportions of biogenic Si and deeper plant roots larger amounts pedogenic Si. Mobile Si was generally balanced in the soils with upward bio-pumping by the shallow-rooted grasses efficiently competing against downward leaching and pore water discharge. Small net annual increases in Si in the present day soils could not have been maintained over the time scale represented by the chronosequence (65 – 225 yrs), implying past changes in environmental conditions (White *et al*., 2012).

Tidal freshwater marsh vegetation, often dominated by reed (*Phragmites australis*) had been contributed to the Si buffering function of tidal marshes, by dissolution of reed biogenic Si (BSi) into the soil pore water and consequent seepage of dissolved Si to the estuary. This Si pool in vegetation could act both as long-term sink for Si along estuaries (should Si remain buried in the sediments) or as a short-term source for dissolved Si (Jacobs*et al*., 2013).

Georgiadis *et al*. (2013) developed a method for sequential extraction of Si fractions from soils based on numerous series of extraction experiments using well-characterizedisolated soil compounds and selected soil samples. The procedure had been developed by first improving and further developing existing specific extraction methods before implementing them as subsequent steps into the sequential procedure. The sequential extraction of Siextracted step by step various Si-fractions, from the most mobile to the most immobile Si fraction in fine earth. It could be carried out in any ordinarily equipped soil science laboratory.

2.5 Adsorption of silicon in soil

Monomeric silicic acid $Si(OH)_4$ was a tetrahedral molecule, consisting of a central Si surrounded by four OH groups. The silica molecule was chemically active. The OH group can bond with other elements through condensation to form polymers or crystal lattice, hydrogen bonds and polar attraction leading to adsorption (McKeague & Cline, 1963a). Adsorption of Si had an important effect on the transport, bioavailability and fate of Si added to the soil. Jones and Handreck (1967) found that reagent grade iron and aluminium oxide meterials adsorbed moderate amount of Si. McKeague & Cline (1963b) reported that aluminium and iron oxides adsorbed high amount of Si, whereas hematite and goethite showed moderate adsorption. Silicate minerals, alkaline earth carbonates and reagant grade aluminium hydro oxide exhibited little or no adsorption. A study conducted by Herbillion andVinhan (1969) indicated that Si was adsorbed by two distinct processes such aschemisorptions and polymerization.

Silicic acid could be adsorbed to the surfaces of various soil components. Adsorption of monosilicic acid in soils depended on soil reaction, soil composition and the specific surface of sorbents and increases with increasing pH and specific surface area of the soil particles. The monosilicic acid could be withdrawn from soil solution through the adsorption onto a variety of solid phases in soils. Pedogenic oxides and hydroxides that were abundant insoils played an important role in adsorption, occlusion and release of silicic acid in soils. Although little Si adsorption had been reported onto secondary clay minerals (Siever and Woodford, 1973). Iron and aluminium oxides were the main soil components with a significant capacity for Si adsorption (Cornelis *et al*., 2010; McKeague and Cline, 1963a). Aluminium oxides were found to be more effective in adsorbing monosilicic acid than iron oxides (Jones and Handreck, 1967; McKeague and Cline, 1963b). Monosilicic acid interacted with Fe-oxide surface OH groups through ligand exchange to form silicate bi-dendate innersphere complex (Hiemstra *et al*., 2007). Silicic acid was specifically adsorbed onto secondary oxides. On Fe oxide surfaces, polysilicicacid might be formed by specific interaction with orthosilicic acid (Dietzel, 2002). Since iron oxides were ubiquitous in soils, they partly control the concentration of H_4SiO_4 in the aqueous phase (Opfergelt *et al*., 2009).

Acidification led to disintegration of clay minerals, which became a source of Si. This phenomenon was observed in very acid soils, *e.g.*, Podzols of temperate or boreal climates and acid topsoils of Luvisols (Sommer *et al*., 2006). Released silica might precipitate at mineral grain surfaces forming amorphous siliceous shells and covers, which had beenobserved by SEM-EDX. Silicon was also chemically adsorbed at surfaces of soil constituents like carbonates, Al hydroxides, and Fe oxides (Pokrovski *et al*., 2003). For mixtures of different phases, e.g., soil horizons, indices of silica reactivity and silica saturation were developed from sorption isotherms (Herbillon *et al*., 1977).

The adsorption and desorption studies of Si onto soil particles of soils under different cropping systems in Louisiana (Tabana *et al.,* 2013) showed that moderate to high adsorption of plant available monosilicic acid occurred in soil. The highest adsorption was observed on the seventh day of incubation of Norwood fine sandy loam soil from Rapides Parish. The trend in adsorption was attributed to the chemical nature of monosilicic acid and the physico-chemical properties of the soil. Across all soil types, the amount of adsorbed monosilicic acid increased with the amount of initial soil Si content and total time of incubation.

Si adsorption on the Al oxide was investigated under changing conditions of pH, total solution anion concentration, reaction time, and order of anion addition. Silicon exhibited a broad maximum extending from pH 6 to 10. The magnitudes of the adsorption maxima for Si remained essentially constant for total reaction times ranging from 10 minutes to 24 days. (Goldberg and Glaubig, 1988).

Iron hydroxides and especially Al hydroxides played a key role in the interaction between the solid and liquid Si phases in soils, which was known for longer time (Farmer and Lumsdon, 1994). Sorption onto mineral surfaces was related to the amount, type, size, and crystallinity of Fe oxides and Al hydroxides. Morphological properties as well as crystallinity of goethites and ferrihydrites were related to the Si concentrations and pH of solutions. Glasauer (1995) explained the interactions between Fe oxides and Si by both, covalent and unspecific electrostatic bonds. At Fe oxide surfaces, polysilicic acid might be formed from orthosilicic acid (Glasauer, 1995; Dietzel, 2002), the latter of which was the dominant species in soil solutions with pH < 8.

Qiu *et al*. (2010) investigated the adsorption of Si in three soils (Lou, Yellow Drab and Purple Paddy soils) at different initial Si concentration, temperature (293 and 303 K) and reaction time. Si adsorption behaviour varied significantly between soil types. In all the three soils, the slope of the adsorption isotherms remained constant as initial concentration increased from 0 to 50 mg L^{-1}, but declined rapidly as initial concentration increased from 50 to 200 mg L^{-1}. This suggested that these soils contained multiple Si adsorption sites. Langmuir, Freundlich and Tempkin equations described the adsorption of Si as function of Si concentration reasonably well, however their goodness of fit curve varied according to soil type.

Interaction of polysilicic and monosilicic acid was studied by Dietzel (2002) via adsorption experiments with lepidocrocite, hematite, feroxyhyte, goethite, akaganeite, magnetite, ferrihydrite and gibbsite. The kinetics of monosilicic acid adsorption followed a first order reaction. At equilibrium monosilicic acid adsorption might be described by surface complexation with an adsorption maximum at pH 9.8. If polysilicic acid was adsorbed to the surface, one part was bound to the surface within a relatively short time. The other part decomposed to monomer in the solution. The polymeric silica at the surface was stabilized at pH < 6. Thus the present results showed that polymerization of silica at the mineral surface had to be considered only in acidic solutions. The experimental results show that this is favoured in slightly alkaline solutions.

2.6 Importance of silicon in crop nutrition

The essentiality of Si for terrestrial plants was extensively debated (Takahashi *et al*., 1990). Epstein (1999) reported that only two groups of plants were known to had an absolute and quantitatively major requirement for Si, *viz.*, Chrysophyceae (diatoms) and Equisitaceae (yellow-brown or golden algae). Silicon was not considered as an essential element for higher plants, but its beneficial effects on growth had been reported in a wide variety of crops, including rice, wheat, barley, and cucumber (Ma and Takahashi, 2002).

There was a general consensus that Si improved the plant resistance to various biotic and abiotic stresses. Silica deposition in leaves was a resistant structural component, providing a more upright position, which favoured light interception, thus promoting photosynthesis (Marschner, 1995). Moreover, biogenic silica in plant tissues created a hard outer layer that serves as a defence against fungal and insect attacks (Belanger *et al*., 2003). Finally, it was widely accepted that Si alleviated the toxicity of Al and other metal ions such as Mn in higher plants (Liang *et al*., 2001).

Tthere was no evidence of Si involved in plant metabolism since no Si bearing organic compound had been identified in higher plants (Knight and Kinrade, 2001). The beneficial effects of Si remain reduced under optimum growth conditions, but were more obvious under stress conditions (Ma *et al*., 2001). The Si accumulators *viz*., wheat (*Triticum aestivum*) and rice (*Oryza sativa*), the premier crops for the nutrition of mankind, were susceptible to a variety of diseases if the Si supply was low (Epstein, 2009). Therefore, soils that were intensively used for cropping are fertilized on a regular basis with silicate amendments (Korndorfer and Lepsch, 2001).

2.7 Silicon uptake mechanism by plants

The uptake of Si mechanisms differed between plant species. In a study using rice, cucumber and tomato, species that accumulate high, medium and low levels of Si, respectively, it was found that transportation of Si from the external solution to the cortical cells was mediated by a transporter. Following uptake by the roots, Si was translocated to the shoot via the xylem. Chemically, silicic acid polymerized to form silica gel ($SiO_2\_nH_2O$) when the concentration of silicic acid exceeded 2 mM. However, the concentration of Si in the xylem sap was usually much higher than 2 mM in rice and wheat, even though the major form of Si in the xylem had been identified as monomeric silicic acid in these plant species.In the shoot, silicic acid was further concentrated through loss of water (transpiration) and was polymerized. The process of Si polymerization converted silicic acid to colloidal silicic acid and finally to silica gel with increasing silicic acid concentration.

In rice plants, more than 90 percent of total Si in the shoot is present in the form of silica gel, whereas the concentration of colloidal plus monomeric Si is kept below 140 – 230 mg Si L^{-1}. A similar pattern of accumulation is observed in cucumber leaves, although the total Si concentration of cucumber is much lower than that of rice. The distribution of Si in the shoot is controlled by transpiration. More Si accumulates in older tissues because this element is not mobile within the plants.

2.8 Role of Si in soil and plants

Since Sommer (1926) demonstrated the favorable effect of Si on rice growth, intensive studies on the essentiality of Si for plants had been undertaken throughout the world. Although the essentiality of Si for plant growth had not yet been established (Epstein, 1994), there was sufficient evidence to suggest that it was an agronomically essential nutrient for achieving and maintaining high yields of rice (Liang *et al.*, 1994).

Si is accumulated primarily in the epidermal tissues of both roots and leaves in the form of a Silica gel (phytoliths). This thickened epidermal silicon-cellulose layer supports the mechanical stability of plants, thereby resisting lodging and also a greater retention of seed, especially in grasses (Savant *et al.*, 1997). Although silicon (Si) has not been recognized as an essential element for plant growth, the beneficial effects of Si have been observed in a wide variety of plant species. The beneficial effects of Si are usually expressed more clearlyin Si-accumulating plants under various abiotic and biotic stress conditions. Silicon is effective in controlling various pests and diseases caused by both fungi and bacteria in different plant species. Silicon also exerts alleviative effects on various abiotic stressesincluding salt stress, metal toxicity, drought stress, radiation damage, nutrient imbalance,high temperature, freezing and so on. These beneficial effects are mainly attributed to the high accumulation of silica on the tissue surface although other mechanisms have also been proposed. (Ma and Yamaji, 2006). The presence of Si in nutrient solutions affects theabsorption and translocation of several macro and micro-nutrients (Epstein, 1994). Increased Si fertilization increases Zinc (Zn) uptake if deficient, especially if P is excessive (Marschner *et al.*, 1995). The effective management of Si can offer several potential benefits including agronomic benefits, induced resistance to stress (abiotic and biotic), and increased productivity of problem soils.

2.8.1 Agronomic benefits

Improved soil fertility

The acidification of soil and leaching of Si have several impacts such as greater availability of toxic ions such as Al, Fe and Mn, which are more soluble at low pH, limited growth and production of crops, phosphorous deficiency caused by aluminium toxicity, deficiencies of cationic nutrients (calcium, magnesium and potassium), reduced activity of micro-organisms (such as the critical nitrification of ammonium-N to nitrate) reduced cationic exchange capacity and low levels of PAS.

Silicon applied as calcium silicate at graded level showed that the soil pH significantly increased. Besides, soil data demonstrated a significant increase in CEC in all calcium silicate treatments indicated that improvement of soil chemical properties and greateryield (Bokhtiar *et al.*, 2012).

Improved plant growth

From several studies, it appears that Si nutrition has direct and indirect beneficial effects on plant growth, largely due to its unique physiological role. In the tropics, excessive vegetative growth of plants can cause low yields. In such environment, the modifying positive effect of an adequate supply of Si on leaf erectness can be beneficial, especially when rice plant density is high and low light intensity likely to limit photosynthesis. According to Agarie *et al.* (1998), the maintenance of photosynthetic activity due to Si fertilization could be one of the reasons for the increased dry matter production and increase in water use efficiency in Si-amended rice plant due to prevention of excessive transpiration.

Increased yield

Silicon has been proven to be influential in maintaining the health of many plant species for decades. Silicon fertilizers are applied to crops in several countries for increased productivity and sustainable production. Rice and horsetail will not grow without Si and cucumbers, soybeans, strawberries and tomatoes have been shown to suffer adverse effects on growth if grown without Si (Epstein, 1994). Members of the grass family in particular accumulate Si and several reports demonstrate the importance of Si nutrition for rice and sugarcane. Large growth and yield responses appear to occur more rapidly with Si fertilization in high Si-accumulator plants than others, but low Si accumulator species also show increased growth and health in the presence of added Si.

Field experiments were conducted in the coastal zone soils of Mangalore and the hilly zone soils of Mudigere and Ponnampet in Karnataka. Overall, using calcium silicate (3 and 4 t ha^{-1}) as a Si source resulted in a significant increase in grain yield over the control treatment (NPK only) and over treatments with applied $CaCO_3$ (Prakash *et al.*, 2010). These studies demonstrated the importance of Si in maximizing the yield potential of rice.

Bridgit and Potty (2007) conducted multilocational trials during *Kharif* and *Rabi* seasons. The study revealed that higher level of potassium (120 kg ha^{-1}), silica (sodium silicate 250 kg ha^{-1}) and lime (150 kg ha^{-1}) along with normal recommendation of KAU for rice cultivation could curtail the ill effects of Fe and Mn and improved the yield of rice substantially in laterite soils.

Interactions of Si with N, P, and K fertilizers

In many cases, yield decreased when N rate was more than optimum. Due to synergistic effect, application of Si had the potential to raise optimum N rate. Fertilizers with N made leaves droopy, whereas Si kept them erect. By adopting proper Si management, erectleaves could easily account for 10 percent increase in the photosynthesis of the canopy and consequently a similar increase in yield (Yoshida, 1981). Yogendra *et al*. (2014) reported that N uptake of both grain and straw was higher when silicon applied along with recommended dose of fertilizers (RDF) of N (100 kg ha^{-1}) compared with leaf colour chart (LCC) based N application (75 kg ha^{-1}). Due to a synergistic effect, the application of Si had the potential to raise the optimum N rate, thus enhancing productivity of existing lowland rice fields.

The beneficial effects of Si under P-deficiency stress had been observed in many plants including rice and barley. Better availability of soil P and enhanced mobility of P from root to stem. Availability of internal P in plants decreased through the uptake of excess Feand Mn. Silicon could alleviate the damage caused by P excess by decreasing the excessive uptake of P, resulting in a decrease in the internal inorganic P concentration. Silicon deposited on the roots and/or Si-induced decrease of transpiration might be responsible for the decreased uptake of P when the P concentration in the medium is high. Si had been found to be deposited in the endodermal cells of roots in many plant species, which may form apoplastic barriers against the radial movement of P across the root. Si fertilization retarded the toxic uptake of phosphorous by roots, such as in cucumbers (Marschner *et al.*, 1990), while promoting its translocation to grain in rice and wheat (Lewin and Reimann, 1969). The mixture of active Si with P fertilizer could increase the efficiency of P fertilization by 40-60 per cent (Matichenkov *et al.*, 2000).

Interactions of applied K and Si in soil seemed to have beneficial effects on rice yields. Silicification of cell walls seemed to be linked with K nutrition. K deficiency reduced the accumulation of Si in the epidermal cells of the leaf blades, thus increasing the susceptibility of the plant to rice blast.

2.8.2 Induced resistance to stress

Biotic stress resistance

Several studies had shown that Si was effective in enhancing the resistance to diseases and pests. Rafi *et al*. (1997) studied the deposition of silicon on the cell wall of wheat leaves and awns. The joint use of scanning electron micrography and X-ray microanalysis of the same trichomes showed the localization of silica in the trichomes. It was the silica in trichomes that lends leaves and awns the roughness and the toughness that impede thepenetration of herbivores and pathogens through the cell walls. It acted as a physical barrier.

Resistance to pest

The application of silicon to crops is a viable component of an integrated management program for insect pests and diseases because it leaves no pesticide residue in food or the environment, is relatively cheap and could easily be integrated with other pest management practices (Laing *et al.*, 2006). Two near-isogeniclines of rice (Oryza sativa L.), CO39 (blast susceptible), and C101LAC (Pi-1) (blast resistant), were hydroponically grown to study the effects of exogenous silicon application on the changes of disease incidence, mineral nutrient concentrations, chlorophyll content, and photochemical efficiency in *Magnaporthe oryzae* infected rice plants. Si amendment in nutrient solution at a concentration of 2.0 mM significantly reduced the disease index of rice plants (Gao *et al.*, 2011). A greenhouse investigation on the effect of silica on morphological traits of rice revealed that 20 g silica fertilization increased stem silica content and decreased 0.11 per cent white head due to stem borer attack, while it showed 18.10 per cent white head when it was not treated with silica fertilizer (Hosseini *et al.*, 2011).

Resistance to disease

Two mechanisms for Si-enhanced resistance to diseases had been proposed (Ma and Yamaji, 2006). One was that Si acted as a physical barrier, where Si was deposited beneath the cuticle such that the Si layer mechanically impeded penetration by fungi, thereby disrupting the infection process. The nutrient solutions amended with Si activated defense mechanisms in dicots (cucumber) by enhancing the activity of chitinases, peroxidises and polyphenoloxydases (Samuels *et al.*, 1991). Chang *et al.* (2002) revealed that silicon fertilizer could shorten the leaf lesion caused by bacterial leaf blight by 5 – 22 per cent. Reducing the size of lesions is directly proportional to the reduction of soluble sugar in leaves caused by the presence of silicon. Application of 200 kg SiO_2 ha^{-1} could reduce the infection of dirty panicle (grain discoloration). Correspondingly rice yield increased by 20 per cent after silica application. Ning *et al*., (2014) reported that both slag-based Si fertilizers tested significantly increased rice growth and yield, but decreased brown spot incidence, with steel slag showing a stronger effect than iron slag. The immobile silicon deposited in host cell walls and papillae sites was the first physical barrier for fungal penetration, while the soluble Si in the cytoplasm enhanced physiological or induced resistance to fungal colonization.

Resistance to abiotic stress

Silicon application to drought stressed maize plants was better to improve the growth and dry matter could be attributed to improved osmotic adjustment, photosynthetic rate and lowered transpiration (Amin *et al*., 2014). Si partially offset the negative impacts of drought stress by increasing the tolerance of wheat by rising proline and glycine betaine accumulation and soluble protein content. Applied Si significantly enhanced the activities of superoxide dismutase, catalase and peroxidase activities under drought stress (Ahmad and Haddad,2011).

Silicon application in rice was effective in alleviating damage caused by climatic stress such as typhoons, low temperature and insufficient sunshine during the summer season (Ma *et al.*, 2001). A typhoon attack usually caused lodging and sterility of rice, resulting in fatal reduction of rice yield. Deposition of Si in rice enhanced the strength of the stem by increasing the thickness of the culm wall and the size of the vascular bundle. Fallah (2012) reported that silicon had positive effects on plant height, internode length, fresh weight, breaking resistance, bending moment, culm thickness, roots, stems, green leaves and total dryweight. The lodging index reduced under silicon treatment compared to the control. Si in the form of silica gel reportedly served to stiffen the stems and leaves of cereals. A sufficient supply of Si had an effect on the stability of culms and serves to decrease the risk of lodging for rice plants. Agarie *et al*. (1998) reported that electrolyte leakage caused by high temperature was lower in leaves grown with Si than in the leaves grown without Si, suggesting that Si was involved in the thermal stability of lipids in cell membranes.

Ma and Yamaji (2006) suggested that the deposition of Si in the roots reducedapoplastic bypass flow and provides binding sites for metals, resulting in a decreased uptake of toxic metals and salts from the roots to the shoots. Matichenkov and Bocharnikova (2008) reported that the leaching of heavy metals (Cu, Pb, Cr, Ni, and Co) was reduced significantly,by over 50 per cent, with the addition of a Si fertilizer (diatomaceous earth). The mechanismsof stabilization by silicon-rich amendments of cadmium, zinc, copper and lead in a multi- metal contaminated acidic soil and the mitigation of metal accumulation in rice were investigated by Gu *et al*. (2011) reported that Si application decreased the phytoavailability ofheavy metals by at least 60 per cent, and further suppressed metal uptake by rice. Williams and Vlamis (1957) discovered for the first time that total Mn in the leaves was unaffected by Si but Si caused Mn to be more evenly distributed instead of being concentrated in discrete necrotic spots. As Si was added to the nutrient solution, the concentration of Mn in leaves decreased and in roots increased thus alleviating the toxic effects of Mn on the plants (Junior *et al*., 2010). Increasing external Si concentration significantly decreased shoot and root As concentrations and total As uptake by rice seedlings (Guo *et al.*, 2005).

Silicon application enhanced growth of salt stressed plants, significantly reduced Na+ content especially in leaves and counter balanced the effects of NaCl on gas exchange (Zuccarini, 2008). Savant *et al*. (1997) reported that Si-fertilization could alleviate sodium uptake in rice, wheat and barley. Liang *et al.* (2006) proposed that Si caused sodium and chloride ions to be more evenly distributed over the whole root section, which improved the salt tolerance of the plants. Therefore ensuring that a plant has sufficient plant available Si would have reduced the effects of salinity.

2.9 Silicon Sources, Fertilization and Rates of Application

Crop residues, animal manures, and composts are all potential sources of Si. Straw from wheat and other small grain crops also return significant amounts of Si to the soil. Wheat straw concentrations range from 0.15 to 1.2 per cent Si depending on the soluble Si concentration of the soil on which it was grown. The Si in crop residues may take many yearsto dissolve and become available for plant uptake. Calcium silicate products are the most commonly applied Si amendments for field application. Steel mill slag by-products are a rich source of calcium silicate. Wollastonite is a naturally occurring mined $CaSiO_3$ and can be a useful Si source when finely ground. Diatomaceous earth (80 to 90 per cent SiO_2) is also usedas a Si source. Potassium silicate and sodium silicate are commonly used materials for horticultural or greenhouse crop applications. They are soluble Si products that can be added to nutrient solutions or used as foliar sprays. However, plants responded better to Si acquired through the root system than from foliar applications (Heckman, 2013).

Liquid silicates such as sodium silicate and potassium silicates were effective for foliar applications and used in greenhouses but were generally uneconomical to use for the rates needed for soil application (Berthelsen *et al.*, 2003).

Calcium metasilicate ($CaSiO_3$, often referred to as simply calcium silicate) from slag had been used by the Hawaii sugar industry for years (Medina-Gonzales *et al*., 1988). Silicate slag had been used extensively in the USA. Slags can be variable in composition andalthough they had high concentrations of total Si, often only a small proportion was easily solubilized (Gascho, 2001). An important consideration with silicate sources derived from industrial by-products was the possible high level of heavy metals associated with their originor processing (Berthelsen *et al.*, 2003). These were not only toxic to plants but leach into waterways causing environmental damage. Other overseas sources of Si included magnesiumsilicate, basalt dust, dolomite and rock phosphate, but these only contain traces of PAS (Savant *et al.,* 1997). The advantage of silicate materials was that they also supply other nutrients such as Ca^{2+}, in the case of $CaSiO_3$ and increase the pH of the soil. In sugarcane trials in Australia, USA-imported calcium silicate showed the best results compared with other silicate sources and it was a slow release amendment, which is ideal for broadcast application every few years (Berthelsen *et al.*, 2003).

Diatomaceous earth is a natural source of Si and has a large surface area due to its structure and is readily soluble due to its amorphous nature. Solubility is an important parameter to consider when selecting the appropriate Si fertilizer as solubility determines the concentration of PAS (Berthelsen *et al.,* 2003; Matichenkov and Bocharnikova, 2008).

de Sousa and Korndorfer (2010) evaluated the silicon supply availability and efficacy of different silicate slag types for rice crops. Si source reactivity was evaluated using five metallurgic slag types and Wollastonite, which is considered a standard in Si studies. Slag E3 and Wollastonite were effective in increasing soil silicon availability, and consequently, the efficacy of supplying silicon for the plants, while the other slag types had low efficacy.

Ebaid and El-refaee (2007) investigated the effect of adding rice husk as an organic fertilizer under different irrigation intervals. The results indicated that increasing rice husk from 0 to 9.6 t ha^{-1} significantly increased root depth, shoot length, crop growth rate and plant height at harvest. Generally, 9.6 t ha^{-1} of rice husk less than eight days irrigation interval saved 14.9 per cent of irrigation water and gave similar grain yield as that of four days irrigation interval without addition of rice husk.

Pot experiments with normal and powdered rice chaff and calcium silicate on growth and yield of rice revealed that both organic and inorganic silicate materials increased the number of grains and the dry weights of grains. The application of powdered rice chaff together with biodecomposer was the most effective treatment (Hossain *et al*., 2001).

According to Sudhakar *et al.* (2004), Si application increased both grain and straw yields of rice under both low and high fertility levels. Basic slag, fly ash, and rice straw compost as sources of Si had shown positive effects on rice grain and straw yield, with basic slag giving a better performance.

The application of the composted rice husk to Oxisol significantly increased soil pH and Ca, Mg, K, sodium (Na), and silicon (Si) ions of *in situ* soil solution but decreased the amounts of toxic ions [aluminum (Al), manganese (Mn), and iron (Fe)]. The rice husk compost increased cocoa growth up to 37 per cent (Anda *et al*., 2008).

Karunakaran *et al*. (2013) evaluated the effect of nanosilica synthesized using rice husk and different sources of silicon on soil properties, total bacterial population and maize seed germination. Colony forming unit (CFU) was doubled in the presence of nanosilica from4 × 10^5 CFU (control) to 8 × 10^5 CFU per gram of soil. The silica and protein content of bacterial biomass clearly showed an increase in uptake of silica with an increase in nanosilica concentration.

An incubation experiment to study the release characteristics of silicon from native soil and applied sources *viz,* Fly Ash (FA), Silicate Solubilizing Bacteria (SSB) and Farm Yard Manure (FYM) showed that application of SSB +FYM recorded the highest extractable Si of 272.2 mg per kg at 60th day followed by FYM (258.0 mg per kg) on 75th day of incubation (Peera *et al*., 2014). A Silicate solubilising bacterium *Bacillus* sp isolated from sugarcane field soil was found to release silicon (Vasanthi *et al.,* 2012). Several microbes like *Bacillus caldolytyicus, Bacillus mucilaginosus var siliceous, Proteus mirabilis, Pseudomonas* and *Penicillium* were found to release silica from natural silicates (Avakyan *et al*., 1986). Muralikannan and Anthomiraj (1998) reported that inoculation of SSB released soluble silica in soils and also from silicate minerals. This bacterium could be used as a bio-fertilizer and found to enhance the growth, suppresses pest and diseases and increase the crop yield. A *Bacillus* species was isolated from granite crusher yard soil and upon inoculation of this SSB to rice field increased the biomass and grain yield.

2.10 Crop response to Si

Silicon exists in all plants grown in soil (Takahashi *et al.*, 1990) and its content in plant tissue ranges from 0.1 to 10 per cent (Epstein, 1999). Silicon is taken up by terrestrial plants from soil solution as uncharged monosilicic acid (H_4SiO_4), transported into the xylem (Casey, 2004) and mainly deposited in transpiration sites where polymerization of hydrated amorphous silica occurs to form phytoliths. Among the plants, silica concentration is found tobe higher in monocotyledons than in dicotyledons. The aerial plant parts accumulate more Si than roots. Si is considered as an agronomicaly essential nutrient and its absence causes imbalances of other nutrients resulting in poor growth, if not death of the plant (Epstein,1994; Savant *et al.*, 1997). Ma and Takahashi (2002) proposed criteria to differentiate non- accumulating plants from accumulating plants based on Si concentration.

1. –Accumulators‖ have a Si concentration over 1 per cent
2. –Excluders‖ have a Si concentration below 0.5 per cent
3. Plants that do not meet these criteria are called –Non-accumulators‖

Meena *et al*. (2014) reported the largest amounts of silicon were absorbed by sugarcane (300 – 700 kg of Si ha^{-1}), rice (150 – 300 kg of Si ha^{-1}), and wheat (50 – 150 kg of Si ha^{-1}). On an average, plants absorb from 50 to 200 kg of Si ha^{-1}. In the plant, silicon was transported from the root to shoot by the transportation stream in the xylem. Soluble monosilicic acid might penetrate through cell membranes passively. After root adsorption, monosilicic acid was translocated rapidly into the leaves of the plant in the transpiration stream. Silicon is concentrated in the epidermal tissue as a fine layer of silicon–cellulose membrane and was associated with pectin and calcium ions. By this means, the double cuticular layer could protect and mechanically strengthen plant structures. With increasing Si concentration in the plant sap, monosilicic acid was polymerized. The chemical nature of polymerized silicon had been identified as silicon gel or biogenic opal, amorphous SiO_2, which was hydrated with water molecules (Ma and Yamaji, 2006).

Repeated cropping and the constant application of chemical fertilizers such as nitrogen, phosphorus and potassium had depleted the amount of Si that was available to plants in the soil. An awareness of Si deficiency in soil was now recognized as being a limiting factor for crop production, particularly in soils that were seemed to be low or limiting in plant available Si and for known Si-accumulating plants such as rice and sugarcane (Ma and Yamaji, 2006).

2.10.1 Si and rice growth

Yoshida (1965) reported that Si was not very mobile in the rice plant and therefore a continued supply of this element would be required during practically all growth stages for healthy and productive development of the plant. Imaizumi and Yoshida (1958) found that rice plants take up Si from diluted acid soluble fraction of soil Si rather than the dilute alkali soluble fraction suggesting that Si available for rice plant was a silicate type and not silica type. They had established a criterion for application of silicate fertilizers to rice plant. The criterion was divided into three classes. A profitable increase in rice yield could be expectedif rice straw had a SiO_2 content of less than 11 per cent or the amount of soluble SiO_2 in soil was lower than 10.5 mg/100g soil (class I). If rice straw had SiO_2 content between 11 and 13 per cent or the amount of available SiO_2 in soil was between 10.5 and 13 mg100 g^{-1} soils, the necessity of application of silicate fertilizers depended on the weather, occurrence of disease and pests and other factors (class II). No increase in rice yield could be expected when therice straw had SiO_2 content higher than 13 per cent or available SiO_2 in soil was higher than 13 mg 100 g^{-1} soil (class III). Takahashi (1995) investigated the effect of soil moisture conditions on the availability of soil Si for rice plant. The amount of Si taken up by the rice plant was largest in submerged soil followed by upland soil.

Okuda and Takahashi (1961) investigated the effect of Si on growth and yield of rice at various growth stages. Compared with the Si supply during vegetative growth stage, the supply during reproductive growth stage was more effective in increasing plant growth and yield. Although the active Si absorption by rice seemed to start after tillering stage or after stem elongation, the most effective period for Si application for increasing yield seemed to beduring the reproductive stage in which its uptake and dry matter production were most vigorous (Kato and Owa, 1990; Chen, 1990). Rice required large amounts of Si for healthy plant growth and development. Under warm subhumid tropical conditions of India, Si

removed by 12 rice cultivars grown on Inceptisol during the dry season varied from 205 to

611 kg Si ha^{-1} when grain yield ranged from 4.6 to 8.4 t ha^{-1} (Nayar *et al*., 1982).

As wet land rice are concerned, soil Eh and organic matter are important factors that influence Si in soil solution. Ponnamperumma (1965) reported that a marked decrease in soil Eh and concurrent increase in solubility of soil Si with submergence time. In one soil with pH 4.8 and organic matter 4.4 per cent, the concentration of Si increased from 24 to 41 ppm in less than 50 days after submergence. This increase in Si had been attributed to its releasefrom ferrisilica complexes under reducing soil conditions. Ma *et al*. (2001) investigated the role of root hairs and lateral roots in the Si uptake using two mutants of rice, one defective in the formation of root hairs (RH2) and another in that of lateral roots (RM109). The results indicated that lateral roots contribute to the Si uptake in rice plant, whereas root hairs did not. Jawahar and Vaiyapuri (2014) observed that increasing levels of silicon increased the grain and straw yield of rice up to 120 kg Si ha^{-1}. This could be due to adequate silicon supply might have been improved the photosynthetic activity which enable rice plant to accumulate sufficient photosynthates which increased dry matter production and these together with efficient translocation resulted in more numbers of filled grains with increased test weight and ultimately led to higher grain and straw yield.

Materials and methods

3. MATERIALS AND METHODS

The project entitled "Silicon availability of tropical soils with respect to rice nutrition" was conducted in the Department of Soil Science and Agricultural Chemisrty, College of Horticulture, Kerala Agricultural University during 2011-2014. This project included both incubation study and field experiments. The incubation study was conducted to assess the release of silicon in different rice growing soils under different water regimes and to ascertain silicon adsorption capacity of different rice growing soils of Kerala. The field experiments to evaluate the efficacy of different sources of silicon in wet land rice and also the residual effect of rice straw incorporation on growth and yield of succeeding crop of rice were conducted at Agronomic Research Station, Chalakudy. The materials used and the methods adopted to achieve the objectives are summarised below.

3.1 Experiment 1

Categorization of major rice growing soils of Kerala according to plant available silicon

3.1.1 Collection of soil samples

Representative soil samples were collected from five different locations representing the major rice growing soils of Kerala as detailed in table 1.

Table.1 Details of sampling locations

Sl. No.	Major rice growing regions/ soil type	Location	Soil taxonomy- subgroup
1	*Kuttanad*	RRS, Moncombu	Aquic Tropaquepts
2	*Kole*	Adat, Thrissur	Aquic Tropaquepts
3	*Pokkali*	RRS, Vyttila	Aquic Ustipsamments
4	Sandy	ARS, Chalakudy	Oxyaquic Ustifluvents
5	Lateritic	RARS, Pattambi	Oxic Tropaquepts

3.1.2. Processing of soil samples and analysis

The soil samples were air dried, processed and sieved through 2 mm sieve. The processed soil samples were analyzed for physico-chemical properties like texture, pH, EC, AEC, CEC, organic carbon, available major nutrients (N, P and K), secondary nutrients (Ca, Mg and S), micronutrients (Fe, Cu, Mn, Zn and B), available and total Si. The proceduresadopted for the characterization of soil samples are given below (Table.2).

Table. 2 Methodology for analysis of soil samples

Sl. No.	Soil parameters	Method	References
1	pH	Potentiometric method using a pH meter (1:2.5soil:water suspension)	Jackson (1958)
2	EC	Conductivity bridge using conductivity meter (1:2.5soil:water suspension)	Jackson (1958)
3	Organic carbon	Wet digestion	Walkley and Black(1934)
	Available N	Alkaline permanganate method using Kjeldahl	*Subbiah* and Asija(1956)
4	Available P	Extracted using Bray No.1 reagent and estimated colorimetrically by reduced molybdate ascorbic acid blue colour method using a spectrophotometer	Bray and Kurtz (1945) Watanabe and Olsen (1965)
5	Available K	Extracted by neutral normal ammonium acetate and estimation using Flame photometer	Jackson (1958)
6	Available Caand Mg	Extracted by neutral normal ammonium acetate and estimation using Atomic AbsorptionSpectrophotometer	Jackson (1958)
7	Available S	Extracted using 0.15% $CaCl_2$ and estimated turbidometrically by $BaCl_2$ using aspectrophotometer	Williams and Steinbergs (1959)
8	Available Fe, Mn, Zn and Cu	Extracted using 0.1M HCl and estimation usingAtomic Absorption Spectrophotometer	Sims and Johnson(1991)
9	Available B	Extracted with hot water and estimated colorimetrically by Azomethine – H usingspectrophotometer	Berger and Truog(1939; Gupta (1972)
10	Available Si	Extracted with 0.5 M acetic acid and estimated colorimetrically by ANSA using spectrophotometer	Korndorfer *et al.* (2001b)

11	Total Si	Digestion with HF (48%) and estimation using ICP-OES	(Tan, 2000).
12	Exchangeable cations and cation exchange capacity	Extracted with 0.1M $BaCl_2$ estimation using Atomic Absorption Spectrophotometer	Hendershot and Duquette (1986)
13	Anion exchange capacity	Extracted with 0.01M phosphoric acid and estimated using ascorbic acid blue colour method	Baruah and Borthakur (1997) Watanabe and Olsen (1965)
14	Soil texture	International pipette method	Robinson (1922)
15	Total sesquioxides	Digested and precipitation with 8N HCl, HNO_3 and ammonium hydroxide. Ignition of precipitated residue in a muffle furnace	Jaiswal (2003)

3.1.3 Fractionation of silicon in soils

Five soil samples from different locations as detailed in table.1 were subjected to fractionation of soil Si. The procedure for the extraction and determination of fractions of Si in soil as given by Georgiadis *et al*. (2013) is presented in fig.1.

Mobile Si (Si_m)

Si from the mobile silica fraction (Si) was extracted with 0.01 M $CaCl_2$ solution using a soil to solution ratio of 1:5. The samples were shaken slowly end-over-end on a horizontal shaker for 24 h, only for 1 min h^{-1} in order to accelerate the extraction but at the same time avoid Si abrasion from mineral grains. Si was estimated using ICP-OES.

Adsorbed Si (Si_{ad})

It was obtained by extraction with 0.01 M acetic acid using a soil to solution ratio of 1:10. After the first step, the samples were rinsed with distilled water, and then 10 ml of the extractant was added to each sample. The samples were then shaken for 24 h. The filtrate was used for estimating adsorbed Si using ICP-OES.

Organic Si (Si_{org})

The samples were treated with 20 ml of 17.5% H_2O_2, manually shaken 4 – 6 times and kept for 1 h at room temperature. Then, 10 ml of 35% H_2O_2 was added and the samples were kept in a water bath at 85 °C, until the reaction is completed. After cooling, it was filtered and Si was estimated using ICP-OES.

Occluded Si (Si_{occ})

The occluded Si was extracted with 0.2 M ammonium oxalate and 0.2 M oxalic acid under UV-light. First, the extractant was applied at daylight and room temperature for 8 h, using a soil to solution ratio of 1:50. Then, the suspensions were irradiated with UV light overnight (with a distance between the sample and the UV lamp of approx. 20 cm). During the whole time the samples were shaken horizontally for 1 min h^{-1}. After shaking, it was filtered and Si was estimated using ICP-OES. Then the four replicates were divided into two by two.

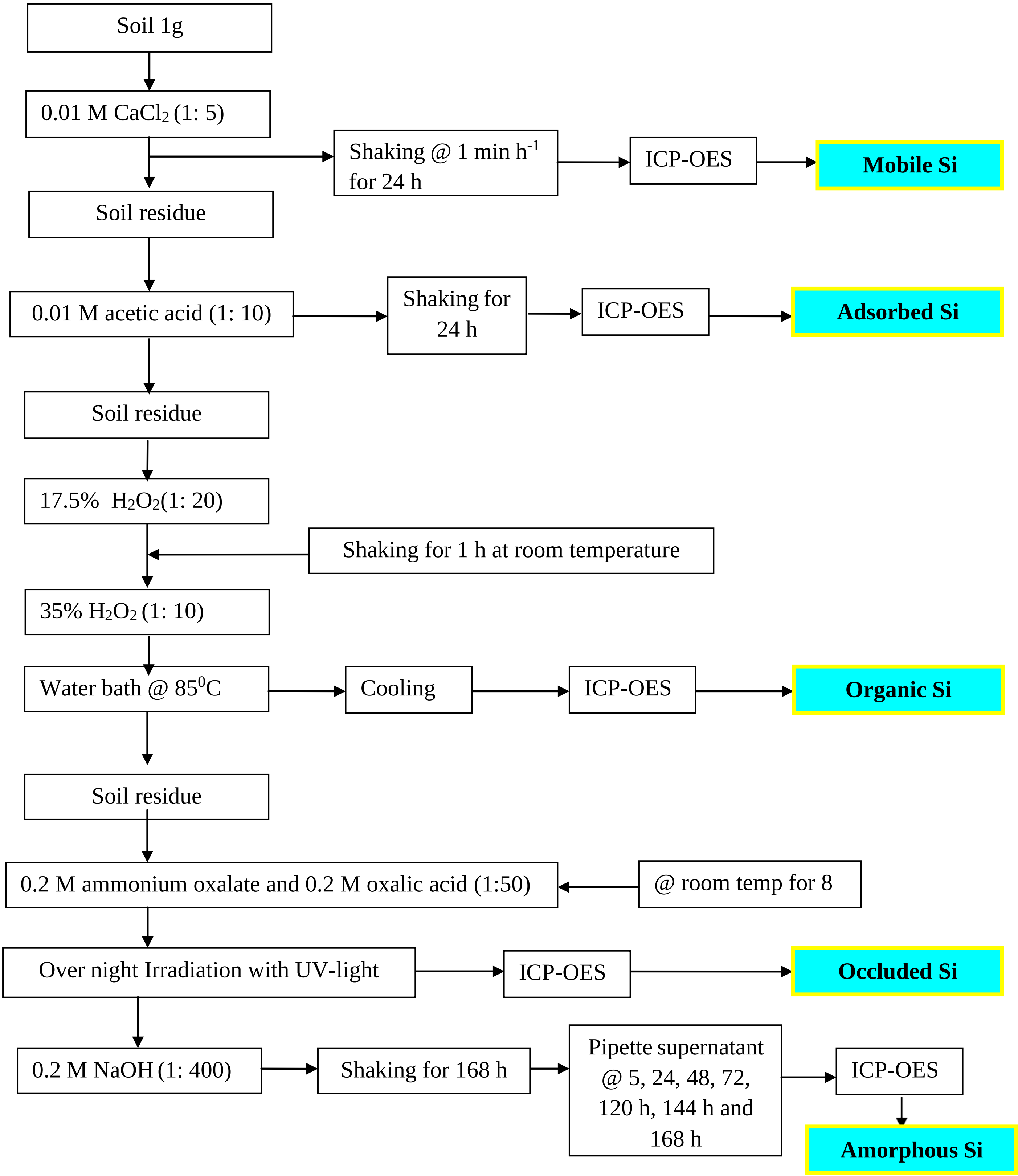
Amorphous Si (Si_{amr})

Amorphous Si was extracted with 0.2 M NaOH solution by shaking slowly for 168 h at room temperature, using a sample to solution ratio of 1:400. 7 ml aliquots were pipetted offthe supernatant solution after 5 h 24 h, 48 h, 72 h, 120 h, 144 h and 168 h, filtered and analyzed for Si.This step provided the amount of total (minerogenic and biogenic) amorphousSi.

Residual Si (Si_{res})

The residual Si was estimated by subtracting the sum of $\mathbf{Si_l + Si_{ad} + Si_{org} + Si_{occ} + Si_{ba} + Si_{ta}}$ from total Si.

Figure. 1. Flow diagram of fractionation of Si in soil



Residual Si = Total Si – ($\mathrm{Si_{m}}$ + $\mathrm{Si_{ad}}$ + $\mathrm{Si_{org}}$ + $\mathrm{Si_{occ}}$ +$\mathrm{Si_{amr}}$)

3.1.4 Adsorption study

The representative soils of five rice growing regions of Kerala were used for adsorption studies. One gram of soil sample from each soil type was equilibrated with different concentrations of silicon (0, 5, 20, 40, 60, 80, 100, 150 and 200 mg L^{-1}) in 20 ml solution of 0.01 M $NaNO_3$ both at 25^0C and 40^0C. Merck standard was used Si source. The soil samples were shaken for 24 hours (equilibration time) to achieve steady state condition (Qiu *et al.*, 2010) and replicated thrice for each soil.

After shaking, the soil solution was filtered through Whatman no. 42 filter paper and Si concentration in the filtrate was measured using ICP-OES. Using the amount of adsorbed Si (Q) and equilibrium Si concentration (I), Q/I curves were drawn for each soil. Best fit curves were obtained using regression equations. Slopes of these curves were considered as the buffer power of each soil. From the data obtained, Q-I curves were plotted with the amount of Si adsorbed on Y axis and the equilibrium concentration of Si in the soil solution on X axis. The Q and I parameters were calculated from the adsorption experiments conducted with increasing the concentration of Si added to one gram of soil. The concentration of Si in solution after equilibration for 24 hours was considered as intensity factor. The amount of Si adsorbed on solid phase per unit weight was considered as the quantity factor. The Q/I curves were fitted with these data and intercepts and slopes were computed from the best fit curves using regression analysis. The slope of the curve is the parameter which explains the buffer power (Si supplying power of soil). The simple linear equation $\Delta Q = bC + K$ was used to obtain the best curve, where b is the buffer power (slopeof the curve) and K is the intercept. By using the data on adsorption the following two adsorption isotherms were then fitted for each soil.

a) Langmuir adsorption isotherm

$$\frac{C}{x/m} = \frac{1}{KM} + \frac{C}{M}$$

where

C= concentration

x/m=amount adsorbed per unit weight of soil

K= bonding energy coefficient

M=adsorption maximum.

b) Freundlich adsorption isotherm

$x/m = KC^{1/n}$, where ‗K‘ and ‗1/n‘ are the Freundlich constants

c) Temkin adsorption isotherm

$x/m = A + B \log C$

A (L g^{-1}) is the Temkin isotherm constant, B (J/mol) is a constant related to heat of sorption

Thermodynamic parameters

Thermodynamic parameters were calculated from the variation of the thermodynamic equilibrium constant, K^0 (Biggar and Cheung, 1973).

$$K^0 = as/ae = \gamma_s Cs / \gamma_e Ce \qquad (2.1)$$

Where:

as = activity of adsorbed solute
ae = activity of solute in equilibrium
Cs = µg of solute adsorbed per mL of solvent in contact with the adsorbed surface
Ce = µg of solute adsorbed per mL of solvent in equilibrium
γ_s = activity coefficient of adsorbed solute
γ_e = activity coefficient of solute in equilibrium solution
Cs was calculated according to the following equation (Fu *et al.*, 1948)

$$Cs = \frac{(\rho_1/M_1)\, A_1}{\dfrac{S}{N\,(x/m)} - \dfrac{A_2}{M_2 \times 10^6}} \qquad (2.2)$$

ρ_1 = density of solvent (density of water g cc^{-1})
M_1 and M_2 molecular weights of solvent and solute respectively (g mol^{-1})
A_1 and A_2 = respective cross sectional areas of solvent and solute molecule (cm^2 $molecule^{-1}$)
N = Avogadro‘s number (6.023×10^{23} molecules mol^{-1})
S = surface area of adsorbent (cm^2 g^{-1})
x/m = specific adsorption (µg g^{-1})

The cross sectional areas (cm^2) of the solvent and solute molecules were estimated from the following equation (Kodera and Osuoshi, 1959)

$$A = 1.091 \times 10^{-16} [(M \times 10^{24}) / (N \times \rho)]^{2/3} \qquad (2.3)$$

Where, M and ρ represent the molecular weight and density respectively

Surface area of soils

About 1.1g of calcium saturated soil samples were taken in shallow small weighing cans and dried to a constant weight over P_2O_5 in evacuated dessiccator. Approximately 3 ml of ethylene glycol monoethyl ether (EGME) was added to each of the dried sample to form mineral absorbate slurry. The slurry was allowed to equilibrate for at least one hour and then kept in evacuated desiccators. The samples were first weighed one hour after the evacuation, then at successively longer time intervals until a constant weight was attained (Carter *et al.* 1965). 2.86 x 10^{-4} g of EGME was required to form a monolayer of 1 m^2. The surface area of the soil was then calculated based on the amount of EGME retained using the following equation:

Surface area

$S(m^2g^{-1}) = (1\ m^2/2.86 \times 10^{-4}) \times$ amount of EGME retained (g)/weight of soil taken (g) (2.4)

In equation (2.2) since S/N (x/m) >> $A_2/M_2 \times 10^6$, the equation is reduced to

$$Cs = \frac{(\rho_1/M_1)\,A_1}{\dfrac{S}{N\,(x/m)}} \qquad (2.5)$$

This can be used to calculate microgram of solute adsorbed per mL of solvent in contact with the adsorbed surface, ie., Cs in g ml^{-1}

At lower concentration, activity coefficient approaches unity and hence $Cs/Ce = K_0$

Values of K_0 were obtained by plotting log (Cs/Ce) Vs Cs and extrapolating to zero.

The standard free energy (ΔG^0) was calculated from

$$\Delta G = -RT\ln K_0 \qquad (2.6)$$

The standard enthalpy (ΔH^0) was obtained from the integrated form of the Vant Hoff equation,

$$\ln K_o / K_1 = -\frac{\Delta H}{R} \left[(1/T_2) - (1/T_1)\right] \tag{2.7}$$

The standard entropy (ΔS^0) was calculated from

$$\Delta S^0 = (\Delta H^0 - \Delta G^0) / T \tag{2.8}$$

Plate 1. Samples in orbital incubator shaker for adsorption study

3.1.5 Preparation of biodecomposed rice husk and rice husk ash

Materials used for preparation of biodecomposed rice husk

Rice husk, rice bran (source: Pavizham rice mill, Kalady, Ernakulam), commercially available effective microorganisms (EM) solution and molasses.

Preparation of biodecomposed rice husk

The compost was prepared following the method suggested by Anda *et al*. (2008). For this, 500 kg of rice husk was thoroughly mixed with 25 kg rice bran to serve as an activator. The Effective Microorganisms (EM) and molasses were added as sources of microbial decomposers and energy for microorganisms respectively and also to promote rice husk composting process. The EM (0.5 L) and molasses (1.5 L) were diluted in 500 L of water. This solution was added to a mixture of rice husk and rice bran and evenly mixed to bring thewater content upto 50 per cent in the composted material. The material was heaped to a height of one meter and covered with jute sac to prevent evaporation and maintain moisture. The compost pile was well turned every two days for the first month and every week for the rest of the compostimg period. The total composting period was three months.

Characterization of composted rice husk

The rice husk and rice husk compost were characterized for elemental composition (C, N, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn and Si), lignin and cellulose. The procedures adopted for the characterization of rice husk and rice husk compost are detailed hereunder (Table.3).

Preparation of rice husk ash

Rice husk was made into ash in tank which were fired using dried coconut husk for a period of 4 -5 hours as indicated by the white colour of ash. It was prepared under controlled condition (Fig.3). The weight of rice husk ash was reduced one by fourth of the weight of rice husk.

Plate 2. Preparation of biodecomposed rice husk

Plate 3. Preparation of rice husk ash

Table.3 Methodology followed for the analysis of biodecomposed rice husk

Sl. No.	Element	Method
1	Total organic carbon	CHNS
2	Total Nitrogen	CHNS
3	Total Phosphorus	Single acid digestion (FCO, 1985) followed by estimation with Vanabdomolybdate phosphoric yellow colour method (Piper, 1966)
4	Total Potassium	Single acid digestion (FCO, 1985) followed by estimation with Flame photometry determination (Jackson, 1958)
5	Total Calcium and magnesium	Single acid digestion (FCO, 1985) followed by estimation using atomic absorption spectrophotometer
6	Total Sulphur	CHNS
7	Total Iron, manganese, zinc and copper	Single acid digestion (FCO, 1985) followed by estimation using atomic absorption spectrophotometer
8	Total Si	Digestion (Ma *et al.,* 2002) and estimation using ICP-OES
9	Lignin	Klason (1923)
10	Cellulose	Sadasivam and Manickam (1992)

Plate 4. Biodecomposed rice husk after three months of composting

Experiment 2

Release of silicon in different soils with different sources of silicon under different water regimes

3.2. Incubation study

The incubation study was conducted for three months with the *Kuttanad* soil (S_1) of Moncombu, *Kole* land soil (S_2) of Thrissur, *Pokkali* soil (S_3) of Vyttila, sandy soil (S_4) of Chalakudi and lateritic soil (S_5) of Pattambi in plastic pots of 1 kg capacity to know the extent of release of available silicon and total silicon from the different sources of silicon added viz., rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate (table.4). All the silicon sources were finely powdered and thoroughly mixed with one kg of each of the experiment soil. Quantity of silicon sources were calculated to provide 45 kg Si ha^{-1} (100 kg SiO_2 ha^{-1}) according to Package of Practice by Kerala Agricultural University (KAU, 2011). The NPK fertilizers were applied at the rate of 90: 45: 45 kg ha^{-1} (KAU POP, 2011). After mixing with the silicon sources and NPK fertilizers, the pots were subjected to two types of water regimes viz., submerged water regime (SWR) and field capacity water regime (FCWR) which was maintained throughout incubation period by adding calculated volume of water followed by thorough mixing. The details of the statistical design and treatment combinations followed are given below (table.5).

Design	: CRD
Replications	3
Treatments	: 10 X 5

Soil types

S_1: Kuttanad

S_2: Kole

S_3: Pokkali

S_4: Sandy

S_5: Lateritic

Table. 4 Details of sources of silicon used as fertilizer

Sl. No.	**Si fertilizer used**	**Sources of Si fertilizer**	**Content of Si present (%)**	**Quantity applied (kg ha^{-1})**	**Mode of application**
1	Biodecomposed rice husk	Pavizham rice mill, Kalady	14.9	301	Soil application
2	Rice husk ash	Pavizham rice mill, Kalady	20.0	225	Soil application
3	Calcium silicate	Harsco Metals, Hyderabad	12.0	375	Soil application
4	Sodium silicate	Sreesai chemicals, Mumbai	22.0	204	Soil application

Treatments

T_1: Absolute control

T_2: Fertilizer as per KAU POP (NPK alone)

T_3: T_2 + Rice husk ash at SWR

T_4: T_2 + Biodecomposed rice husk at SWR

T_5: T_2 + Calcium silicate at SWR

T_6: T_2 + Sodium silicate at SWR

T_7: T_2 + Rice husk ash at FCWR

T_8: T_2 + Biodecomposed rice husk at FCWR

T_9: T_2 + Calcium silicate at FCWR

T_{10}: T_2 + Sodium silicate at FCWR

The incubated samples were subsampled at specified intervals for estimating pH, EC, ORP, available and total Si. During incubation study, the pH, EC and redox potential of soil under each treatment were analysed continuously for first two weeks, once in a week for next one month and then at monthly intervals with the use of pH meter, conductivity meter and redox meter respectively. Available Si and total Si in the soil was analysed by drawing samples at 1, 2 and 3 months during the period of incubation. The procedures adopted for these analyses are given in table.2 of section 3.1.2.

Table.5 Treatment combinations in the incubation experiment

Sl.No.	Treatment combinations				
	Kuttanad **soil**	***Kole*** **soil**	***Pokkali*** **soil**	**Sandy soil**	**Lateritic soil**
1	S_1 T_1	S_2 T_1	S_3 T_1	S_4 T_1	S_5 T_1
2	S_1 T_2	S_2 T_2	S_3 T_2	S_4 T_2	S_5 T_2
3	S_1 T_3	S_2T_3	S_3 T_3	S_4 T_3	S_5T_3
4	S_1 T_4	S_2 T_4	S_3 T_4	S_4 T_4	S_5 T_4
5	S_1 T_5	S_2 T_5	S_3 T_5	S_4 T_5	S_5T_5
6	S_1 T_6	S_2 T_6	S_3 T_6	S_4T_6	S_5 T_6
7	S_1 T_7	S_2 T_7	S_3 T_7	S_4 T_7	S_5 T_7
8	S_1 T_8	S_2 T_8	S_3 T_8	S_4 T_8	S_5 T_8
9	S_1 T_9	S_2 T_9	S_3 T_9	S_4 T_9	S_5 T_9
10	S_1 T_{10}	S_2 T_{10}	S_3 T_{10}	S_4 T_{10}	S_5 T_{10}

Plate 5. Incubation study with different sources of Si at different water regimes

Experiment 3

Field study to evaluate the efficacy of different sources of silicon including rice straw in wetland rice

3.3. Field experiment 1

Among five rice growing soils, the sandy soil showed the lowest plant available Si. So this soil was selected for doing field experiment to get maximum response to Si fertilizers. This was conducted on rice variety Uma at Agronomic Research Station, Chalakudy during 2013-2014 virippu (Kharif) season to evaluate the efficacy of different sources of silicon in wetland rice.

The sources of silicon used in this field experiment were rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate and were applied to thequantity required to supply 45 kg of Si ha^{-1}(100 kg SiO_2 ha^{-1}). The quantity of silicon and NPK fertilizers were applied according to the recommendation by KAU POP (KAU, 2011). Recommended dose of lime was applied in all the plots except calcium silicate applied plots. In calcium silicate applied plots, the quantity of lime was applied after calculating theneutralizing value of calcium silicate. The experiment plot was laid out in a randomised blockdesign with six treatments in four replications. The plot size was 20 m^2. The treatment details are given below.

Design: RBD
Treatments: 6
Replications: 4
Rice variety: Uma

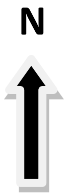
Treatments

T_1: Absolute control
T_2: Fertilizer as per KAU POP (NPK alone)
T_3: T_2 + Rice husk ash
T_4: T_2 + Biodecomposed rice husk
T_5: T_2 + Calcium silicate
T_6: T_2 + Sodium silicate

Plate 6. Field preparation for rice cultivation

Plate 7. Field prepared for rice cultivation

Fig. 2 Lay out of the experiment plot



R1	**T5**	**T4**	**T3**	**T2**	**T6**	**T1**
R2	**T2**	**T6**	**T4**	**T1**	**T3**	**T5**
R3	**T1**	**T3**	**T6**	**T4**	**T5**	**T2**
R4	**T6**	**T2**	**T5**	**T3**	**T1**	**T4**

Plate 8. Transplanting of rice seedlings

Plate 9. Fertilizer application of rice crop

Plate 10. Over view of field at tillering stage of rice

Plate 11. Over view of field at harvesting stage of rice

Plate 12. Harvesting of rice crop

3.3.1 Land preparation

The experimental area was ploughed well and plots of 5m x 4m were prepared by constructing bunds of 30 cm width and height. Irrigation and drainage channels were provided between each plot. Lay out of the experiment plot was given in fig.2

3.3.2. Planting

21 days old seedlings were transplanted at a spacing of 15 cm x 10 cm in the plot of 20 m^2 size.

3.3.3. Collection and analysis of soil and plant samples

Soil and plant samples were collected at tillering, panicle initiation (PI) and harvest stage and analysed for nutrient content.

3.3.4. Soil analysis

The soil samples were air dried, processed and sieved through 2 mm sieve. The processed soil samples were analyzed for physico-chemical properties like texture, pH, EC, AEC, CEC, organic carbon, available major nutrients (N, P and K), secondary nutrients (Ca, Mg and S), micronutrients (Fe, Cu, Mn, Zn and B), available Al and Si. The procedures adopted for the characterization of soil samples are detailed in 3.1.2.

3.3.5. Plant analysis

Plant samples were collected from each plot at tillering, panicle initiation and harvest stage. The collected samples were washed thoroughly with water, put in paper bag and dried inan oven at 60^0C. They were then powdered in stainless steel grinder and used for the analysis (table.6).

3.6.3. Biometric observations

The observations on number of tillers per hill, plant height, root weight and root volume were recorded at tillering, panicle initiation and harvest. In addition to this, number of panicles per hill, number of spikelets per panicle, filled grains per panicles, unfilled grains per panicles and thousand grain weight and the weight of grain and straw were recorded after harvest.

Table.6 Methodology followed for plant analysis

Sl. No.	Element	Method
1	Nitrogen	CHNS
2	Phosphorus	Single acid digestion of leaf sample followed by filtration. Vanabdomolybdate phosphoric yellow colour in nitric acid system (Piper, 1966)
3	Potassium	Single acid digestion of leaf sample followed by filtration. Flame photometry determination (Jackson, 1958)
4	Calcium and magnesium	Single acid digestion of leaf sample followed by filtration. The filtrate was collected, analysed for Ca and Mg using ICP-OES (Piper, 1966)
5	Sulphur	CHNS
6	Iron, manganese, zinc, copper, boron and aluminium	Single acid digestion of leaf sample followed by filtration. The filtrate was collected and analyzed for Fe, Mn, Zn, Cu, B and Al using ICP-OES (Piper, 1966)
7	Silicon	Ma *et al*. (2002). Estimation by ICP-OES
8	Electrolyte leakage	Lutts *et al.* (1996)
9	Catalase activity	Barber (1980)
10	Peroxidase activity	Upadhyaya (2007)

Residual effect of rice straw incorporation on growth and yield of succeeding crop of rice

3.3.7 Field experiment 2

The second field experiment was conducted during mundakan (Rabi) season to study the residual effect of rice straw incorporation on growth and yield of succeeding crop of rice. After the harvest and threshing of first crop, the straw obtained from each plot under particulartreatment was cut into small pieces and incorporated into the same plot. These plots were kept under submerged condition to enhance the decomposition of rice straw. After one month of rice straw incorporation, the field was ploughed well and plots size of 5m x 4m was ensured with proper restructuring of bund as well. Irrigation and drainage channels were provided between each plot. Rice seedlings (21 days old) were transplanted in these plots. Manures and fertilizers were not applied.

Analysis of soil and plant samples

Soil and plant samples were collected at tillering, panicle initiation and harvest stage and analysed for nutrient content as per the procedures detailed in 3.1.2.

Biometric observations

Biometric observations of second crop were taken at tillering, panicle initiation (PI) and harvest stage as per the procedure detailed in 3.6.3

Statistical analysis

Correlation studies of data were carried out by the method suggested by Panse and Sukatme (1978). Correlation and regression analysis of data generated in various experiments were carried out based on the method suggested by Cox (1987) using SPSS package. Path coefficient analysis was carried out in OPSTAT package. Analysis of variance in CRD and RBD was made in OPSTAT package. Adsorption isotherm equations were fitted using STATISTICA package.

Plate 13. Cutting of rice straw of first crop

Plate 14. Rice straw incorporated plots

Plate 15. Field preparation for succeeding rice

Plate 16. Transplanting of succeeding rice crop

Plate 17. Over view of succeeding rice field

Plate 18. Harvesting of succeeding rice crop

Results

4. Results

The results of experiment conducted to study the silicon availability of tropical soils with respect to rice nutrition with three experiments to achieve the objectives are presented in this chapter. The experiments were conducted at College of Horticulture, Vellanikkara and Agronomic Research Station, Chalakudy during 2011 – 2014.

Experiment 1

4.1 Characterization of major rice growing soils of Kerala

Representative soil samples collected from five rice growing regions of Kerala *viz.*, *Kuttanad, Kole* land, *Pokkali*, sandy and lateritic soils were analyzed to study the physico-chemical properties and nutrient status of the soils to categorize them according to plant available Si.

4.1.1 Physico-chemical properties of rice growing soils of Kerala

The data on physico-chemical properties of major rice growing soils are presented in table.7. The *Kuttanad* soil was clayey in texture with a sand, silt and clay per cent of 21.55, 33.53 and 44.93 respectively. It was acidic in reaction with a pH of 4.4. The EC was 0.18 dS m^{-1}. This soil registered 2.70 per cent of organic carbon. The CEC and AEC of soil were 8.60 cmol (+) kg^{-1} and 3.49 cmol (-) kg^{-1} respectively. The silica: sesquioxide ratio of soil was 12.00.

The *Kole* land soil was clayey in texture with a sand, silt and clay per cent of 29.73, 24.30 and 45.98 respectively. It was acidic in reaction with a pH of 4.7. The EC was 0.18 dS m^{-1}. This soil recorded 3.60 per cent of organic carbon. The CEC and AEC of soil were 9.64 cmol (+) kg^{-1} and 2.21 cmol (-) kg^{-1} respectively. The silica: sesquioxide ratio of soil was 1.81.

The *Pokkali* soil was loamy in texture with a sand, silt and clay per cent of 48.53, 30.45 and 21.03 respectively. It was acidic in reaction with a pH of 3.4. The EC was 1.68 dS m^{-1}. This soil recorded 3.30 per cent of organic carbon. The CEC and AEC of soil were 12.84 cmol (+) kg^{-1} and 3.70 cmol (-) kg^{-1} respectively. The silica: sesquioxide ratio of soil was 3.54.

The sandy soil was sandy in texture with a sand, silt and clay per cent of 89.20, 5.10 and 5.70 respectively. It was acidic in reaction with a pH of 5.1. The EC was 0.30 dS m^{-1}. This soil recorded 0.60 per cent of organic carbon. The CEC and AEC of soil were 3.93 cmol (+) kg^{-1} and 5.34 cmol (-) kg^{-1} respectively. The silica: sesquioxide ratio of soil was 15.26.

The lateritic soil was sandy clay loam in texture with a sand, silt and clay per cent of 60.60, 10.08 and 29.33 respectively. It was acidic in reaction with a pH of 5.1. The EC was 0.05 dS m^{-1}. This soil recorded 1.20 per cent of organic carbon. The CEC and AEC of soil were 7.14 cmol (+) kg^{-1} and 3.35 cmol (-) kg^{-1} respectively. The silica: sesquioxide ratio of soil was 1.94.

4.1.2 Nutrient status of major rice growing soils of Kerala

The data on nutrient status of major rice growing soils are presented in table.8. In *Kuttanad* soil, available N, P and K were 333.00, 13.81 and 515.20 kg ha^{-1} respectively. The secondary nutrients *viz.,* available Ca and Mg were 318.58 and 23.58 mg kg^{-1} respectively. The available micronutrients *viz*. Fe, Cu, Mn, Zn and B were 423.13, 0.49, 6.00, 2.79 and 0.08 mg kg^{-1} respectively. The plant available and toal Si were 11.27 kg ha^{-1} and 191.2 g kg^{-1} respectively.

In *Kole* land soil, available N, P and K were 481.51, 20.53 and 170.61 kg ha^{-1} respectively. The secondary nutrients *viz.,* available Ca and Mg were 518.72 and 25.28 mg kg^{-1} respectively. The available micronutrients *viz*. Fe, Cu, Mn, Zn and B were 492.63, 2.71, 9.44, 3.38 and 0.03 mg kg^{-1} respectively. The plant available and toal Si was 34.91 kg $ha^{-1}$and 91.8 g kg^{-1} respectively.

In *Pokkali* soil, available N, P and K were 447.90, 64.96 and 230.72 kg ha^{-1} respectively. The secondary nutrients *viz.,* available Ca and Mg were 142.55 and 26.17 mg kg^{-1} respectively. The available micronutrients *viz*. Fe, Cu, Mn, Zn and B were 623.47, 0.32, 6.16, 4.58 and 0.23 mg kg^{-1} respectively. The plant available Si and total Si was 23.85 kg ha^{-1} and 182.1g kg^{-1} respectively.

In sandy soil, available N, P and K were 182.33, 159.41 and 44.43 kg ha^{-1} respectively. The secondary nutrients *viz.,* available Ca and Mg were 63.40 and 10.24 mg kg^{-1} respectively. The available micronutrients *viz*. Fe, Cu, Mn, Zn and B were 131.60, 0.76, 0.17, 1.43 and 0.31

mg kg^{-1} respectively. The plant available and total Si was 7.7 mg kg^{-1} and 176.6 g kg^{-1} respectively.

In lateritic soil, available N, P and K were 282.70, 17.17 and 284.11 kg ha^{-1} respectively. The secondary nutrients *viz.*, available Ca and Mg were 257.30 and 22.51 mg kg^{-1} respectively. The available micronutrients *viz*. Fe, Cu, Mn, Zn and B were 184.27, 4.06, 18.06, 2.51 and 0.18 mg kg^{-1} respectively. The plant available and total Si was 16.30 kg ha^{-1} and 99.8 g kg^{-1} respectively.

4.1.3 Status of exchangeable cations in major rice growing soils of Kerala

The data on status of exchangeable cations in major rice growing soils are presented in table.9. In *Kuttanad* soil, exchangeable Ca (4.06 cmol (+) kg^{-1}) was found to be the dominant cation followed by Mg (1.97 Cmol(+) kg^{-1}), Na (1.54 cmol(+) kg^{-1}), Al (0.61 cmol(+) kg^{-1}) andK (0.35 cmol(+) kg^{-1}). The exchangeable Fe and Mn were very negligible in quantity. The exchangeable Cu and Zn were under detectable range.

In *Kole* land soil, exchangeable Ca (4.48 cmol(+) kg^{-1}) was found to be the dominant cation followed by exchangeable Mg (2.05 Cmol(+) kg^{-1}), Na (1.54 Cmol(+) kg^{-1}), Al (0.51 cmol(+) kg^{-1}) and K (0.51 cmol(+) kg^{-1}). The exchangeable Fe and Mn were very negligible in quantity. The exchangeable Cu and Zn were under detectable range.

In *Pokkali* soil, exchangeable Ca (3.52 cmol(+) kg^{-1}) and Na (3.52 Cmol(+) kg^{-1}) were the dominant cations followed by Al (2.70 cmol(+) kg^{-1}), Mg (2.27 cmol(+) kg^{-1}), K (0.45 cmol(+) kg^{-1}) and Fe (0.34 cmol(+) kg^{-1}). The exchangeable Zn and Mn were very negligible in quantity. The exchangeable Cu was below detectable range.

In sandy soil, exchangeable Na (1.44 C mol(+) kg^{-1}) was found to be the dominant cation followed by exchangeable Ca (1.16 cmol(+) kg^{-1}), Mg (0.91 cmol(+) kg^{-1}), K (0.28 cmol(+) kg^{-1})and Al (0.13 cmol(+) kg^{-1}). The exchangeable Fe was very negligible in quantity. The exchangeable Cu, Zn and Mn were beyond detectable range.

In lateritic soil, exchangeable Ca (3.31 cmol(+) kg^{-1}) was found to be the dominant cationfollowed by exchangeable Mg (1.82 cmol(+) kg^{-1}), Na (1.55 cmol(+) kg^{-1}), and K (0.40 cmol(+) kg^{-1}). The exchangeable Al and Mn were very negligible in quantity. The exchangeable Fe, Cu and Zn were beyond detectable range.

Table.7 Physico-chemical properties of major rice growing soils of Kerala

Soil type	pH	EC d Sm^{-1}	OC %	AEC cmol(-) kg^{-1}	CEC cmol(+) kg^{-1}	SiO_2/R_2O_3	Sand	Silt	Clay	Textural class
							%			
Kuttanad	4.4	0.18	2.70	3.49	8.60	12.00	21.55	33.53	44.93	Clay
Kole	4.7	0.18	3.60	2.21	9.64	1.81	29.73	24.30	45.98	Clay
Pokkali	3.4	1.68	3.30	3.70	12.84	3.54	48.53	30.45	21.03	Loam
Sandy	5.1	0.30	0.60	5.34	3.93	15.26	89.20	5.10	5.70	Sand
Laterite	5.1	0.05	1.20	3.35	7.14	1.94	60.60	10.08	29.33	Sandy clay loam

Table.8 Nutrient status of major rice growing soils of Kerala

Soil type	Av.N	Av.P	Av.K	Av.Ca	Av.Mg	Av.Fe	Av.Cu	Av.Mn	Av.Zn	Av.B	Av.Si	Total Si
	kg ha^{-1}			mg kg^{-1}								g kg^{-1}
Kuttanad	333.00	13.81	515.20	318.58	23.58	423.13	0.49	6.00	2.79	0.08	11.27	191.2
Kole	481.51	20.53	170.61	518.72	25.28	492.63	2.71	9.44	3.38	0.03	34.91	91.8
Pokkali	447.90	64.96	230.72	142.55	26.17	623.47	0.32	6.16	4.58	0.23	23.85	182.1
Sandy	182.33	159.41	44.43	63.40	10.24	131.60	0.76	0.17	1.43	0.31	7.70	176.6
Laterite	282.70	17.17	284.11	257.30	22.51	184.27	4.06	18.06	2.51	0.18	16.30	99.8

Table.9 Status of exchangeable cations in major rice growing soils of Kerala

Soil type	Ex.Na	Ex.K	Ex.Ca	Ex.Mg	Ex.Fe	Ex.Cu	Ex.Zn	Ex.Mn	Ex.Al
	C mol(+) kg^{-1}								
Kuttanad	1.54	0.35	4.06	1.97	0.04	ND	ND	0.02	0.61
Kole	1.87	0.51	4.48	2.05	0.04	ND	ND	0.18	0.51
Pokkali	3.52	0.45	3.52	2.27	0.34	ND	0.01	0.02	2.70
sandy	1.44	0.28	1.16	0.91	0.01	ND	ND	ND	0.13
Lateritic	1.55	0.40	3.31	1.82	0.00	ND	ND	0.03	0.02

Av. – Available ; Ex.- Exchangeable; ND- not detectable

4.1.4 Correlation between plant available Si (PAS) and soil parameters

In the present study, no correlation was obtained between PAS and soil properties like pH and EC. But significant positive correlation existed between PAS and organic carbon, available nitrogen, available calcium, available magnesium, available iron, available zinc, available manganese, exchangeable potassium, exchangeable calcium, exchangeable magnesium and cation exchange capacity. The correlation of PAS with available boron, anion exchange capacity and silica: sesquioxide ratio was negative, but significant (Table.10).

The results of categorization of major rice growing soils of Kerala showed that the amount of plant available Si present in these soils had good correlation with various physico-chemical properties and available and exchangeable nutrients. Even though the content of total Si was very high in all these soils, plant available Si content was very much low. It finger out that the dissolved or plant available Si in soil is a part of dynamic system. A large variety of Si fraction may occur in the soil. The amount of available Si for plant uptake depends on pools and fluxes of these Si fractions present in soil. Therefore, quantification of Si pools is needed for better understanding of biogeochemical processes involving in the availability of Si in soil- water-plant system. Such quantification requires a sequential extraction method for various Si fractions in soil. An attempt was done to know the different fractions of Si present in these soils and results are presented below.

Table.10 Correlation between plant available Si (PAS) and soil parameters

Soil parameters	PAS	OC	N	Ca	Mg	Fe	Zn	Mn	B	AEC	CEC	SiO_2/R_2O_3	Ex. K	Ex. Ca	Ex. Mg
PAS	-														
OC	0.773^{**}	-													
N	0.893^{**}	0.966^{**}	-												
Ca	0.695^{**}	0.586^{*}	0.638^{*}	-											
Mg	0.675^{**}	0.851^{**}	0.861^{**}	0.606^{*}	-										
Fe	0.655^{**}	0.961^{**}	0.907^{**}	-	0.787^{**}	-									
Zn	0.684^{**}	0.892^{**}	0.893^{**}	-	0.856^{**}	0.937^{**}	-								
Mn	0.849^{**}	0.516^{*}	0.635^{*}	0.868^{**}	-	-	-	-							
B	-0.719^{**}	-0.748^{**}	-0.758^{**}	-0.966^{**}	-0.702^{**}	-0.563^{*}	-	-0.806^{**}	-						
AEC	-0.816^{**}	-0.753^{**}	-0.825^{**}	-0.912^{**}	-0.855^{**}	-0.575^{*}	-0.592^{*}	-0.778^{**}	0.917^{**}	-					
CEC	0.659^{**}	0.907^{**}	0.893^{**}	-	0.882^{**}	0.948^{**}	0.995^{**}	-	-	-0.613^{*}	-				
SiO_2/R_2O_3	-0.791^{**}	-0.546^{*}	-0.701^{**}	-0.514^{*}	-0.761^{**}	-0.436	-0.657^{**}	-0.562^{*}	-	0.773^{**}	-0.630^{*}	-			
Ex. K	0.961^{**}	0.819^{**}	0.925^{**}	0.701^{**}	0.830^{**}	0.702^{**}	0.780^{**}	0.757^{**}	-0.731^{**}	-0.890^{**}	0.765^{**}	-0.894^{**}	-		
Ex. Ca	0.681^{**}	0.828^{**}	0.830^{**}	0.827^{**}	0.933^{**}	0.700^{**}	0.681^{**}	0.576^{*}	-0.896^{**}	-0.945^{**}	0.724^{**}	-0.650^{**}	0.798^{**}	-	
Ex. Mg	0.647^{**}	0.872^{**}	0.869^{**}	0.527^{*}	0.992^{**}	0.837^{**}	0.903^{**}	-	-0.647^{**}	-0.800^{**}	0.927^{**}	-0.724^{**}	0.805^{**}	0.900^{**}	-

PAS – plant available Si (** significant at 1.00 % level, * significant at 5.00 % level)

4.1.5 Fractionation of silicon in five major rice growing soils of Kerala

Five soil samples, representing major rice growing regions of Kerala were subjected to fractionation of soil silicon employing the standard procedure. The results are presented in table.11

Table.11 Fractions of Si in five major rice growing soils

	mg kg^{-1}						g kg^{-1}
Soil type	**Mobile Si**	**Adsorbed Si**	**Organic Si**	**Occluded Si**	**Amorphous Si**	**Residual Si**	**Total Si**
Kuttanad	19.6	5.1	420.4	474.3	32876.0	157584.6	191.2
Kole	33.3	27.0	366.6	1035.9	45954.6	44345.1	91.8
Pokkali	39.0	10.1	811.1	404.9	29596.0	151237.9	182.1
Sandy	2.9	3.3	36.8	201.7	3902.4	172420.9	176.6
Lateritic	20.2	16.6	452.9	412.3	62614.0	36293.0	99.8

Mobile Si

The mobile Si ranged from 2.9 to 39.0 mg kg^{-1}. The highest value of mobile Si was recorded in *Pokkali* soils of Vyttila and the lowest value was recorded in sandy soils of Chalakudy. The *Kole* land soils also showed high value for mobile silicon.

Adsorbed Si

The content of adsorbed Si ranged from 3.3 to 27.0 mg kg^{-1}. The highest value of adsorbed Si was recorded in *Kole* and the lowest value was recorded in sandy soils of Chalakudy. The soils of *Kuttanad* also registered lower value of adsorbed Si.

Organic Si

The lowest value of organic Si (36.8 mg kg^{-1}) was recorded in sandy soils of Chalakudy and the highest (811.1 mg kg^{-1}) in *Pokkali* soils of Vyttila. *Kuttanad*, *Kole* and lateritic soils recorded 420.4, 366.6 and 452.9 mg kg^{-1} of organic Si respectively.

Occluded Si

The occluded Si was in the range of 201.7 to 1035.9 mg kg^{-1}. The highest value of occluded Si was associated with *Kole* land soil and the lowest with sandy soil.

Amorphous Si

The amorphous Si was lowest in sandy soils (3902.4 mg kg^{-1}) and highest in lateritic soils of Pattambi (62614.0 mg kg^{-1}). *Kuttanad, Kole* and *Pokkali* soils recorded 32876.0, 45954.6 and 29596.0 mg kg^{-1} of amorphous Si respectively.

Residual Si

The residual Si content ranged from 36293.0 to 172420.9 mg kg^{-1}. The highest value of residual Si was observed in sandy soils and lowest in lateritic soils. *Kuttanad* and *Pokkali* soils also showed very high content of residual Si among different fractions estimated.

Percentage distribution of silicon fractions in five major rice growing soils

The percentage distribution of silicon fractions in soil are presented in table.12. In*Kuttanad* soil, residual Si (82.41 per cent) was the dominant Si fraction followed by amorphous (17.19 per cent), occluded (0.25 per cent), organic (0.22 per cent) and mobile Si (0.10 per cent). Adsorbed Si (0.003 per cent) was the least fraction present in this soil.

In *Kole* land soil, amorphous Si (50.08 per cent) was the dominant Si fraction followed by residual (48.33 per cent), occluded (1.13 per cent), organic (0.40 per cent) and mobile Si (0.04 per cent). Adsorbed Si (0.03 per cent) was the least fraction present in this soil.

In *Pokkali* soil, residual (83.05 per cent) was the dominant Si fraction followed by amorphous Si (16.25 per cent), organic (0.46 per cent), occluded (0.22 per cent) and mobile Si (0.02 per cent). Adsorbed Si (0.006 per cent) was the least fraction present in this soil.

In sandy soil, residual (97.65 per cent) was the dominant Si fraction followed by amorphous Si (2.21 per cent), occluded (0.11 per cent) and organic (0.02 per cent). Mobile Si (0.002 per cent) and adsorbed Si (0.002 per cent) were the least fractions present in this soil.

In lateritic soil, amorphous Si (62.73 per cent) was the dominant Si fraction followed by residual (36.36 per cent), organic (0.45 per cent) and occluded (0.41 per cent). Mobile Si (0.02 per cent) and adsorbed Si (0.02 per cent) were the least fractions present in this soil.

Correlation between different fractions of silicon and plant available silicon in soil

The correlation between different fractions of Si and PAS are given in table.13. The plant available Si had significant positive correlation with mobile Si (0.824^{**}), adsorbed Si (0.875^{**}) and occluded Si (0.863^{**}). The residual Si (-0.592^{*}) and total Si (-0.594^{*}) had significant negative correlation with plant available silicon in soil. The mobile Si had positive significant correlation with adsorbed (0.571^{*}), organic (0.856^{**}) and occluded Si (0.581^{*}). The adsorbed Si had positive significant correlation with occluded Si (0.868^{**}) and amorphous Si (0.696^{**}) and negative correlation with residual Si (-0.887^{**}) and total Si (-0.896^{**}). The occluded Si had significant negative correlation with residual Si (-0.631^{*}) and total Si (-0.638^{*}). The amorphousSi had significant negative correlation with residual (-0.872^{**}) and total Si (-0.739^{**}). Theresidual Si had significant positive correlation with total Si (0.975^{**}) and significant negative correlation with adsorbed, occluded and amorphous silicon. Among the different Si fractions studied, the organic Si showed correlation only with mobile Si.

Path Analysis

Path coefficient analysis of different fractions of Si indicating the direct and indirect effects on plant available Si in major rice growing soils are given in table.14. The mobile Si had high direct positive effect (0.693) on plant available Si. The indirect effect of adsorbed, occludedand total Si through mobile Si was moderate and positive. The residual Si had indirect moderate negative effect on available Si through mobile Si. The direct effect of adsorbed Si on plant available Si was low (0.192). The indirect effects of mobile and occluded Si through adsorbed Si on available Si were low and that of total Si through adsorbed Si was very high and positive.

The occluded Si had moderate direct effect (0.231) on plant available Si. The indirect effects of adsorbed, mobile and total Si through occluded Si were low, moderate and high respectively on available Si in soil. The residual Si had high negative indirect effect on available Si through occluded Si. The direct effect of residual Si on available Si was very high and positive (1.305). The indirect effects of mobile, adsorbed and occluded Si through residual Si were low and negative. The total Si had very high negative indirect effect on available Si through residual Si.

The total Si had very high negative direct effect (-1.388) on plant available Si. The indirect effects of mobile, adsorbed and occluded Si through total Si were low and negative; while residual Si had very high positive indirect effect through total Si on plant available Si in soil.

4.1.9. Correlation between fractions of Si and soil parameters

The correlation coefficients for fractions of Si with physico-chemical properties of soil are presented in table.15 Mobile Si had significant positive correlation with silt (0.700**), EC (0.560*), OC (0.907**) and CEC (0.960**); sand (-0.633*), pH (-0.645**), AEC (-0.746**) and SiO_2/R_2O_3 (-0.787**) had significant negative correlation with mobile Si in soil. The adsorbed Si had significant positive correlation only with clay (0.554*) content of soils, but had significant negative correlation with EC (-0.207), AEC (-0.835**) and SiO_2/R_2O_3 (-0.823**). Silt (0.669**), EC (0.711**), OC (0.694**) and CEC (0.694**) were positively correlated with organic Si, while pH (-0.742**) and SiO_2/R_2O_3 (-0.638*) were negatively with this fraction of Si. The occluded Si had significant positive correlation with clay (0.765**) and OC (0.689**) and significant negative correlation with sand (-0.669**), AEC (-0.887**) and SiO_2/R_2O_3 (-0.581*). There was a significant positive correlation of clay (0.631*) and negative correlation of AEC (- 0.764**) and SiO_2/R_2O_3 (-0.820**) with amorphous Si. The residual Si had significant positive correlation with AEC (0.708**) and SiO_2/R_2O_3 (0.796**). The pH (-0.552*) was negatively correlated with total Si, while AEC (0.619*) and SiO_2/R_2O_3 (0.715**) showed a positive correlation.

Table.12 Per cent distribution of fractions of Si in five major rice growing soils

	%					
Soil Type	**Mobile Si**	**Adsorbed Si**	**Organic Si**	**Occluded Si**	**Amorphous Si**	**Residual Si**
Kuttanad	0.01	0.003	0.22	0.25	17.19	82.41
Kole	0.04	0.03	0.40	1.13	50.08	48.33
Pokkali	0.02	0.006	0.46	0.22	16.25	83.05
Sandy	0.002	0.002	0.02	0.11	2.21	97.65
Lateritic	0.02	0.02	0.45	0.41	62.73	36.36

Table.13 Correlation between different fractions of Si and plant available Si in soil

Si fractions	**Plant available Si**	**Mobile Si**	**Adsorbed Si**	**Organic Si**	**Occluded Si**	**Amorphous Si**	**Residual Si**	**Total Si**
Plant available Si								
Mobile Si	0.824^{**}							
Adsorbed Si	0.875^{**}	0.571^{*}						
Organic Si	-	0.856^{**}	-					
Occluded Si	0.863^{**}	0.581^{*}	0.868^{**}	-				
Amorphous Si	-	-	0.696^{**}	-	-			
Residual Si	-0.592^{*}	-	-0.887^{**}	-	-0.631^{*}	-0.872^{**}		
Total Si	-0.594^{*}	-	-0.896^{**}	-	-0.638^{*}	-0.739^{**}	0.975^{**}	

PAS – plant available Si (** significant at 1.00 % level, * significant at 5.00 % level)

Table.14 Path coefficient of different fractions of Si with plant available Si in soil

Si fractions	Mobile Si	Adsorbed Si	Occluded Si	Residual Si	Total Si	Correlation Coefficient of fractions of Si with plant available Si
Mobile Si	**0.693**	0.110	0.135	-0.429	0.317	**0.824****
Adsorbed Si	0.395	**0.192**	0.201	-1.157	1.244	**0.875****
Occluded Si	0.403	0.167	**0.231**	-0.823	0.886	**0.863****
Residual Si	-0.228	-0.170	-0.146	**1.305**	-1.353	**-0.592***
Total	-0.158	-0.172	-0.148	1.272	**-1.388**	**-0.594***

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

4.1.10 Correlation of fractions of Si with available and exchangeable nutrients

The correlation coefficient of fractions of Si with available and exchangeable nutrients is presented in table.16. Mobile Si had high positive significant correlation with available N (0.949**), Mg (0.906**), Fe (0.891**), Zn (0.966**), Exchangeable Na (0.755**), Ex. K (0.904**), Ex. Ca (0.776**), Mg (0.922**) and Ex. Al (0.710**) and negative significant correlation with available B (-0.582*). Adsorbed Si had significant positive correlation with available N (0.648**), Ca (0.797**), Mg (0.538**), Mn (0.915**), exchangeable K (0.86**) and Ex. Ca (0.916**) and a significant negative correlation with available B (-0.703**). Organic Si was positively correlated with available N (0.690**), Mg (0.832**), Fe (0.772**), Zn (0.921**), exchangeable Na (0.827**), Ex. K (0.612**), Ex. Ca (0.593**), Ex. Mg (0.881*8) and Ex. Al (0.818**).
Occluded Si had significant positive correlation with available N (0.762**), Ca (0.938**), Mg (0.586**), Mn (0.958**), exchangeable K (0.819**), Ex. Ca (0.760**) and Ex. Mg (0.526**) and a negative correlation with available B (-0.928**). Available Ca (0.615**), Mg (0.689**), exchangeable K (0.634**), Ex. Ca (0.687**) and Ex. Mg (0.614**) were positively correlated with amorphous Si. Residual Si had significant negative correlation with available Ca (- 0.669**), Mn (-0.696**) and exchangeable K (-0.645**). The total Si also had significant negative correlation with available Ca (-0.634**), Mn (-0.754**) and exchangeable K (- 0.591**).

The results of fractions of Si in major rice growing soils showed that varying degree of Si fractions present in these soils and their interrelationship with various physico-chemical properties and available and exchangeable nutrients. It also showed the correlation between Si fractions and plant available Si. The exchange and release of these Si fractions are mainly influenced by adsorption of Si on soil particles which in turn affects the availability of Si forplant uptake. For better understanding of adsorption behavior of Si in soil, adsorption study was conducted through widely accepted adsorption isotherms to know the quantity-intensity relationship. The results of adsorption study are presented below.

Table.15 Correlation between fractions of Si and soil parameters

	Sand	Silt	Clay	pH	EC	OC	AEC	CEC	SiO_2/R_2O_3
Mobile Si	-0.633*	0.700**	-	-0.645**	0.560*	0.907**	-0.746**	0.960**	-0.787**
Adsorbed Si	-	-	0.554*	-	-	-	-0.835**	-	-0.823**
Organic Si	-	0.669**	-	-0.742**	0.711**	0.694**	-	0.922**	-0.638*
Occluded Si	-0.669**	-	0.765**	-	-	0.689**	-0.887**	-	-0.581*
Amorphous Si	-	-	0.631*	-	-	-	-0.764**	-	-0.820**
Residual Si	-	-	-	-	-	-	0.708**	-	0.796**
Total Si	-	-	-	-0.552*	-	-	0.619*	-	0.715**

Table.16 Correlation between fractions of Si with available and exchangeable nutrients

	N	Ca	Mg	Fe	Zn	Mn	B	Ex. Na	Ex. K	Ex. Ca	Ex. Mg	Ex. Al
Mobile Si	0.949**	-	0.906**	0.891**	0.966**	-	-0.582*	0.755**	0.904**	0.776**	0.922**	0.710**
Adsorbed Si	0.648**	0.797**	0.538*	-	-	0.915**	-0.703**	-	0.860**	0.619*	-	-
Organic Si	0.690**	-	0.832**	0.772**	0.921**	-	-	0.827**	0.612*	0.593*	0.881**	0.818**
Occluded Si	0.762**	0.938**	0.586*	-	-	0.958**	-0.928**	-	0.819**	0.760**	0.526*	-
Amorphous Si	-	0.615*	0.689**	-	-	-	-	-	0.634*	0.687**	0.614*	-
Residual Si	-	-0.669**	-	-	-	-0.696**	-	-	-0.645**	-	-	-
Total Si	-	-0.634*	-	-	-	-0.754**	-	-	-0.591*	-	-	-

(** significant at 1.00 % level, * significant at 5.00 % level)

Adsorption study

4.1.11. Q-I relationship

Quantity – intensity relationship of Si in five major rice growing soils at two temperatures *viz*. 25^0C and 40^0C were studied.

The calculated values of both b and K at 25^0C and 40^0C are presented in table.17 and 18 respectively. The highest value of buffer power (b) was recorded in *Kuttanad* (2.17 L kg^{-1}) soil and the lowest value was recorded in lateritic (1.45 L kg^{-1}) soils at 25^0C, whereas at 40^0C, the buffer power was highest in sandy (1.14 L kg^{-1}) soil and lowest in *Kuttanad* (-0.73 L kg^{-1}) soil. All soils except sandy soils of Chalakudy showed a negative buffer power at 40^0C.

The intercept of soils (K) varied from -143.80 mg kg^{-1} (sandy soil) to 97.05 mg kg^{-1} (*Kole*) at 25^0C. The lowest and highest values of K were found as -609.10 and 1013.00 mg kg^{-1} insandy and *Kuttanad* soils respectively at 40^0C.

4.1.12 Adsorption isotherms

The equilibrium Si concentration and the amount of Si adsorbed by each soil were used to test the fitness of data to the adsorption isotherms *viz*., Langmuir, Freundlich and Temkin adsorption equations. The data obtained from the adsorption experiments fitted well with Freundlich and Temkin equations at 25^0C and not with Langmuir equation. But the data obtained for equilibrium Si concentration and the amount of Si adsorbed by each soil at 40^0C could not be fitted to any adsorption equations.

The equations for Freundlich isotherms at 25^0C are represented in table.19. The data for all the soils could be described by the linear form of Freundlich equation. In this equation, K_F is defined as the amount of Si adsorbed at unit soil solution concentration of Si. At 25^0C, the values of K_F ranged between 0.103 to 1.382 mg kg^{-1}. The constant ‗1/n' related to adsorption intensity of the soil. The *Kole* land soil showed highest adsorption intensity of Si, whereas sandy soils of Chalakudy and *Pokkali* soils of Vyttila showed lowest adsorption intensity.

The equations for Temkin isotherms at 25^0C are represented in table.20. The data for all the soils except sandy soils could be explained by the linear form of Temkin equation. In this equation, A is intercept and B is the slope of the equation. A (L g^{-1}) is the Temkin isotherm

Table.17 Buffer power (b) and intercept of Q/I curve of the soils for Si adsorption at 25^0 C

Sl. No.	Soil Type	Intercept of the Q/I curve (K) (mg kg^{-1})	Buffer power (b) (L kg^{-1})
1	*Kuttanad*	-20.82	2.17
2	*Kole*	97.05	1.81
3	*Pokkali*	7.18	1.98
4	Sandy	-143.80	1.99
5	Lateritic	90.03	1.45

Table.18 Buffer power (b) and intercept of Q/I curve of the soils for Si adsorption at 40^0C

Sl. No.	Soil Type	Intercept of the Q/I curve (K) (mg kg^{-1})	Buffer power (b) (L kg^{-1})
1	*Kuttanad*	1013.00	-0.73
2	*Kole*	358.80	-0.42
3	*Pokkali*	947.70	-0.63
4	Sandy	-609.10	1.14
5	Lateritic	984.70	-0.66

constant, B (J mol^{-1}) is a constant related to heat of sorption. The value of A ranged from -1193.59 to -547.24 and value of B ranged from 691.29 to 929.36.

4.1.13 Thermodynamics of Si adsorption in soil

The specific surface area and thermodynamic parameters *viz.*, equilibrium constant (K_0), free energy (ΔG^0), changes in enthalpy (ΔH), and entropy (ΔS^0) are listed in table.21.

The lowest surface area of 6.36 m^2 g^{-1} was recorded in sandy soils of Chalakudi and recorded the largest surface area of 66.55 m^2 g^{-1} in *Pokkal*i soils of Vyttila.

Sandy soils of Chalakudi and *Pokkali* soils of Vyttila recorded highest and lowest values of K_0 *viz*., 10.20 and 9.00, and 6.07 and 5.69 at 25^0C and 40^0C respectively.

The free energy change (ΔG^0) values were negative for all the soils. The maximum of -1.07 kcal mol^{-1} was recorded for ΔG^0 at 25^0C in *Pokkali* soils of Vyttila and minimum of -1.37 kcal mol^{-1} in sandy soils of Chalakudi, whereas *Kole* land (-0.98 kcal mol^{-1}) soils recorded maximum and sandy (-1.36 kcal mol^{-1}) soils of Chalakudy recorded minimum ΔG^0 at 40^0C.

The change in enthalpy (ΔH) was negative for all the soils. The highest values of ΔH was noticed in *Pokkali* (-0.80 kcal mol^{-1}) and *Kuttanad* (-0.79 kcal mol^{-1}) soils and the lowest in *Kole* land (-3.23 kcal mol^{-1}) soils.

The change in entropy (ΔS^0) was negative except for *Kuttanad* and *Pokkali* soils at 25^0C and 40^0C. The maximum ΔS^0 (0.001 kcal mol^{-1} K^{-1}) was recorded in *Kuttanad* and *Pokkali* soils. The minimum ΔS^0 (-0.007 kcal mol^{-1} K^{-1}) was recorded in *Kole* land soils at both temperatures.

Table.19Freundlich adsorption characteristics of the soils for Si adsorption at 25^0C

Sl. No.	Soil	Freundlich Equation	K_F (mg kg^{-1})	1/n	n	Variance of exploration (%)
1	Sandy	Log x/m=0.133+1.03 log C	1.357	1.03	0.97	98.62
2	*Kole*	Log x/m=-0.988+1.50 log C	0.103	1.50	0.67	87.13
3	*Kuttanad*	Log x/m= -0.474+1.31 log C	0.335	1.31	0.76	96.20
4	Lateritic	Log x/m= -0.418+1.25 log C	0.382	1.25	0.80	92.65
5	*Pokkali*	Log x/m=0.133+1.03 log C	1.356	1.03	0.97	98.20

Table.20 Temkin adsorption characteristics of the soils for Si adsorption at 25^0C

Sl. No.	Soil	Temkin Equation	A	B	Variance of exploration (%)
1	Sandy	NS	-	-	-
2	*Kole*	x/m= -1146.03+919.69 log C	-1146.03	919.69	72.52
3	*Kuttanad*	x/m= -547.24+691.29 log C	-547.24	691.29	55.51
4	Lateritic	x/m= -796.51+730.32 log C	-796.51	730.32	65.62
5	*Pokkali*	x/m= -1193.59+929.36 log C	-1193.59	929.36	65.98

Table.21 Thermodynamic parameters for adsorption of Si in soil

Sl.No.	Soil	Surface area (m^2 g^{-1})	K_0		ΔG^0 (kcal mol^{-1})		ΔH (kcal mol^{-1})	ΔS (kcal mol^{-1} K^{-1})	
			25^0C	40^0C	25^0C	40^0C		25^0C	40^0C
1	*Kuttanad*	59.00	6.27	5.88	-1.08	-1.10	-0.79	0.001	0.001
2	*Kole*	62.65	6.26	4.82	-1.08	-0.98	-3.23	-0.007	-0.007
3	*Pokkali*	66.55	6.07	5.69	-1.07	-1.08	-0.80	0.001	0.001
4	Sandy	6.36	10.20	9.00	-1.37	-1.36	-1.55	-0.001	-0.001
5	Lateritic	30.83	6.55	5.55	-1.11	-1.06	-2.05	-0.003	-0.003

Preparation of biodecomposed rice husk

4.1.14 Bio-chemical characterization of biodecomposed rice husk

The compost was prepared following the method suggested by Anda *et al*. (2008). After three months of composting, the matured biodecomposed rice husk (BRH) and raw rice husk (RRH) were analyzed for elemental composition (P, K, Ca, Mg, S, Fe, Cu, Mn, Zn and Si), lignin and cellulose content. The bio-chemical properties of RRH and BRH are furnished in table.22.

The lignin and cellulose content decreased from 30.80 and 50.28 to 26.20 and 30.26 per cent respectively, during composting. The effect was more pronounced in case of cellulose. The total carbon content reduced from 39.75 per cent in RRH to 35.62 per cent in BRH. Total nitrogen, phosphorus, calcium, magnesium, iron and manganese content increased from 0.46, 0.70, 0.062, 0.227, 0.146 and 0.015 per cent in RRH to 0.69, 1.05, 0.083, 0.300, 0.166 and 0.022 percent in BRH, respectively. The content of silicon was increased by the process of composting. It increased from 12.23 in RRH to 14.91 per cent in BRH.

Sulphur, potassium and copper were low in BRH as compared to RRH. The sulphur content reduced from 5.83 per cent to 5.20 per cent during composting. The per cent reduction ofpotassium and copper was from 0.16 and 0.011 in RRH to 0.14 and 0.002 in BRH. The change inzinc content was very much negligible during composting.

Table.22 Bio-chemical composition of RRH and BRH

Parameters	**Content in %**	
	Raw Rice Husk (RRH)	**Biodecmposed Rice Husk (BRH)**
Lignin	30.80	26.20
Cellulose	50.28	30.26
Carbon	39.75	35.62
Nitrogen	0.46	0.69
Sulphur	5.83	5.20
Phosphorus	0.70	1.05
Potassium	0.16	0.14
Calcium	0.062	0.083
Magnesium	0.227	0.300
Iron	0.146	0.166
Copper	0.011	0.002
Manganese	0.015	0.022
Zinc	0.003	0.004
Silicon	12.23	14.91

Experiment 2

Release of silicon in different rice growing soils added with various Si sources underdifferent water regimes

An incubation experiment was conducted to know the extent of release of silicon after the addition of different sources of silicon such as rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate in five rice growing soils *viz. Kuttanad* soil (S_1) of Moncombu, *Kole* land soil (S_2) of Adat, *Pokkali* soil (S_3) of Vyttila, sandy soil (S_4) of Chalakudi, and lateritic soils of Pattambi (S_5) under submerged water regime (SWR) and field capacity water regime (FCWR). The incubated sample was sub-sampled at definite time intervals to determine the pH, EC, available Si and total Si. The pH, EC and ORP were estimated at biweekly intervalsfollowed by weekly intervals for next one month and thereafter at monthly interval. Estimationof available and total Si was done at monthly intervals up to three months.

4.2.1 Effect of different Si sources and soil type on available soil Si under different water regimes after one month of incubation

The data on the available Si estimated after one month of incubation are given intable.23. In *Kuttanad* soil, the highest (281.3 mg kg^{-1}) available Si was recorded in T_6 (T_2 + Sodium silicate at SWR) which was significantly superior and on par with T_7, T_5, T_4 and T_1. T_1 (Absolute control) recorded the lowest (12.0 mg kg^{-1}) available Si in soil after one month of incubation.

In *Kole* land soil, T_5 (T_2 + calcium silicate at aswr) recorded highest available Si (358.5 mg kg^{-1}) which was on par with T_4 and T_8, whereas the lowest (37.9 mg kg^{-1}) available Si was estimated in T_1 (Absolute control).

In *Pokkali* soils of Vyttila, the lowest (25.8 mg kg^{-1}) available Si was seen in T_1 (Absolute control), whereas T_{10} (T_2 + Sodium silicate at FCWR) recorded the highest (490.50 mg kg^{-1}) available Si which was significantly superior to all other treatments. This was followed by T_8 which was on par with T_9.

Table. 23 Effect of different Si sources and soil type on available soil Si (mg kg^{-1}) under different water regimes after one month of incubation

Soil Type	T_1	T_2 (KAU POP)	Submerged water regimes				Field capacity water regimes				Mean A
			T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	
			T_2 + RHA	T_2 + BRH	T_2 + CS	T_2 + SS	T_2 + RHA	T_2 + BRH	T_2 + CS	T_2 + SS	
S_1	12.00 (3.96)	25 (5.5)	228.6 (15.6)	215.7 (15.2)	235.5 (15.8)	281.3 (17.3)	247.8 (16.2)	132.4 (12.0)	205.7 (14.8)	214.2 (15.1)	212.4
S_2	37.90 (6.66)	80 (9.44)	219.4 (15.2)	244.3 (27.8)	358.8 (18.9)	274.6 (17.1)	235.9 (15.7)	241.6 (27.7)	226.1 (15.5)	257.5 (16.5)	401.3
S_3	25.80 (5.57)	60.6 (8.28)	109.7 (10.9)	174.2 (13.7)	175.3 (13.8)	154.1 (12.9)	183.7 (14.0)	397.9 (20.4)	390.6 (20.2)	490.5 (22.6)	221.6
S_4	11.98 (3.96)	27.8 (5.77)	143.1 (12.4)	59.7 (8.2)	100.3 (10.5)	74.8 (9.1)	123.5 (11.6)	117.8 (11.3)	96.8 (10.3)	76.1 (9.2)	89.6
S_5	17.65 (4.70)	35.1 (6.49)	264.4 (16.6)	329.8 (18.7)	299.9 (17.6)	232.0 (15.7)	272.3 (16.9)	330.4 (18.7)	293.9 (17.4)	412.2 (20.8)	292.6
Mean B	21.07	45.87	193.0	304.7	233.9	203.4	212.6	344.0	242.6	290.1	

*Values in paranthesis are transformed values

Factors	**C.D.**	**SE(d)**	**SE(m)**
Factor(A)	0.668	0.336	0.238
Factor(B)	0.945	0.475	0.336
Factor(A X B)	2.112	1.063	0.752

In sandy soils of Chalakudi, the highest (143.1 mg kg^{-1}) available Si was recorded in T_3: T_2 + Rice husk ash at SWR which was on par with T_5, T_7, and T_8. The lowest (11.98 mg kg^{-1}) Si was estimated in T_1: Absolute control.

In lateritic soils of Pattambi, the highest (412.2 mg kg^{-1}) available Si was observed in T_{10}: T_2 + Sodium silicate at FCWR, followed by 330.4mg kg^{-1} in T_8: T_2 + Biodecomposed Rice husk at FCWR which was on par with T_4, T_2, T_5, T_9, T_7 and T_3. The lowest (17.65 mg kg^{-1}) Si was estimated in T_1: Absolute control.

A comparison of treatment means showed the highest (401.3 mg kg^{-1}) value in *Kole* land soil followed by lateritic soil (292.6 mg kg^{-1}), while sandy soils of Chalakudi recorded the lowest (89.6 mg kg^{-1}) value for treatment mean.

Among the different treatments, the highest available Si was found in T_8: T_2 + Biodecomposed Rice husk at FCWR in all soils except *Kuttanad* soil. The available Si was lowest in T_1: Absolute control in all soils.

4.2.2 Effect of different Si sources and soil type on available soil Si under different water regimes after two months of incubation

The data on the available Si estimated after two months of incubation are given in table.24. In *Kuttanad* soil, available Si was highest (352.6 mg kg^{-1}) in T_4: T_2 + Biodecomposed Rice husk at SWR which was significantly superior to all other treatments. The second highest (260.9 mg kg^{-1}) available Si was recorded in T_3: T_2 + Rice husk ash at SWR which was on par with T_2. T_1: Absolute control recorded the lowest (12.0 mg kg^{-1}) available Si in soil after second month of incubation.

In *Kole* land soil, T_6: T_2 + Sodium silicate at SWR recorded highest available Si (520.4 mg kg^{-1}) which was on par with T_5, whereas the lowest (37.9 mg kg^{-1}) available Si was estimatedin T_1: Absolute control.

In *Pokkali* soils of Vyttila, the lowest (25.8 mg kg^{-1}) available Si was observed in T_1: Absolute control. T_6: T_2 + Sodium silicate at SWR recorded the highest (264.9 mg kg^{-1}) available Si which was significantly superior and on par with T_7.

Table.24 Effect of different Si sources and soil type on available soil Si ((mg kg^{-1})) under different water regimes after two months of incubation

Soil Type			**Submerged water regimes**				**Field capacity water regimes**				
			T_3	**T_4**	**T_5**	**T_6**	**T_7**	**T_8**	**T_9**	**T_{10}**	
	T_1	**T_2 (KAU POP)**	**T_2 + RHA**	**T_2 + BRH**	**T_2 + CS**	**T_2 + SS**	**T_2 + RHA**	**T_2 + BRH**	**T_2 + CS**	**T_2 + SS**	**Mean A**
S_1	12.00 (3.96)	22.0 (5.2)	260.9 (16.6)	352.6 (19.3)	229.0 (15.6)	208.8 (15.0)	196.0 (14.5)	153.5 (12.9)	179.9 (13.8)	139.7 (12.3)	217.7
S_2	37.90 (6.66)	75.0 (9.2)	301.0 (17.9)	236.8 (15.9)	490.7 (22.7)	520.4 (23.3)	396.0 (20.4)	370.8 (19.8)	357.8 (19.4)	357.4 (19.4)	334.8
S_3	25.80 (5.57)	55.0 (7.9)	183.3 (14.0)	155.1 (12.9)	174.1 (13.7)	264.9 (16.8)	235.0 (15.8)	231.0 (15.7)	227.7 (15.6)	183.0 (14.0)	173.1
S_4	11.98 (3.96)	23.0 (5.3)	48.2 (7.4)	51.7 (7.7)	41.0 (6.9)	58.3 (8.1)	70.6 (8.9)	48.3 (7.4)	71.1 (8.9)	52.3 (7.7)	48.5
S_5	17.65 (4.70)	27.0 (5.7)	166.8 (13.4)	146.4 (12.6)	215.6 (15.2)	217.0 (15.2)	196.5 (14.5)	202.2 (14.7)	194.2 (14.4)	184.2 (14.1)	188.0
Mean B	21.07	40.4	192.0	188.5	230.1	253.9	218.8	201.1	206.1	183.3	

*Values in paranthesis are transformed values

Factors	**C.D.**	**SE(d)**	**SE(m)**
Factor(A)	0.287	0.145	0.102
Factor(B)	0.406	0.204	0.145
Factor(A X B)	0.909	0.457	0.323

In sandy soils of Chalakudi, available Si was highest (71.1 mg kg^{-1}) in T_9: T_2 + Calcium silicate at FCWR which was on par with T_6, and T_7. The lowest (11.98 mg kg^{-1}) Si was estimated in T_1: Absolute control and T_2: Fertilizer as per KAU POP.

In lateritic soils of Pattambi, the highest (217.0 mg kg^{-1}) available Si was observed in T_6: T_2 + Sodium silicate at SWR which was on par with T_5, T_7 T_8 and T_9. The lowest (17.65 mg kg^{-1}) Si was estimated in T_1: Absolute control.

A comparison of treatment means showed the highest (334.8 mg kg^{-1}) value in *Kole* land soil followed by *Kuttanad* soil (217.7 mg kg^{-1}), while sandy soils of Chalakudi recorded the lowest (48.5 mg kg^{-1}) value for treatment mean.

Among the different treatments, the highest available Si was found in T_6: T_2 + Sodium silicate at SWR in all soils except *Kuttanad* and sandy soils where T_4 and T_9 recorded the highest values respectively. The lowest available Si was recorded in T_1: Absolute control in all soils.

4.2.3 Effect of different Si sources and soil type on available soil Si under different water regimes after three months of incubation

The data on the available Si estimated after three months of incubation are given in the table.25. In *Kuttanad* soil, the highest (101.4 mg kg^{-1}) available Si was recorded in T_9: (T_2 + calcium silicate at FCWR) which was significantly superior over all other treatments. The second highest (97.2 mg kg^{-1}) available Si was recorded in T_3: T_2 + RHA at FCWR which was on par with T_3. T_1: Absolute control recorded the lowest (12.0 mg kg^{-1}) available Si in soil after second month of incubation.

In *Kole* land soil, T_5: (T_2 + calcium silicate at SWR) recorded highest available Si (120.1 mg kg^{-1}) which was on par with T_5, whereas the lowest (37.9 mg kg^{-1}) available Si was estimated in T_1: Absolute control.

In *Pokkali* soils of Vyttila, the lowest (25.8 mg kg^{-1}) available Si was seen in T_1:Absolute control. T_6: T_2 + Sodium silicate at SWR recorded the highest (134.3 mg kg^{-1}) availableSi which was significantly superior over all other treatments.

In sandy soils of Chalakudi, the highest (61.3 mg kg^{-1}) available Si was recorded in T_7: T_2 + Rice husk ash at FCWR. The second highest available Si was recorded with T_6. The lowest (11.98 mg kg^{-1}) Si was estimated in T_1: Absolute control.

Table.25 Effect of different Si sources and soil type on available soil Si (mg kg^{-1}) under different water regimes after three months of incubation

Soil type	**T_1**	**T_2 (KAU POP)**	**Submerged water regimes**				**Field capacity water regimes**				**Mean A**
			T_3	**T_4**	**T_5**	**T_6**	**T_7**	**T_8**	**T_9**	**T_{10}**	
			T_2 + RHA	**T_2 + BRH**	**T_2 + CS**	**T_2 + SS**	**T_2 + RHA**	**T_2 + BRH**	**T_2 + CS**	**T_2 + SS**	
S_1	12.00 (3.96)	22.0 (5.2)	97.2 (10.4)	84.6 (9.7)	60.7 (8.3)	75.5 (9.2)	64.4 (8.5)	81.0 (9.5)	101.4 (10.6)	91.3 (10.0)	91.7
S_2	37.90 (6.66)	60.0 (8.2)	103.6 (10.7)	83.5 (9.6)	120.1 (11.4)	112.9 (11.1)	83.8 (9.6)	109.6 (10.9)	83.1 (9.6)	86.3 (9.8)	102.3
S_3	25.80 (5.57)	50.0 (7.6)	115.8 (11.3)	80.4 (9.5)	101.5 (10.6)	134.3 (12.1)	110.8 (11.1)	99.7 (10.5)	107.5 (10.9)	66.4 (8.6)	89.1
S_4	11.98 (3.96)	23.0 (5.3)	39.8 (6.8)	43.0 (7.1)	30.9 (6.1)	53.8 (7.8)	61.3 (8.3)	38.0 (6.6)	34.1 (6.3)	31.1 (6.1)	37.7
S_5	17.65 (4.70)	27.0 (5.7)	126.1 (11.7)	133.7 (12.1)	122.5 (11.5)	182.6 (14.0)	113.9 (11.2)	131.7 (12.0)	152.0 (12.9)	138.1 (12.3)	138.3
Mean B	21.07	36.4	96.5	85.1	87.2	111.8	86.9	92.0	95.6	82.6	

*Values in paranthesis are transformed values

Factors	**C.D.**	**SE(d)**	**SE(m)**
Factor(A)	0.104	0.052	0.037
Factor(B)	0.147	0.074	0.052
Factor(A X B)	0.328	0.165	0.117

In lateritic soils of Pattambi, the highest (182.6 mg kg^{-1}) available Si was observed in T_6: T_2 + Sodium silicate at SWR which was on par with T_1. The lowest (17.65 mg kg^{-1}) Si was estimated in T_1: Absolute control.

A comparison of treatment means showed the highest (138.3 mg kg^{-1}) value in lateritic soil followed by *Kole, Kuttanad* and *Pokkali* soils, while sandy soils of Chalakudi recorded the lowest (37.7 mg kg^{-1}) value of treatment mean.

4.2.4 Effect of different Si sources and soil type on total soil Si under different water regimes after one month of incubation

The data on the total Si estimated after one month of incubation are given in the table.26.

In *Kuttanad* soil, the highest (218.4 g kg^{-1}) total Si was recorded in T_8: T_2 + Biodecomposed Rice husk at FCWR. There was no significant difference between treatments with respect to total Si. T_5: T_2 + Calcium silicate at SWR recorded the lowest (144.4 g kg^{-1}) total Si in soil after one month of incubation.

In *Kole* land soil, T_4: T_2 + Biodecomposed Rice husk at SWR recorded highest total Si (680.7g kg^{-1}) which was significantly superior to all other treatments, whereas the lowest (108.2 g kg^{-1}) total Si was associated with T_1: Absolute control.

In *Pokkali* soils of Vyttila, total Si was lowest (111.0 g kg^{-1}) in T_1: Absolute control. T_7: T_2 + Rice husk ash at FCWR recorded the highest (168.2 g kg^{-1}) value of total Si.

In sandy soils of Chalakudi, total Si was highest (428.2 g kg^{-1}) in T_{10}: T_2 + Sodium silicate at FCWR which was significantly superior to all other treatments. The lowest (187.3 g kg^{-1}) total Si was estimated in T_1: Absolute control.

In lateritic soils of Pattambi, the highest (202.2 g kg^{-1}) total Si was observed in T_4: T_2 + Biodecomposed Rice husk at SWR which was on par with T_5 and T_{10}. The lowest (113.9 g kg^{-1}) Si was estimated in T_1: Absolute control.

A comparison of treatment means showed the highest (328.4 g kg^{-1}) value in sandy soil followed by *Kole* soil (239.8 g kg^{-1}), while *Pokkali* soils of Vyttila recorded the lowest (149.5 g kg^{-1}) for treatment mean.

Among the different treatments, the lowest total Si was recorded in T_1: Absolute control in all soils.

4.2.5 Effect of different Si sources and soil type on total soil Si under different water regimes after two months of incubation

The data on the total Si estimated after second month of incubation are given in the table.27.

In *Kuttanad* soil, total Si was highest (206.3 g kg^{-1}) in T_9: T_2 + Calcium silicate at FCWR which was significantly superior over T_5 and on par with all other treatments. The lowest (122.2 g kg^{-1}) total Si was recorded in T_5: T_2 + Calcium silicate at SWR after two month of incubation.

In *Kole* land soil, T_7: T_2 + Rice husk ash at FCWR recorded highest total Si (205.6 g kg^{-1}) which was significantly superior over control, whereas the lowest (92.4 g kg^{-1}) total Si was estimated in T_1: Absolute control.

In *Pokkali* soils of Vyttila, the lowest (84.7 g kg^{-1}) total Si was seen in T_1: Absolute control. T_7: T_2 + Rice husk ash at FCWR recorded the highest (146.5 g kg^{-1}) total Si which was significantly differs from other treatments. The second highest total Si was estimated in T_3.

In sandy soils of Chalakudi, the highest (403.5 g kg^{-1}) total Si was recorded in T_{10}: T_2 + Sodium silicate at FCWR. The second highest total Si was estimated in T_8 followed by T_9, T_7 and T_5. The lowest (175.8 g kg^{-1}) Si was estimated in T_1: Absolute control.

In lateritic soils of Pattambi, the highest (182.6 g kg^{-1}) total Si was observed in T_2: Fertilizer as per KAU POP which was on par with all other treatments except control. The lowest(95.0 g kg^{-1}) Si was estimated in T_1: Absolute control.

A comparison of treatment means showed the highest (309.3 g kg^{-1}) value in sandy soil followed by *Kuttanad* soil (168.7 g kg^{-1}), *Kole* land (162.8), lateritic (152.1 g kg^{-1}), while *Pokkali* soils of Vyttila recorded the lowest (124.4 g kg^{-1}) value of treatment mean.

Among the different treatments, the highest available Si was found in T_1: Absolute control in case of *Kuttanad* and *Kole* land soils whereas T_6: T_2 + Sodium silicate at SWR recorded highest available Si among treatments in case of *Pokkali* and lateritic soils. It waslowest for T_2: Fertilizer as per KAU POP in all soils except *Kole* land and lateritic soils.

Table.26 Effect of different Si sources and soil type on total soil Si (g kg^{-1}) under different water regimes after one month of incubation

Soil Type	T_1	T_2 (KAU POP)	Submerged water regimes				Field capacity water regimes				Mean
			T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	
			T_2 + RHA	T_2 + BRH	T_2 + CS	T_2 + SS	T_2 + RHA	T_2 + BRH	T_2 + CS	T_2 + SS	
S_1	211.2 (15.0)	173.1 (13.7)	171.8 (13.6)	148.1 (12.7)	144.4 (12.5)	189.0 (14.2)	212.6 (15.1)	218.4 (15.3)	216.6 (15.2)	212.1 (15.1)	189.7
S_2	108.2 (10.9)	194.0 (14.4)	209.3 (15.0)	680.7 (23.0)	187.3 (14.2)	198.3 (14.6)	224.2 (15.5)	202.0 (14.7)	190.1 (14.3)	204.2 (14.8)	239.8
S_3	110.0 (11.0)	152.3 (12.8)	155.3 (13.0)	138.2 (12.3)	151.3 (12.8)	161.3 (13.2)	168.2 (13.5)	147.1 (12.6)	155.0 (12.9)	156.0 (13.0)	149.5
S_4	187.3 (14.2)	233.9 (15.8)	311.1 (18.1)	249.0 (16.3)	342.9 (19.0)	305.0 (18.0)	401.3 (20.5)	411.0 (20.8)	413.9 (20.8)	428.2 (21.2)	328.4
S_5	113.9 (11.2)	175.3 (13.7)	185.9 (14.1)	202.2 (14.7)	199.3 (14.6)	149.3 (12.7)	172.2 (13.6)	142.3 (12.4)	161.2 (13.2)	201.2 (14.7)	170.3
Mean	146.1	185.7	206.7	283.6	205.0	200.6	235.7	224.2	227.4	240.3	

*Values in paranthesis are transformed values

Factors	**C.D.**	**SE(d)**	**SE(m)**
Factor A	1.478	0.455	0.322
Factor B	2.090	0.643	0.455
Factor(A X B)	4.674	1.439	1.017

4.2.6 Effect of different Si sources and soil type on total soil Si under different water regimes after three months of incubation

The data on the total Si estimated after three months of incubation are given in the table.28.

In *Kuttanad* soil, the highest (185.5 g kg^{-1}) total Si was recorded in T_9: T_2 + Calcium silicate at FCWR. In this soil, total Si did not differ significantly with respect to treatments. T_2: Fertilizer as per KAU POP recorded the lowest (103.9 g kg^{-1}) total Si in soil after three month of incubation.

In *Kole* land soil, T_7: T_2 + Rice husk ash at FCWR recorded highest total Si (184.8 g kg^{-1}) which was significantly superior over control and on par with other treatments, whereas the lowest (64.3 g kg^{-1}) total Si was estimated in T_1: Absolute control.

In *Pokkali* soils of Vyttila, the lowest (76.7 g kg^{-1}) total Si was seen in T_1: Absolute control. T_4: T_2 + Biodecomposed Rice husk at SWR recorded the highest (405.2 g kg^{-1}) total Si which was significantly superior over all other treatments. The second highest total Si was estimated in T_7 (132.5 g kg^{-1}) which was on par with all other treatments.

In sandy soils of Chalakudi, the highest (392.5 g kg^{-1}) total Si was recorded in T_{10}: T_2 + Sodium silicate at FCWR. The second highest total Si was estimated in T_9 followed by T_8 T_7, and T_5. The lowest (154.4 g kg^{-1}) Si was estimated in T_1: Absolute control.

In lateritic soils of Pattambi, the highest (163.9 g kg^{-1}) total Si was observed in T_4: T_2 + Biodecomposed Rice husk at SWR. The second highest (162.4 g kg^{-1}) total Si was recorded in T_{10}. T_4 was on par with all other treatments. The lowest (78.2 g kg^{-1}) Si was estimated in T_1: Absolute control.

A comparison of treatment means showed the highest (292.5 g kg^{-1}) value in lateritic soil followed by sandy soil (154.0 g kg^{-1}), *Kole* land (147.2 g kg^{-1}) and *Pokkali* soils of Vyttila (142.6 g kg^{-1}), whereas *Kuttanad* soil recorded the lowest (109.9 g kg^{-1}) value of mean of total Si.

Table.27 Effect of different Si sources and soil type on total soil Si (g kg^{-1}) under different water regimes after two months of incubation

			Submerged water regimes				**Field capacity water regimes**				
			T_3	**T_4**	**T_5**	**T_6**	**T_7**	**T_8**	**T_9**	**T_{10}**	
Soil Type	**T_1**	**T_2 (KAU POP)**	**T_2 + RHA**	**T_2 + BRH**	**T_2 + CS**	**T_2 + SS**	**T_2 + RHA**	**T_2 + BRH**	**T_2 + CS**	**T_2 + SS**	**Mean A**
S_1	192.3 (14.4)	142.4 (12.4)	147.4 (12.6)	125.0 (11.7)	122.2 (11.6)	168.2 (13.5)	197.6 (14.6)	195.8 (14.5)	206.3 (14.9)	190.1 (14.3)	168.7
S_2	92.4 (10.1)	188.4 (14.2)	178.0 (13.8)	155.9 (13.0)	113.9 (11.2)	172.5 (13.6)	205.6 (14.8)	174.6 (13.7)	164.5 (13.3)	182.1 (14.0)	162.8
S_3	84.7 (9.7)	126.2 (11.7)	144.0 (12.5)	115.0 (11.2)	102.2 (10.6)	131.1 (12.0)	146.5 (12.6)	129.4 (11.9)	137.4 (12.2)	127.9 (11.8)	124.4
S_4	175.8 (13.8)	242.5 (16.1)	297.5 (17.7)	194.7 (14.5)	333.9 (18.8)	274.8 (17.1)	384.1 (20.1)	397.2 (20.4)	389.4 (20.2)	403.5 (20.6)	309.3
S_5	95.0 (10.2)	168.2 (13.5)	165.5 (13.4)	182.6 (14.0)	172.6 (13.6)	128.3 (11.8)	155.5 (13.0)	124.4 (11.7)	146.4 (12.6)	182.1 (14.0)	152.1
Mean B	128.0	173.5	186.5	154.6	168.9	175.0	217.9	204.3	208.8	217.1	

*Values in paranthesis are transformed values

Factors	**C.D.**	**SE(d)**	**SE(m)**
Factor(A)	1.000	0.009	0.007
Factor(B)	1.414	0.013	0.009
Factor(A X B)	3.161	0.029	0.021

Table.28 Effect of different Si sources and soil type on total soil Si (g kg^{-1}) under different water regimes after three months of incubation

Soil type	**T_1**	**T_2 (KAU POP)**	**Submerged water regimes**				**Field capacity water regimes**				**Mean**
			T_3	**T_4**	**T_3**	**T_4**	**T_3**	**T_4**	**T_3**	**T_4**	
			T_2 + RHA	**T_2 + BRH**	**T_2 + RHA**	**T_2 + BRH**	**T_2 + RHA**	**T_2 + BRH**	**T_2 + RHA**	**T_2 + BRH**	
S_1	168.9 (13.5)	103.9 (10.7)	132.9 (12.0)	105.7 (10.8)	115.3 (11.2)	134.2 (12.1)	147.9 (12.7)	167.9 (13.5)	185.5 (14.1)	170.6 (13.6)	143.3
S_2	64.3 (8.5)	166.2 (13.4)	176.3 (13.8)	143.0 (12.5)	104.1 (10.7)	155.2 (13.0)	184.8 (14.1)	166.1 (13.4)	137.9 (12.2)	171.2 (13.6)	146.9
S_3	76.7 (9.3)	118.6 (11.4)	121.6 (11.5)	405.2 (18.0)	99.4 (10.5)	127.6 (11.8)	132.5 (12.0)	115.1 (11.2)	120.0 (11.5)	116.9 (11.3)	143.4
S_4	154.4 (12.9)	226.5 (15.6)	273.9 (17.1)	194.7 (14.5)	293.0 (17.6)	272.1 (17.0)	365.1 (19.6)	375.0 (19.9)	380.3 (20.0)	392.5 (20.3)	292.8
S_5	78.2 (9.3)	154.9 (12.9)	147.6 (12.6)	163.9 (13.3)	161.3 (13.2)	114.3 (11.2)	138.9 (12.3)	105.6 (10.8)	125.2 (11.7)	162.4 (13.2)	135.2
Mean B	108.5	154.0	170.5	202.5	154.6	160.7	193.9	186.0	189.8	202.7	

*Values in paranthesis are transformed values

Factors	**C.D.**	**SE(d)**	**SE(m)**
Factor(A)	1.613	0.022	0.015
Factor(B)	2.281	0.031	0.022
Factor(A X B)	5.099	0.068	0.048

4.2.7 Changes in pH, EC and ORP during incubation

The pH, EC and redox potential estimated after 1, 5, 10, 15, 30, 60 and 90 days after incubation (DAI) are presented in table.29- 33.

In *Kuttanad* soil, the highest pH of 6.2 was recorded 15 DAI and the lowest of 5.12 on first day of incubation. Among treatments, highest pH was observed in T_6 and T_5 throughout the incubation period. The EC was found to be highest (0.51 dS m^{-1}) on 5 DAI and the lowest (0.28 dS m^{-1}) was recorded on 90 DAI. The ORP was found to be the highest (167.43 mV) on 90 DAI and lowest (56.05 mV) on 10 DAI. It was negative in T_3, T_4, T_5 and T_6 up to 15 days of incubation. Highest ORP was recorded in T_1 and T_2 throughout the incubation period.

In *Kole* land soil, the highest pH of 5.91 was recorded on 10 DAI, whereas the lowest mean pH (4.8) was on first day of incubation, much similar to *Kuttanad* soil. Among treatments, highest pH was observed in T_3 and T_4 throughout the incubation period. The EC was found to be highest (0.616 dS m^{-1}) on 5 DAI and lowest (0.391 dS m^{-1}) on 15 DAI. The ORP was found to behighest (164.4 mV) on first day of incubation and lowest (95.06 mV) on 10 DAI. ORP was foundto be negative in T_3, T_4, T_5 and T_6 throughout incubation period. Highest ORP was recorded inT_1 and T_2.

Table.29 Effect of different Si sources on changes in pH, EC and ORP of *Kuttanad* soil during incubation

Soil property	**Treatment**	**Days of incubation**						
		1	**5**	**10**	**15**	**30**	**60**	**90**
pH	T_1	4.09	4.10	4.11	4.10	4.10	4.09	4.10
	T_2	4.36	5.89	5.29	5.38	5.38	4.36	4.34
	T_3	5.45	6.25	6.78	6.92	6.50	6.53	6.46
	T_4	5.83	6.55	6.81	6.18	6.59	5.49	6.55
	T_5	6.39	6.79	6.86	6.96	6.49	6.72	6.47
	T_6	6.43	6.76	6.83	6.67	6.69	6.38	6.53
	T_7	4.75	5.22	6.58	6.59	5.50	6.48	5.38
	T_8	4.72	5.02	6.44	7.37	5.29	6.41	5.21
	T_9	4.47	4.64	5.86	5.21	5.24	5.66	4.84
	T_{10}	4.71	4.81	6.1	6.87	5.25	5.26	5.11
Mean		**5.12**	**5.60**	**6.17**	**6.23**	**5.70**	**5.74**	**5.50**
EC dS m^{-1}		**1**	**5**	**10**	**15**	**30**	**60**	**90**
	T_1	0.22	0.22	0.22	0.22	0.22	0.21	0.21
	T_2	0.33	0.38	0.34	0.29	0.33	0.32	0.36
	T_3	0.54	0.8	0.43	0.24	0.38	0.37	0.30
	T_4	0.63	0.78	0.46	0.54	0.27	0.41	0.41
	T_5	0.69	0.57	0.42	0.26	0.23	0.35	0.26
	T_6	0.75	0.66	0.42	0.33	0.25	0.37	0.34
	T_7	0.39	0.48	0.35	0.42	0.48	0.32	0.18
	T_8	0.39	0.44	0.43	0.45	0.45	0.37	0.24
	T_9	0.40	0.35	0.39	0.45	0.45	0.31	0.3
	T_{10}	0.31	0.46	0.41	0.47	0.51	0.40	0.19
Mean		**0.47**	**0.51**	**0.39**	**0.37**	**0.36**	**0.34**	**0.8**
ORP mV		**1**	**5**	**10**	**15**	**30**	**60**	**90**
	T_1	367.3	391.0	367.3	357.7	357.7	367.3	366.7
	T_2	367.3	395.7	367.3	357.0	357.0	364.7	363.7
	T_3	-4.3	-53.7	-53.7	-31.7	73.3	82.3	115.0
	T_4	-11.3	-37.0	-51.7	-42.3	59.7	94.3	118.0
	T_5	-2.0	-91.3	-72.0	-48.0	48.7	65.0	117.3
	T_6	-22.3	-94.3	-60.7	-26.3	40.7	43.3	106.7
	T_7	157.7	237.7	39.0	217.7	116.7	118.3	112.2
	T_8	228.3	218.3	-6.0	209.0	121.0	116.8	119.2
	T_9	271.3	232.3	-22.0	218.0	160.7	132.8	134.9
	T_{10}	230.3	206.3	53.0	180.7	159.0	122.5	120.6
Mean		**158.2**	**140.5**	**56.0**	**139.2**	**149.6**	**150.7**	**167.4**

Table.30 Effect of different Si sources on changes in pH, EC and ORP of *Kole* land soil during incubation

Soil property	**Treatment**	**Days of incubation**						
		1	**5**	**10**	**15**	**30**	**60**	**90**
pH	**T_1**	4.32	4.32	4.32	4.32	4.32	4.29	4.55
	T_2	5.16	5.79	5.16	5.16	5.16	5.16	5.00
	T_3	4.93	6.60	6.60	6.47	6.50	6.26	6.09
	T_4	4.72	6.58	6.59	6.25	6.52	6.38	6.63
	T_5	4.62	6.48	6.49	6.45	6.4	6.4	6.33
	T_6	4.97	6.58	6.64	6.27	6.33	5.25	5.56
	T_7	4.75	5.05	6.42	5.20	5.15	6.16	5.36
	T_8	4.81	5.61	6.01	5.33	5.14	5.52	6.64
	T_9	4.57	5.09	5.65	5.22	5.28	6.17	6.65
	T_{10}	4.79	5.24	5.23	5.32	5.27	5.28	5.70
Mean		**4.76**	**5.73**	**5.91**	**5.60**	**5.61**	**5.69**	**5.81**
EC dS m^{-1}		**1**	**5**	**10**	**15**	**30**	**60**	**90**
	T_1	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	T_2	0.32	0.32	0.32	0.32	0.32	0.32	0.32
	T_3	0.59	0.87	0.55	0.43	0.45	0.49	0.52
	T_4	0.68	0.84	0.55	0.3	0.38	0.35	0.56
	T_5	0.52	0.90	0.57	0.35	0.41	0.49	0.53
	T_6	0.54	0.77	0.56	0.45	0.43	0.52	0.53
	T_7	0.49	0.53	0.52	0.5	0.51	0.51	0.59
	T_8	0.25	0.56	0.47	0.47	0.61	0.39	0.48
	T_9	0.27	0.55	0.49	0.46	0.59	0.51	0.44
	T_{10}	0.10	0.64	0.40	0.45	0.57	0.51	0.54
Mean		**0.40**	**0.62**	**0.46**	**0.39**	**0.45**	**0.43**	**0.47**
ORP mV		**1**	**5**	**10**	**15**	**30**	**60**	**90**
	T_1	362.7	386.3	395	345.7	362.7	357.7	362.7
	T_2	360.7	387.0	390.3	349.7	360.7	357.7	360.7
	T_3	-22.0	-62.3	-43.0	20.0	-97.3	-50.3	-65.3
	T_4	-21.7	-74.3	-65.3	4.3	-75.7	-70.3	-68.7
	T_5	-30.0	-70.7	-65.3	-11.3	-68.0	-59.0	-63.0
	T_6	-18.3	-84.0	-58.7	-28.3	-46.0	-43.0	-58.7
	T_7	267.3	88.0	70.3	78.0	170.3	194.0	152.7
	T_8	282.3	122.7	115	128	212.3	210	186.7
	T_9	277.7	157.0	81.3	163.3	227.0	209.7	174.3
	T_{10}	185.3	189.0	131.0	176.0	222.7	177.7	165.7
Mean		**164.4**	**103.9**	**95.1**	**122.5**	**126.9**	**128.4**	**114.7**

In *Pokkali* soil, the highest pH of 4.16 was recorded 15 DAI and the lowest pH of 3.30 was recorded 60 DAI. Among treatments, highest pH was observed in T_3, T_4, T_5 and T_6 during first 15 days of incubation. The EC was found to be highest (3.78 dS m^{-1}) on 5 DAI and the lowest (1.453 dS m^{-1}) on 30 DAI. The ORP was found to be highest (393.99 mV) on first day of incubation and lowest (250.43 mV) was on 10 DAI. ORP was lowest in T_3. The highest ORP was recorded in T_1 and T_2 throughout the incubation period.

In sandy soils of Chalakudi, the pH was recorded as highest (6.40) on first and thenth DAI, while the lowest (5.08) mean pH was recorded on 60 DAI. The EC observed to be highest (0.379 dS m^{-1}) and lowest (0.19 dS m^{-1}) on 5 and 60 DAI, respectively. The ORP was found tobe highest (332.66 mV) on 90 DAI. The lowest (131.16 mV) mean ORP was recorded on first day of incubation.

In lateritic soils of Pattambi, the highest (6.28) pH was recorded on 10 DAI and the lowest (5.472) on 90 DAI. Among treatments, highest pH was observed in T_6 and T_5 throughout the incubation period. The EC was found to be highest (0.411 dS m^{-1}) on 5 DAI and lowest (0.246 dS m^{-1}) was recorded on 30 DAI. The ORP was found to be highest (210.84 mV) on first day of incubation and lowest (88.97 mV) was on 5 DAI. Highest ORP was recorded in T_1 and T_2 throughout incubation period.

The results of second experiment on release of Si in different rice growing soils added with Si fertilizers showed that the release of added Si was highest in *Kole* land soil and lowest in sandy soil. Irrespective of soils, treatment with sodium silicate released more Si into soil solutionfor plant uptake. As it was pot experiment without any crop, it would not give clear information about field condition. In order to get a better idea about release of Si under field condition, a fieldexperiment was conducted with an objective to evaluate the efficacy of different sources of silicon including rice straw in wet land rice ecosystem. Among five rice growing soils, sandy soils of Chalakudy recorded the lowest plant available Si. So the field experiment was conductedat ARS, Chalakudy.

Table.31 Effect of different Si sources on changes in pH, EC and ORP of *Pokkali* soil during incubation

Soil property	**Treatment**	**Days of Incubation**						
		1	**5**	**10**	**15**	**30**	**60**	**90**
pH	**T_1**	3.26	3.26	3.26	3.26	3.26	3.26	3.26
	T_2	3.36	3.59	4.09	4.03	3.36	3.36	3.36
	T_3	3.92	5.67	5.21	5.39	3.42	3.60	3.73
	T_4	3.84	5.34	4.83	4.42	3.34	3.30	3.44
	T_5	3.77	4.27	4.96	4.32	3.27	3.25	3.18
	T_6	3.62	3.63	4.61	4.54	3.27	3.48	3.26
	T_7	3.96	3.49	3.53	3.14	3.17	3.23	3.34
	T_8	3.89	3.57	3.49	3.19	3.21	3.29	3.21
	T_9	3.89	3.58	3.81	3.9	3.85	3.14	3.16
	T_{10}	3.91	3.65	3.83	3.73	3.9	3.12	3.15
Mean		**3.74**	**4.00**	**4.16**	**3.99**	**3.41**	**3.30**	**3.30**
EC dS m^{-1}		**1**	**5**	**10**	**15**	**30**	**60**	**90**
	T_1	1.72	1.72	1.72	1.72	1.72	1.72	1.72
	T_2	2.22	3.02	2.15	2.15	2.15	2.15	2.15
	T_3	3.22	5.50	2.82	1.51	1.07	1.63	2.12
	T_4	3.16	5.31	2.85	1.5	1.33	1.40	1.32
	T_5	4.62	5.23	2.94	1.67	1.54	1.51	1.38
	T_6	3.78	6.07	3.14	1.4	1.61	1.21	1.29
	T_7	3.11	2.82	2.11	1.31	1.18	1.35	1.27
	T_8	2.98	2.75	1.53	1.21	1.14	1.22	1.22
	T_9	3.02	2.61	1.81	1.08	1.23	1.12	1.08
	T_{10}	2.89	2.77	1.84	1.17	1.56	1.29	1.17
Mean		**3.07**	**3.78**	**2.29**	**1.47**	**1.45**	**1.46**	**1.47**
ORP mV		**1**	**5**	**10**	**15**	**30**	**60**	**90**
	T_1	424.3	424.7	388.3	365.3	363.7	424.3	424.3
	T_2	430.3	385.3	376.7	362.3	363	400.3	398.0
	T_3	401.3	144.0	84.70	137.0	171.3	191.0	215.0
	T_4	375.3	117.7	125.0	113.7	222.3	249.3	252.0
	T_5	395.3	147.7	141.3	138.3	176.0	218.7	265.0
	T_6	376.0	160.7	146.3	162.3	185	203.3	240.0
	T_7	392.7	397.0	261.0	258.3	303.7	387.3	476.0
	T_8	386.7	327.3	342.7	314.7	340.3	365.3	409.0
	T_9	372.0	295.3	295.0	332.3	353.0	383.7	403.3
	T_{10}	386.0	256.7	343.3	331.0	384.3	384.3	416.0
Mean		**394.0**	**265.6**	**250.4**	**251.5**	**286.3**	**320.8**	**349.9**

Table.32 Effect of different Si sources on changes in pH, EC and ORP of sandy soil during incubation

Soil property	**Treatment**	**Days of incubation**						
		1	**5**	**10**	**15**	**30**	**60**	**90**
pH	**T_1**	5.36	5.36	5.36	5.36	5.36	5.36	5.36
	T_2	6.20	4.88	6.56	6.11	5.86	5.32	5.27
	T_3	6.56	6.99	6.74	6.07	6.36	4.97	6.16
	T_4	6.55	6.64	6.6	5.74	6.11	5.21	5.76
	T_5	6.33	6.43	6.32	5.42	5.89	5.10	5.25
	T_6	6.47	6.56	6.47	5.45	5.70	5.10	5.67
	T_7	6.33	6.88	6.48	5.64	5.22	5.26	5.36
	T_8	6.66	6.37	6.32	5.52	5.10	4.94	5.31
	T_9	6.63	6.61	6.47	5.62	5.16	4.76	5.31
	T_{10}	6.95	6.55	6.65	5.82	4.38	4.74	5.31
Mean		**6.40**	**6.34**	**6.40**	**5.68**	**5.52**	**5.08**	**5.48**
EC dS m^{-1}		**1**	**5**	**10**	**15**	**30**	**60**	**90**
	T_1	0.07	0.07	0.07	0.07	0.07	0.07	0.05
	T_2	0.15	0.20	0.20	0.20	0.20	0.21	0.20
	T_3	0.48	0.42	0.24	0.25	0.23	0.23	0.12
	T_4	0.54	0.45	0.22	0.15	0.16	0.19	0.11
	T_5	0.60	0.50	0.26	0.33	0.38	0.27	0.20
	T_6	0.51	0.42	0.18	0.28	0.30	0.28	0.24
	T_7	0.25	0.51	0.38	0.31	0.21	0.13	0.16
	T_8	0.29	0.40	0.36	0.35	0.27	0.28	0.21
	T_9	0.27	0.43	0.34	0.40	0.32	0.10	0.14
	T_{10}	0.15	0.39	0.42	0.36	0.40	0.14	0.25
Mean		**0.33**	**0.38**	**0.27**	**0.27**	**0.25**	**0.19**	**0.17**
ORP mV		**1**	**5**	**10**	**15**	**30**	**60**	**90**
	T_1	250.7	404.7	382.7	341.7	321.7	314.0	316.3
	T_2	292.0	358.7	380.3	343.7	325.3	333.0	366.0
	T_3	-45.7	94.7	281.3	306.7	263.7	282.0	583.0
	T_4	-54.0	82.3	245.3	268.3	275.7	279.7	541.3
	T_5	-67.7	85.7	239.0	266.7	294.0	311.0	231.7
	T_6	-77.7	98.0	225.3	258.0	288.3	282.7	305.3
	T_7	175.3	10.7	89.7	245.3	312.7	318.0	242.0
	T_8	269.0	27.7	129.3	262.3	319.3	317.3	165.0
	T_9	285.7	103.0	73.0	271.3	329.7	314.0	246.0
	T_{10}	284.0	153.3	120.3	283.3	353.3	312.0	330.0
Mean		**131.2**	**141.9**	**216.6**	**284.7**	**308.4**	**306.4**	**332.7**

Table.33 Effect of different Si sources on changes in pH, EC and ORP of lateritic soil during incubation

Soil property	Treatment	Days of incubation						
		1	**5**	**10**	**15**	**30**	**60**	**90**
pH	**T_1**	5.07	5.07	5.13	5.07	5.07	5.07	5.07
	T_2	5.24	5.27	6.09	5.30	5.30	5.30	5.31
	T_3	6.00	6.30	6.48	5.59	5.53	6.51	6.00
	T_4	6.21	6.36	6.59	6.06	5.41	6.55	5.31
	T_5	6.19	6.40	6.56	6.30	6.24	6.60	5.65
	T_6	6.44	6.47	6.63	6.21	6.10	6.21	5.04
	T_7	5.84	6.37	6.31	5.80	5.54	6.30	5.63
	T_8	5.85	6.45	6.23	5.83	6.04	6.21	6.33
	T_9	5.87	6.33	6.16	6.02	5.60	6.16	5.06
	T_{10}	5.81	6.41	6.55	6.20	5.90	5.90	5.32
Mean		**5.85**	**6.14**	**6.27**	**5.84**	**5.67**	**6.08**	**5.47**
		1	**5**	**10**	**15**	**30**	**60**	**90**
EC dS m^{-1}	**T_1**	0.08	0.08	0.08	0.08	0.08	0.08	0.08
	T_2	0.18	0.21	0.19	0.18	0.18	0.20	0.18
	T_3	0.37	0.48	0.29	0.34	0.33	0.28	0.36
	T_4	0.47	0.52	0.30	0.31	0.31	0.28	0.32
	T_5	0.35	0.36	0.30	0.24	0.20	0.12	0.16
	T_6	0.44	0.52	0.32	0.29	0.25	0.27	0.29
	T_7	0.36	0.41	0.33	0.31	0.28	0.34	0.32
	T_8	0.36	0.58	0.32	0.3	0.27	0.31	0.34
	T_9	0.35	0.54	0.34	0.3	0.28	0.35	0.37
	T_{10}	0.39	0.41	0.37	0.3	0.28	0.36	0.41
Mean		**0.34**	**0.41**	**0.28**	**0.27**	**0.25**	**0.26**	**0.28**
		1	**5**	**10**	**15**	**30**	**60**	**90**
ORP mV	**T_1**	371.7	387.0	371.7	354.7	359.7	359.7	359.7
	T_2	368.3	367.0	368.3	344.0	353.7	353.7	353.7
	T_3	152.7	-96.0	33.0	84.7	123.0	155.3	172.0
	T_4	172.0	-95.3	28.3	103.3	116.7	148.0	174.7
	T_5	144.7	-65.3	-16.7	86.3	122.7	89.3	161.7
	T_6	148.3	-25.0	-35.0	70.3	106.7	77.7	133.7
	T_7	186.7	99.0	51.7	43.7	122.0	120.7	146.0
	T_8	185.3	113.3	89.0	58.3	129.0	173.0	186.0
	T_9	191.7	94.0	106.3	36.0	93.3	177.0	215.7
	T_{10}	187.0	111.0	108.3	15.0	38.3	156.0	186.0
Mean		**210.8**	**89.0**	**110.5**	**119.6**	**156.5**	**181.0**	**208.9**

Experiment 3

Field study to evaluate the efficacy of different sources of silicon in wetland rice

4.3 Field experiment 1

After incubation study, a field experiment was conducted to study the release of silicon in sandy soil of Chalakudy under wet land rice cultivation. It was conducted at Agronomic Research Station, Chalakudy to evaluate the efficacy of different sources of silicon in wetland rice. The different sources of silicon used in this field experiment were rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate.

4.3.1 Biometric observations

4.3.1.1 No. of Tillers per hill

The number of tillers per hill at tillering, panicle initiation and harvest stages are presented in table.34. The application of different sources of silicon had significant effect on number of tillers at different stages and also showed significant effect on treatments.

At tillering stage, maximum (8.28) number of tillers was observed in T_6 (T_2 + Sodium silicate) and the minimum (5.85) in T_1 (Absolute control). Both T_6 and T_1 differed significantly from all other treatments. The treatments *viz*., T_3 (T_2 + Rice husk ash), T_4 (T_2 + Biodecomposed Rice husk) and T_5 (T_2 + Calcium silicate) were on par followed by T_2 (Fertilizer as per KAU POP).

At panicle initiation stage, the number of tillers in T_2, T_3, T_4, T_5 and T_6 were on par and differed significantly from T_1. The treatment T_6 showed maximum (10.73) number of tillers followed by T_3 and T_5. The minimum (5.86) number of tillers was observed in T_1.

At harvest stage, all treatments except T_1 were on par and T_1 also varied significantly from all other treatments. T_6 showed maximum (7.13) and T_1 showed minimum (4.78) number oftillers at harvest.

4.3.1.2 Plant height

The results pertaining to plant height recorded at tillering, panicle initiation and harvesting stages are given in table.35. The treatments with different sources of Si had significant effect on plant height at tillering, panicle initiation and harvesting stages.

At tillering stage, the plant height was found to ranged from 47.03cm (T_1: Absolute control) to 56.00 cm (T_3: T_2 + Rice husk ash). T_3 was significantly superior to all other treatments. T_4, T_5 and T_6 were on par followed by T_2 and T_1.

At panicle initiation stage, maximum plant height was recorded in T_6 (77.38 cm) and minimum in T_1 (61.50 cm). T_6 and T_5 were significantly superior and on par. T_3, T_4 and T_5 were on par followed by T_6.

At harvesting stage, T_2, T_3, T_4, T_5 and T_6 were on par and significantly varied from T_1. The maximum (91.85 cm) plant height was recorded in T_5 and T_6 and the minimum (79.10 cm) was in T_1.

4.3.1.3. Root weight

The root weight recorded at tillering, panicle initiation and harvest stages are furnished in table.36. The application of different sources of silicon had significant effect on root weight only at panicle initiation stage. However a significant difference existed with respect to the treatments. At tillering stage, maximum (10.57 g) root weight was recorded in T_6 (T_2 + Sodium silicate) and the minimum (6.34 g) was noticed in T_1 (Absolute control).

At panicle initiation stage, treatments had significant effect on root weight. The treatment T_3 was found to be significantly superior (17.78 g) to all other treatments followed by T_5 (13.77 g) > T_6 (13.18 g) = T_2 (13.17 g) > T_4 (11.50 g) >T_1 (7.33 g).

At harvest stage, treatments had no significant effect. T_3 showed maximum (11.19 g) and T_1 showed minimum (6.00 g) root weight at this stage.

Table.34 Effect of different sources of Si on number of tillers of rice at different growth stages

Treatments	**Tillering**	**Panicle initiation**	**Harvest**
T_1(Absolute control)	5.85^c	5.86^b	4.78^b
T_2 (Fertilizer as per KAU POP)	7.33^b	9.80^a	6.70^a
T_3 (T_2 + Rice husk ash)	7.68^{ab}	10.70^a	6.85^a
T_4 (T_2 + Biodecomposed Rice husk)	7.70^{ab}	9.83^a	6.93^a
T_5 (T_2 + Calcium silicate)	7.55^{ab}	10.70^a	6.93^a
T_6 (T_2 + Sodium silicate)	8.28^a	10.73^a	7.13^a
CD(0.05)	0.904	1.184	0.814

Table.35 Effect of different sources of Si on plant height (cm) of rice at different growth stages

Treatments	**Tillering**	**Panicle initiation**	**Harvest**
T_1(Absolute control)	47.03^c	61.50^c	79.10^b
T_2 (Fertilizer as per KAU POP)	52.38^b	71.68^b	89.00^a
T_3 (T_2 + Rice husk ash)	56.00^a	73.26^b	90.65^a
T_4 (T_2 + Biodecomposed Rice husk)	54.03^{ab}	72.73^b	90.35^a
T_5 (T_2 + Calcium silicate)	53.90^{ab}	77.20^a	91.85^a
T_6 (T_2 + Sodium silicate)	54.05^{ab}	77.38^a	91.85^a
CD(0.05)	2.77	3.77	5.04

Table.36 Effect of different sources of Si on root weight (g) of rice at different growth stages

Treatments	Tillering	Panicle initiation	Harvest
T_1(Absolute control)	6.34	7.33^{c}	6.00
T_2 (Fertilizer as per KAU POP)	10.49	13.17^{b}	9.91
T_3 (T_2 + Rice husk ash)	8.33	17.78^{a}	11.19
T_4 (T_2 + Biodecomposed Rice husk)	8.82	11.50^{bc}	9.88
T_5 (T_2 + Calcium silicate)	7.73	13.77^{ab}	10.48
T_6 (T_2 + Sodium silicate)	10.57	13.18^{b}	10.22
CD(0.05)	NS	4.495	NS

Table.37 Effect of different sources of Si on root volume (mL) of rice at different growth stages

Treatments	Tillering	Panicle initiation	Harvest
T_1(Absolute control)	11.50	27.75^{c}	14.17
T_2 (Fertilizer as per KAU POP)	17.75	37.50^{ab}	19.17
T_3 (T_2 + Rice husk ash)	16.00	43.75^{a}	17.50
T_4 (T_2 + Biodecomposed Rice husk)	18.75	31.75^{bc}	17.67
T_5 (T_2 + Calcium silicate)	15.50	35.00^{bc}	16.67
T_6 (T_2 + Sodium silicate)	18.25	35.50^{bc}	17.67
CD(0.05)	NS	8.151	NS

4.3.1.4. Root volume

The root volume recorded at tillering, panicle initiation and harvest stage are presented in table.37. A significant variation in root volume could be noticed at panicle initiation stage.

The maximum (18.75 mL) root volume was recorded in T_4 (T_2 + Biodecomposed Rice husk) and the minimum (11.50 mL) was recorded in T_1 (Absolute control) at tillering stage.

At panicle initiation stage, root weight significantly varied with respect to treatments. The treatment T_3 (43.75 mL) recorded maximum root volume followed by T_2 (37.50 mL). T_4, T_5 and T_6 were on par. The minimum root volume was recorded in T_1 (27.75 mL).

At harvest, there was no significant difference among treatments on root volume. The root volume found to vary from 14.17 mL in T_1 to 19.17 mL in T_2.

4.3.1.5. Number of panicles per hill

The data on the number of panicle per hill is presented in the table.38. There was significant difference between the treatments with respect to the number of panicle per hill. T_5 (7.20) recorded maximum number of panicles per hill and it was significantly superior to all others. T_6 and T_2 followed by T_5 were on par. The minimum (4.85) number of panicles per hill was associated with T_1 (Absolute control).

4.3.1.6. Number of spikelets per panicle

The data on the number of spikelets per panicle is presented in the table.39. The treatments from T_2 to T_6 were on par and significantly differed from T_1 (absolute control), which recorded the minimum (8.15) number of spikelets per panicle. The maximum number of spikelets per panicle was observed in T_2 (8.80).

4.3.1.7. Number of Filled grains per panicle

The data on the number of filled grains per panicle is given in table.40. There was no significant difference between the treatments with respect to the number of filled grains per panicle. The minimum number of filled grains per panicle was noticed in T_1 (64.93) and the maximum in T_2 (82.38).

Table.38 Effect of different sources of Si on number of panicles/hill, no. of spikelets/panicle, no.of filled grains/panicle, no. of unfilled grains/panicles and thousand grain weight of rice at harvest

Treatments	No. of panicles/hill	No. of spikelets/panicle	No.of filled grains/panicle	No. of unfilled grains/panicles	Thousand grain weight (g)
T_1(Absolute control)	4.85^{c}	8.15^{b}	64.93	21.85^{b}	25.55^{bc}
T_2 (Fertilizer as per KAU POP)	6.35^{ab}	8.80^{a}	82.38	16.38^{a}	24.93^{c}
T_3 (T_2 + Rice husk ash)	6.10^{abc}	8.63^{a}	72.75	12.78^{a}	25.88^{bc}
T_4 (T_2 + Biodecomposed Rice husk)	5.76^{bc}	8.73^{a}	78.70	13.28^{a}	27.08^{ab}
T_5 (T_2 + Calcium silicate)	7.20^{a}	8.68^{a}	81.93	15.23^{a}	28.10^{a}
T_6 (T_2 + Sodium silicate)	6.65^{ab}	8.55^{a}	78.90	14.30^{a}	26.08^{bc}
CD(0.05)	1.361	0.389	NS	3.788	2.008

Table.39 Effect of different sources of Si on grain and straw yield (t ha^{-1}) of rice

Treatments	Grain (t ha^{-1})	Straw (t ha^{-1})
T_1(Absolute control)	4.34^{d}	4.04^{b}
T_2 (Fertilizer as per KAU POP)	6.26^{c}	6.55^{a}
T_3 (T_2 + Rice husk ash)	6.38^{bc}	6.83^{a}
T_4 (T_2 + Biodecomposed Rice husk)	6.51^{b}	6.42^{a}
T_5 (T_2 + Calcium silicate)	6.90^{a}	6.75^{a}
T_6 (T_2 + Sodium silicate)	6.54^{b}	6.89^{a}
CD(0.05)	0.22	0.86

4.3.1.8. Number of unfilled grains per panicle

The data on the number of unfilled grains per panicle is presented in table.38. Only T_1 was significantly different from all other treatments with respect to number of unfilled grains per panicles. T_1 recorded the maximum (21.85) number of unfilled grains per panicle and T_3 the minimum (12.78).

4.3.1.9. Thousand grain weight

Data in table.38 showed that the maximum thousand grain weight was recorded in T_4 (28.10g) and it was superior to all the treatments. The minimum thousand grain weight was recorded in T_2 (24.93g).

4.3.1.10. Grain and straw yield

Grain yield and straw yield recorded in t ha^{-1} are presented in table.39. The maximum grain yield of 6.90 t ha^{-1} was recorded in treatment T_5 (T_2 + Calcium silicate) and this was significantly superior to all others. This was followed by T_6 (T_2 + Sodium silicate), T_4 (T_2 + Biodecomposed Rice husk), T_3 (T_2 + Rice husk ash) and T_2 (Fertilizer as per KAU POP). The minimum grain yield of 4.68 t ha^{-1} was recorded in T_1 (Absolute control). The treatments had a significant effect on grain yield.

The maximum straw yield of 6.89 t ha^{-1} was recorded in T_6 and the minimum in T_1 (8.06 t ha^{-1}). The treatments from T_2 to T_6 were on par and were significantly different from T_1.

4.3.1.11 Effect of different sources of Si on Si uptake by grain and straw of rice

Table.40 Effect of different sources of Si on Si uptake by grain and straw of rice

Treatments	Si uptake by Grain (kg ha^{-1})	Si uptake by Straw (kg ha^{-1})
T_1(Absolute control)	89.6^{b}	54.4^{d}
T_2 (Fertilizer as per KAU POP)	115.2^{b}	78.0^{c}
T_3 (T_2 + Rice husk ash)	161.7^{a}	107.5^{b}
T_4 (T_2 + Biodecomposed Rice husk)	161.4^{a}	85.5^{c}
T_5 (T_2 + Calcium silicate)	159.9^{a}	89.6^{c}
T_6 (T_2 + Sodium silicate)	162.4^{a}	194.4^{a}
CD(0.05)	27.39	16.43

Data on the uptake of Si by grain as well as straw and the total uptake are given in table.40. The uptake of Si by grains varied significantly with respect to the treatments. The treatments containing silicon were on par and significantly different from treatments without Si. The Si uptake by grain was highest (162.4 kg ha^{-1}) in T_6 (T_2 + Sodium silicate) and lowest (89.6 kg ha^{-1}) in T_1 (Absolute control).

The treatments showed high significant difference with respect to Si uptake by straw. The Si uptake by straw was maximum (194.4 kg ha^{-1}) in T_6 (T_2 + Sodium silicate) which was on par with T_2, T_3, T_4 and T_5. The absolute control (T_1) showed the minimum (54.4 kg ha^{-1}) Si uptake by straw.

4.3.2. Soil analysis

4.3.2.1. Initial electro-chemical properties of experiment field

The initial electro-chemical properties of soil, collected from experimental field (ARS, Chalakudi), are presented in table.41. The soil was sandy in texture with a sand, silt and clay per cent of 89.2, 5.10 and 5.70 respectively. It was acidic in reaction with a pH of 5.11. The EC was 0.28 d Sm^{-1}. The field soil registered 0.60 per cent of organic carbon. The available N, P and K were 182.33, 159.41and 44.43 kg ha^{-1} respectively. The secondary nutrients *viz.,* available Ca, Mg and S prior to experiment were 63.40, 10.24 and 12.4 mg kg^{-1} respectively. The available micronutrients *viz*. Fe, Cu, Mn, Zn and B were 131.30, 0.76, 0.17, 1.43 and 0.31 mg kg^{-1} respectively. The soil contained 170.70 mg kg^{-1} of Al. The plant available Si prior to experiment was 17.24 kg ha^{-1} (7.7 mg kg^{-1}). The CEC and AEC of soil were 3.93 C mol (+) kg^{-1} and 5.34 C mol (-) kg^{-1} respectively. The silica: sesquioxide ratio of soil was 15.26.

Table.41 Initial Physico-chemical properties of soil of experimental field

Properties	Value
I.Physical properties	
Sand %	89.20
Silt %	5.10
Clay %	5.70
Textural class	Sandy
II. Electro-chemical properties	
pH	5.11
EC (dS m^{-1})	0.28
OC (%)	0.60
CEC (C mol (+) kg^{-1})	3.93
AEC (C mol (-) kg^{-1})	5.34
SiO_2:R_2O_3	15.26
III. Primary nutrients	
Available N (kg ha^{-1})	182.33
Available P (kg ha^{-1})	159.41
Available K (kg ha^{-1})	44.43
IV. Secondary nutrients	
Available Ca (mg kg^{-1})	63.40
Available Mg (mg kg^{-1})	10.24
Available S (mg kg^{-1})	12.40
V. Micronutrients	
Available Fe (mg kg^{-1})	131.60
Available Cu (mg kg^{-1})	0.76
Available Mn (mg kg^{-1})	0.17
Available Zn (mg kg^{-1})	1.43
Available B (mg kg^{-1})	0.31
VI. Beneficial elements	
Available Al (mg kg^{-1})	170.70
Available Si (kg ha^{-1})	17.24

4.3.2.2. Effect of different sources of Si on soil properties at tillering stage

The data on the electrochemical properties and nutrient contents of the soil at tillering stage are presented in table.42.

The application of different sources of Si had significant effect on pH, plant available Si and available Cu at tillering stage. Electrical conductivity, available N, P, K, Ca, Mg, S, Fe, Zn, Mn, B and Al content of the soils of the experimental plots were not significantly influenced by any the treatments at this stage. The content of available P, Ca, S, Zn and Al were found to be lowest in T_4 where biodecomposed rice husk was applied as a Si source. The highest values of available K, Fe, Mn and Zn were recorded in Absolute control (T_1).

The soil pH in different treatments was found to vary from 5.09 (T_1: Absolute control) to 6.10 (T_3). Among the treatment T_3 (T_2 + Rice husk ash) was significantly superior to all other treatments followed by T_6: T_2 + Sodium silicate (6.01), T_4: T_2 + Biodecomposed Rice husk (5.72) and T_2: Fertilizer as per KAU POP (5.75). The treatments, T_4 and T_2 were on par. The lower pH was recorded in T_1: Absolute control which was on par with T_5: T_2 + Calcium silicate (5.31).

Among different treatment with different sources of Si, the highest plant available Si was recorded in T_3: T_2 + Rice husk ash (22.7 kg ha^{-1}) which was significantly superior to all other treatments and was on par with T_6: T_2 + Sodium silicate (21.1 kg ha^{-1}) followed by T_5: T_2 + Calcium silicate (19.9), T_4: T_2 + Biodecomposed Rice husk (16.6 kg ha^{-1}) and T_2: Fertilizer as per KAU POP (15.6 kg ha^{-1}). T_1 (Absolute control) showed the lowest value (12.6 kg ha^{-1}) of Si.

The available N content of soils at tillering stage varied from 166.2 to 205.4 kg ha^{-1}. The available N was highest in T_3: T_2 + Rice husk ash (205.4 kg ha^{-1}) followed by T_5 (197.6 kg ha^{-1}), T_1: Absolute control (194.5 kg ha^{-1}), T_6: T_2 + Sodium silicate (194.4 kg ha^{-1}) and T_2: Fertilizer as per KAU POP (188.1 kg ha^{-1}). The lowest available N content was recorded in T_4: T_2 + Biodecomposed Rice husk (166.2 kg ha^{-1}).

Among different treatments, the highest available P was recorded in T_5: T_2 + Calcium silicate (158.6 kg ha^{-1}) followed by T_2: Fertilizer as per KAU POP (153.9kg ha^{-1}), T_3: T_2 + Rice husk ash (151.9kg ha^{-1}), T_1: Absolute control (151.3kg ha^{-1}) and T_6: T_2 + Sodium silicate (149.3 kg ha^{-1}). The available P status was lowest in T_4: T_2 + Biodecomposed Rice husk (145.8 kg ha^{-1}).

The highest value of available K was registered in T_1: Absolute control (38.9 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (24.1 kg ha^{-1}), T_4: T_2 + Biodecomposed Rice husk (22.4kg ha^{-1}), T_5: T_2 + Calcium silicate (21.8 kg ha^{-1}) and T_6: T_2 + Sodium silicate (20.0 kg ha^{-1}). It was lowest in T_2: Fertilizer as per KAU POP (20.4 kg ha^{-1}).

The highest value for available Ca was recorded in T_6: T_2 + Sodium silicate (237.4 mg kg^{-1}) followed by T_1: Absolute control (204.2 mg kg^{-1}), T_2: Fertilizer as per KAU POP (180.8 mg kg^{-1}), T_3: T_2 + Rice husk ash (165.9 mg kg^{-1}) and T_5: T_2 + Calcium silicate (145.9 mg kg^{-1}). The lowest available Ca content was recorded in T_4: T_2 + Biodecomposed Rice husk (139.7 mg kg^{-1}).

Among different treatments, the available Mg was found highest in T_6: T_2 + Sodium silicate (10.2 mg kg^{-1}) followed by T_3: T_2 + Rice husk ash (9.9 mg kg^{-1}), T_1: Absolute control (9.7 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (9.5 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (8.7 mg kg^{-1}). The lowest value for available Mg was recorded in T_5: T_2 + Calcium silicate (8.6 mg kg^{-1}).

The treatment T_2: Fertilizer as per KAU POP recorded highest (8.3 mg kg^{-1}) available S followed by T_5: T_2 + Calcium silicate (7.2 mg kg^{-1}), T_3: T_2 + Rice husk ash (7.0 mg kg^{-1}), T_6: T_2 + Sodium silicate (6.97 mg kg^{-1}), T_1: Absolute control (6.87 mg kg^{-1}) and it was lowest in T_4: T_2 + Biodecomposed Rice husk (6.70 mg kg^{-1}).

The available Fe was highest in T_1: Absolute control (43.3 mg kg^{-1}) followed by T_5: T_2 + Calcium silicate (41.9 mg kg^{-1}), T_3: T_2 + Rice husk ash (40.4 mg kg^{-1}), T_2: Fertilizer as per KAU POP (37.1 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (33.5 mg kg^{-1}) and T_6: T_2 + Sodium silicate (30.9 mg kg^{-1}).

The available Cu status of soil varied significantly with respect to treatments. Among the treatments, T_6: T_2 + Sodium silicate recorded significantly highest (0.55 mg kg^{-1}) value followed by T_2: Fertilizer as per KAU POP (0.51 mg kg^{-1}) which was on par with T_5: T_2 + Calcium silicate (0.46 mg kg^{-1}) and T_3: T_2 + Rice husk ash (0.46 mg kg^{-1}). The lowest value was recorded in T_4: T_2 + Biodecomposed Rice husk (0.25 mg kg^{-1}).

Among the different treatments, T_1: Absolute control (0.57 mg kg^{-1}) recorded the highest Available Mn followed by T_6: T_2 + Sodium silicate (0.54 mg kg^{-1}), T_3: T_2 + Rice husk ash (0.48 mg kg^{-1}), T_2: Fertilizer as per KAU POP (0.37 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (0.35 mg kg^{-1}). The lowest value of (0.34 mg kg^{-1}) was recorded in T_5 (T_2 + Calcium silicate).

Among different treatments, T_1: Absolute control (1.37 mg kg^{-1}) recorded the highest available Zn followed by T_3: T_2 + Rice husk ash (1.34 mg kg^{-1}), T_2: Fertilizer as per KAU POP (1.34 mg kg^{-1}), T_5: T_2 + Calcium silicate (1.21 mg kg^{-1}) and T_6: T_2 + Sodium silicate (0.54 mg kg^{-1}). The lower value for available Zn was noticed in T_4: T_2 + Biodecomposed Rice husk (1.06 mg kg^{-1}).

The highest values of available boron was estimated in T_6: T_2 + Sodium silicate (0.61 mg kg^{-1}) followed by T_5: T_2 + Calcium silicate (0.60 mg kg^{-1}), T_2: Fertilizer as per KAU POP (0.55 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (0.54 mg kg^{-1}), T_1: Absolute control (0.46 mg kg^{-1}) and T_3: T_2 + Rice husk ash (0.43 mg kg^{-1}).

The available aluminium was found highest in T_6: T_2 + Sodium silicate (128.6 mg kg^{-1}) followed by T_2: Fertilizer as per KAU POP (124.3 mg kg^{-1}), T_3: T_2 + Rice husk ash (119.7 mg kg^{-1}), T_5: T_2 + Calcium silicate (118.7 mg kg^{-1}) and T_1: Absolute control (110.3 mg kg^{-1}) The lower value for available T_4: T_2 + Biodecomposed Rice husk (97.1 mg kg^{-1}).

4.3.2.3. Effect of different sources of Si on soil properties at panicle initiation stage

The results pertaining to the electrochemical properties and nutrient status of soil at panicle initiation stage are presented in table.43. The data showed that pH, available Si and available S alone were significantly influenced by treatments.

Among the treatments, the pH of T_5: T_2 + Calcium silicate (6.11) was significantly superior to all other treatments followed by T_4: T_2 + Biodecomposed Rice husk (5.99), T_3: T_2 + Rice husk ash (5.93), T_2: Fertilizer as per KAU POP (5.73) which was on par with T_6: T_2 + Sodium silicate (5.67). The lower pH was recorded in T_1: Absolute control (5.49).

Table.42 Effect of different sources of Si on soil properties at tillering stage

Treatments	pH	EC	Si	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
		d Sm^{-1}	**kg ha^{-1}**				**mg kg^{-1}**								
T_1 (C)	5.1^{c}	0.04	12.6^{d}	194.5	151.3	38.9	204.2	9.7	6.87	43.3	0.38^{bc}	0.57	1.37	0.46	110.3
T_2(POP)	5.8^{b}	0.07	15.6^{cd}	188.1	153.9	20.4	180.8	8.7	8.32	37.1	0.51^{ab}	0.37	1.34	0.55	124.3
T_3(POP + RHA)	6.1^{a}	0.06	22.7^{a}	205.4	151.9	24.1	165.9	9.9	7.00	40.4	0.46^{ab}	0.48	1.34	0.43	119.7
T_4(POP + BRH)	5.7^{b}	0.05	16.6^{bc}	166.2	145.8	22.4	139.7	9.5	6.70	33.3	0.25^{c}	0.35	1.06	0.54	97.1
T_5(POP + CS)	5.3^{c}	0.06	19.9^{ab}	197.6	158.6	21.8	145.9	8.6	7.20	41.9	0.46^{ab}	0.34	1.21	0.60	118.6
T_6(POP + SS)	6.0^{ab}	0.05	21.1^{a}	194.4	149.3	21.0	237.4	10.2	6.97	30.9	0.55^{a}	0.54	1.18	0.61	128.6
CD(0.05)	0.335	NS	3.837	NS	NS	NS	NS	NS	NS	NS	0.169	NS	NS	NS	NS

Table.43 Effect of different sources of Si on soil properties at panicle initiation stage

Treatments	pH	EC	Si	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
		d Sm^{-1}	**kg ha^{-1}**				**mg kg^{-1}**								
T_1 (C)	5.49^{d}	0.03	14.6^{c}	139.5	132.2	10.9	86.8	6.4	0.98^{d}	38.75	0.56	0.62	1.12	0.27	101.7
T_2(POP)	5.73^{c}	0.04	21.5^{ab}	161.5	147.8	13.2	153.8	5.5	3.83^{abc}	33.45	0.63	0.56	1.04	0.27	102.7
T_3(POP + RHA)	5.93^{b}	0.04	23.9^{a}	142.7	146.9	10.9	177.9	5.3	2.60^{c}	32.95	0.58	0.53	1.00	0.23	99.1
T_4(POP + BRH)	5.99^{ab}	0.04	15.1^{bc}	158.4	149.6	10.6	213.8	5.8	5.18^{a}	33.13	0.61	0.69	0.97	0.26	112.6
T_5(POP + CS)	6.11^{a}	0.04	16.6^{bc}	158.4	146.7	8.4	226.5	5.5	4.33^{ab}	42.53	0.58	0.75	1.00	0.23	108.1
T_6(POP + SS)	5.67^{c}	0.03	26.8^{a}	172.5	157.6	11.2	199.3	6.5	2.88^{ab}	31.93	0.62	0.72	0.99	0.37	107.9
CD(0.05)	0.162	NS	6.752	NS	NS	NS	NS	NS	1.471	NS	NS	NS	NS	NS	NS

The electrical conductivity of soils did not show much variation with regard to treatments.

Among the different sources of Si applied, the highest plant available Si was recorded in T_6: T_2 + Sodium silicate (26.8 kg ha^{-1}) which was on par with T_3: T_2 + Rice husk ash (23.9 kg ha^{-1}) and significantly superior to all other treatments. They were followed by T_2: Fertilizer as per KAU POP (21.5 kg ha^{-1}), T_5: T_2 + Calcium silicate (16.6 kg ha^{-1}), T_4: T_2 + Biodecomposed Rice husk (15.5 kg ha^{-1}). T_5 and T_4 were on par. T_1 (Absolute control) showed lowest value of Si as 14.6 kg ha^{-1}.

The highest available N was estimated in T_6: T_2 + Sodium silicate (172.5 kg ha^{-1})followed by T_2: Fertilizer as per KAU POP (161.5 kg ha^{-1}), T_4: T_2 + Biodecomposed Rice husk, T_5: T_2 + Calcium silicate (158.4 kg ha^{-1}) and T_3: T_2 + Rice husk ash (142.7 kg ha^{-1}). The lowestN content was recorded in T_1: Absolute control (139.5 kg ha^{-1}).

Among different treatments, the highest available P was recorded in T_6: T_2 + Sodium silicate (157.6 kg ha^{-1}) followed by T_4: T_2 + Biodecomposed Rice husk (149.6 kg ha^{-1}), T_2: Fertilizer as per KAU POP (147.8 kg ha^{-1}), T_3: T_2 + Rice husk ash (146.9 kg ha^{-1}), T_5: T_2 + Calcium silicate (146.7 kg ha^{-1}) and T_1: Absolute control (132.2 kg ha^{-1}).

The highest value of available K was estimated in T_2: Fertilizer as per KAU POP (13.2 kg ha^{-1}) followed by T_6: T_2 + Sodium silicate (11.2 kg ha^{-1}), T_1: Absolute control and T_3: T_2 + Rice husk ash (10.9 kg ha^{-1}) and T_4: T_2 + Biodecomposed Rice husk (10.6 kg ha^{-1}). The lowest K content was recorded in T_5: T_2 + Calcium silicate (8.4 kg ha^{-1}).

The highest value of available Ca was recorded in T_5: T_2 + Calcium silicate (226.5 mg kg^{-1}) followed by T_4: T_2 + Biodecomposed Rice husk (213.8 mg kg$^{-1,}$) T_6: T_2 + Sodium silicate (199.3 mg kg^{-1}), T_3: T_2 + Rice husk ash (177.9 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (153.8 mg kg^{-1}). The lowest Ca content was recorded in T_1: Absolute control (86.8 mg kg^{-1}).

Among different treatments, the available Mg was found highest in T_6: T_2 + Sodium silicate (6.5 mg kg^{-1}) followed by T_1: Absolute control (6.4 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (5.8 mg kg^{-1}), T_5: T_2 + Calcium silicate (5.5 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (5.5 mg kg^{-1}). The lowest Mg content was recorded in T_3: T_2 + Rice husk ash (5.3 mg kg^{-1}).

The available Sulphur was recorded highest in T_4: T_2 + Biodecomposed Rice husk (5.18 mg kg^{-1}) and significantly superior which was followed by T_5: T_2 + Calcium silicate (4.32 mg kg^{-1}), T_2: Fertilizer as per KAU POP (3.83 mg kg^{-1}) T_6: T_2 + Sodium silicate (2.88 mg kg^{-1}), T_3: T_2 +Rice husk ash (2.60 mg kg^{-1}) and T_1: Absolute control (0.98 mg kg^{-1}).

The available Fe was highest in T_5: T_2 + Calcium silicate (42.53 mg kg^{-1}) followed by T_1:Absolute control (38.75 mg kg^{-1}), T_2: Fertilizer as per KAU POP (33.45 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (33.13 mg kg^{-1}) and T_3: T_2 + Rice husk ash (32.95 mg kg^{-1}) and T_6:T_2 + Sodium silicate (31.93 mg kg^{-1}).

Among treatments, T_2: Fertilizer as per KAU POP (0.63 mg kg^{-1}) recorded highest value of Cu followed by T_6: T_2 + Sodium silicate (0.61 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (0.61 mg kg^{-1}). They were followed by T_5: T_2 + Calcium silicate (0.58 mg kg^{-1}) and T_3: T_2 +Rice husk ash (0.58 mg kg^{-1}). The lowest value was recorded in T_1: Absolute control (0.56 mg kg^{-1}).

Among different treatments, T_5: T_2 + Calcium silicate (0.75 mg kg^{-1}) recorded highest available Mn followed by T_6: T_2 + Sodium silicate (0.72 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (0.69 mg kg^{-1}), T_1: Absolute control (0.62 mg kg^{-1}) T_2: Fertilizer as per KAU POP (0.56 mgkg^{-1}) and T_3: T_2 + Rice husk ash (0.53 mg kg^{-1}),.

Among different treatments, T_1: Absolute control (1.12 mg kg^{-1}) recorded highest available Zn followed by T_2: Fertilizer as per KAU POP (1.03 mg kg^{-1}), T_3: T_2 + Rice husk ash and T_5: T_2 + Calcium silicate (1.00 mg kg^{-1}) and T_6: T_2 + Sodium silicate (0.99 mg kg^{-1}). The lower Zn value was noticed in T_4: T_2 + Biodecomposed Rice husk (0.97 mg kg^{-1}).

The highest value of available boron was estimated in T_6: T_2 + Sodium silicate (0.37 mg kg^{-1}) followed by T_1: Absolute control (0.27 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (0.27 mg kg^{-1}). T_4: T_2 + Biodecomposed Rice husk recorded a value of 0.26 mg kg^{-1}. The available Bin T_5: T_2 + Calcium silicate and T_3: T_2 + Rice husk ash was 0.23 mg kg^{-1}.

The available aluminium was found highest in T_4: T_2 + Biodecomposed Rice husk(112.56 mg kg^{-1}) followed by T_5: T_2 + Calcium silicate (108.08 mg kg^{-1}), T_6: T_2 + Sodiumsilicate (107.85 mg kg^{-1}), T_2: Fertilizer as per KAU POP (102.73 mg kg^{-1}), T_1: Absolute control (101.73 mg kg^{-1}) and T_3: T_2 + Rice husk ash (99.08 mg kg^{-1}).

Table.44 Effect of different sources of Si on soil properties of soil at Harvest

Treatments	pH	EC dS m^{-1}	OC %	CEC (C mol (+) kg^{-1})	AEC (C mol (-) kg^{-1})	SiO_2:R_2O_3
T_1 (C)	5.69^{b}	0.048^{c}	0.72^{bc}	3.00^{bc}	6.75^{b}	10.60^{d}
T_2(POP)	6.16^{a}	0.058^{bc}	0.63^{c}	2.96^{c}	6.43^{c}	11.32^{b}
T_3(POP + RHA)	6.13^{a}	0.063^{b}	0.65^{c}	3.11^{a}	7.12^{a}	8.62^{f}
T_4(POP + BRH)	6.19^{a}	0.058^{bc}	0.78^{ab}	3.01^{bc}	6.64^{bc}	12.27^{a}
T_5(POP + CS)	6.11^{a}	0.050^{c}	0.86^{a}	3.11^{a}	6.81^{b}	10.06^{e}
T_6(POP + SS)	6.17^{a}	0.080^{a}	0.70^{bc}	3.07^{ab}	6.68^{bc}	10.99^{c}
CD(0.05)	0.106	0.010	0.097	0.075	0.255	0.170

Table.45 Effect of different sources of Si on nutrient content of soil at Harvest

Treatments	Si	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
	kg ha^{-1}				mg kg^{-1}								
T_1 (C)	20.20	269.7	205.9	64.96	129.2^{c}	12.2^{a}	5.66	52.6	0.96	0.24^{b}	1.56^{ab}	0.09^{b}	160.9
T_2(POP)	17.10	257.2	208.5	63.84	328.1^{ab}	10.6^{bc}	4.86	50.5	1.24	0.40^{a}	1.82^{a}	0.09^{b}	188.7
T_3(POP + RHA)	28.10	296.4	225.8	70.56	321.1^{ab}	11.6^{ab}	5.37	58.6	1.20	0.05^{c}	1.66^{a}	0.13^{ab}	195.6
T_4(POP + BRH)	29.38	272.8	225.1	75.32	345.1^{a}	11.2^{ab}	5.04	51.2	1.10	0.04^{c}	1.40^{b}	0.18^{a}	172.7
T_5(POP + CS)	21.73	277.5	222.6	66.08	291.7^{b}	12.6^{a}	6.57	50.1	1.09	0.09^{c}	1.60^{ab}	0.10^{b}	225.3
T_6(POP + SS)	17.45	249.3	205.9	58.24	317.4^{ab}	9.6^{c}	5.63	42.8	1.06	0.06^{c}	1.36^{b}	0.18^{a}	162.2
CD(0.05)	NS	NS	NS	NS	49.330	1.519	NS	NS	NS	0.070	0.260	0.067	NS

4.3.2.4. Effect of different sources of Si on soil properties at harvest stage

The data on electrochemical properties and nutrient status of soil at harvest are presented in table.44 and 45. The pH, EC, CEC, AEC, SiO_2: R_2O_3, available Ca, Mg, Mn, Zn and B were found to be significantly influenced by treatments.

The pH of soils in different treatments showed significant variation. Among the treatments, T_4: T_2 + Biodecomposed Rice husk (6.19) was significantly superior to T_1: Absolute control (5.69) and on par with T_6: T_2 + Sodium silicate (6.07), T_2: Fertilizer as per KAU POP (6.16), T_3: T_2 + Rice husk ash (6.13) and T_5: T_2 + Calcium silicate (6.11).

The EC of soils in different treatments was found to vary significantly. The EC of T_6: T_2 + Sodium silicate (0.08 dS m^{-1}) recorded a significantly higher value followed by T_3: T_2 + Rice husk ash (0.063 dS m^{-1}) and T_4: T_2 + Biodecomposed Rice husk (0.058 dS m^{-1}) which was on par with T_2: Fertilizer as per KAU POP (0.058 dS m^{-1}). The treatment, T_5: T_2 + Calcium silicate (0.050 dS m^{-1}) was on par with T_1: Absolute control (0.048 dS m^{-1}).

The organic carbon content of soil was found highest in T_5: T_2 + Calcium silicate (0.86 per cent) followed by T_4: T_2 + Biodecomposed Rice husk (0.78 per cent), T_1: Absolute control (0.72 per cent) and T_6: T_2 + Sodium silicate (0.70 per cent). The lower values of OC were recorded in T_3: T_2 + Rice husk ash (0.65 per cent) and T_2: Fertilizer as per KAU POP (0.63 per cent). The treatments, T_1 and T_6 and T_3 and T_2 were on par.

The cation exchange capacity of the soil was highest in T_5: T_2 + Calcium silicate (3.11 C mol (+) kg^{-1}) and T_3: T_2 + Rice husk ash (3.11 C mol (+) kg^{-1}) which were significantly superior to all others. T_6: T_2 + Sodium silicate recorded 3.07 C mol (+) $kg^{-1}$of CEC followed by T_4: T_2 + Biodecomposed Rice husk (3.01 C mol (+) kg^{-1}) and T_1: Absolute control (3.01 C mol (+) kg^{-1}). The lower CEC of 2.96 C mol (+) kg^{-1} was recorded in T_2 (Fertilizer as per KAU POP).

The anion exchange capacity of soil was found highest in T_3: T_2 + Rice husk ash (7.12 C mol (-) kg^{-1}) followed by T_5: T_2 + Calcium silicate (6.81 C mol (-) kg^{-1}) and T_1: Absolute control (6.75 C mol (-) kg^{-1}). T_5 was on par with T_2. The AEC of T_6: T_2 + Sodium silicate recorded (6.68 C mol (-) kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (6.64 C mol (-) kg^{-1}) were on par. The lowest AEC was recorded in T_2: Fertilizer as per KAU POP (6.43 C mol (-) kg^{-1}).

Among different treatments, T_4: T_2 + Biodecomposed Rice husk (12.27) recorded highest value of SiO_2:R_2O_3 which was significantly superior over all other treatments and was followed by T_2: Fertilizer as per KAU POP (11.32), T_6: T_2 + Sodium silicate recorded (10.99), T_1: Absolute control (10.60), T_5: T_2 + Calcium silicate (10.06) and T_3: T_2 + Rice husk ash (8.62).

The plant available Si was highest in T_4: T_2 + Biodecomposed Rice husk (29.34 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (28.1 kg ha^{-1}), T_5: T_2 + Calcium silicate (21.73 kg ha^{-1}), T_1: Absolute control (20.20) and T_6: T_2 + Sodium silicate (17.45 kg ha^{-1}). The treatment, T_2:Fertilizer as per KAU POP (17.1 kg ha^{-1}) showed lowest value for PAS.

The available N content of soils in different treatments varied from 166.2 to 205.4 kg ha^{-1}. The highest value was estimated in T_3: T_2 + Rice husk ash (205.4 kg ha^{-1}) followed by T_5 (197.6 kg ha^{-1}), T_1: Absolute control (194.5 kg ha^{-1}), T_6: T_2 + Sodium silicate (194.4 kg ha^{-1}) and T_2: Fertilizer as per KAU POP (188.1 kg ha^{-1}). The lowest N content was recorded in T_4: T_2 + Biodecomposed Rice husk (166.2 kg ha^{-1}).

Among different treatments, the highest available P was recorded in T_3: T_2 + RHA (225.8 kg ha^{-1}) followed by T_4: T_2 + Biodecomposed Rice husk (225.1 kg ha^{-1}), T_5: T_2 + Calcium silicate (222.6 kg ha^{-1}), T_2: Fertilizer as per KAU POP (208.5 kg ha^{-1}), T_6: T_2 + Sodium silicate (205.9 kg ha^{-1}) and T_1: Absolute control (205.9 kg ha^{-1}).

The highest value of available K was estimated in T_4: T_2 + Biodecomposed Rice husk (75.32 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (70.56 kg ha^{-1}), T_5: T_2 + Calcium silicate (66.08 kg ha^{-1}), T_1: Absolute control and T_2: Fertilizer as per KAU POP (63.84 kg ha^{-1}). The lowest K content was observed in T_6: T_2 + Sodium silicate (58.24 kg ha^{-1}).

The highest value of available Ca was recorded in T_4: T_2 + Biodecomposed Rice husk (345.1 mg kg^{-1}) followed by T_2: Fertilizer as per KAU POP (328.1 mg kg^{-1}), T_3: T_2 + Rice husk ash (321.1 mg kg^{-1}) T_6: T_2 + Sodium silicate (317 mg kg^{-1}) and T_5: T_2 + Calcium silicate (91.7 mg kg^{-1}). The lowest Ca content was recorded in T_1: Absolute control (129.2 mg kg^{-1}).

Among the different treatments, available Mg was found highest in T_5: T_2 + Calcium silicate (12.6 mg kg^{-1}) with a significant effect and was on par with T_1: Absolute control (12.18 mg kg^{-1}) followed by T_3: T_2 + Rice husk ash (11.58 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk

(11.18 mg kg^{-1}), and T_2: Fertilizer as per KAU POP (10.60 mg kg^{-1}). The lowest Mg content was recorded in T_6: T_2 + Sodium silicate (9.6 mg kg^{-1}).

The available Sulphur was recorded highest in T_5: T_2 + Calcium silicate (6.57mg kg^{-1}) followed by T_1: Absolute control (5.67 mg kg^{-1}), T_6: T_2 + Sodium silicate (5.63 mg kg^{-1}), T_3: T_2 + Rice husk ash (5.37 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (5.04 mg k g^{-1}) and T_2: Fertilizer as per KAU POP (4.85 mg kg^{-1}).

The available Fe was highest in T_3: T_2 + Rice husk ash (58.55 mg kg^{-1}) followed by T_1: Absolute control (52.63 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (51.15 mg kg^{-1}), T_2: Fertilizer as per KAU POP (50.50 mg kg^{-1}), T_5: T_2 + Calcium silicate (50.13 mg kg^{-1}) and T_6: T_2 + Sodium silicate (42.80 mg kg^{-1}).

Among the treatments, T_2: Fertilizer as per KAU POP (1.24 mg kg^{-1}) recorded the highest value for Cu followed by T_3: T_2 + Rice husk ash (1.20 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (1.10 mg kg^{-1}) and T_6: T_2 + Sodium silicate (1.09 mg kg^{-1}). The lowest value was recorded in T_1: Absolute control (0.96 mg kg^{-1}).

With regard to available Mn, T_2: Fertilizer as per KAU POP (0.40 mg kg^{-1}) recorded the highest value followed by T_1: Absolute control (0.24 mg kg^{-1}), T_5: T_2 + Calcium silicate (0.18 mg kg^{-1}) T_6: T_2 + Sodium silicate (0.06 mg kg^{-1}), T_3: T_2 + Rice husk ash (0.05 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (0.04 mg kg^{-1}).

Value for available Zn was also highest in T_2: Fertilizer as per KAU POP (1.82 mg kg^{-1}) followed by T_3: T_2 + Rice husk ash (1.66 mg kg^{-1}), T_5: T_2 + Calcium silicate (1.60 mg kg^{-1}), T_1: Absolute control (1.56 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (1.40 mg kg^{-1}). The lower Zn value was noticed in T_6: T_2 + Sodium silicate (1.36 mg kg^{-1}).

The available B was found to be varying significantly with respect to treatments. The highest value of available boron was estimated in T_6: T_2 + Sodium silicate (0.18 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (0.18 mg kg^{-1}) followed by T_3: T_2 + Rice husk ash (0.13 mg kg^{-}1) T_5: T_2 + Calcium silicate (0.10 mg kg^{-1}), T_1: Absolute control (0.09 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (0.09 mg kg^{-1}).

The treatment T_5: T_2 + Calcium silicate registered highest (225.3 mg kg^{-1}) value for available Al followed by T_3: T_2 + Rice husk ash (195.6 mg kg^{-1}), T_2: Fertilizer as per KAU POP (188.7 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (172.7 mg kg^{-1}), T_6: T_2 + Sodium silicate (162.2 mg kg^{-1}) and T_1: Absolute control (160.2 mg kg^{-1}).

4.3.3 Plant analysis

4. 3.3.1 Effect of different sources of Si on nutrient content in shoot at tillering stage

The analytical data on nutrient contents in shoot is presented in table.46. The contents of Si, N, P and S in shoot at tillering stage were found to be significantly affected by treatments.

Among the treatments, the Si content was highest in T_4: T_2 + Biodecomposed Rice husk (4.92 per cent) followed by T_5: T_2 + Calcium silicate (4.83 per cent), T_6: T_2 + Sodium silicate (4.62 per cent), T_3: T_2 + Rice husk ash (4.36 per cent), T_2: Fertilizer as per KAU POP (3.82 per cent). The content of Si was lowest in T_1: Absolute control (3.64 per cent).

The nitrogen content in shoot was highest in T_2: Fertilizer as per KAU POP (1.62 per cent) followed by T_4: T_2 + Biodecomposed Rice husk (1.43 per cent), T_5: T_2 + Calcium silicate (1.38 per cent), T_6: T_2 + Sodium silicate (1.30 per cent) and T_3: T_2 + Rice husk ash (1.24 per cent). It was lowest in T_1: Absolute control (1.18 per cent).

The highest P content in shoot was recorded in T_5: T_2 + Calcium silicate (0.26 per cent) which was significantly superior over T_1: Absolute control (0.17 per cent) and on par with T_2: Fertilizer as per KAU POP (0.22 per cent), T_3: T_2 + Rice husk ash (0.23 per cent), T_4: T_2 + Biodecomposed Rice husk (0.22 per cent) and T_6: T_2 + Sodium silicate (0.23 per cent).

The treatment T_5: T_2 + Calcium silicate (1.57 per cent) recorded highest K content in shoot followed by T_3: T_2 + Rice husk ash (1.47 per cent), T_6: T_2 + Sodium silicate (1.43 percent), T_4: T_2 + Biodecomposed Rice husk (1.39 per cent), T_1: Absolute control (1.33 per cent)and T_2: Fertilizer as per KAU POP (1.31 per cent).

The Ca content of shoot was found to be highest in T_5: T_2 + Calcium silicate (0.48 per cent) followed by T_3: T_2 + Rice husk ash (0.44 per cent), T_6: T_2 + Sodium silicate (0.43 per cent),

T_4: T_2 + Biodecomposed Rice husk (0.41 per cent) and T_2: Fertilizer as per KAU POP (0.41 per cent). The lowest calcium content was recorded in T_1: Absolute control (0.38 per cent).

Among the different treatments, the percentage of Mg contained in shoot was found to be highest in T_3: T_2 + Rice husk ash (0.19 per cent) and T_5: T_2 + Calcium silicate (0.19 per cent) followed by T_6: T_2 + Sodium silicate (0.18 per cent) and T_2: Fertilizer as per KAU POP (0.18 per cent). The Mg content in T_4: T_2 + Biodecomposed rice was 0.17 per cent and that of T_1: Absolute control was 0.15 per cent.

The S content of shoot was highest in T_1: Absolute control (0.33 per cent) which was significantly superior over all others. The S content of shoot in all other treatments were on par.

The treatment T_3: T_2 + Rice husk ash (0.075 per cent) recorded highest Fe content in shoot followed by T_4: T_2 + Biodecomposed Rice husk (0.070 per cent) and T_5: T_2 + Calcium silicate (0.071 per cent). The treatment, T_6: T_2 + Sodium silicate recorded a value of 0.066 per cent, whereas it was 0.049 and 0.046 per cent respectively in T_1 and T_2.

The copper content in shoot was found to vary from 0.001 (T_1: Absolute control) to 0.024 (T_5: T_2 + Calcium silicate) per cent. Treatment T_3 (T_2 + RHA) recorded 0.016 per cent of Cu in shoot. In remaining treatments, the percentage of Cu was very less.

The manganese content was highest in T_1: Absolute control (0.027 per cent) followed by T_5: T_2 + Calcium silicate (0.019 per cent), T_3: T_2 + Rice husk ash (0.017 per cent), T_4: T_2 + Biodecomposed Rice husk (0.017 per cent), T_2: Fertilizer as per KAU POP (0.015 per cent) and T_6: T_2 + Sodium silicate (0.014 per cent).

The percentage of Zn content in shoot was varied from 0.004 per cent (T_2: Fertilizer as per KAU POP) to 0.010 per cent (T_1: Absolute control). It was seen that Zn content was very less in shoots.It was observed that the percentage of boron content was also very less in shoots. It was ranged from 0.006 to 0.009 (T_2: Fertilizer as per KAU POP) per cent.

The highest Al content was seen in T_1: Absolute control (0.13 per cent), where as T_2: Fertilizer as per KAU POP recorded a lower (0.08) content of Al. The treatments, T_5 (T_2 + Calcium silicate), T_4 (T_2 + Biodecomposed Rice husk) and T_3 (T_2 + Rice husk ash) contained 0.12 per cent of Al in shoots.

Table.46 Effect of different sources of Si on nutrient content in shoot at tillering stage

Treatments	Si	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
	%												
T_1 (C)	3.64^{c}	1.18^{c}	0.17^{b}	1.33	0.38	0.15	0.33^{a}	0.049	0.001	0.027	0.010	0.006	0.13
T_2(POP)	3.82^{bc}	1.62^{a}	0.22^{a}	1.31	0.41	0.18	0.24^{b}	0.046	0.002	0.015	0.004	0.009	0.08
T_3(POP + RHA)	4.36^{abc}	1.24^{bc}	0.23^{a}	1.47	0.44	0.19	0.21^{b}	0.075	0.016	0.017	0.007	0.007	0.12
T_4(POP + BRH)	4.92^{a}	1.43^{ab}	0.22^{a}	1.39	0.41	0.17	0.19^{b}	0.070	0.002	0.017	0.007	0.007	0.12
T_5(POP + CS)	4.83^{a}	1.38^{bc}	0.26^{a}	1.57	0.48	0.19	0.21^{b}	0.071	0.024	0.019	0.009	0.006	0.12
T_6(POP + SS)	4.62^{ab}	1.30^{bc}	0.23^{a}	1.43	0.43	0.18	0.21^{b}	0.066	0.004	0.014	0.005	0.006	0.11
CD(0.05)	0.915	0.214	0.045	NS	NS	NS	0.064	NS	NS	NS	NS	NS	NS

Table.47 Effect of different sources of Si on nutrient content in shoot at panicle initiation stage

Treatments	Si	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
	%												
T_1 (C)	3.85^{d}	0.45^{d}	0.16^{a}	0.70	0.43^{c}	0.12	0.09^{b}	0.06	0.001	0.04^{a}	0.02	0.005	0.06
T_2(POP)	4.26^{bcd}	0.69^{ab}	0.09^{b}	0.99	0.53^{ab}	0.18	0.21^{a}	0.05	0.001	0.03^{b}	0.02	0.005	0.05
T_3(POP + RHA)	4.52^{bc}	0.74^{a}	0.09^{b}	1.13	0.54^{ab}	0.17	0.11^{b}	0.06	0.001	0.03^{b}	0.02	0.005	0.06
T_4(POP + BRH)	4.64^{ab}	0.58^{c}	0.13^{ab}	0.94	0.48^{bc}	0.16	0.09^{b}	0.06	0.001	0.03^{b}	0.03	0.007	0.07
T_5(POP + CS)	4.15^{cd}	0.62^{bc}	0.13^{ab}	1.21	0.52^{ab}	0.18	0.12^{b}	0.07	0.001	0.03^{b}	0.02	0.005	0.07
T_6(POP + SS)	5.05^{a}	0.66^{abc}	0.10^{b}	1.13	0.55^{a}	0.15	0.11^{b}	0.07	0.001	0.02^{b}	0.02	0.006	0.08
CD(0.05)	0.436	0.099	0.043	NS	0.071	NS	0.068	NS	NS	0.007	NS	NS	NS

4.3.3.2 Effect of different sources of Si on nutrient content in shoot at panicle initiation stage

The results pertaining to the nutrient content in shoot at panicle initiation stage are presented in table.47. The contents of Si, N, P, Ca, S and Mn in shoot at panicle initiation stage were found to be significantly varied with respect to treatments.

Among treatments, the percentage of Si content was highest in T_6: T_2 + Sodium silicate (5.05 per cent) which was significantly superior and followed by T_4: T_2 + Biodecomposed Rice husk (4.64 per cent), T_3: T_2 + Rice husk ash (4.52 per cent), T_2: Fertilizer as per KAU POP (4.26 per cent) and T_5: T_2 + Calcium silicate (4.15 per cent). The Si content was lowest in T_1: Absolute control (3.85 per cent).

The treatments had significant effect on nitrogen content. The nitrogen content in shoot was highest in T_3: T_2 + Rice husk ash (0.74 per cent) followed by T_2: Fertilizer as per KAU POP (0.69 per cent), T_6: T_2 + Sodium silicate (0.66 per cent), T_5: T_2 + Calcium silicate (0.62 per cent) and T_4: T_2 + Biodecomposed Rice husk (0.58 per cent). T_1: Absolute control (0.45 per cent) recorded the lowest N content in shoot.

The content of phosphorous also showed significant difference among treatments. The highest P content in shoot was recorded in T_1: Absolute control (0.16 per cent) followed by T_4: T_2 + Biodecomposed Rice husk (0.13 per cent) which was on par with T_5: T_2 + Calcium silicate (0.13 per cent). T_2: Fertilizer as per KAU POP (0.09 per cent), T_3: T_2 + Rice husk ash (0.09 per cent) and T_6: T_2 + Sodium silicate (0.10 per cent) were also on par.

The potassium content of shoot was highest in T_5: T_2 + Calcium silicate (1.21 per cent) followed by T_3: T_2 + Rice husk ash and T_6: T_2 + Sodium silicate with 1.13 per cent of K. T_2: Fertilizer as per KAU POP, T_4: T_2 + Biodecomposed Rice husk and T_1: Absolute control contained 0.99, 0.94 and 0.70 per cent of K, respectively.

The calcium content was observed to be significantly varied among treatments. The highest content of Ca was seen in T_6: T_2 + Sodium silicate (0.55 per cent) which was superior over all other treatments. T_2, T_4 and T_5 were on par with T_3. The lowest Ca content was recorded in T_1: Absolute control (0.43 per cent).

Among different treatments, the Mg content was highest in T_5: T_2 + Calcium silicate and T_2: Fertilizer as per KAU POP with a value of 0.18 per cent. It was followed by T_3 (T_2 + Rice husk ash), T_4 (T_2 + Biodecomposed Rice husk), T_6 (T_2 + Sodium silicate) and T_1 (Absolute control) with 0.17, 0.16, 0.15 and 0.12 per cent of Mg, respectively.

The highest content of sulphur was observed in T_2: Fertilizer as per KAU POP (0.21 per cent) and significantly superior. All other treatments were on par with respect to S content in shoot.

The iron content in shoot was found highest (0.07 per cent) in T_5 (T_2 + Calcium silicate) and T_6 (T_2 + Sodium silicate) and lowest (0.05 per cent) in T_2 (Fertilizer as per KAU POP). T_1, T_3 and T_4 contained 0.06 per cent of Fe.

The copper content was found to be in not detectable level. There was not much variation in percentage of Zn and B in shoots with respect to treatments.

Among treatments, the percentage of Al in shoot was highest in T_6: T_2 + Sodium silicate (0.08 per cent) followed by T_4 and T_5 with a value of 0.07 per cent. T_1 (Absolute control) and T_3 T_3 (T_2 + Rice husk ash) recorded 0.06 per cent of Al. The lower Al content was seen in T_2: Fertilizer as per KAU POP with a value of 0.05 per cent.

4. 3.3.3 Effect of different sources of Si on nutrient content in rice shoot at harvest stage

The results pertaining to the nutrient content in shoot at harvest stage are presented in table.48. The contents of Si, N and S in shoot at harvest stage were found to be significantly varied with respect to treatments.

Among treatments, the percentage of Si content was highest in T_6: T_2 + Sodium silicate (2.83 per cent) which was significantly superior to all other treatment. It was followed by T_3: T_2 + Rice husk ash (1.58 per cent), T_5: T_2 + Calcium silicate (1.34 per cent), T_4: T_2 + Biodecomposed Rice husk (1.33 per cent) and T_2: Fertilizer as per KAU POP (1.20 per cent). T_4 was on par with T_5. The Si content was lowest in T_1: Absolute control (1.35 per cent).

Table.48 Effect of different sources of Si on nutrient contents in rice shoot at harvest

Treatments	Si	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
	%												
T_1 (C)	1.35^{c}	0.49^{c}	0.05	1.02	0.23	0.08	0.05^{d}	0.07	ND	0.02	0.01	0.003	0.09
T_2(POP)	1.20^{c}	0.58^{ab}	0.07	1.16	0.29	0.09	0.068^{abc}	0.07	ND	0.02	0.01	0.002	0.12
T_3(POP + RHA)	1.58^{b}	0.56^{b}	0.07	1.33	0.30	0.10	0.055^{cd}	0.05	ND	0.02	0.01	0.002	0.08
T_4(POP + BRH)	1.33^{c}	0.61^{a}	0.07	1.26	0.28	0.09	0.075^{ab}	0.06	ND	0.02	0.02	0.002	0.08
T_5(POP + CS)	1.34^{c}	0.62^{a}	0.07	1.36	0.28	0.10	0.081^{a}	0.05	ND	0.02	0.01	0.003	0.08
T_6(POP + SS)	2.83^{a}	0.51^{c}	0.07	1.18	0.26	0.09	0.060^{bcd}	0.05	ND	0.02	0.01	0.002	0.07
CD(0.05)	0.183	0.036	NS	NS	NS	NS	0.02	NS	-	NS	NS	NS	NS

Table.49 Effect of different sources of Si on nutrient contents in rice grain at harvest

Treatments	Si	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
	%												
T_1 (C)	2.07^{bc}	1.07^{d}	0.135^{b}	0.16	0.046	0.080	0.067	0.004	ND	0.004	0.002	0.001	0.007
T_2(POP)	1.84^{c}	1.42^{d}	0.138^{ab}	0.16	0.047	0.074	0.076	0.004	ND	0.003	0.002	0.001	0.008
T_3(POP + RHA)	2.54^{a}	1.26^{b}	0.135^{b}	0.16	0.049	0.072	0.054	0.004	ND	0.003	0.002	0.001	0.006
T_4(POP + BRH)	2.48^{ab}	1.17^{c}	0.153^{a}	0.18	0.053	0.081	0.069	0.004	ND	0.003	0.002	0.001	0.007
T_5(POP + CS)	2.32^{ab}	1.35^{a}	0.130^{b}	0.15	0.054	0.070	0.067	0.003	ND	0.003	0.002	0.002	0.007
T_6(POP + SS)	2.49^{ab}	1.16^{c}	0.150^{a}	0.18	0.049	0.078	0.060	0.004	ND	0.004	0.002	0.002	0.008
CD(0.05)	0.446	0.081	0.015	NS	NS	NS	NS	NS	-	NS	NS	NS	NS

*ND- Not Detectable

The treatments had significant effect on nitrogen content. The nitrogen content in shoot was highest in T_5: T_2 + Calcium silicate (0.62 per cent) and on par with T_4: T_2 + Biodecomposed Rice husk (0.61 per cent) and followed by T_2: Fertilizer as per KAU POP (0.58 per cent), T_3: T_2 + Rice husk ash (0.55 per cent) and T_6: T_2 + Sodium silicate (0.51 per cent). T_1: Absolute control (0.49 per cent) recorded the lowest N content in shoot.

The phosphorous content in all treatment except control was recorded as 0.07 per cent, where as in T_1: Absolute control, it was 0.05 per cent.

The potassium content of shoot was highest in T_5: T_2 + Calcium silicate contained 1.36 per cent of K followed by T_3: T_2 + Rice husk ash (1.33 per cent), T_4: T_2 + Biodecomposed Rice husk (1.26 per cent) T_6: T_2 + Sodium silicate (1.18 per cent), T_2: Fertilizer as per KAU POP (1.17 per cent) and T_1: Absolute control (1.02 per cent).

The highest content of Ca was seen in T_3: T_2 + Rice husk ash (0.30 per cent) followed by T_2, T_4 and T_5 with a Ca content of 0.28 per cent. T_6: T_2 + Sodium silicate and T_1: Absolute control contained 0.26 and 0.23 per cent of Ca, respectively.

Among different treatments, the Mg content was ranged from 0.08 to 0.10 per cent and did not show much variation.

The sulphur content in shoot at harvest stage was found be varied significantly among treatments. The highest content of sulphur was observed in T_5: T_2 + Calcium silicate (0.081) which was significantly superior followed by T_4: T_2 + Biodecomposed Rice husk (0.075 per cent), T_2: Fertilizer as per KAU POP (0.070 per cent), T_6: T_2 + Sodium silicate (0.060 per cent), T_3: T_2 + Rice husk ash (0.055 per cent) and T_1: Absolute control (0.050 per cent).

The iron content in shoot was found highest (0.07 per cent) in T_1 (Absolute control) and T_2 (Fertilizer as per KAU POP) followed by T_4: T_2 + Biodecomposed Rice husk (0.06 per cent). T_4 (T_2 + Biodecomposed Rice husk), T_5 (T_2 + Calcium silicate) and T_6 (T_2 + Sodium silicate) contained 0.05 per cent of Fe.

The manganese, zinc and boron did not show much variation in their percentage of content with respect to treatments. The copper content was below detectable range.

Among treatments, the percentage of Al in shoot was highest in T_2: Fertilizer as per KAU POP with a value of 0.12 per cent followed by T_1: Absolute control (0.09 per cent). The treatments, T_3 to T_5 recorded a value of 0.08 per cent of Al in shoot. The lower value of Al was seen in T_6: T_2 + Sodium silicate (0.07 per cent).

4.3.3.4 Effect of different sources of Si on nutrient content in rice grain at harvest stage

The results pertaining to the nutrient content in grain at harvest stage are presented in table.49. The treatments had significant effect on Si, N and P contents in grain at harvest stage and others remain non-significant.

Among treatments, the percentage of Si content was highest in T_3: T_2 + Rice husk ash (2.54 per cent) which was significantly superior to all other treatment. It was followed by T_6: T_2 + Sodium silicate (2.49 per cent) which was on par with T_4: T_2 + Biodecomposed Rice husk (2.48 per cent) and T_5: T_2 + Calcium silicate (2.32 per cent). T_1 (Absolute control) recorded 2.07 per cent of Sin in grain. The Si content was lowest in T_2: Fertilizer as per KAU POP (1.84 per cent).

Among treatments, the percentage of N was highest in T_5: T_2 + Calcium silicate (1.35 per cent) which was significantly varied from all other treatment. It was followed by T_3: T_2 + Rice husk ash (1.26 per cent), T_4: T_2 + Biodecomposed Rice husk (1.17 per cent), T_6: T_2 + Sodium silicate (1.16 per cent), T_2: Fertilizer as per KAU POP (1.42 per cent) and T_1: Absolute control (1.07 per cent). T_2 was on par with T_1.

Among treatments, the percentage of P was highest in T_4: T_2 + Biodecomposed Rice husk (0.153 per cent) and T_6: T_2 + Sodium silicate (0.150 per cent) and significantly varied from other treatments. T_2: Fertilizer as per KAU POP contained 0.138 per cent of P. T_5: T_2 + Calcium silicate (0.130 per cent) was on par with T_3: T_2 + Rice husk ash (0.135 per cent) and T_1: Absolutecontrol (0.135 per cent).

The potassium content was highest in T_6: T_2 + Sodium silicate and T_4: T_2 + Biodecomposed Rice husk with value of 0.18 per cent followed by T_3, T_2 and T_1 with a value of 0.16 per cent.

The highest content of Ca was seen in T_5: T_2 + Calcium silicate (0.054 per cent) followed by T_4: T_2 + Biodecomposed Rice husk (0.053 per cent) and T_3: T_2 + Rice husk ash and T_6: T_2 + Sodium silicate with 0.30 per cent. The lowest Ca content was estimated in T_1: Absolute control (0.029 per cent).

Among treatments, Mg content was recorded as highest in T_4: T_2 + Biodecomposed Rice husk and T_1: Absolute control with a value of 0.08 per cent. It was followed by T_6: T_2 + Sodium silicate (0.078 per cent), T_2: Fertilizer as per KAU POP (0.074 per cent), T_3: T_2 + Rice husk ash (0.072 per cent) and T_5: T_2 + Calcium silicate (0.070 per cent).

Among treatments, S content was highest in T_2: Fertilizer as per KAU POP (0.076 per cent) followed by T_4: T_2 + Biodecomposed Rice husk (0.069 per cent), T_5: T_2 + Calcium silicate and T_1: Absolute control with 0.067 per cent and T_6: T_2 + Sodium silicate (0.06 per cent). The lower value of S was recorded in T_3: T_2 + Rice husk ash (0.054 per cent).

The micronutrients *viz.*, manganese, zinc boron and aluminium did not show much variation in their percentage of content with respect to treatments. The copper content was below detectable range.

4.3.3.5 Effect of different sources of Si on electrolyte leakage in leaf of rice at different growth stages

The data on effect of treatments on electrolyte leakage in leaf of rice plant at different growth stages were presented in table.50. At 45 and 60 days after transplanting (DAT), treatments had no significant effect on electrolyte leakage (EL), but at 90 DAT, EL varied significantly with respect to treatments.

At 45 DAT, EL was found to be highest in T_6: T_2 + Sodium silicate (23.8 per cent) followed by T_4: T_2 + Biodecomposed Rice husk (23.3 per cent), T_5: T_2 + Calcium silicate (22.5 per cent), T_2: Fertilizer as per KAU POP (21.3 per cent) and T_3: T_2 + Rice husk ash (21.3 per cent). EL was lowest in T_1: Absolute control (20.4 per cent).

At 60 DAT, the highest value of EL was recorded in T_3: T_2 + Rice husk ash (70.5 per cent) followed by T_4: T_2 + Biodecomposed Rice husk (66.8 per cent), T_6: T_2 + Sodium silicate

(65.6 per cent), T_2: Fertilizer as per KAU POP (59.4 per cent) and T_1: Absolute control (50.7 per cent). EL was found to be lower in T_5: T_2 + Calcium silicate (50.1 per cent).

At 90 DAT, EL was significantly varied over treatments. The highest EL was recorded in T_3: T_2 + Rice husk ash (54.5 per cent) followed by T_2: Fertilizer as per KAU POP (49.7 per cent), T_6: T_2 + Sodium silicate (48.1 per cent), T_4: T_2 + Biodecomposed Rice husk (47.2 percent). T_6 and T_4 were on par. The lower value of EL was seen in T_5: T_2 + Calcium silicate (43.3 per cent) and T_1: Absolute control (43.2 per cent) and both were on par.

4.3.3.6 Effect of different sources of Si on catalase activity (µmole $H_2O_2min^{-1}g^{-1}$) in leaf of rice at different growth stages

The data on effect of treatments on catalase activity, the enzyme that in leaf of rice plant at different growth stages are presented in table.51. At 45 and 60 days after transplanting (DAT), treatments had significant effect on catalase activity. But it was non significant effect at 90 DAT.

At 45 DAT, calase activity was found to be highest in T_1: Absolute control (16.8 µmole $H_2O_2min^{-1}g^{-1}$) followed by T_4: T_2 + Biodecomposed Rice husk (16.2 µmole $H_2O_2min^{-1}g^{-1}$), T_6: T_2 + Sodium silicate (15.3 µmole $H_2O_2min^{-1}g^{-1}$), T_2: Fertilizer as per KAU POP (13.4 µmole

Table.50 Effect of different sources of Si on electrolyte leakage (%) in rice leaf at different growth stages

Treatments	Electrolyte Leakage (%)		
	45 DAT	**60 DAT**	**90 DAT**
T_1 (C)	20.4	50.7	43.2^{c}
T_2(POP)	21.3	59.4	49.7^{ab}
T_3(POP + RHA)	21.3	70.5	54.5^{a}
T_4(POP + BRH)	23.3	66.8	47.2^{bc}
T_5(POP + CS)	22.5	50.1	43.3^{c}
T_6(POP + SS)	23.8	65.6	48.1^{bc}
CD(0.05)	NS	NS	5.251

Table.51 Effect of different sources of Si on catalase activity in rice leaf at different growth stages

Treatments	Catalase activity (µmole H_2O_2min^{-1}g^{-1})		
	45 DAT	**60 DAT**	**90 DAT**
T_1 (C)	16.8^{a}	62.5^{a}	19.5
T_2(POP)	13.4^{c}	51.9^{b}	19.3
T_3(POP + RHA)	12.6^{cd}	44.5^{c}	17.4
T_4(POP + BRH)	16.2^{ab}	62.3^{a}	18.8
T_5(POP + CS)	11.4^{d}	40.7^{c}	19.8
T_6(POP + SS)	15.3^{b}	61.9^{a}	19.8
CD(0.05)	1.456	4.196	NS

Table.52 Effect of different sources of Si on peroxidase activity in rice leaf at different growth stages

Treatments	Peroxidase activity (µmole H_2O_2min^{-1}g^{-1})		
	45 DAT	**60 DAT**	**90 DAT**
T_1 (C)	4.5^{e}	22.1^{e}	44.4^{c}
T_2(POP)	3.2^{f}	24.8^{e}	63.9^{bc}
T_3(POP + RHA)	5.9^{c}	56.1^{a}	129.6^{a}
T_4(POP + BRH)	7.1^{b}	48.7^{b}	121.1^{a}
T_5(POP + CS)	5.2^{d}	35.8^{d}	102.4^{ab}
T_6(POP + SS)	15.9^{a}	44.6^{c}	93.9^{abc}
CD(0.05)	0.560	3.031	54.667

$H_2O_2min^{-1}g^{-1}$) and T_3: T_2 + Rice husk ash (12.6 µmole $H_2O_2min^{-1}g^{-1}$). Catalase activity was lowest in T_5: T_2 + Calcium silicate (11.4 µmole $H_2O_2min^{-1}g^{-1}$).

At 60 DAT, the highest value of catalase activity was recorded in T_1: Absolute control (62.5 µmole $H_2O_2min^{-1}g^{-1}$) followed by T_4: T_2 + Biodecomposed Rice husk (62.3 µmole $H_2O_2min^{-1}g^{-1}$) and T_6: T_2 + Sodium silicate (61.9 µmole $H_2O_2min^{-1}g^{-1}$). T_1 was on par with T_4 and T_6. T_2: Fertilizer as per KAU POP recorded 51.9 µmole $H_2O_2min^{-1}g^{-1}$ of catalase activity.T_3: T_2 + Rice husk ash (44.5 µmole $H_2O_2min^{-1}g^{-1}$) and T_5: T_2 + Calcium silicate (40.7 µmole $H_2O_2min^{-1}g^{-1}$) were on par.

At 90 DAT, the highest value of catalase activity was recorded in T_6: T_2 + Sodium silicate (19.8 µmole $H_2O_2min^{-1}g^{-1}$) and T_5: T_2 + Calcium silicate (19.8 µmole $H_2O_2min^{-1}g^{-1}$) followed by T_1: Absolute control (19.5 µmole $H_2O_2min^{-1}g^{-1}$), T_2: Fertilizer as per KAU POP(19.3 µmole $H_2O_2min^{-1}g^{-1}$) and T_4: T_2 + Biodecomposed Rice husk (18.8 µmole $H_2O_2min^{-1}g^{-1}$) and. The lowest catalase activity was recorded in T_3: T_2 + Rice husk ash (17.4 µmole $H_2O_2min^{-1}g^{-1}$).

4.3.3.7 Effect of different sources of Si on peroxidase activity (µmole $H_2O_2min^{-1}g^{-1}$) in leaf of rice at different growth stages

The results pertaining to the effect of treatments on peroxidase activity in rice leaf at different growth stages are furnished in table.52. The treatments had significant effect on peroxidase activity at 45, 60 and 90 DAT.

At 45 DAT, peroxidase activity was found highest in T_6: T_2 + Sodium silicate (15.9 µmole $H_2O_2min^{-1}g^{-1}$) which was significantly superior over all other treatments. It was followed by T_4: T_2 + Biodecomposed Rice husk (7.1 µmole $H_2O_2min^{-1}g^{-1}$), T_3: T_2 + Rice husk ash (5.9 µmole $H_2O_2min^{-1}g^{-1}$), T_5: T_2 + Calcium silicate (5.2 µmole $H_2O_2min^{-1}g^{-1}$) and T_1: Absolute control (4.5 µmole $H_2O_2min^{-1}g^{-1}$). T_2: Fertilizer as per KAU POP (3.2 µmole $H_2O_2min^{-1}g^{-1}$) recorded the lowest peroxidase activity.

At 60 DAT, peroxidase activity was found highest in T_3: T_2 + Rice husk ash (56.1 µmole $H_2O_2min^{-1}g^{-1}$) which was significantly superior over all other treatments. It was followed by T_4: T_2 + Biodecomposed Rice husk (48.7 µmole $H_2O_2min^{-1}g^{-1}$), T_6: T_2 + Sodium silicate (44.6 µmole

$H_2O_2min^{-1}g^{-1}$), T_5: T_2 + Calcium silicate (35.8 µmole $H_2O_2min^{-1}g^{-1}$) and T_2: Fertilizer as per KAU POP (24.8 µmole $H_2O_2min^{-1}g^{-1}$). Peroxidase activity was lowest in T_1: Absolute control (22.1 µmole $H_2O_2min^{-1}g^{-1}$).

At 90 DAT, peroxidase activity was found highest in T_3: T_2 + Rice husk ash (129.6 µmole $H_2O_2min^{-1}g^{-1}$) which was significantly superior and on par with T_4: T_2 + Biodecomposed Rice husk (121.1 µmole $H_2O_2min^{-1}g^{-1}$). It was followed by T_5: T_2 + Calcium silicate (102.4 µmole $H_2O_2min^{-1}g^{-1}$), T_6: T_2 + Sodium silicate (93.9 µmole $H_2O_2min^{-1}g^{-1}$) and T_2: Fertilizer as per KAU POP (63.9 µmole $H_2O_2min^{-1}g^{-1}$). The lowest value of 44.4 µmole $H_2O_2min^{-1}g^{-1}$ was associated with T_1: Absolute control for peroxidase activity.

Rice straw is a rich source of Si. The incorporation of rice straw into soil after harvest of crop may be a low cost method to increase the availability of Si to soil solution and thereby decreasing depletion of Si from leading to accumulation on above ground plant part. With this view, further study was conducted to know the residual effect of rice straw incorporation on growth and yield of succeeding rice crop.

Residual effect of rice straw incorporation on growth and yield of succeeding crop of rice

Field experiment 2

After first field experiment, the straw obtained from each plot under particular treatment was cut into small pieces and incorporated into the same plot. No fertilizers or manures were applied additionally. Observations of biometric characters and analysis of soil and plant samples were carried out as done for the first field experiment.

4.3.4 Biometric observations

4.3.4.1 No. of Tillers per hill

The number of tillers per hill at tillering, panicle initiation and harvest stages are presented in table.53. The application of different sources of silicon to the first crop had no significant effect on number of tillers at any stages, though it varied significantly with respect to the treatments.

At tillering stage, maximum (5.23) number of tillers was observed in T_5 (T_2 + Calcium silicate) followed by T_6 (T_2 + Sodium silicate) and T_2 (Fertilizer as per KAU POP) with a value of 4.70. T_3 (T_2 + Rice husk ash) and T_1 (Absolute control) recorded 4.68 no.of tillers. The minimum (4.65) number of tillers was noticed in T_4 (T_2 + Biodecomposed Rice husk).

At panicle initiation stage, T_5 (T_2 + Calcium silicate) showed maximum (5.43) number of tillers followed by T_2: Fertilizer as per KAU POP (5.12). The lowest no. of tillers was observed in T_1: Absolute control (5.00).

At harvest stage, tiller count was maximum (4.80) in T_5 (T_2 + Calcium silicate) and T_2: Fertilizer as per KAU POP and minimum (4.48) in T_3 (T_2 + Rice husk ash).

4.3.4.2 Plant height

The results on plant height, recorded at tillering, panicle initiation and harvesting stages presented in table.53. Here also no significant effect could be seen on plant height consequent to application of Si to the previous crop.

At tillering stage, the plant height was found to ranged from 31.4 cm (T_4: T_2 + Biodecomposed Rice husk and T_2: Fertilizer as per KAU POP to 32.1 cm (T_5: T_2 + Calcium silicate).

At panicle initiation stage, maximum plant height was recorded in T_6: T_2 + Sodium silicate (49.6 cm) and minimum in T_1: Absolute control (44.4 cm).

At harvesting stage, the maximum (55.9 cm) plant height was registered in T_6: T_2 + Sodium silicate and the minimum (52.0cm) in T_1: Absolute control. With regard to plant heightat harvest stage, T_6 was followed by T_3: T_2 + Rice husk ash (54.8 cm), T_4: T_2 + Biodecomposed Rice husk (53.8), T_5: T_2 + Calcium silicate (53.1) and T_2: Fertilizer as per KAU POP (52.5).

4.3.4.3. Root weight

The root weight recorded at tillering, panicle initiation and harvest stages are provided in table.54. The application of different sources of silicon to the previous crop had no significant effect on root weight of succeeding crop.

At tillering stage, the maximum (1.05 g) root weight was recorded in T_6 (T_2 + Sodium silicate) and the minimum (0.89 g) was noticed in $T_{2:}$ Fertilizer as per KAU POP.

At panicle initiation stage, the treatment T_4: T_2 + Biodecomposed Rice husk (1.50 g) recorded highest root weight followed by T_1: Absolute control (1.40 g), T_6: T_2 + Sodium silicate and minimum (1.11 g), $T_{2:}$ Fertilizer as per KAU POP (1.09 g) and T_3 (0.96 g). The lowest root weight was recorded by T_5: T_2 + Calcium silicate (0.90 g).

At harvest stage, T_5 showed the maximum (1.18 g) and T_3 showed the minimum (0.83 g) root.

4.3.4.4. Root volume

The root volume recorded at tillering, panicle initiation and harvest stage are shown in table.54. The maximum (3.38 mL) root volume was recorded in T_6: T_2 + Sodium silicate and minimum (2.75 mL) was recorded in T_1 (Absolute control) at tillering stage.

At panicle initiation stage, the treatment T_1 (4.69 mL) recorded maximum root volume followed by T_2 (4.06 mL). The minimum root volume was recorded in T_4 (3.19 mL).

At harvest, the root volume found highest in T_5: T_2 + Calcium silicate (3.63), followed by T_6: T_2 + Sodium silicate and minimum (3.45 mL), T_2 (3.38 mL), T_3 (3.20 mL) and T_4 (2.95). The lowest root volume was recorded in T_1 (2.68). Statistical significance was not there on root volume at any of the stage.

4.3.4.5. Number of panicles per hill

The data on the number of panicle per hill is presented in table.55. There was significant difference between the treatments with respect to the number of panicle per hill. T_5 (5.90) recorded maximum number of panicles per hill and it was significantly superior to all other treatments and followed by T_4 (5.38), T_3 (4.46). T_6 and T_2 were on par. The minimum (4.05) number of panicle per hill was recorded in T_1.

4.3.4.6. Number of spikelets per panicle

The data on the number of spikelets per panicle is presented in the table.55. The treatments from T_3 to T_6 were on par and significantly differ from T_1. The maximum number of spikelets per panicle was observed in T_5 (8.43) followed by T_4 (8.25), T_3 (7.00), T_2 (6.38) and T_6 (6.33). The minimum no. of spikelet was recorded in T_1 (5.00).

4.3.4.7. Number of filled grains per panicle

The data on the number of filled grains per panicle is given in the table.55. The treatments had significant effect on number of filled grains per panicle. The minimum number offilled grains per panicle was registered in T_3 (30.75) and the maximum was in T_5 (61.25). T_5 was significantly superior and on par with T_6 (61.00) which was followed by T_2 (52.25), T_4 (48.00) and T_1 (43.50).

4.3.4.8. Number of unfilled grains per panicle

The maximum number of unfilled grains per panicle was recorded in T_1 (17.50), followed by T_3 (17.00), T_6 (16.50) and T_2 (15.50). The minimum number was noticed in T_4 (14.25) (table.55).

4.3.4.9. Thousand grain weight

The data (table.55) showed that the maximum thousand grain weight was recorded in T_6 (22.21 g) followed by T_1, T_5, T_2 and T_3. The minimum thousand grain weight was observed in T_4 (22.03 g).

4.3.4.10. Residual effect of rice straw incorporation on Grain and straw yield

Grain yield and straw yield recorded in t ha^{-1} are presented in table.56. The maximum grain yield of 1.78 t ha^{-1} was recorded in treatment T_6 (T_2 + sodium silicate) followed by T_4: T_2 + Biodecomposed Rice husk (1.68 t ha^{-1}), T_3: T_2 + Rice husk ash (1.66 t ha^{-1}), T_5: T_2 + Calcium silicate (1.40 t ha^{-1}) and T_1: Absolute control (1.39 t ha^{-1}).The minimum of 1.35 t ha^{-1} was recorded in T_2.

The maximum straw yield of 2.41t ha^{-1} was recorded in T_4 followed by T_3, T_6, T_1, and T_2, while the minimum was recorded in T_5 (1.86 t ha^{-1}).

4.3.4.11 Residual effect of rice straw incorporation on Si uptake by grain and straw of rice

Data on the uptake of Si by grain as well as straw and the total uptake are given in table.57. The Si uptake by grain was highest (5.11 t ha^{-1}) in T_6 (T_2 + Sodium silicate) followedby T_4: T_2 + Biodecomposed Rice husk (4.95 t ha^{-1}), T_3: T_2 + Rice husk ash (4.72 t ha^{-1}), T_5: T_2 + Calcium silicate (4.06 t ha^{-1}) and lowest (3.46 t ha^{-1}) in T_2.

The treatments showed high significant difference with respect to Si uptake by straw. The uptake of Si by straw was maximum (2.60 t ha^{-1}) in T_3 which was superior and on par with T_5: T_2 + Calcium silicate (2.42 t ha^{-1}). It was followed by T_6: T_2 + Sodium silicate (2.17), T_4: T_2 + Biodecomposed Rice husk (2.14t ha^{-1}) and T_1: Absolute control (1.11t ha^{-1}). The minimum (0.95 t ha^{-1}) uptake of Si was associated with T_2: Fertilizer as per KAU POP.

The total uptake of Si by rice plant was highest in T_3 with an uptake of 7.32 t Si ha^{-1}. The lowest total Si uptake was found as 4.41 t ha^{-1} in T_2.

Table.53 Residual effect of rice straw incorporation on no.of tillers and plant height of rice

Treatments	Number of tillers			Plant height (cm)		
	Tillering	Panicle initiation	Harvest	Tillering	Panicle initiation	Harvest
T_1 (C)	4.68	5.00	4.70	31.6	44.4	52.0
T_2(POP)	4.70	5.12	4.48	31.4	46.1	52.5
T_3(POP + RHA)	4.68	5.03	4.48	32.3	47.6	54.8
T_4(POP + BRH)	4.65	5.05	4.75	31.4	45.5	53.8
T_5(POP + CS)	5.23	5.43	4.80	32.1	47.6	53.1
T_6(POP + SS)	4.70	5.03	4.65	32.0	49.6	55.9
CD(0.05)	NS	NS	NS	NS	NS	NS

Table.54 Residual effect of rice straw incorporation on root weight (g) and root volume (mL) of rice

Treatments	Root weight (g)			Root volume (ml)		
	Tillering	Panicle initiation	Harvest	Tillering	Panicle initiation	Harvest
T_1 (C)	1.01	1.40	0.94	2.75	4.69	2.68
T_2(POP)	0.89	1.09	0.99	3.13	4.06	3.38
T_3(POP + RHA)	1.01	0.96	0.84	3.00	3.25	3.20
T_4(POP + BRH)	0.90	1.50	0.97	2.88	3.19	2.95
T_5(POP + CS)	0.98	0.90	1.18	2.88	4.13	3.63
T_6(POP + SS)	1.05	1.11	0.95	3.38	3.75	3.45
CD(0.05)	NS	NS	NS	NS	NS	NS

Table.55 Residual effect of rice straw incorporation on number of panicles/hill, no. of spikelets/panicle, no.of filled grains/panicle, no. of unfilled grains/panicles and thousand grainweight of rice

Treatments	No. of panicles/ hill	No. of spikelets/ panicle	No.of filled grains/ panicle	No. of unfilled grains/ panicles	Thousand grain weight (g)
T_1 (C)	4.05^{c}	5.00^{a}	43.50^{bc}	17.50	21.95
T_2(POP)	3.90^{c}	6.38^{b}	52.25^{ab}	15.50	21.65
T_3(POP + RHA)	4.46^{bc}	7.00^{b}	30.75^{c}	17.00	22.08
T_4(POP + BRH)	5.38^{ab}	8.25^{b}	48.00^{ab}	13.50	22.03
T_5(POP + CS)	5.90^{a}	8.43^{b}	61.25^{a}	14.25	21.87
T_6(POP + SS)	3.90^{c}	6.33^{b}	61.00^{a}	16.50	22.21
CD(0.05)	1.001	0.964	16.205	NS	NS

Table.56 Residual effect of rice straw incorporation on grain and straw yield (t ha^{-1}) of rice

Treatments	**Grain (t ha^{-1})**	**Straw (t ha^{-1})**
T_1 (C)	1.39	2.01
T_2(POP)	1.35	2.00
T_3(POP + RHA)	1.66	2.37
T_4(POP + BRH)	1.68	2.41
T_5(POP + CS)	1.40	1.86
T_6(POP + SS)	1.78	2.07
CD(0.05)	NS	NS

Table.57 Residual effect of rice straw incorporation on Si uptake by grain and straw of rice

Treatments	**Grain**	**Straw**	**Total uptake**
	kg ha^{-1}		
T_1 (C)	35.5	11.1^{bc}	46.6
T_2 (POP)	34.6	9.5^{c}	44.1
T_3 (POP + RHA)	47.2	26.0^{a}	73.2
T_4 (POP + BRH)	49.6	21.4^{abc}	70.9
T_5 (POP + CS)	40.63	24.2^{a}	64.8
T_6 (POP + SS)	51.1	21.7^{ab}	72.8
CD(0.05)	NS	1.194	NS

4.3.5. Soil analysis

4.3.5.1. Residual effect of rice straw incorporation on soil properties before transplanting

The data on soil properties before transplanting are presented in table.58 and table.59. The application of different sources of Si to the first crop had significant effect on available, Si, Ca, CEC, AEC and SiO_2:R_2O_3.

The pH of soils in different treatments was found to vary from 5.22 (T_1: Absolute control) to 5.66 (T_4: T_2 + Biodecomposed Rice husk). T_4 was followed by T_6: T_2 + Sodium silicate (5.52) and T_5: T_2 + Calcium silicate (5.51), T_3: T_2 + Rice husk ash (5.48) and T_4 (5.72) and T_2: Fertilizer as per KAU POP (5.75).

The EC of T_3: T_2 + Rice husk ash (0.07 dS m^{-1}) and T_4: T_2 + Biodecomposed Rice husk (0.07 dS m^{-1}) recorded higher value followed by T_6: T_2 + Sodium silicate (0.06 dS m^{-1}), T_5: T_2 + Calcium silicate (0.06 dS m^{-1}) and T_2: Fertilizer as per KAU POP (0.06 dS m^{-1}). The lowest EC was noticed in T_1: Absolute control (0.05 dS m^{-1}).

The treatments had significant effect on organic carbon content in soil before transplanting of rice. It was found highest in T_5: T_2 + Calcium silicate (0.97 per cent) and it varied significantly from other treatments. It was followed by T_3: T_2 + Rice husk ash (0.80 per cent), T_4: T_2 + Biodecomposed Rice husk (0.74 per cent), T_1: Absolute control (0.72 per cent),T_2: Fertilizer as per KAU POP (0.61 per cent) and T_6: T_2 + Sodium silicate (0.70 per cent). T_3 was on par with T_4. T_1 was on par with T_6 and T_2.

The cation exchange capacity of the soil was highest in T_5: T_2 + Calcium silicate (3.11 C mol (+) kg^{-1}) and T_3: T_2 + Rice husk ash (3.11 C mol (+) kg^{-1}) which were significantly superior with respect to other treatments. T_6: T_2 + Sodium silicate recorded 3.07 C mol (+) $kg^{-1}$of CEC followed by T_4: T_2 + Biodecomposed Rice husk (3.01 C mol (+) kg^{-1}) and T_1: Absolute control (3.01 C mol (+) kg^{-1}). The lowest CEC was recorded in T_2: Fertilizer as per KAU POP (2.96 C mol (+) kg^{-1}).

The anion exchange capacity of soil was found highest in T_3: T_2 + Rice husk ash (7.12 C mol (-) kg^{-1}) followed by T_5: T_2 + Calcium silicate (6.81 C mol (-) kg^{-1}) and T_1: Absolute control (6.75 C mol (-) kg^{-1}). T_5 was on par with T_2. The AEC of T_6: T_2 + Sodium silicate recorded (6.68

C mol (-) kg^{-1}) and that of T_4: T_2 + Biodecomposed Rice husk was 6.64 C mol (-) kg^{-1} and these were on par. The lowest AEC was recorded in T_2: Fertilizer as per KAU POP (6.43 C mol (-) kg^{-1}).

Among different treatments, T_4: T_2 + Biodecomposed Rice husk (12.27) recorded highest value of SiO_2:R_2O_3 which was significantly superior over other treatments and was followed by T_2: Fertilizer as per KAU POP (11.32), T_6: T_2 + Sodium silicate recorded (10.99), T_1: Absolute control (10.60), T_5: T_2 + Calcium silicate (10.06) and T_3: T_2 + Rice husk ash (8.62).

Among different treatment with different sources of Si, the highest (29.6 kg ha^{-1}) plant available Si was recorded in T_1 (Absolute control) followed by T_4: T_2 + Biodecomposed Rice husk (20.03 kg ha^{-1}), T_6: T_2 + Sodium silicate (19.95 kg ha^{-1}), T_5: T_2 + Calcium silicate (19.40 kgha^{-1}) and T_2: Fertilizer as per KAU POP (16.48 kg ha^{-1}). T_3: T_2 + Rice husk ash (15.23 kg ha^{-1}) showed lowest value of Si as 12.6 kg ha^{-1}.

The available N content of soils at in treatments varied from 210.1 to 238.3 kg ha^{-1}. The highest available N was estimated in T_1: Absolute control (238.3 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (228.9 kg ha^{-1}), T_4: T_2 + Biodecomposed Rice husk (221.1 kg ha^{-1}), T_6: T_2 + Sodium silicate (215.6 kg ha^{-1}) and T_2: Fertilizer as per KAU POP (214.8 kg ha^{-1}). The lowest available N was recorded in T_5 (210.1 kg ha^{-1}).

Among different treatments, the highest available P was recorded in T_6: T_2 + Sodium silicate (202.6 kg ha^{-1}) followed by T_5: T_2 + Calcium silicate (191.6 kg ha^{-1}), T_4: T_2 + Biodecomposed Rice husk (195.9 kg ha^{-1}), T_1: Absolute control (190.7 kg ha^{-1}) and T_2: Fertilizer as per KAU POP (190.5 kg ha^{-1}). The lowest P content in soil was recorded in T_3: T_2 + Rice husk ash (173.2 kg ha^{-1}).

The highest value of available K was estimated in T_1: Absolute control (38.9 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (24.1 kg ha^{-1}), T_4: T_2 + Biodecomposed Rice husk (22.4kg ha^{-1}), T_5: T_2 + Calcium silicate (21.8 kg ha^{-1}) and T_6: T_2 + Sodium silicate (20.0 kg ha^{-1}). The available K content was recorded lowest in T_2: Fertilizer as per KAU POP (20.4 kg ha^{-1}).

The highest value of available Ca was recorded in T_4: T_2 + Biodecomposed Rice husk (196.6 mg kg^{-1}) which was significantly superior over T_1: Absolute control (54.1 mg kg^{-1}) and on par with T_6: T_2 + Sodium silicate (181.6 mg kg^{-1}) followed by T_3: T_2 + Rice husk ash (179.9 mg kg^{-1}), T_5: T_2 + Calcium silicate (174.1 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (169.6 mg kg^{-1}).

Among different treatments, the available Mg was found highest in T_1: Absolute control (7.6 mg kg^{-1}) followed by T_5: T_2 + Calcium silicate (7.4 mg kg^{-1}), T_6: T_2 + Sodium silicate (7.1 mg kg^{-1}), T_3: T_2 + Rice husk ash (7.1 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (6.6 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (6.6 mg kg^{-1}).

The available Sulphur was recorded highest in T_6: T_2 + Sodium silicate (13.5 mg kg^{-1}) followed by T_2: Fertilizer as per KAU POP (13.2 mg kg^{-1}), T_3: T_2 + Rice husk ash (12.1 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (9.6 mg kg^{-1}), T_1: Absolute control (8.8 mg kg^{-1}) and T_5: T_2 + Calcium silicate (8.5 mg kg^{-1}).

The available Fe was highest in T_4: T_2 + Biodecomposed Rice husk (69.7 mg kg^{-1}) followed by T_3: T_2 + Rice husk ash (60.8 mg kg^{-1}), T_1: Absolute control (59.6 mg kg^{-1}) T_5: T_2 + Calcium silicate (55.7 mg kg^{-1}), T_6: T_2 + Sodium silicate (48.9 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (42.0 mg kg^{-1}).

Among treatments, T_6: T_2 + Sodium silicate (1.01 mg kg^{-1}) recorded highest value of available Cu followed by T_3: T_2 + Rice husk ash (0.98 mg kg^{-1}), T_5: T_2 + Calcium silicate (0.96 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (0.93 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (0.87 mg kg^{-1}). The lowest value was recorded in T_1: Absolute control (0.75 mg kg^{-1}).

The available Mn status of soil was highest in T_1: Absolute control (0.49 mg kg^{-1})followed by T_6: T_2 + Sodium silicate (0.45 mg kg^{-1}), T_3: T_2 + Rice husk ash (0.42 mg kg^{-1}), T_4:T_2 + Biodecomposed Rice husk (0.41 mg kg^{-1}), T_5: T_2 + Calcium silicate (0.39 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (0.37 mg kg^{-1}).

In case of available Zn, T_6: T_2 + Sodium silicate registered the highest (1.87 mg kg^{-1}) value followed by T_3: T_2 + Rice husk ash (1.85 mg kg^{-1}), T_5: T_2 + Calcium silicate (1.82 mg kg^{-1})T_4: T_2 + Biodecomposed Rice husk (1.79 mg kg^{-1}) and T_1: Absolute control (1. 73 mg kg^{-1}). T_2: Fertilizer as per KAU POP recorded the lowest (1.71 mg kg^{-1}) value of available Zn.

Table.58 Residual effect of rice straw incorporation on soil properties before transplanting of second crop

Treatments	**pH**	**EC** **dS m^{-1}**	**OC** **%**	**CEC** **cmol (+) kg^{-1}**	**AEC** **cmol (-) kg^{-1}**	**$SiO_2:R_2O_3$**
T_1 (C)	5.22	0.05	0.68^{b}	3.01^{c}	6.75^{b}	10.60^{d}
T_2(POP)	5.45	0.06	0.61^{b}	3.10^{ab}	6.43^{c}	11.32^{b}
T_3(POP + RHA)	5.48	0.07	0.80^{ab}	3.15^{a}	7.12^{a}	8.62^{f}
T_4(POP + BRH)	5.66	0.07	0.74^{ab}	3.08^{bc}	6.64^{bc}	12.27^{a}
T_5(POP + CS)	5.51	0.06	0.97^{a}	3.13^{ab}	6.81^{b}	10.06^{e}
T_6(POP + SS)	5.52	0.06	0.54^{b}	3.12^{ab}	6.68^{bc}	10.99^{c}
CD(0.05)	NS	NS	0.265	0.076	0.255	0.170

Table.59 Residual effect of rice straw incorporation on nutrient status of soil before transplanting of second crop

Treatments	**Si**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Cu**	**Mn**	**Zn**	**B**	**Al**
	kg ha^{-1}				**mg kg^{-1}**								
T_1 (C)	21.09	238.3	190.7	63.0	54.1^{b}	7.6	8.8	59.6	0.75	0.49	1.73	0.18	174.7
T_2(POP)	16.47	214.8	190.5	54.9	169.6^{a}	6.6	13.2	42.0	0.87	0.38	1.71	0.12	200.3
T_3(POP + RHA)	15.21	228.9	173.2	63.6	179.9^{a}	7.1	12.1	60.8	0.98	0.42	1.85	0.22	212.8
T_4(POP + BRH)	20.01	221.1	195.9	66.1	196.6^{a}	6.6	9.6	69.7	0.93	0.41	1.79	0.21	187.4
T_5(POP + CS)	19.41	210.1	191.6	59.4	174.1^{a}	7.4	8.5	55.7	0.96	0.39	1.82	0.13	225.6
T_6(POP + SS)	19.94	215.6	202.6	60.5	181.6^{a}	7.1	13.5	48.9	1.01	0.45	1.87	0.14	205.8
CD(0.05)	NS	NS	NS	NS	36.756	NS	NS	NS	NS	NS	NS	NS	NS

Table.60 Residual effect of rice straw incorporation on soil properties at tillering stage of second crop

Treatments	pH	EC	Si	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
		dSm^{-1}	kg ha^{-1}				mg kg^{-1}								
T_1 (C)	6.15	0.10	21.73	213.3	183.3	94.1	174.3^{c}	9.9	16.0	59.5	1.2	2.6	2.2	0.20	200.3
T_2(POP)	6.20	0.10	24.75	217.9	188.3	94.9	207.5^{a}	9.6	15.6	56.0	1.3	2.8	1.9	0.23	232.9
T_3(POP + RHA)	6.21	0.10	17.35	216.4	193.7	76.4	199.6^{ab}	9.2	11.7	53.7	1.1	2.2	2.0	0.14	207.4
T_4(POP + BRH)	6.26	0.10	22.78	202.3	195.6	77.3	186.9^{bc}	9.3	15.1	57.2	1.2	2.5	1.7	0.18	198.4
T_5(POP + CS)	6.27	0.10	18.10	200.7	181.5	82.1	201.5^{ab}	9.4	17.1	54.9	1.1	2.7	1.8	0.15	210.9
T_6(POP + SS)	6.24	0.11	20.25	214.8	176.9	91.0	188.4^{abc}	9.6	14.5	53.4	1.3	2.2	2.0	0.21	237.1
CD(0.05)	NS	NS	NS	NS	NS	NS	20.453	NS	NS	NS	NS	NS	NS	NS	NS

Table.61 Residual effect of rice straw incorporation on soil properties at panicle initation stage of second crop

Treatments	pH	EC	Si	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
		dSm^{-1}	kg ha^{-1}				mg kg^{-1}								
T_1 (C)	5.06^{c}	0.05^{b}	15.2	185.0	192.7	126.0	159.7^{c}	10.1	16.1	56.1	0.64	1.12	1.95	0.08^{b}	209.4
T_2(POP)	5.32^{b}	0.06^{a}	18.7	185.1	198.8	113.7	212.5^{ab}	9.8	13.7	50.4	0.74	1.56	2.39	0.08^{b}	240.2
T_3(POP + RHA)	5.47^{ab}	0.06^{a}	21.6	183.5	206.5	140.6	217.2^{ab}	10.1	13.7	54.9	0.70	1.78	2.06	0.16^{a}	228.3
T_4(POP + BRH)	5.52^{a}	0.06^{a}	21.4	180.3	201.9	121.8	194.8^{b}	9.8	19.3	53.3	0.62	1.76	1.97	0.13^{ab}	210.2
T_5(POP + CS)	5.47^{a}	0.06^{a}	23.2	181.9	212.7	137.2	225.0^{a}	10.1	14.8	59.1	1.02	1.60	2.33	0.16^{a}	241.5
T_6(POP + SS)	5.44^{ab}	0.06^{a}	19.7	197.6	194.3	130.2	206.8^{ab}	9.9	13.3	48.1	0.73	1.26	2.06	0.07^{b}	221.1
CD(0.05)	0.149	0.010	NS	NS	NS	NS	28.449	NS	NS	NS	NS	NS	NS	0.06	NS

The highest values of available boron was estimated in T_3: T_2 + Rice husk ash (0.22 mg kg^{-1}) followed by T_4: T_2 + Biodecomposed Rice husk (0.21 mg kg^{-1}), T_1: Absolute control (0.18 mg kg^{-1}), T_6: T_2 + Sodium silicate (0.14 mg kg^{-1}), T_5: T_2 + Calcium silicate (0.13 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (0.55 mg kg^{-1}).

The available aluminium was found highest in T_5: T_2 + Calcium silicate (225.6 mg kg^{-1}) followed by T_3: T_2 + Rice husk ash (212.8 mg kg^{-1}), T_6: T_2 + Sodium silicate (205.8 mg kg^{-1}), T_2: Fertilizer as per KAU POP (200.3 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (187.4 mg kg^{-1}) and T_1: Absolute control (174.7 mg kg^{-1}).

4.3.5.2. Residual effect of rice straw incorporation on soil properties at tillering stage

The data on soil properties at tillering stage are presented in table.60. The residual effect of treatment had no significant effect on electro-chemical properties and nutrient status of soil except available Ca at tillering stage.

The pH of soils in different treatments was found to vary from 6.15 (T_1: Absolute control) to 6.27 (T_5). Among the treatments, T_4: T_2 + Biodecomposed Rice husk recorded a pHof 6.26 followed by T_6: T_2 + Sodium silicate (6.24), T_3: T_2 + Rice husk ash (6.21) and T_2: Fertilizer as per KAU POP (6.20).

Among different sources experimented with Si, the highest plant available Si was recorded in T_2: Fertilizer as per KAU POP (24.75 kg ha^{-1}) followed by T_4: T_2 + Biodecomposed Rice husk (22.78 kg ha^{-1}), T_1: Absolute control (21.73), T_6: T_2 + Sodium silicate (20.25 kg ha^{-1}) and T_5: T_2 + Calcium silicate (18.1 kg ha^{-1}). T_3: T_2 + Rice husk ash showed lowest (17.35 kg ha^{-1}) value of Si.

The highest available N was estimated in T_2: Fertilizer as per KAU POP (217.9 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (216.4 kg ha^{-1}), T_6: T_2 + Sodium silicate (214.8 kg ha^{-1}), T_1: Absolute control (213.3 kg ha^{-1}) and T_4: T_2 + Biodecomposed Rice husk (202.3 kg ha^{-1}). The lowest N content was recorded in T_5 (200.7 kg ha^{-1}).

Among different treatments, the available P was highest in T_4: T_2 + Biodecomposed Rice husk (195.6 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (193.7 kg ha^{-1}), T_2: Fertilizer as per

KAU POP (188.3 kg ha^{-1}) and T_1: Absolute control (188.3 kg ha^{-1}) and T_5: T_2 + Calcium silicate (181.5 kg ha^{-1}). The lowest P content was recorded in T_6: T_2 + Sodium silicate (176.9 kg ha^{-1}).

The highest value of available K was estimated in T_2: Fertilizer as per KAU POP (94.9 kg ha^{-1}) followed by T_1: Absolute control (94.1 kg ha^{-1}), T_6: T_2 + Sodium silicate (91.0 kg ha^{-1}), T_5: T_2 + Calcium silicate (82.1 kg ha^{-1}) and T_4: T_2 + Biodecomposed Rice husk (77.3 kg ha^{-1}). The lowest K content was recorded in T_3: T_2 + Rice husk ash (76.4 kg ha^{-1}).

The treatments had significant effect on available Ca content of soil at tillering stage. The highest value of available Ca was recorded in T_2: Fertilizer as per KAU POP (207.5 mg kg^{-1}) , significantly varied from all other treatments followed by T_5: T_2 + Calcium silicate (201.5 mg kg^{-1}), T_3: T_2 + Rice husk ash (199.6 mg kg^{-1}), T_6: T_2 + Sodium silicate (188.4 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (186.9 mg kg^{-1}). T_5 and T_3 were on par. The lowest Ca content was associated with T_1: Absolute control (174.3 mg kg^{-1}).

Among different treatments, the available Mg was found highest in T_1: Absolute control (9.9 mg kg^{-1}) followed by T_2: Fertilizer as per KAU POP (9.6 mg kg^{-1}), T_5: T_2 + Calcium silicate (9.4 mg kg^{-1}), T_6: T_2 + Sodium silicate (9.6 mg kg^{-1}), T_3: T_2 + Rice husk ash (9.3 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (9.3 mg kg^{-1}).

The available Sulphur was recorded highest in T_5: T_2 + Calcium silicate (17.1 mg kg^{-1}) followed by T_1: Absolute control (16.1 mg kg^{-1}), T_2: Fertilizer as per KAU POP (15.6 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (15.2 mg kg^{-1}), T_6: T_2 + Sodium silicate (14.5 mg kg^{-1}) and lower in T_3: T_2 + Rice husk ash (11.7 mg kg^{-1}).

The available Fe was highest in T_1: Absolute control (59.5 mg kg^{-1}) followed by T_4: T_2 + Biodecomposed Rice husk (57.1 mg kg^{-1}), T_2: Fertilizer as per KAU POP (56.0 mg kg^{-1}), T_5: T_2 + Calcium silicate (54.9 mg kg^{-1}), T_3: T_2 + Rice husk ash (53.7 mg kg^{-1}) and T_6: T_2 + Sodium silicate (53.4 mg kg^{-1}).

The available Cu content varied significantly with respect to treatments. Among the treatments, T_6: T_2 + Sodium silicate (0.55 mg kg^{-1}) recorded significantly highest value followed by T_2: Fertilizer as per KAU POP (0.51 mg kg^{-1}) which was on par with T_5: T_2 + Calcium silicate

(0.46 mg kg^{-1}) and T_3: T_2 + Rice husk ash (0.46 mg kg^{-1}). The lowest value was recorded in T_4: T_2 + Biodecomposed rice husk (0.25 mg kg^{-1}).

Among different treatments, T_2: Fertilizer as per KAU POP (2.8 mg kg^{-1}) recordedhighest available Mn followed by T_5: T_2 + Calcium silicate (2.7 mg kg^{-1}), T_1: Absolute control (2.6 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (2.5 mg kg^{-1}), T_6: T_2 + Sodium silicate (2.6 mgkg^{-1}) and T_3: T_2 + Rice husk ash (2.2 mg kg^{-1}).

Highest available Zn in soil was recorded in T_1: Absolute control (2.2 mg kg^{-1}) followed by T_3: T_2 + Rice husk ash (2.0 mg kg^{-1}), T_6: T_2 + Sodium silicate (2.0 mg kg^{-1}), T_2: Fertilizer as per KAU POP (1.9 mg kg^{-1}) and T_5: T_2 + Calcium silicate (1.9 mg kg^{-1}). The lower value of Zn was noticed in T_4: T_2 + Biodecomposed Rice husk (1.7 mg kg^{-1}).

The highest value for available boron was estimated in T_2: Fertilizer as per KAU POP (0.23 mg kg^{-1}) followed by T_6: T_2 + Sodium silicate (0.21 mg kg^{-1}) T_1: Absolute control (0.20 mgkg^{-1}), T_4: T_2 + Biodecomposed Rice husk (0.18 mg kg^{-1}), T_5: T_2 + Calcium silicate (0.15 mg kg$^{- 1}$), and T_3: T_2 + Rice husk ash (0.14 mg kg^{-1}).

The available aluminium was found highest in T_6: T_2 + Sodium silicate (237.1 mg kg^{-1}) followed by T_2: Fertilizer as per KAU POP (232.9 mg kg^{-1}), T_5: T_2 + Calcium silicate (210.9 mg kg^{-1}), T_3: T_2 + Rice husk ash (207.4 mg kg^{-1}), T_1: Absolute control (200.3 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (198.4 mg kg^{-1}).

4.3.5.2. Effect of rice straw incorporation on soil properties at panicle initiation stage

The results pertaining to the soil properties at panicle initiation stage are presented in table.61. The data showed that pH, EC available Ca and available B were significantly influenced by treatments unlike other parameters that remained non significant.

Among treatments, the pH of T_4: T_2 + Biodecomposed Rice husk (5.51) was significantly superior and on par with T_5: T_2 + Calcium silicate (5.47) followed by T_3: T_2 + Rice husk ash (5.47), T_6: T_2 + Sodium silicate (5.44), T_2: Fertilizer as per KAU POP (5.32). The lower pH was recorded in T_1: Absolute control (5.06).

The EC of T_1: Absolute control (0.05 dSm^{-1}) differ significantly from all other treatments which were on par (0.06 dSm^{-1})

The highest plant available Si was recorded in T_5: T_2 + Calcium silicate (23.2 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (21.6 kg ha^{-1}), T_4: T_2 + Biodecomposed Rice husk (21.4 kg ha^{-1}), T_6: T_2 + Sodium silicate (19.7 kg ha^{-1}), T_2: Fertilizer as per KAU POP (18.7 kg ha^{-1}). T_1 (Absolute control) showed lowest (15.2 kg ha^{-1}) value of for plant available Si.

The highest available N was estimated in T_6: T_2 + Sodium silicate (197.6 kg ha^{-1})followed by T_2: Fertilizer as per KAU POP (185.1 kg ha^{-1}), T_1: Absolute control (185.0 kg ha^{-1}), T_3: T_2 + Rice husk ash (183.5 kg ha^{-1}) and T_5: T_2 + Calcium silicate (181.9 kg ha^{-1}). The lowestN content was recorded in T_4: T_2 + Biodecomposed Rice husk (180.3 kg ha^{-1}).

Available P was highest in T_5: T_2 + Calcium silicate (212.7 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (206.5 kg ha^{-1}), T_4: T_2 + Biodecomposed Rice husk (201.9 kg ha^{-1}), T_2: Fertilizer as per KAU POP (198.8 kg ha^{-1}) and T_6: T_2 + Sodium silicate (194.3 kg ha^{-1}), whereas T_1: Absolute control recorded the lowest (192.7 kg ha^{-1}) available P.

The highest value of available K was estimated in T_3: T_2 + Rice husk ash (140.6 kg ha^{-1}) followed by T_5: T_2 + Calcium silicate (137.2 kg ha^{-1}), T_6: T_2 + Sodium silicate (130.2 kg ha^{-1}), T_1: Absolute control (126.0 kg ha^{-1}) and T_4: T_2 + Biodecomposed Rice husk (121.8 kg ha^{-1}). The lowest K content was recorded in T_2: Fertilizer as per KAU POP (113.7 kg ha^{-1}).

The treatments exhibited a significant effect on deciding available Ca of soil. The highest value of available Ca was recorded in T_5: T_2 + Calcium silicate (225.0 mg kg^{-1}) which was significantly superior over others. It was followed by T_3: T_2 + Rice husk ash (217.2 mg kg^{-1}), T_2: Fertilizer as per KAU POP (212.5 mg kg^{-1}), T_6: T_2 + Sodium silicate (206.8 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (194.8 mg kg^{-1}). The lowest Ca content was recorded in T_1: Absolute control (159.7 mg kg^{-1}). T_3, T_2 and T_6 were on par.

Among different treatments, the available Mg was found highest in T_5: T_2 + Calcium silicate, T_3: T_2 + Rice husk ash and T_1: Absolute control with 10.1 mg kg^{-1} Mg followed by T_6: T_2 + Sodium silicate (9.9 mg kg^{-1}). In T_4 (T_2 + Biodecomposed Rice husk) and T_2 (Fertilizer as per KAU POP), Mg content was recorded as 9.8 mg kg^{-1}.

The available sulphur was recorded highest in T_4: T_2 + Biodecomposed Rice husk (19.3 mg kg^{-1}) followed by T_1: Absolute control (16.1 mg kg^{-1}), T_5: T_2 + Calcium silicate (14.8 mg kg^{-}

^{1}), T_2: Fertilizer as per KAU POP (13.7 mg kg^{-1}) and T_3: T_2 + Rice husk ash (13.7 mg kg^{-1}). T_6: T_2 + Sodium silicate (13.3 mg kg^{-1}) recorded the lowest content of S in soil.

The available Fe was highest in T_5: T_2 + Calcium silicate (59.1 mg kg^{-1}) followed by T_1: Absolute control (56.1 mg kg^{-1}), T_3: T_2 + Rice husk ash (54.9 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (53.3 mg kg^{-1}), T_2: Fertilizer as per KAU POP (50.4 mg kg^{-1}) and T_6: T_2 + Sodium silicate (48.1mg kg^{-1}).

Among treatments, T_5: T_2 + Calcium silicate (1.0 mg kg^{-1}) recorded highest value of Cu followed by T_2: Fertilizer as per KAU POP (0.72 mg kg^{-1}), T_6: T_2 + Sodium silicate (0.71 mg kg^{-1}), T_3: T_2 + Rice husk ash (0.70 mg kg^{-1}) and T_1: Absolute control (0.64 mg kg^{-1}). The lowest value was recorded in T_4: T_2 + Biodecomposed Rice husk (0.62 mg kg^{-1}).

Among different treatments, T_3: T_2 + Rice husk ash (1.8 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (1.8 mg kg^{-1}) recorded highest available Mn followed by T_5: T_2 + Calcium silicate (1.6 mg kg^{-1}), T_2: Fertilizer as per KAU POP (1.6 mg kg^{-1}), T_6: T_2 + Sodium silicate (1.3 mg kg^{-1}) and T_1: Absolute control (1.1 mg kg^{-1}).

Among different treatments, T_2: Fertilizer as per KAU POP (2.38 mg kg^{-1}) recorded highest available Zn followed by T_5: T_2 + Calcium silicate (2.33 mg kg^{-1}), T_3: T_2 + Rice husk ash(2.06 mg kg^{-1}), T_6: T_2 + Sodium silicate (2.05 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (1.97mg kg^{-1}). The lowest value of Zn was noticed in T_1: Absolute control (1.95 mg kg^{-1}).

Different treatments had significant effect on available B. The highest available boron was estimated in T_5: T_2 + Calcium silicate (0.16) and T_3: T_2 + Rice husk ash (0.16 mg kg^{-1}) followed by T_4: T_2 + Biodecomposed Rice husk recorded a value of (0.13 mg kg^{-1}), T_1: Absolute control (0.08 mg kg^{-1}) and T_2: Fertilizer as per KAU POP (0.08 mg kg^{-1}). The available B was lowest in T_6: T_2 + Sodium silicate (0.07 mg kg^{-1}).

The available aluminium was found highest in T_5: T_2 + Calcium silicate (241.5 mg kg^{-1}) followed by T_2: Fertilizer as per KAU POP (240.2 mg kg^{-1}), T_3: T_2 + Rice husk ash (228.3 mg kg^{-1}), T_6: T_2 + Sodium silicate (221.1 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (210.2 mg kg^{-1}) and T_1: Absolute control (209.4 mg kg^{-1}).

4.3.5.3. Effect of rice straw incorporation on soil properties at harvest stage

The data on soil properties at harvest are presented in table.62 and 63. The AEC, SiO_2: R_2O_3, available S and B were found to vary significantly with respect to treatment.

Highest pH of 6.06 noticed in T_4: T_2 + Biodecomposed Rice husk followed by T_5: T_2 + Calcium silicate (6.03), T_6: T_2 + Sodium silicate (5.96), T_2: Fertilizer as per KAU POP (5.95), T_3: T_2 + Rice husk ash (5.89) and T_1: Absolute control (5.69).

The EC of T_6: T_2 + Sodium silicate (0.06 dS m^{-1}) was the highest followed by T_3: T_2 + Rice husk ash (0.05 dS m^{-1}) T_4: T_2 + Biodecomposed Rice husk (0.05 dS m^{-1}), T_2: Fertilizer as per KAU POP (0.05 dS m^{-1}), T_5: T_2 + Calcium silicate (0.05 dS m^{-1}) and T_1: Absolute control (0.04 dS m^{-1}).

The organic carbon content of soil was found highest in T_5: T_2 + Calcium silicate (0.61 per cent) followed by T_3: T_2 + Rice husk ash (0.59 per cent), T_1: Absolute control (0.56 per cent),T_6: T_2 + Sodium silicate (0.56 per cent) and T_4: T_2 + Biodecomposed Rice husk (0.55 per cent). The lowest (0.49 per cent) value of OC was recorded in T_2: Fertilizer as per KAU POP.

The cation exchange capacity of the soil was highest in T_5: T_2 + Calcium silicate (3.13 C mol (+) kg^{-1}) followed by T_3: T_2 + Rice husk ash (3.12 C mol (+) kg^{-1}), T_6: T_2 + Sodium silicate (3.09 C mol (+) kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (3.09 C mol (+) kg^{-1}) and T_2: Fertilizer as per KAU POP (3.06 C mol (+) kg^{-1}). The lowest (2.99 C mol (+) kg^{-1}) CEC was recorded in T_1: Absolute control.

The anion exchange capacity of soil was found highest in T_5: T_2 + Calcium silicate (6.88 C mol (-) kg^{-1}) followed by T_6: T_2 + Sodium silicate recorded (6.87 C mol (-) kg^{-1}), T_3: T_2 + Rice husk ash (6.78 C mol (-) kg^{-1}) and T_1: Absolute control (6.77 C mol (-) kg^{-1}) and T_2: Fertilizer as per KAU POP (6.43 C mol (-) kg^{-1}). T_5 was on par with T_6. The lowest AEC was recorded in T_4: T_2 + Biodecomposed Rice husk (6.39 C mol (-) kg^{-1}).

Table.62 Residual effect of rice straw incorporation on electro-chemical properties of soil at harvest stage of second crop

Treatments	**pH**	**EC** dSm^{-1}	**OC** %	**CEC** C mol (+) kg^{-1}	**AEC** C mol (-) kg^{-1}	$SiO_2:R_2O_3$
T_1 (C)	5.73	0.04	0.56	3.10	6.77^{ab}	8.72^{cd}
T_2(POP)	5.95	0.05	0.49	3.06	6.56^{bc}	9.68^{b}
T_3(POP + RHA)	5.90	0.05	0.59	3.11	6.78^{ab}	9.80^{b}
T_4(POP + BRH)	6.06	0.05	0.55	3.09	6.39^{c}	8.80^{c}
T_5(POP + CS)	6.03	0.05	0.61	3.16	6.88^{a}	8.62^{d}
T_6(POP + SS)	5.96	0.06	0.56	3.09	6.87^{a}	10.09^{a}
CD(0.05)	NS	NS	NS	NS	0.24	0.115

Table.63 Residual effect of rice straw incorporation on nutrient status of soil at harvest stage of second crop

Treatments	**Si**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Cu**	**Mn**	**Zn**	**B**	**Al**
	kg ha^{-1}												
T_1 (C)	17.4	161.5	177.9	48.5	112.0	7.9	4.9^{c}	38.2	0.86	0.46	1.19	0.01^{d}	135.1
T_2(POP)	18.3	156.8	184.7	46.2	157.7	7.8	8.8^{bc}	40.9	1.03	0.70	1.40	0.03^{c}	172.9
T_3(POP + RHA)	20.1	156.8	198.5	49.0	123.9	7.4	7.9^{bc}	42.6	0.98	0.54	1.30	0.03^{cd}	136.4
T_4(POP + BRH)	17.7	169.3	174.1	46.5	147.4	6.9	13.7^{a}	44.7	0.94	0.80	1.27	0.06^{b}	156.9
T_5(POP + CS)	27.6	144.3	182.5	50.4	154.3	7.4	14.9^{a}	42.6	0.90	0.58	1.30	0.20^{a}	181.7
T_6(POP + SS)	13.9	144.3	183.6	54.6	145.9	7.6	10.7^{ab}	30.9	0.80	0.68	1.18	0.05^{b}	139.0
CD(0.05)	NS	NS	NS	NS	NS	NS	4.602	NS	NS	NS	NS	0.016	NS

Among the different treatments, T_6: T_2 + Sodium silicate recorded highest (10.09) value of SiO_2:R_2O_3 which was significantly superior over other treatments. This was followed by T_3:T_2 + Rice husk ash (9.80), T_2: Fertilizer as per KAU POP (9.68), T_4: T_2 + Biodecomposed Rice husk (8.80), T_5: T_2 + Calcium silicate (8.62) and T_1: Absolute control (8.72).

Among different Si sources, the highest plant available Si was recorded in T_5: T_2 + Calcium silicate (27.60 kg ha^{-1}) followed by T_3: T_2 + Rice husk ash (20.05 kg ha^{-1}), T_2: Fertilizeras per KAU POP (18.30 kg ha^{-1}), T_4: T_2 + Biodecomposed Rice husk (17.7 kg ha^{-1}), and T_1: Absolute control (17.38 kg ha^{-1}). T_6: T_2 + Sodium silicate (13.98 kg ha^{-1}) showed lowest value ofSi.

The available N was highest in T_4: T_2 + Biodecomposed Rice husk (169.3 kg ha^{-1}) followed by T_1: Absolute control (161.5 kg ha^{-1}), T_3: T_2 + Rice husk ash (156.8 kg ha^{-1}), T_2: Fertilizer as per KAU POP, (156.8 kg ha^{-1}) T_5 (144.3 kg ha^{-1}) and T_6: T_2 + Sodium silicate (144.3kg ha^{-1}).

The highest available P was recorded in T_3: T_2 + Rice husk ash (198.5 kg ha^{-1}) followed by T_2: Fertilizer as per KAU POP (184.7 kg ha^{-1}), T_6: T_2 + Sodium silicate (183.6 kg ha^{-1}), T_5: T_2 + Calcium silicate (182.5 kg ha^{-1}), T_1: Absolute control (177.9 kg ha^{-1}) and T_4: T_2 + Biodecomposed Rice husk (174.1 kg ha^{-1}).

The highest value of available K was recorded in T_6: T_2 + Sodium silicate (54.6 kg ha^{-1}) followed by T_5: T_2 + Calcium silicate (50.4 kg ha^{-1}), T_3: T_2 + Rice husk ash (49.0 kg ha^{-1}), T_1: Absolute control (48.1 kg ha^{-1}) and T_4: T_2 + Biodecomposed Rice husk (46.5 kg ha^{-1}). The lowest content of K was recorded in T_2: Fertilizer as per KAU POP (46.2 kg ha^{-1}).

The highest value of available Ca was recorded in T_2: Fertilizer as per KAU POP (157.7 mg kg^{-1}) followed by T_5: T_2 + Calcium silicate (154.3 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (147.4 mg kg^{-1}), T_6: T_2 + Sodium silicate (145.9 mg kg^{-1}) and T_3: T_2 + Rice husk ash (123.9 mg kg^{-1}). The lowest content of Ca was recorded in T_1: Absolute control (112.0 mg kg^{-1}).

Among different treatments, the available Mg was found highest in T_1: Absolute control (7.9 mg kg^{-1}) followed by T_2: Fertilizer as per KAU POP (7.8 mg kg^{-1}), T_6: T_2 + Sodium silicate

(7.6 mg kg^{-1}), T_5: T_2 + Calcium silicate (7.4 mg kg^{-1}) and T_4: T_2 + Biodecomposed Rice husk (6.9 mg kg^{-1}). The Mg content was recorded the lowest in T_3: T_2 + Rice husk ash (7.4 mg kg^{-1}).

The available Sulphur was recorded highest in T_5: T_2 + Calcium silicate (14.9 mg kg^{-1}) which was significantly superior and on par with T_4: T_2 + Biodecomposed Rice husk (13.7 mg k g^{-1}) followed by T_6: T_2 + Sodium silicate (10.6 mg kg^{-1}), T_2: Fertilizer as per KAU POP (8.8 mg kg^{-1}), T_3: T_2 + Rice husk ash (7.9 mg kg^{-1}) and T_1: Absolute control (4.9 mg kg^{-1}). T_2 was on par with T_3.

The available Fe was highest in T_4: T_2 + Biodecomposed Rice husk (44.7 mg kg^{-1}) followed by T_3: T_2 + Rice husk ash (42.6 mg kg^{-1}) and T_5: T_2 + Calcium silicate (42.6 mg kg^{-1}), T_2: Fertilizer as per KAU POP (40.9 mg kg^{-1}), T_1: Absolute control (38.2 mg kg^{-1}) and T_6: T_2 + Sodium silicate (30.9 mg kg^{-1}).

Among treatments, T_2: Fertilizer as per KAU POP (1.03 mg kg^{-1}) recorded highest value of Cu followed by T_3: T_2 + Rice husk ash (0.98 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (0.94 mg kg^{-1}), T_5: T_2 + Calcium silicate (0.89 mg kg^{-1}) and T_6: T_2 + Sodium silicate (0.81 mg kg^{-1}). The lowest value was recorded in T_1: Absolute control (0.86 mg kg^{-1}).

Among different treatments, T_4: T_2 + Biodecomposed Rice husk (0.80 mg kg^{-1}) recorded highest value for available Mn followed by T_2: Fertilizer as per KAU POP (0.70 mg kg^{-1}), T_6: T_2 + Sodium silicate (0.68 mg kg^{-1}), T_5: T_2 + Calcium silicate (0.58 mg kg^{-1}), T_3: T_2 + Rice husk ash (0.54 mg kg^{-1}) and T_1: Absolute control (0.46 mg kg^{-1}).

Among different treatments, T_2: Fertilizer as per KAU POP (1.40 mg kg^{-1}) recorded highest available Zn followed by T_3: T_2 + Rice husk ash (1.30 mg kg^{-1}), T_5: T_2 + Calcium silicate(1.30 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (1.27 mg kg^{-1}) and T_1: Absolute control (1.19 mg kg^{-1}). The lowest Zn content in soil was noticed in T_6: T_2 + Sodium silicate (1.18 mg kg^{-1}).

The available B was found to be inluenced significantly with different Si sources in preceding crop. The highest value of available boron was estimated in T_5: T_2 + Calcium silicate (0.20 mg kg^{-1}) followed by T_4: T_2 + Biodecomposed Rice husk (0.06 mg kg^{-1}), T_6: T_2 + Sodium silicate (0.05 mg kg^{-1}), T_2: Fertilizer as per KAU POP (0.03 mg kg^{-1}) T_3: T_2 + Rice husk ash (0.03 mg kg^{-}1) and T_1: Absolute control (0.01 mg kg^{-1}).

The available aluminium was found highest in T_5: T_2 + Calcium silicate (181.7 mg kg^{-1}) followed by T_2: Fertilizer as per KAU POP (172.9 mg kg^{-1}), T_4: T_2 + Biodecomposed Rice husk (156.9 mg kg^{-1}), T_6: T_2 + Sodium silicate (139.0 mg kg^{-1}), T_3: T_2 + Rice husk ash (136.4 mg kg^{-1}) and T_1: Absolute control (135.1 mg kg^{-1}).

4.3.6 Plant analysis

4.3.6.1 Residual effect of rice straw incorporation on nutrient content in shoot at tillering stage of second crop

The analytical data on nutrient content in shoot are represented in table.64. The N in shoot at tillering stage was found to vary significantly, whereas all other nutrients did not show any significant difference with respect to treatments.

Among the treatments, the Si content in shoot was highest in T_6: T_2 + Sodium silicate (1.94 per cent), followed by T_3: T_2 + Rice husk ash (1.44 per cent), T_5: T_2 + Calcium silicate (1.38 per cent), T_4: T_2 + Biodecomposed Rice husk (1.29 per cent) and T_2: Fertilizer as per KAU POP (1.07 per cent). The Si content was lowest in T_1: Absolute control (1.04 per cent).

The nitrogen content in shoot was highest in T_4: T_2 + Biodecomposed Rice husk (1.98 per cent) and varied significantly from others. It was followed by T_1: Absolute control (1.52 per cent), T_3: T_2 + Rice husk ash (1.34 per cent), T_6: T_2 + Sodium silicate (1.32 per cent) and T_2: Fertilizer as per KAU POP (1.34 per cent). T_2 was on par with T_3 and T_6.T_5: T_2 + Calciumsilicate (1.18 per cent) recorded the lowest N content in shoot.

All treatments except T_1: Absolute control (0.12 per cent) recorded a P content of 0.13 per cent in shoot.

The treatment T_4: T_2 + Biodecomposed Rice husk (1.75 per cent) recorded higher K content in shoot followed by T_2: Fertilizer as per KAU POP (1.72 per cent), T_3: T_2 + Rice husk ash (1.71 per cent), T_1: Absolute control (1.70 per cent), T_6: T_2 + Sodium silicate (1.64 per cent) and T_5: T_2 + Calcium silicate (1 .54per cent).

The Ca content of shoot was found to be highest in T_5: T_2 + Calcium silicate (1.17 per cent) and T_4: T_2 + Biodecomposed Rice husk (0.17 per cent) followed by T_6: T_2 + Sodium silicate (0.16 per cent) and T_3: T_2 + Rice husk ash (0.16 per cent) and T_2: Fertilizer as per KAU

POP (0.15 per cent). The lowest calcium content was recorded in T_1: Absolute control (0.14 per cent).

Among different treatments, the percentage of Mg content in shoot was found to be highest in T_1: Absolute control (0.075 per cent) followed by T_6: T_2 + Sodium silicate (0.073 per cent), T_4: T_2 + Biodecomposed rice (0.070 per cent), T_5: T_2 + Calcium silicate (0.068 per cent) T_3: T_2 + Rice husk ash (0.065 per cent) and T_2: Fertilizer as per KAU POP (0.065 per cent).

The highest content of S in shoot was observed in T_2 (Fertilizer as per KAU POP), T_3 (T_2 + Rice husk ash) and T_4 (T_2 + Biodecomposed rice) as 0.29 per cent. It was followed by T_1: Absolute control (0.27 per cent), T_6: T_2 + Sodium silicate (0.23 per cent) and T_5: T_2 + Calcium silicate (0.21 per cent).

The treatment T_4: T_2 + Biodecomposed Rice husk (0.015 per cent) recorded highest Fe content in shoot. 0.014 and 0.013 per cent of Fe were observed in T_1 and T_6, and T_2 respectively. This was followed by T_3: T_2 + Rice husk ash (0.012 per cent) and T_5: T_2 + Calcium silicate (0.011 per cent).

The manganese content was highest in T_5: T_2 + Calcium silicate (0.016 per cent) followed by T_2: Fertilizer as per KAU POP (0.012 per cent) and, T_3: T_2 + Rice husk ash (0.011 per cent) and T_4: T_2 + Biodecomposed Rice husk (0.011 per cent). The lowest Mn content was seen in T_6: T_2 + Sodium silicate (0.010 per cent) and T_1: Absolute control (0.010 per cent).

The percentage of Zn content in shoot varied from 0.002 per cent (T_6: T_2 + Sodium silicate) to 0.004 per cent (T_1: Absolute control). It was seen that the shoots contained very less amount of Zn.

As against other elements, boron content was also very less in shoots and the value recorded in all treatments was 0.001 per cent. The copper content in shoot was not in detectable range.

The highest Al content was seen in T_4: T_2 + Biodecomposed Rice husk (0.029) followed by T_1: Absolute control (0.028 per cent), T_6: T_2 + Sodium silicate (0.026 per cent), T_2: Fertilizer as per KAU POP (0.023) and T_3: T_2 + Rice husk ash (0.019) and T_5: T_2 + Calcium silicate (0.019).

Table.64 Residual effect of rice straw incorporation on nutrient content in shoot at tillering stage of second crop

Treatments	**Si**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Cu**	**Mn**	**Zn**	**B**	**Al**
	%												
T_1 (C)	1.04	1.52^{b}	0.12	1.70	0.14	0.08	0.27	0.014	ND	0.010	0.004	0.001	0.028
T_2(POP)	1.07	1.32^{bc}	0.13	1.72	0.15	0.07	0.29	0.013	ND	0.012	0.003	0.001	0.023
T_3(POP + RHA)	1.44	1.34^{bc}	0.13	1.71	0.16	0.07	0.29	0.012	ND	0.011	0.003	0.001	0.019
T_4(POP + BRH)	1.29	1.98^{a}	0.13	1.73	0.17	0.07	0.29	0.015	ND	0.011	0.003	0.001	0.029
T_5(POP + CS)	1.38	1.18^{c}	0.13	1.54	0.17	0.07	0.21	0.011	ND	0.016	0.003	0.001	0.019
T_6(POP + SS)	1.94	1.32^{bc}	0.13	1.64	0.16	0.07	0.23	0.014	ND	0.010	0.002	0.001	0.026
CD(0.05)	NS	0.310	NS	NS	NS	NS	NS	NS	-	NS	NS	NS	NS

Table.65 Residual effect of rice straw incorporation on nutrient content in shoot at panicle initiation stage of second crop

Treatments	**Si**	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
	%												
T_1 (C)	0.89	0.69^{d}	0.13	1.09	0.19	0.09	0.13	0.012	ND	0.032	0.009	0.002	0.015
T_2(POP)	0.88	0.84^{ab}	0.15	1.12	0.19	0.08	0.15	0.012	ND	0.028	0.007	0.001	0.012
T_3(POP + RHA)	1.60	0.89^{a}	0.15	1.13	0.21	0.09	0.15	0.013	ND	0.034	0.008	0.001	0.016
T_4(POP + BRH)	0.84	0.78^{bc}	0.15	1.10	0.21	0.09	0.14	0.013	ND	0.030	0.007	0.001	0.015
T_5(POP + CS)	0.92	0.69^{d}	0.15	1.06	0.20	0.08	0.12	0.013	ND	0.033	0.008	0.002	0.015
T_6(POP + SS)	1.16	0.72^{cd}	0.14	1.12	0.21	0.09	0.13	0.013	ND	0.028	0.008	0.001	0.015
CD(0.05)	NS	0.083	NS	NS	NS	NS	NS	NS	-	NS	NS	NS	NS

4.3.6.2 Effect of rice straw incorporation on nutrient content in shoot at panicle initiation stage

The results pertaining to the nutrient content in shoot at panicle initiation stage are presented in table.65. The N content varied significantly with respect to treatments.

Among treatments, the percentage of Si content was highest in T_3: T_2 + Rice husk ash (1.60 per cent) followed by T_6: T_2 + Sodium silicate (1.16 per cent), T_5: T_2 + Calcium silicate (0.92 per cent), T_2: Fertilizer as per KAU POP and T_1: Absolute control (0.89 per cent). The lowest (0.84 per cent) Si was registered in T_4: T_2 + Biodecomposed Rice husk.

The treatments had significant effect on nitrogen content. The nitrogen content in shoot was highest in T_3: T_2 + Rice husk ash (0.89 per cent) followed by T_2: Fertilizer as per KAU POP (0.84 per cent), T_4: T_2 + Biodecomposed Rice husk (0.78 per cent), T_6: T_2 + Sodium silicate (0.72 per cent) and T_5: T_2 + Calcium silicate and T_1: Absolute control (0.69 per cent).

The highest P content in shoot was recorded in T_4: T_2 + Biodecomposed Rice husk, T_5: T_2 + Calcium silicate, T_2: Fertilizer as per KAU POP (0.15 per cent) and T_3: T_2 + Rice husk ash recorded a similar value of 0.15 per cent P in shoot. This was followed by T_6: T_2 + Sodium silicate (0.14 per cent) and T_1: Absolute control (0.13 per cent).

The potassium content of shoot was highest in T_3: T_2 + Rice husk ash (1.13 per cent) followed by T_6: T_2 + Sodium silicate and T_2: Fertilizer as per KAU POP (1.12 per cent) followed by T_4: T_2 + Biodecomposed Rice husk (1.10 per cent), T_1: Absolute control (1.09 per cent) and T_5: T_2 + Calcium silicate (1.06 per cent).

The content of Ca was highest in T_6: T_2 + Sodium silicate, T_3: T_2 + Rice husk ash and T_4: T_2 + Biodecomposed Rice husk (0.21 per cent) followed by T_5: T_2 + Calcium silicate (0.20 per cent) and, T_2: Fertilizer as per KAU POP and T_1: Absolute control (0.19 per cent).

Among different treatments, the Mg content in shoot was 0.09 per cent in T_1 (Absolute control), T_3 (T_2 + Rice husk ash), T_4 (T_2 + Biodecomposed Rice husk) and T_6 (T_2 + Sodium silicate) and 0.08 per cent in T_5: T_2 + Calcium silicate and T_2: Fertilizer as per KAU POP.

The highest content of sulphur was observed in T_2: Fertilizer as per KAU POP and T_3 (T_2 + Rice husk ash) as 0.15 per cent followed by T_1 (Absolute control) and T_6 (T_2 + Sodium silicate) with 0.13 per cent.

The manganese content of shoot was highest in T_3: T_2 + Rice husk ash (0.03 per cent) followed by T_5: T_2 + Calcium silicate (0.033 per cent), T_1: Absolute control (0.031 per cent), T_4: T_2 + Biodecomposed Rice husk (0.030 per cent), T_6: T_2 + Sodium silicate (0.028 per cent) and T_2: Fertilizer as per KAU POP (0.028 per cent).

The copper content was below detectable range. There was not much variation in percentage of Fe, Zn, Al and B in shoots with respect to treatments.

4.3.6.3 Effect of rice straw incorporation on nutrient content in shoot at harvest stage

The results pertaining to the nutrient content in shoot at harvest stage are presented in table.66. The contents of Si and N in shoot at harvest stage were found to vary significantly with respect to treatments.

Among treatments, the percentage of Si was highest in T_5: T_2 + Calcium silicate (1.23 per cent) which was significantly superior to all other treatment. It was followed by T_3: T_2 + Rice husk ash (1.12 per cent), T_6: T_2 + Sodium silicate (1.08 per cent), T_4: T_2 + Biodecomposed Rice husk (0.88 per cent), T_1: Absolute control (0.56 per cent) and T_2: Fertilizer as per KAU POP (0.54 per cent). T_1 was on par with T_2 and, T_6 was on par with T_3.

The treatments had significant effect on nitrogen content. The nitrogen content in shoot was highest in T_3: T_2 + Rice husk ash (0.70 per cent) and significantly superior over others, followed by T_6: T_2 + Sodium silicate (0.64 per cent), T_4: T_2 + Biodecomposed Rice husk (0.63 per cent), T_5: T_2 + Calcium silicate (0.61 per cent), T_2: Fertilizer as per KAU POP (0.60 per cent)and T_1: Absolute control (0.59 per cent). T_6 was on par with T_1, T_2, T_4 and T_5.

The highest P content in shoot was recorded in T_4: T_2 + Biodecomposed Rice husk (0.07 per cent), T_5: T_2 + Calcium silicate (0.07 per cent) and T_3: T_2 + Rice husk ash (0.07 per cent) followed by T_2: Fertilizer as per KAU POP (0.06 per cent), T_6: T_2 + Sodium silicate (0.05 per cent) and T_1: Absolute control (0.05 per cent).

The highest K content in shoot was recorded in T_6: T_2 + Sodium silicate (1.44 per cent) followed by T_4: T_2 + Biodecomposed Rice husk (1.36 per cent), T_5: T_2 + Calcium silicate (1.33 per cent), T_3: T_2 + Rice husk ash (1.27 per cent) and, T_2: Fertilizer as per KAU POP (1.25 per cent) and T_1: Absolute control (1.25 per cent).

The Ca content was highest in T_3: T_2 + Rice husk ash and T_2: Fertilizer as per KAU POP as 0.25 per cent followed by T_4: T_2 + Biodecomposed Rice husk (0.24 per cent), T_5: T_2 + Calcium silicate (0.23 per cent), T_6: T_2 + Sodium silicate (0.23 per cent) and T_1: Absolute control(0.22 per cent).

The Mg content was highest in T_4: T_2 + Biodecomposed Rice husk (0.080 per cent) and T_5: T_2 + Calcium silicate (0.080 per cent) followed by T_1: Absolute control (0.078 per cent) and T_2: Fertilizer as per KAU POP (0.078 per cent) and T_3: T_2 + Rice husk ash (0.075 per cent). The lowest content of Mg in shoot was seen in T_6: T_2 + Sodium silicate (0.073 per cent).

The highest content of sulphur was observed in T_3: T_2 + Rice husk ash (0.19 per cent) followed by T_1: Absolute control (0.13 per cent), T_2: Fertilizer as per KAU POP (0.12 per cent) T_4: T_2 + Biodecomposed Rice husk (0.11 per cent), T_6: T_2 + Sodium silicate (0.10 per cent) and T_5: T_2 + Calcium silicate (0.09).

The content of manganese, zinc, boron and aluminium in shoot did not show much variation with respect to treatments. The copper content was below detectable range.

4.3.6.4 Effect of rice straw incorporation on nutrient content in grain at harvest stage

The results pertaining to the nutrient content in grain at harvest stage are presented in table.67. The treatments had significant effect only on N, Ca, S, Fe and Si contents in grain at harvest stage and others remain non-significant.

Among the treatments, the percentage of Si content was highest in T_4: T_2 + Biodecomposed Rice husk (2.94 per cent) which was significantly superior to all other treatments. It was followed by T_5: T_2 + Calcium silicate (2.93 per cent), T_6: T_2 + Sodium silicate (2.86 per cent), T_3: T_2 + Rice husk ash (2.84 per cent) and T_2: Fertilizer as per KAU POP (2.56 per cent). T_4 was on par with $T_{3,}$ T_5 and T_6. The Si content was lowest in T_1: Absolute control (2.55 per cent).

Table.66 Residual effect of rice straw incorporation on nutrient content in shoot at harvest stage of second crop

Treatments	**Si**	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
	%												
T_1 (C)	0.56^{c}	0.59^{b}	0.05	1.26	0.22	0.08	0.13	0.01	ND	0.04	0.01	0.001	0.01
T_2(POP)	0.54^{c}	0.60^{b}	0.06	1.25	0.25	0.08	0.12	0.01	ND	0.04	0.01	0.001	0.01
T_3(POP + RHA)	1.12^{ab}	0.70^{a}	0.07	1.27	0.25	0.08	0.19	0.01	ND	0.04	0.01	0.001	0.01
T_4(POP + BRH)	0.88^{b}	0.63^{b}	0.07	1.36	0.24	0.08	0.11	0.01	ND	0.03	0.01	0.001	0.01
T_5(POP + CS)	1.23^{a}	0.61^{b}	0.07	1.33	0.23	0.08	0.09	0.01	ND	0.04	0.01	0.001	0.01
T_6(POP + SS)	1.08^{ab}	0.64^{b}	0.05	1.44	0.23	0.07	0.10	0.01	ND	0.03	0.01	0.001	0.01
CD(0.05)	0.310	0.058	NS	NS	NS	NS	NS	NS	-	NS	NS	NS	NS

Table.67 Residual effect of rice straw incorporation on nutrient content in grain at harvest stage of second crop

Treatments	**Si**	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B	Al
	%												
T_1 (C)	2.54^{b}	0.78^{b}	0.15	0.19	0.03^{b}	0.08	0.044^{b}	0.004^{ab}	ND	0.005	0.002	0.001	0.003
T_2(POP)	2.56^{b}	0.96^{a}	0.16	0.20	0.03^{b}	0.08	0.035^{c}	0.004^{b}	ND	0.004	0.002	0.001	0.002
T_3(POP + RHA)	2.84^{a}	0.99^{a}	0.15	0.20	0.04^{a}	0.08	0.036^{c}	0.004^{ab}	ND	0.006	0.002	0.001	0.003
T_4(POP + BRH)	2.94^{a}	0.99^{a}	0.15	0.20	0.03^{b}	0.08	0.041^{b}	0.005^{a}	ND	0.004	0.002	0.001	0.003
T_5(POP + CS)	2.93^{a}	0.95^{a}	0.15	0.19	0.03^{b}	0.07	0.042^{b}	0.003^{b}	ND	0.005	0.002	0.001	0.002
T_6(POP + SS)	2.85^{a}	0.99^{a}	0.15	0.19	0.04^{a}	0.08	0.049^{a}	0.005^{a}	ND	0.005	0.002	0.001	0.004
CD(0.05)	0.210	0.064	NS	NS	0.005	NS	0.004	0.001	-	NS	NS	NS	NS

Among the treatments, the percentage of N was highest in T_4: T_2 + Biodecomposed Rice husk (0.99 per cent), T_3: T_2 + Rice husk ash (0.99 per cent) and T_6: T_2 + Sodium silicate (0.99 per cent) which were significantly superior over T_1: Absolute control (0.78 per cent) and on par with T_5: T_2 + Calcium silicate (0.95 per cent) and T_2: Fertilizer as per KAU POP (0.96 per cent).

Among the treatments, the percentage of P was highest in T_2: Fertilizer as per KAU POP (0.16 per cent). T_1, T_3, T_4, T_5 and T_6 recorded 0.15 per cent of P in grain.

The potassium content in T_1 and T_5 was 0.19 per cent; where as it was 0.18 per cent in T_2, T_3, T_4 and T_6.

The treatments had significant effect on Ca content in grain. T_3: T_2 + Rice husk ash and T_6: T_2 + Sodium silicate recorded 0.04 per cent of Ca in grain and was significantly superior over others. T_5: T_2 + Calcium silicate, T_4: T_2 + Biodecomposed Rice husk, T_2: Fertilizer as per KAU POP and T_1: Absolute control registered a Ca content of 0.03 per cent in grain.

Among the treatments, change in Mg content was negligible.

Sulphur content showed significant difference with respect to treatments. The highest S content was seen in T_6: T_2 + Sodium silicate (0.049 per cent) and was significantly superior over others, followed by T_1: Absolute control (0.044 per cent), T_5: T_2 + Calcium silicate (0.042 per cent), T_4: T_2 + Biodecomposed Rice husk (0.041 per cent), T_3: T_2 + Rice husk ash (0.036 per cent) and T_2: Fertilizer as per KAU POP (0.035 per cent). T_1 was on par with T_2, T_3, T_4 and T_5.

The iron content in grain differs significantly with respect to treatments. The highest value was recorded in T_6: T_2 + Sodium silicate and T_4: T_2 + Biodecomposed Rice husk as 0.005 per cent. T_1, T_2 and T_3 were on par with a value of 0.004 per cent. T_5 contained lower content of Fe. The micronutrients *viz.,* manganese, zinc, boron and the beneficial element aluminium didnot show much variation in their content in relation to treatments. The copper content was below detectable range.

4.3.6.4 Effect of rice straw incorporation on electrolyte leakage in leaf of rice at different growth stages

The data on effect of treatments on electrolyte leakage in leaf of rice plant at different growth stages are presented in table.68. The treatments had no significant effect on EL.

At 45 DAT, EL was found to be highest in T_4: T_2 + Biodecomposed Rice husk (64.7 per cent) followed by T_2: Fertilizer as per KAU POP (61.6 per cent), T_1: Absolute control (57.9 per cent), T_3: T_2 + Rice husk ash (57.4 per cent) and T_6: T_2 + Sodium silicate (50.6 per cent), whereas, the lowest EL was noticed in T_5: T_2 + Calcium silicate (49.5 per cent).

At 60 DAT, the highest value of EL was recorded in T_4: T_2 + Biodecomposed Rice husk (61.2 per cent) followed by T_6: T_2 + Sodium silicate (57.7 per cent), T_2: Fertilizer as per KAU POP and T_1: Absolute control (57.6 per cent) and T_3: T_2 + Rice husk ash (56.9 per cent). EL was found to be lowest (48.6 per cent) in T_5: T_2 + Calcium silicate.

The highest EL was recorded in T_2: Fertilizer as per KAU POP (61.6 per cent) followed by T_1: Absolute control (55.2 per cent), T_3: T_2 + Rice husk ash (54.8 per cent), T_4: T_2 + Biodecomposed Rice husk (54.7 per cent) and T_6: T_2 + Sodium silicate (53.4 per cent). The lowest value of EL was seen in T_5: T_2 + Calcium silicate (45.4 per cent).

4.3.6.5 Effect of rice straw incorporation on catalase activity (µmole $H_2O_2 min^{-1} g^{-1}$) in rice leaf at different growth stages

The data on effect of treatments on catalase activity in leaf of rice plant at different growth stages are presented in table.69. The treatments had no significant effect on catalase activity.

At 45 DAT, catalase activity was found to be highest in T_6: T_2 + Sodium silicate (12.7 µmole $H_2O_2 min^{-1} g^{-1}$) followed by T_5: T_2 + Calcium silicate (12.1 µmole $H_2O_2 min^{-1} g^{-1}$), T_1: Absolute control (10.8 µmole $H_2O_2 min^{-1} g^{-1}$) and T_2: Fertilizer as per KAU POP (10.7 µmole $H_2O_2 min^{-1} g^{-1}$). Among the treatments, lowest (10.1 µmole $H_2O_2 min^{-1} g^{-1}$) catalase activity was noticed in T_3: T_2 + Rice husk ash and T_4: T_2 + Biodecomposed Rice husk

At 60 DAT, the highest value of catalase activity was recorded in T_3: T_2 + Rice husk ash (21.2 µmole $H_2O_2 min^{-1} g^{-1}$) followed by T_6: T_2 + Sodium silicate (20.9 µmole $H_2O_2 min^{-1} g^{-1}$) and T_5: T_2 + Calcium silicate (20.9 µmole $H_2O_2 min^{-1} g^{-1}$), T_4: T_2 + Biodecomposed Rice husk (20.8 µmole $H_2O_2 min^{-1} g^{-1}$) and T_2: Fertilizer as per KAU POP (20.7 µmole $H_2O_2 min^{-1} g^{-1}$), whereas lowest (20.3 µmole $H_2O_2 min^{-1} g^{-1}$) was noticed in T_1: Absolute control.

At 90 DAT, the highest value of catalase activity was recorded in T_3: T_2 + Rice husk ash (16.3 µmole $H_2O_2min^{-1}g^{-1}$) followed by T_1: Absolute control (16.2 µmole $H_2O_2min^{-1}g^{-1}$) and T_2: Fertilizer as per KAU POP (16.2 µmole $H_2O_2min^{-1}g^{-1}$), T_5: T_2 + Calcium silicate (16.0 µmole $H_2O_2min^{-1}g^{-1}$), T_4: T_2 + Biodecomposed Rice husk (15.6 µmole $H_2O_2min^{-1}g^{-1}$) and T_6: T_2 + Sodium silicate (15.3 µmole $H_2O_2min^{-1}g^{-1}$).

4.3.6.5 Effect of rice straw incorporation on peroxidase activity (µmole $H_2O_2min^{-1}g^{-1}$) in rice leaf at different growth stages

The results pertaining to the effect of treatments on peroxidase activity in rice leaf at different growth stages are given in table.70. The treatments effect was significant on peroxidase activity only at 90 DAT.

At 45 DAT, peroxidase activity was found highest in T_3: T_2 + Rice husk ash (64.9 µmole $H_2O_2min^{-1}g^{-1}$) followed by T_1: Absolute control (53.3 µmole $H_2O_2min^{-1}g^{-1}$), T_6: T_2 + Sodium silicate (51.0 µmole $H_2O_2min^{-1}g^{-1}$), T_4: T_2 + Biodecomposed Rice husk (50.9 µmole $H_2O_2min^{-1}g^{-1}$) and T_5: T_2 + Calcium silicate (48.6 µmole $H_2O_2min^{-1}g^{-1}$), whereas lowest (41.8 µmole $H_2O_2min^{-1}g^{-1}$) was recorded in T_2: Fertilizer as per KAU POP.

Peroxidase activity at 60 DAT was found highest in T_3: T_2 + Rice husk ash (75.4 µmole $H_2O_2min^{-1}g^{-1}$) followed by T_5: T_2 + Calcium silicate (70.6 µmole $H_2O_2min^{-1}g^{-1}$), T_6: T_2 + Sodium silicate (66.6 µmole $H_2O_2min^{-1}g^{-1}$), T_4: T_2 + Biodecomposed Rice husk (64.5 µmole $H_2O_2min^{-1}g^{-1}$), and T_1: Absolute control (62.4 µmole $H_2O_2min^{-1}g^{-1}$). T_2: Fertilizer as per KAU POP (59.1.8 µmole $H_2O_2min^{-1}g^{-1}$) recorded the lowest peroxidase activity.

Peroxidase activity at 90 DAT was found highest in T_3: T_2 + Rice husk ash (179.3 µmole $H_2O_2min^{-1}g^{-1}$) which was significantly superior over others, followed by T_1: Absolute control (148.2 µmole $H_2O_2min^{-1}g^{-1}$), T_2: Fertilizer as per KAU POP (141.9 µmole $H_2O_2min^{-1}g^{-1}$), T_6: T_2 + Sodium silicate (130.9 µmole $H_2O_2min^{-1}g^{-1}$) and T_4: T_2 + Biodecomposed Rice husk (118.9 µmole $H_2O_2min^{-1}g^{-1}$). T_5: T_2 + Calcium silicate (108.4 µmole $H_2O_2min^{-1}g^{-1}$) recorded the lowest peroxidase activity.

Table.68 Residual effect of rice straw incorporation on electrolyte leakage (%) in rice leaf at different growth stages of second crop

Treatments	**Electrolyte leakage (%)**		
	45 DAT	**60 DAT**	**90 DAT**
T_1 (C)	57.9	57.6	55.2
T_2(POP)	61.6	57.7	61.6
T_3(POP + RHA)	57.4	56.9	54.8
T_4(POP + BRH)	64.7	61.2	54.7
T_5(POP + CS)	49.4	48.6	45.4
T_6(POP + SS)	50.6	57.7	53.4
CD(0.05)	NS	NS	NS

Table.69 Residual effect of rice straw incorporation on catalase activity in rice leaf at different growth stages of second crop

Treatments	**Catalase activity (µmole H_2O_2min^{-1}g^{-1})**		
	45 DAT	**60 DAT**	**90 DAT**
T_1 (C)	10.8	20.3	16.2
T_2(POP)	10.7	20.7	16.2
T_3(POP + RHA)	10.1	21.2	16.3
T_4(POP + BRH)	10.1	20.8	15.6
T_5(POP + CS)	12.1	20.9	16.0
T_6(POP + SS)	12.7	20.9	15.3
CD(0.05)	NS	NS	NS

Table.70 Residual effect of rice straw incorporation on peroxidase activity in rice leaf at different growth stages of second crop

Treatments	**Peroxidase activity (µmole H_2O_2min^{-1}g^{-1})**		
	45 DAT	60 DAT	90 DAT
T_1 (C)	53.3	62.4	148.2^{b}
T_2(POP)	41.8	59.1	141.9^{bc}
T_3(POP + RHA)	64.9	75.4	179.3^{a}
T_4(POP + BRH)	50.9	64.5	118.9^{de}
T_5(POP + CS)	48.6	70.6	108.4^{e}
T_6(POP + SS)	51.0	66.6	130.9^{cd}
CD(0.05)	NS	NS	16.592

Discussion

Discussion

The results obtained from laboratory studies and field investigations on silicon availability of tropical soils with respect to rice nutrition during 2011-2014 are discussed in this chapter.

Experiment 1

Representative soil samples collected from five rice growing regions of Kerala *viz.*, *Kuttanad*, *Kole* land, *Pokkali*, sandy and lateritic soils were analyzed to study the physico-chemical properties and nutrient status of the soils to categorize them according to plant available Si. These soil samples were also subjected to fractionation of Si and adsorption study.

5.1 Characterization of major rice growing soils of Kerala

5.1.1 Physico-chemical properties and available nutrient status

The data on physico-chemical properties of major rice growing soils are presented in table.6. Among different soils, *Pokkali* and *Kuttanad* soils were extremely acidic in nature. The acid release from sulfuric horizon might be the reason for the extreme acidity of these soils (Thampatti and Jose, 2000). The *Kole* land soils are very strongly acidic in reaction, whereas sandy soils of Chalakudi and lateritic soils of Pattambi come under the strongly acidic range (fig.3). Among different soils, *Pokkali* soil showed higher EC (fig.4). It might be due to seawater or brackish water intrusion into *Pokkali* field. Eventhough the *Kuttanad* and *Kole* lands aresituated below mean sea level, the bunds built on the mouth of river restrict the entry of sea water and thereby lowering the electrical conductivity. The process of laterization would have lowered the EC of lateritic soil of Pattambi which leads to leaching out of basic cations and deposition of iron and aluminium oxides on surface horizons.

Higher organic carbon content was observed in *Kole*, *Kuttanad* and *Pokkali* soils. These soils come under the soil fertility class 9 and are with high fertility status. Continuous cultivation of high yielding rice varieties followed by incorporation of rice straw into these fields and fish/prawn cultivation would lead to enrichment of organic matter in these soils. Sandy soils of Chalakudi recorded lowest organic carbon. It might be due to association of free or labile fraction of organic matter which is easily lost from light-textured sandy soils.

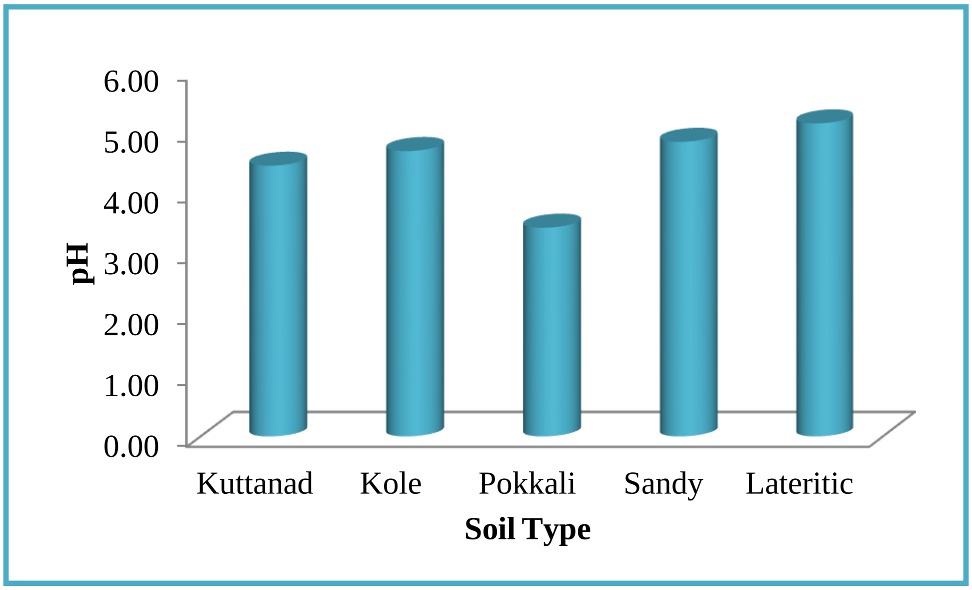


Fig.3 pH of major rice growing soils of Kerala

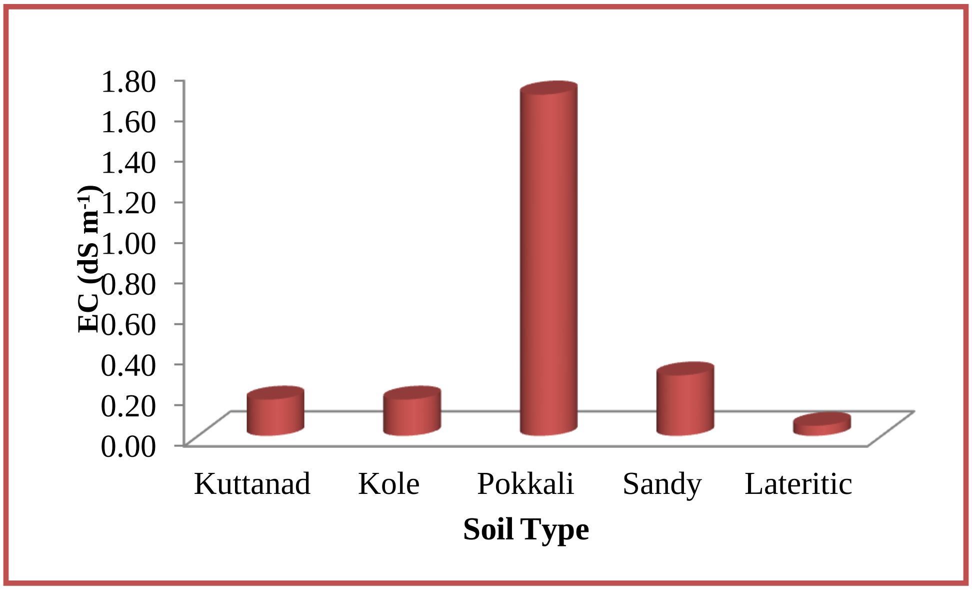


Fig.4 Electrical conductivity of major rice growing soils of Kerala

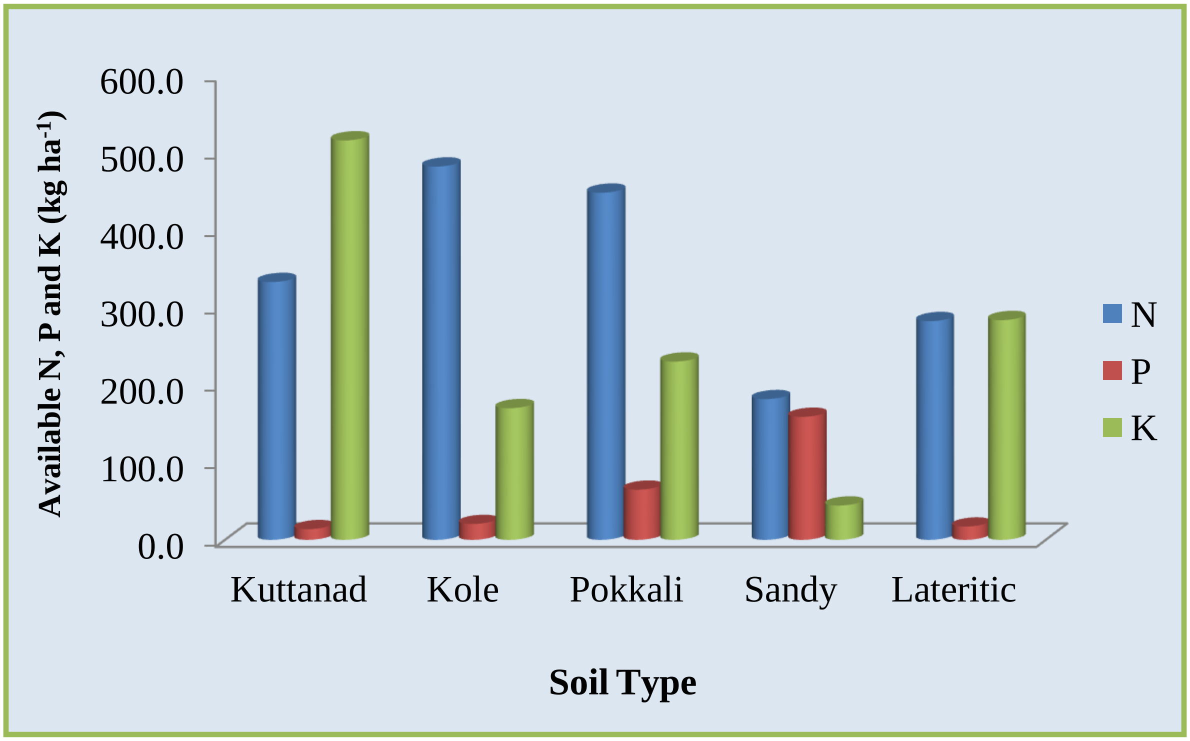


Fig.5 Primary nutrients status of major rice growing soils of Kerala

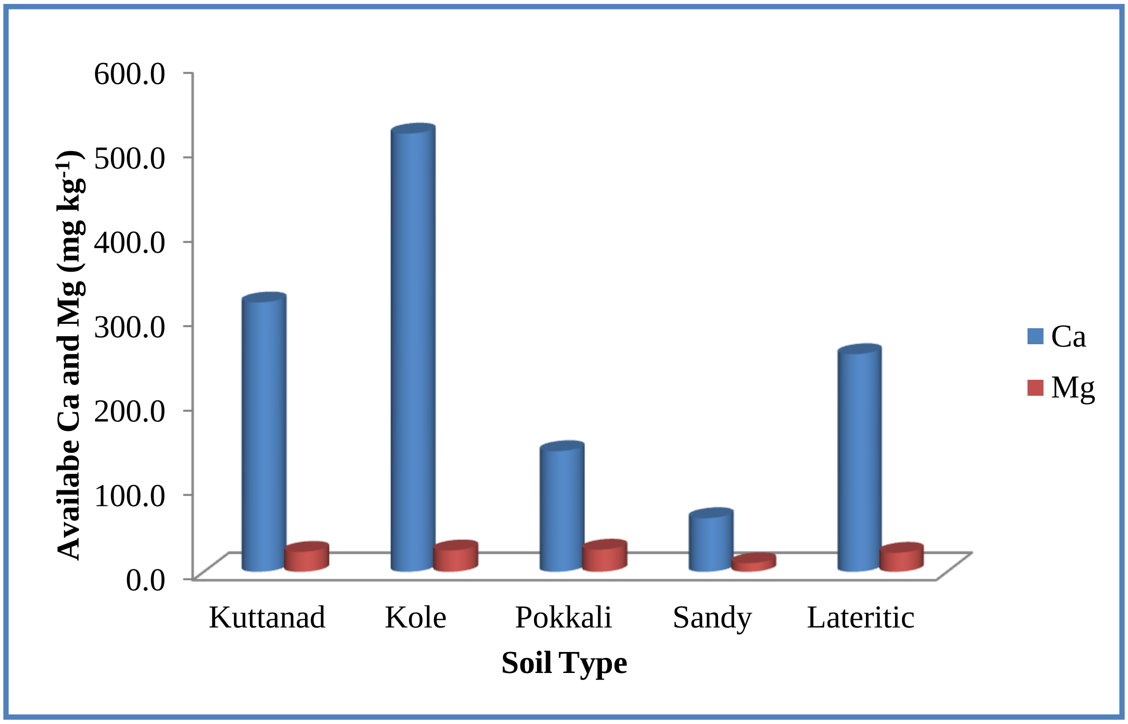


Fig.6 Available calcium and magnesium status of major rice growing soils of Kerala

The lowest CEC was noticed in sandy soils of Chalakudy and highest in *Pokkali* soils of Vyttila. Sandy soils with very little organic matter (OM) have a low CEC, but heavy clay soils with high levels of OM have a much greater capacity to hold cations. Both the clay particles and the organic matter have negatively charged sites that attract and hold positively charged particles. The lower the CEC, the faster will be the decline in soil pH with time which emphasis sandy soils need to be limed more often than clay soils. Higher CEC of *Pokkali* soils was also reported by Kuruvila (1974), Santhosh (2013) and Joseph (2014). The highest AEC was recorded in sandysoils of Chalakudy and the lowest in *Kole* lands. *Kole* and *Kuttanad* soils are clayey soils with more of 2:1 clay mineral. Soils containing montmorillonite generally exhibit low AEC.   Dean and Rubins (1947) reported that the sandy soils which do not have excess amount of Ca or Mg, substitute phosphate ion for hydroxyl ion. An appreciable amount of AEC may occur only on those soils containing high amounts of Al and Fe oxides or hydroxides with low amounts of soil organic substances. This may be the reason for higher AEC of sandy soils of Chalakudi. The highest silica: sesquioxide ratio was recorded in sandy soils of Chalakudy and the lowest in *Kole* lands. This could be ascribed due to the presence of higher amount of silicate minerals in sand fraction.

The data on nutrient status of major rice growing soils are presented in table.7 and fig.5, 6, 7 and 8. The highest available N was found in *Kole* land soil followed by *Pokkali* and *Kuttanad* soils. It might be due to the presence of more organic carbon in these soils. The available N showed significantly positive correlation with organic carbon. The available N statusof *Kole, Kuttanad, Pokkali* and lateritic soils were in medium range. The sandy soils of Chalakudi with low organic carbon recorded the lowest available N. The interdependence of available N with soil organic carbon has been reported by many researchers. The available P wasfound highest in sandy soils of Chalakudy which can be ascribed due to continuous application of P-fertilizers and less P-fixation. *Kole, Kuttanad* and *Pokkali* soils are rich in hydroxides of iron and aluminium besides being clayey in texture. Due to large surface area of these hydroxides, P gets fixed and become less available (Thampati, 1997). As kaolinite is the dominant clay in lateritic soil, there is more chance of phosphate adsorption and less release of soluble P into soil solution (Rajan and Rao, 1978). The available P status of *Kole, Kuttanad* and lateritic soils are in medium range and that of *Pokkali* and sandy soils are in high range (fig.5).

The lowest available K was recorded in sandy soils of Chalakudy and the highest in *Kuttanad* soils (fig.5). Potassium was deficient in sandy soils. *Kole* and *Pokkali* soils were medium in available K, whereas *Kuttand* and lateritic soils were high in available K. Fine textured soils possess larger amounts of available K compared to coarse textured sandy (Chalakudi) soils. Even though K fixation is reported more in 2:1 type clay minerals, thedominant form in *Kuttanad* soils, the available K was more in this soil. It may due to the less adsorption of K by montmorillonite under submerged condition.

Available calcium was very low in sandy soils of Chalakudy and *Pokkali* soils of Vyttila. Lateritic soils are medium in available Ca status. The nature of clay minerals influences the availability of Ca in soils. Highest available Ca was estimated in *Kole* land soil followed by *Kuttanad* soil where 2:1 type clay minerals are present. Major rice growing tracts of Kerala were found to be deficient (<120 mg kg^{-1}) in available magnesium. The soils with low pH and CEC and high levels of K or Ca decrease Mg availability to the crop. Leaching due to heavy rainfall also may cause low availability of Mg in soil (fig.6).

Iron content was very high in all the soils (fig.7). Presence of oxides and hydroxides of iron and leaching of basic cations from the surface layers of the soils due to heavy rainfall maybe the reason for high available Fe contents in these soils. Sandy soils of Chalakudy were deficient in available Mn (fig.8). Remaining soils are sufficient in available Mn. Lateritic soil recorded the highest value of available Mn. The lowest value of available Zn was recorded in sandy soils of Chalakudy and the highest in *Pokkali* soils of Vyttila (fig.9). All soils are sufficient in available Zn. The lowest available copper was recorded in *Pokkali* soils and highest in lateritic soils of Pattambi (fig.10). Sandy, *Kuttanad* and *Pokkali* soils were deficient inavailable Cu with a value of < 1.0 mg kg^{-1}. Copper is retained very strongly in organic soils and such in soluble complexes are responsible for low availability of Cu in *Pokkali* and *Kuttanad* soils which are rich in organic matter. The available boron was ranged from 0.03 to 0.31 mg kg^{-1}.All soils were deficient in available boron. Higher value of available B in *Pokkali* and sandysoils might be due to sea/river water intrusion into these areas.

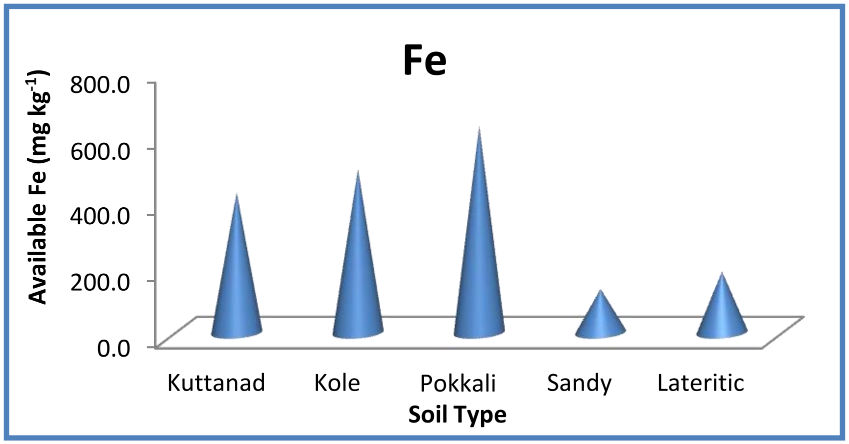


Fig.7 Available Fe status of rice growing soils of Kerala

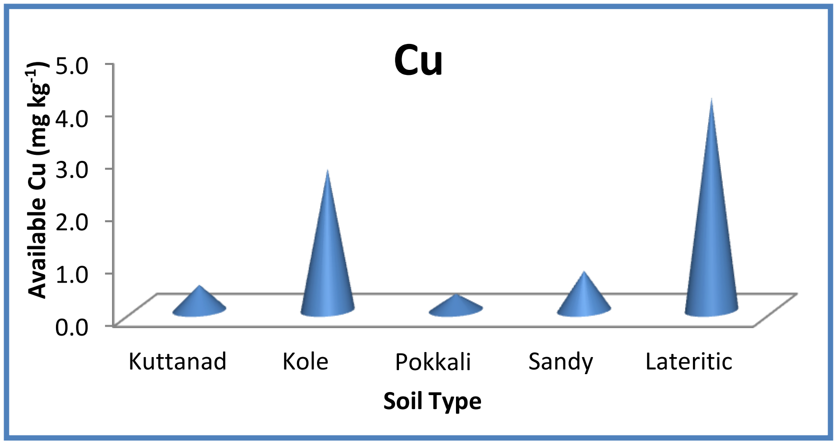


Fig.8 Available Cu status of rice growing soils of Kerala

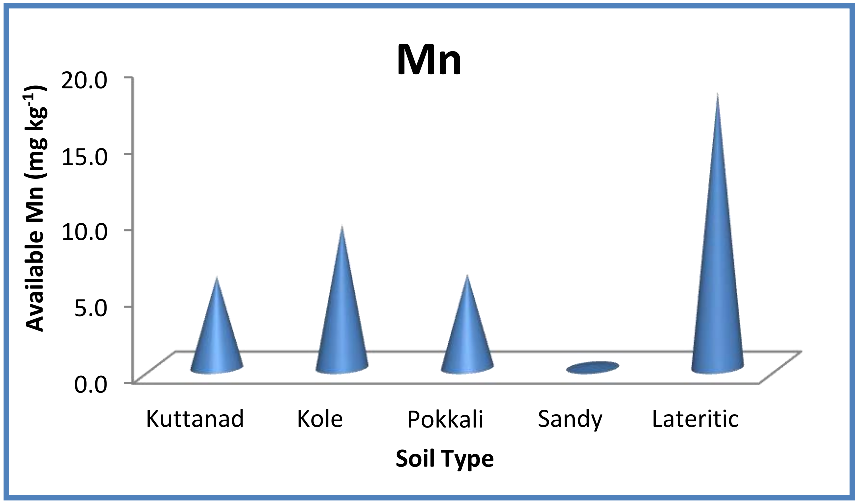


Fig.9 Available Mn status of rice growing soils of Kerala

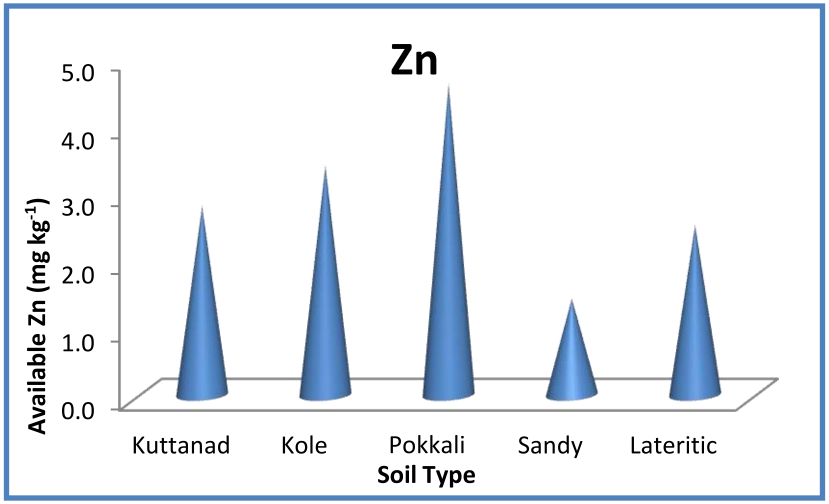


Fig.10 Available Zn status of rice growing soils of Kerala

5.1.2 Exchangeable cations, cation exchange capacity

In all soils except sandy soils of Chalakudi, the most dominant cation in exchangeable site was calcium, whereas exchangeable Na was the dominant cation in sandy soils. The reasons for low values of exchangeable Ca in sandy soils could be that the parent material on which soil has developed is poor in bases (Tomasic *et al*., 2013)

The order of dominance of exchangeable cations was Ca > Mg > Na > Al > K in *Kuttanad* soil, Ca > Mg > Na > Al = K > Mn in *Kole* land soil, Ca = Na > Al > Mg > K > Fe in *Pokkali* soil, Na > Ca > Mg > K > Al in sandy soil, and Ca > Mg > Na > K > Al in lateritic soils.Exchangeable Cu, Fe, Mn and Zn were very much negligible in quantity. In *Pokkali* soil,exchangeable Ca and exchangeable Na were estimated in equal quantity. Santhosh (2013) also reported higher quantity of exchangeable Na in *Pokkali* soil.

Sand fraction in soils ranged from 21.55 to 89.20 per cent. The highest value of sand was estimated in sandy soils and the lowest in *Kuttanad*. Silt fraction ranged from 5.10 per cent in sandy soils to 33.53 per cent in *Kuttanad* soils. The lowest clay content of 5.7 per cent was recorded in sandy soils and the highest value of 45.98 per cent was recorded in *Kole*. *Kuttanad* and *Kole* land soils were clayey in texture, whereas *Pokkali* soils were loamy in nature. Chalakudi soil was sandy and lateritic soil of Pattambi was sandy loam in texture.

5.1.3 Plant Available Silicon

The plant available silicon (PAS) ranged from 7.70 mg kg^{-1} in sandy soils to 34.91 mg kg^{-1} in *Kole* land soil (table.7 and fig.11). All rice growing soils under study were found to be deficient in plant available Si (< 47 mg kg^{-1}) (Narayanaswamy and Prakash, 2009). As wetland rice soils are concerned, soil Eh and organic matter are important factors that influence Si in soil solution. Ponnamperuma (1965) reported a marked decrease in soil Eh and concurrent increase insolubility of soil Si with submergence time. This increase in Si has attributed to its release from ferrisilica complex under reducing soil conditions. Srivastava *et al.* (1994) reported that due to desilication in soils of humid tropical climates, silica is highly depleted. In warm subhumid and humid tropical ecoregions, a high degree of weathering, mainly as desilication, has resulted in

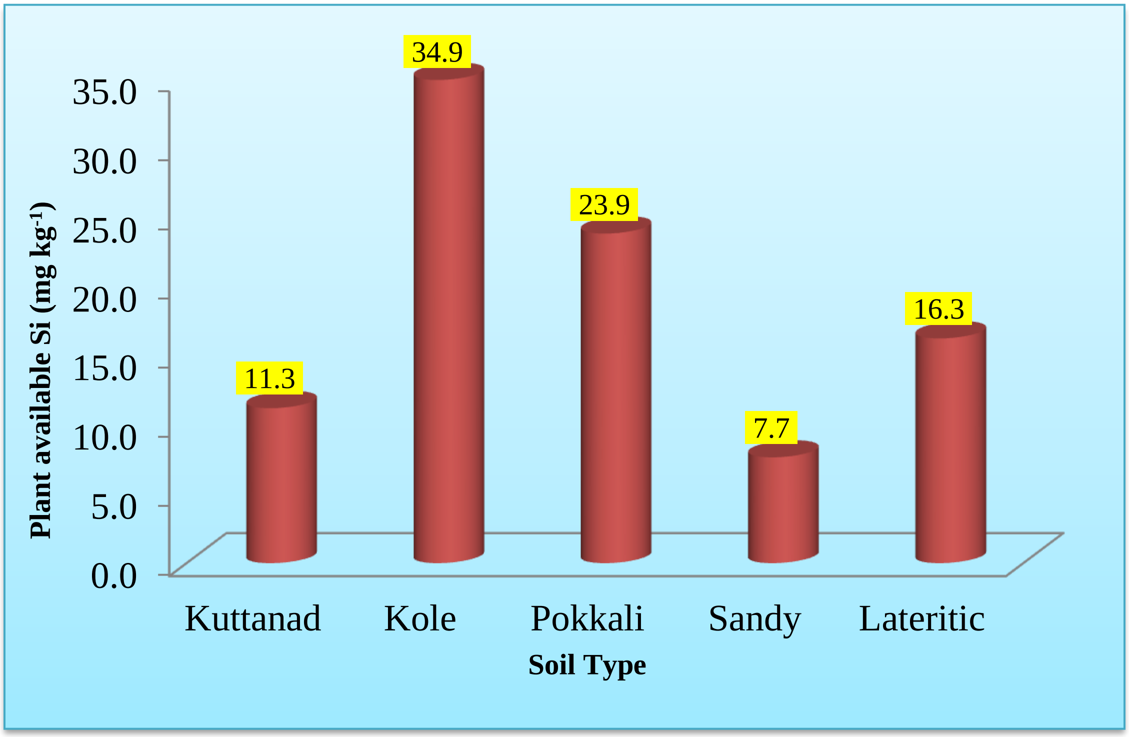


Fig.11 Plant available Si status of major rice growing soils of Kerala

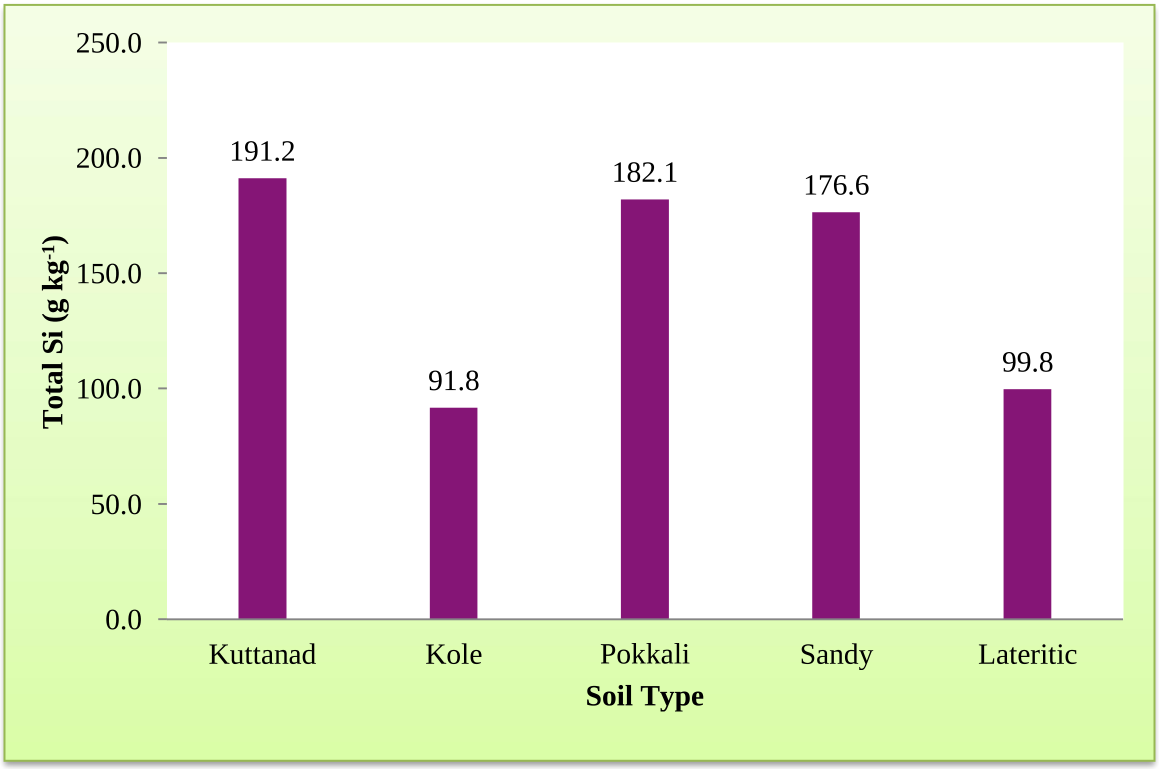


Fig.12 Distribution of total Si in major rice growing soils of Kerala

the development of soils rich in iron and aluminum oxides and low in nutrient bases and Si. This could be one of the reasons for low available Si in major rice growing tracts of Kerala. As a result of Si leaching, the soluble Si content of tropical soils, such as Ultisols and Oxisols, is generally 5 to 10 times less than in most temperate soils (Friesen *et al.*, 1994). Savant *et al*. (1997) reported that Si depletion can occur in traditional rice soils from continuous monoculture of high yielding cultivars with intensive cultivation practices, especially if farmers are not replacing the Si removed by rice.

Despite Si being one of the most abundant elements and found in most soils in substantial quantities, various classes of soils, mainly sandy ones, are low in available Si (Marschner, 1995). Clay soils with higher concentrations of phyllosilicates (minerals that release Si and Al^{3+}) show higher concentration of Si than sandy soils. Although the sand fraction consists mostly of quartz (SiO_2), the chemical decomposition of this mineral is complex, which makes sandy soils more responsive than clay soils to silicate application (Dematte *et al.*, 2011).

The results of the present study are in agreement with those of Nayar *et al*. (1982). They revealed that the available Si extracted by different extractants in soils of Kerala ranged from 8 to 435 mg kg^{-1}. Subramanian and Gopalaswamy (1991) reported that the soils of Coimbatore (Tamilnadu) contained 29 to 80 mg kg^{-1} available Si. Nayar *et al.* (1977) reported that the available Si extracted by NaOAc ranged from 8 to 278 mg kg^{-1} in soils of Orissa. Gontijo (2000) observed that soil Si values decreased with increased content of the sand in the soil. He further found that a soil having high percentage of sand tends to show low available Si contents due to their poor capacity to supply Si to plants.

5.1.4 Correlation between plant available Si and soil parameters

The correlation coefficient for plant available silicon with electrochemical properties and other nutrient elements are given in the table.12. The available Si had significant positive correlation with organic carbon, available nitrogen, available calcium, available magnesium, available iron, available zinc, available manganese, exchangeable potassium, exchangeable calcium, exchanageable magnesium and cation exchange capacity. McKeague and Cline (1963b) reported that substitution of Mg, Ca and K into silica lattice weakens silicate minerals, making them weather more easily and release more Si into soil solution. Fifty six years of experiments shows that the continuous application of rice straw compost and silica fertilizer has revealed a significant impact on increasing OM and available silica contents in surface and subsurface soils (Kim *et al*., 2010). Lalljee (2008) also reported that the soil Si is positively correlated with several soil parameters. Mongia and Chhabra (2000) reported a positive correlation of silica with extractable iron in alkali soils. The available boron, anion exchange capacity and silica: sesquioxide ratio had significant negative correlation with available Si. Phonde *et al.* (2014) reported that plant available Si content in soil increased with pH, clay content, exchangeable cations and cation exchange capacity of the soil.

A stepwise regression analysis including all the parameters that were significantly correlated with plant available silicon (PAS) finally yielded the following equation.

1. PAS = -28.588 + 118.684** Ex. K ($R^2 = 0.917$)

2. PAS = -30.464 + 159.149** Ex. K – 0.663**Mg ($R^2 = 0.966$)

3. PAS = -47.205 + 190.378** Ex. K – 0.631**Mg + 0.520** SiO_2/R_2O_3 ($R^2 = 0.986$)

The above equations clearly indicate the effects of Ex. K, available Mg and SiO_2/R_2O_3 in governing the availability of plant available Si in soil solution. It clearly indicates that exchangeable potassium is the single most important factor in predicting plant available Si status in soil by explaining 91.7 per cent variability.

5.1.5 Total Si

The highest total Si was recorded in *Kuttanad* soil followed by *Pokkali* and Sandy soils of Chalakudi (fig.12). *Kole* land soil recorded the lowest total Si. *Kuttanad* is located below mean sea level where all marine sediments are deposited through backwater/sea water intrusion. Soils in this area had vast organic deposits through monoculturing of rice throughout year. They would have also developed from silicate minerals. All these factors could have contributed to thehighest total Si in *Kuttanad* soil. Though, *Kole* land soil is similar to *Kuttanad* soil in several aspects; *Kole* land soil recorded the lowest total Si in the present study. Even though theconcentration of total Si was very high in all these soils, plant available Si concentration wasvery much low. It fingers out that the dissolved or plant available Si in soil is a part of dynamic system. A large variety of Si fraction may occur in all the soils. The amount of available Si for plant uptake depends on pools and fluxes of these Si fractions present in soil.

The results of categorization of major rice growing soils of Kerala showed that theamount of plant available Si present in these soils had good correlation with various physico- chemical properties and available and exchangeable nutrients. Even though the concentration of total Si was very high in all these soils, plant available Si concentration was very much low. It finger out that the dissolved or plant available Si in soil is a part of dynamic system. A large variety of Si fraction may occur in the soil. The amount of available Si for plant uptake depends on pools and fluxes of these Si fractions present in soil. Therefore, quantification of Si pools is needed for better understanding of biogeochemical processes involving in the availability of Si insoil-water-plant system. Such quantification requires a sequential extraction method for various Si fractions in soil. An attempt was done to know the different fractions of Si present in these soils and results are presented below.

5.1.5. Fractionation of Silicon in soil

Five soil samples, representing major rice growing regions of Kerala were subjected to sequential extraction of fractions of silicon in soil. The data on Si fractions in the major rice growing regions of Kerala represented in table.10 are discussed below.

According to Danilova *et al*., (2010), a large variety of silicon fractions may occur in soils. Soil particles can adsorb dissolved silicic acid from the soil solution. Silica can also be a part of sesquioxides or remain bound to organic matter. Amorphous silica exists in the form of biogenic (e.g. phytoliths) and minerogenic opal (e.g. silica cutans). Moreover, Si in the form of dissolved silicic acid is retained in the soil solution. In addition, many primary and secondary crystalline silicates (e.g. quartz, feldspar, micas and clay minerals) are also generally found in soils. The fractions of Si obtained in this present study were mobile, adsorbed, organic, occluded,amorphous and residual Si.

Mobile Si (Mob-Si)

This fraction represents the immediately available Si fraction of the readily soluble Si pool. The highest value of mobile Si was recorded in *Pokkali* soils of Vyttila and the lowest

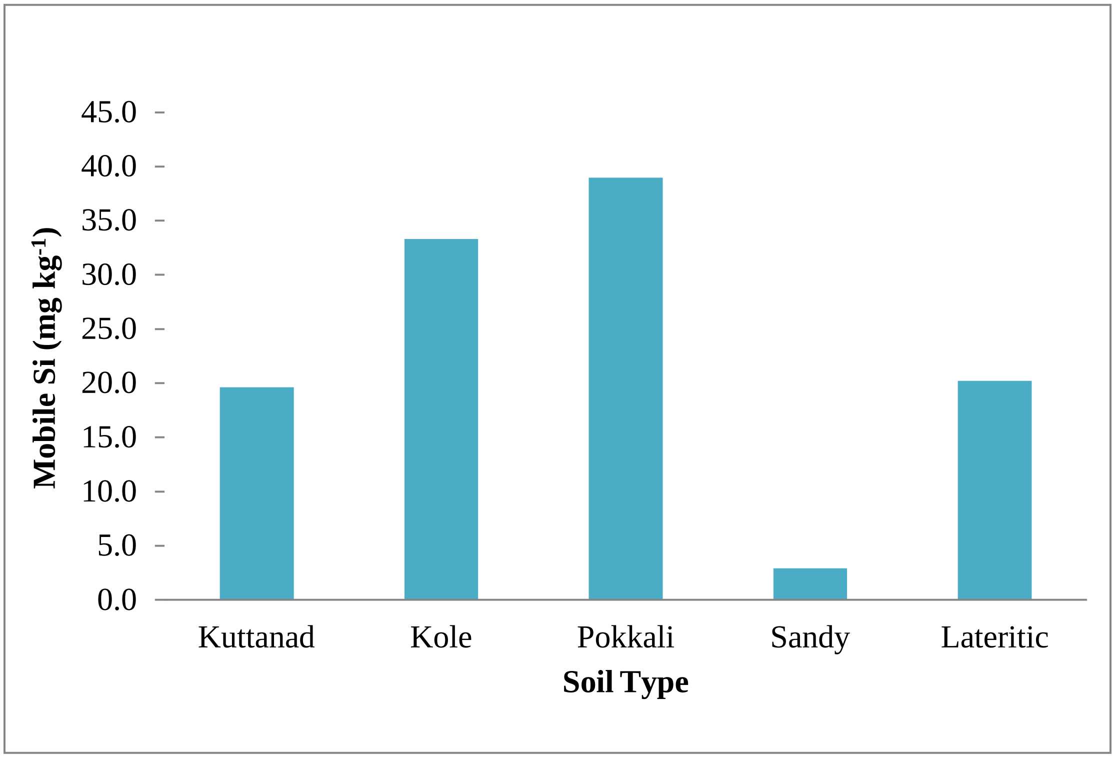


Fig.13 Distribution of mobile Si in major rice growing soils of Kerala

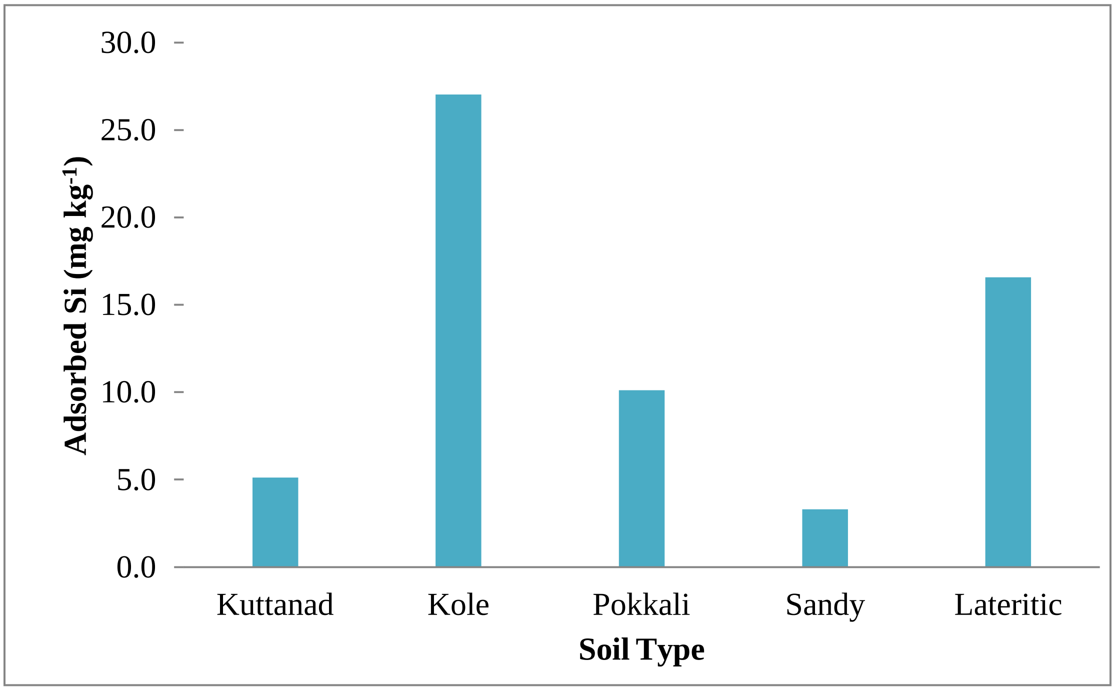


Fig.14 Distribution of adsorbed Si in major rice growing soils of Kerala

value was recorded in sandy soils of Chalakudy (fig.13). The Kole soils also showed high value of mobile silicon. *Pokkali*, *Kole*, *Kuttanad* and lateritic soils have clay content more than 20 per cent showed higher concentration of mobile Si than sandy soil. These results are in agreement with findings of Georgiadis *et al*. (2013) who reported highest mobile Si concentrations in soils of SW-Germany which have clay concentration exceeding 20 per cent. The clay mineral surface would act as a major source of mobile Si. This could be the reason for higher concentration of mobile Si in *Pokkali* and *Kole* land soils noticed in the present study.

The plant available Si had significant positive correlation with mobile Si which in turn was significantly and positively correlated with silt, EC, OC, CEC, available N, Mg, Fe, Zn, Exchangeable Na, K, Ca, Mg and Al. Sand, pH, AEC, SiO_2/R_2O_3 and available B had significant negative correlation with mobile Si in soil. The significant positive correlation of organic carbon with mobile Si revealed that a major proportion of mobile Si was present in organic layer and topsoil (Georgiadis *et al.*, 2013). This is confirmed with the findings of Morsy (2008). McKeague and Cline (1963b) reported that the amount of mobile silicon decreased with increasing pH. The percentage distribution of mobile Si was very low in all soils (0.002 to 0.036per cent). Danilova *et al.* (2010) also reported that amount mobile Si was very small in soil of SW Germany. Cornelis *et al.* (2011) reported that $CaCl_2$-extractable Si content represents a very small amount of the Si pool (0.3 - 1.7 per cent) in forest soils of France.

A stepwise regression analysis including all the parameters significantly correlated with mobile Si finally yielded the following equation.

1. Mob-Si = -11.23 + 11.65**Zn (R^2= 0.922)
2. Mob-Si = -25.48 + 7.785**Zn + 64.109** Ex. K (R^2= 0.989)

The above equations clearly indicate that zinc is the single most important factor in predicting mobile Si status, explaining 92.2 per cent variability.

Adsorbed Si (Ad-Si)

Adsorbed Si is the main immediate insoluble source of Si in soil solution. This fraction constituted the silicic acid adsorbed by the soil minerals *viz.*, smectite, gibbsite, goethite, kaolin etc. Silicon is chemically adsorbed at surfaces of soil constituents like carbonates, hydroxides and oxides (McKeague and Cline, 1963a). Iron and Al hydroxides especially play a key role in the interaction between the solid and liquid Si phases in soils. Sorption onto mineral surfaces is related to the amount, type, size, and crystallinity of Fe oxides and Al hydroxides. At Fe oxide surfaces, polysilicic acid might be formed from orthosilicic acid the latter of which is the dominant species in soil solutions with $pH < 8$ (Dietzel, 2002). The interaction of monosilicic acid with solid surfaces can be described as a surface complexation, and polymerization of polysilicic acid at the mineral surface is likely to occur under acidic conditions (Dietzel 2002). Sauer *et al.* (2006) reported that acetic acid (CH_3COOH) and some acetates (particularly $CH_3COO^{-}NH_4{}^{+}$, $CH_3COO^{-}Na^{+}$), are used to remove soluble Si and some of the exchangeable Sifrom soils. Under alkaline conditions the monosilicic acid may polymerize and adsorb to the mineral surfaces as polysilicic acid or precipitate. Higher extraction efficiency of acetic acid for soil and clay mineral samples indicated that desorption efficiency was pH-dependent (Georgiadis*et al.*, 2013).

The highest value of adsorbed Si was recorded in *Kole* land soil and the lowest in sandy soils of Chalakudy (fig.14). The soils of *Kuttanad* also showed lower value of adsorbed Si. The adsorbed Si also constituted very small per cent to total Si. This result was confirmed with the findings of Danilova *et al.* (2010). The adsorbed Si had significant positive correlation with clay, available N, Ca, Mg, Mn, exchangeable K and Ca content of soils, but had significant negative correlation with EC, AEC, SiO_2/R_2O_3 and available B. The plant available Si had significant positive correlation with adsorbed Si. The significant negative correlation of adsorbed Si with AEC and positive correlation with clay content of soil obtained in the present study is in agreement with the findings of Georgiadis *et al.* (2013).

A stepwise regression analysis including all the parameters that were significantly correlated with adsorbed Si finally yielded the following equation.

1. $\text{Ad-Si} = 6.819 + 0.225^{**}\text{Mn}$ $(R^2= 0.825)$
2. $\text{Ad-Si} = 13.153 + 0.162^{**}\text{Mn} - 0.693^{**}\ SiO_2/R_2O_3$ $(R^2= 0.973)$
3. $\text{Ad-Si} = 19.513 + 0.180^{**}\text{Mn} - 0.854^{**}\ SiO_2/R_2O_3 - 0.016^{**}\text{N}$ $(R^2= 0.994)$

The above equations clearly indicated that manganese was the single most important factor in predicting adsorbed Si status explaining 82.5 per cent variability.

Organic Si (Org-Si)

Si in soil organic matter (SOM) was obtained through destruction of SOM. The lowest value of organic Si was recorded in sandy soils of Chalakudy and the highest in *Pokkali* soils of Vyttila (fig.15). The highest organic Si recorded in *Pokkali* soils explains the clear role of organic matter in the retention of Si which in turn has a positive significant correlation with CEC. *Kuttanad, Kole* land and lateritic soil also recorded higher concentration of organic Si. The percentage distribution of organic Si ranged from 0.021 to 0.454 per cent. The plant available Si had no significant correlation with organic Si. Silt, EC, OC, CEC, available N, Mg, Fe, Zn, exchangeable Na, K, Ca, Mg and Al were positively correlated with organic Si, while pH and SiO_2/R_2O_3 were negatively correlated with this fraction of Si. The significant positive correlation of organic Si with organic carbon revealed that this fraction was associated with soil organic matter. Significant positive correlation of CEC, exchangeable Na, K, Ca, Mg and Al withorganic Si could be due to direct effect of soil organic matter. This could be the reason for higher concentration of organic Si in *Pokkali, Kuttanad* and *Kole* land soils.

A stepwise regression analysis including all the parameters that were significantly correlated with organic Si finally yielded the following equation.

1. Org. Si = -228.256 + 219.864**Zn ($R^2 = 0.841$)
2. Org. Si = -130.396 + 349.428**Zn – 1.385**N ($R^2 = 0.920$)
3. Org. Si = -205.512 + 575.443**Zn -2.776**N -223.672**EC ($R^2 = 0.990$)

The above equations clearly indicated that zinc was the single most important factor in predicting organic Si status explaining 84.1 per cent variability.

Occluded Si (Occl-Si)

It is the fraction of Si which is associated with pedogenic oxides and hydroxides in soil. This content of Si is bound to poorly crystalline constituents (allophane and imogolite). Pedogenic oxides and hydroxides that are abundant in soils play an important role in adsorption, occlusion and release of silicic acid in soils. The highest value of occluded Si was found in *Kole* and the lowest in sandy soil. The presence of aluminium and iron oxides and hydroxidesdecrease the amount of silicon in soil solution (Jones and Hendreck, 1967). This might be the

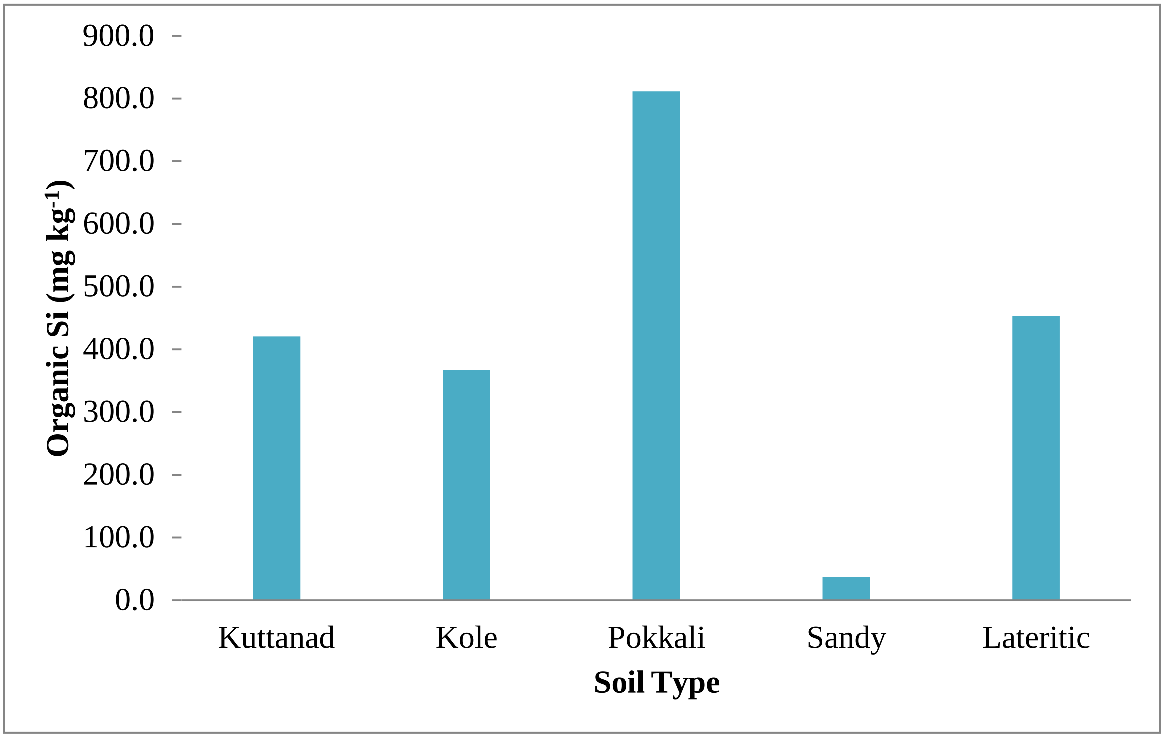


Fig.15 Distribution of organic Si in major rice growing soils of Kerala

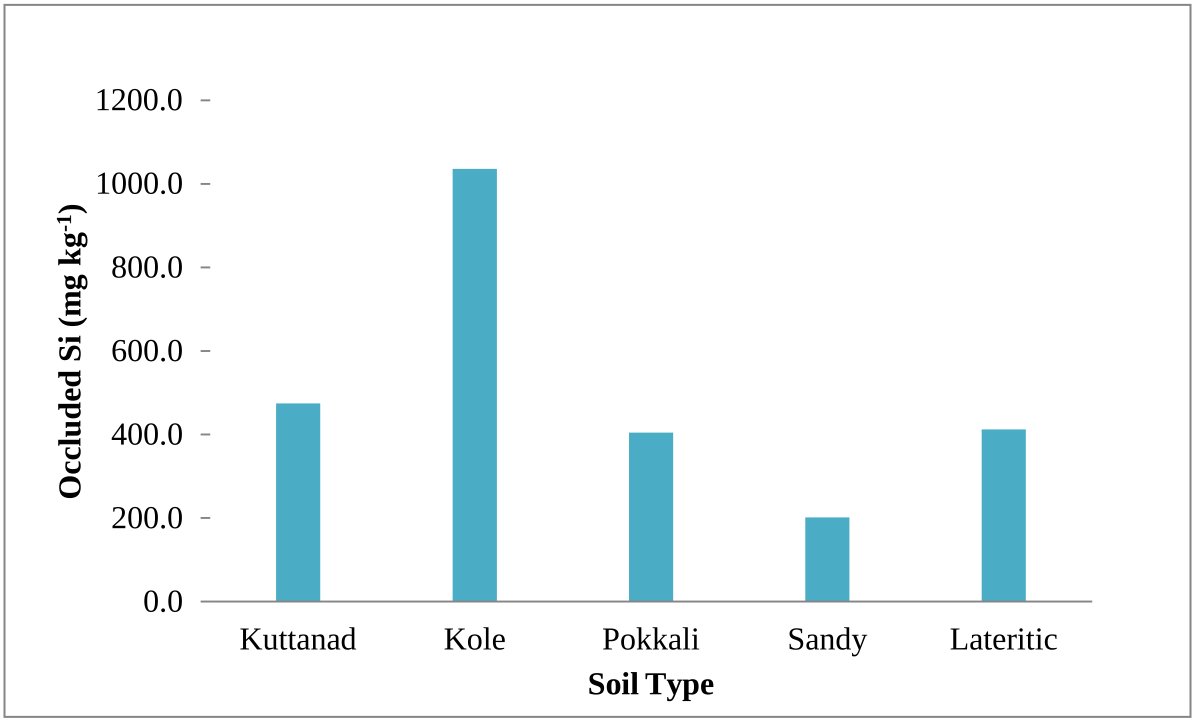


Fig.16 Distribution of occluded Si in major rice growing soils of Kerala

reason for higher concentration of occluded Si obtained in *Kole* land soil in this study. It constituted 0.11 to 1.13 per cent of total Si (fig.16).

Danilov *et al.* (2010) reported that the amounts of Si occluded in sesquioxides are very small in the upper horizons of all pedons and that increased with depth. In this study, occluded Si had significant positive correlation with plant available Si, clay, OC, available N, Ca, Mg, Mn, exchangeable K, Ca and Mg significant negative correlation with sand, AEC, SiO_2/R_2O_3 and available B. Goldberg and Glaubig (1988) reported that silicon adsorption was much greater than B adsorption indicating that some of the sorption sites showed anion preference. He also reported that soil Si content tends to be decreased with time lapse because of processes such as occlusion and adsorption onto Al and Fe oxides. Also, monosilicic acid reacts with Al and forms slightly soluble aluminosilicates. The adsorption of dissolved silica depends on the chemical composition of the solution, the mineral surface and also on the nature of the dissolved silica (Dietzel, 2002). Here the available and exchangeable Ca showed a significant positive correlation with occluded Si. Adequately, it is supported by the results of Alvarez *el al.,* (1976) who stated that Si adsorption was weak on gibbsite in the absence of Ca. There were specific interactions of Ca, silicate and phosphate ions with surface hydroxyls of gibbsite.

A stepwise regression analysis including all the parameters significantly correlated with occluded Si finally yielded the following equation.

1. Occl-Si = 314.587 + 7.660**Mn (${R^2} = 0.912$)
2. Occl-Si = 518.245 + 6.584**Mn – 3.545**Sand (${R^2} = 0.990$)

The above equations clearly indicated that manganese was the single most important factor in predicting occluded Si status explaining 91.2 per cent variability.

Amorphous Si (Am-Si)

The amorphous silica pool includes pedogenic and biogenic silica. Pedogenic amorphous silica corresponds to the non-crystalline inorganic fraction, such as opal formed at supersaturated soluble Si levels, volcanic glasses, and opal coatings on secondary minerals. The biogenic silica pool in soil is comprised of phytoliths and microorganism remains *viz*., diatoms and sponge spicules (Sauer *et al.* 2006; Sommer *et al*. 2006). Phytoliths are hydrous amorphous silica (opal-A; SiO_2. nH_2O) that polymerizes in plants and can return to the topsoil within organic.

The deposition of diatoms, plant debris and sediments during incoming tide results in an import of amorphous Si (ASi) to tidal marshes. Especially young marshes that frequently inundate and still increase in elevation, act as a sink for ASi. It includes diatom and plant bound biogenic Si (BSi) and products of various binding processes such as formation of allophanes, precipitation on mineral surfaces, chemical adsorption on surfaces of carbonates, aluminum hydroxides and iron hydroxides or the formation of polysilicic acid on Fe oxidate surfaces. Part of the ASi is dissolved again to DSi and becomes available for plants and diatoms via the soil pore water (Jacobs *et al.,* 2013). The rate at which Si is released from plant litter is independent of cellulose hydrolysis, which suggests that most of the litter-Si is contained in the phytoliths asa pure ―inorganic‖ pool, and not complexed with organic matter (Fraysse *et al.,* 2009).

The lowest amorphous Si was recorded in sandy soils and highest in lateritic soils of Pattambi (fig.17). The occurrence of pedogenic iron oxides and hydroxides in lateritic soil could be the reason for highest concentration of amorphous Si in Pattambi soil. *Kuttanad, Kole* and *Pokkali* soils recorded higher concentration of amorphous Si. It might be due to litter deposition and presence of humus layer consists of phytoliths in these soils capable of adsorbing Si. The amorphous Si found to constitute 2.21 to 62.73 per cent of total Si. The percentage distribution of amorphous Si was more in *Kole* and lateritic soils. It was the second largest fraction in soil. This result is supported by the findings of Danilova *et al.* (2010) who reported that Si extracted by and NaOH (amorphous silicon) constituted the largest fraction of extractable Si in almost all soil samples of SW Germany.

There was a significant positive correlation of clay and negative correlation of AEC and SiO_2/R_2O_3 with amorphous Si. Available Ca, Mg, exchangeable K, Ca and Mg were positively correlated with amorphous Si. Sauer and Burghardt (2006) reported that amorphous Si rises with increasing amount of water soluble Mg. Although these correlations may not necessarily indicate a causal relationship, it suggests that Mg enhances the precipitation of amorphous silica. This relationship was to be expected, due to the decreasing solubility of amorphous silica with decreasing pH. They conclude that not only the chemical conditions, but also the water dynamics play an important role in the formation and distribution of amorphous silica in a soil profile.

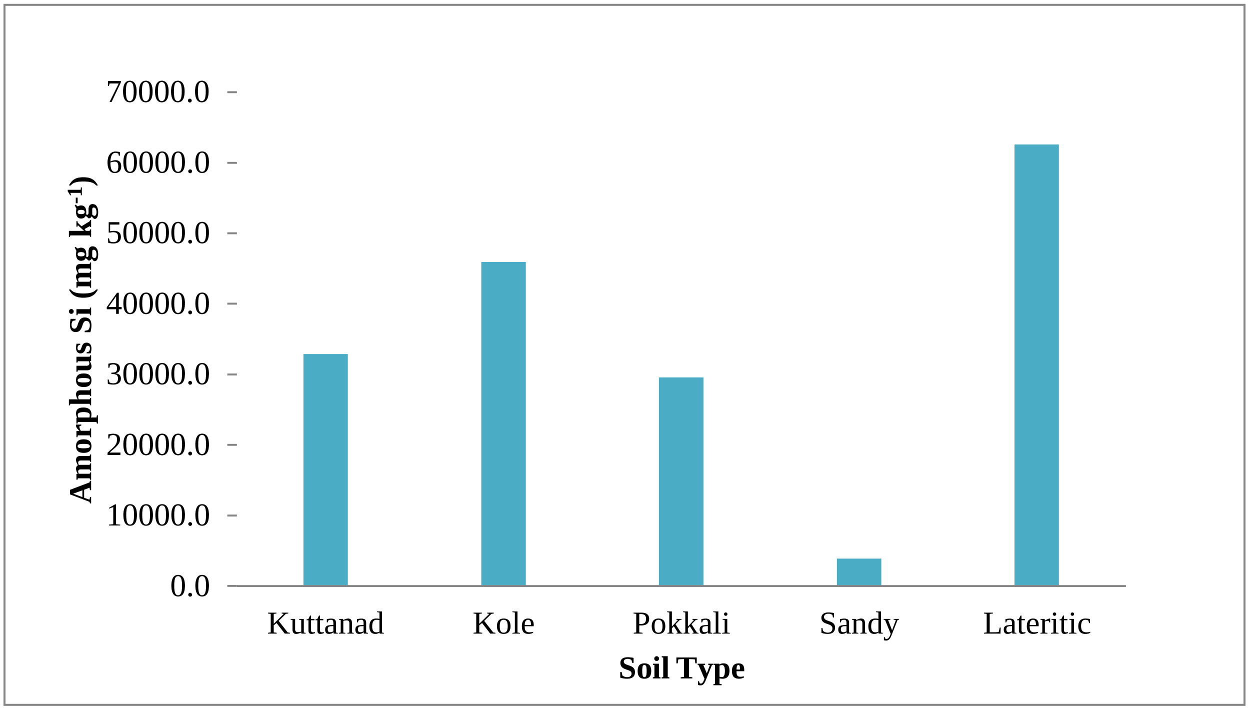


Fig.17 Distribution of amorphous Si in major rice growing soils of Kerala

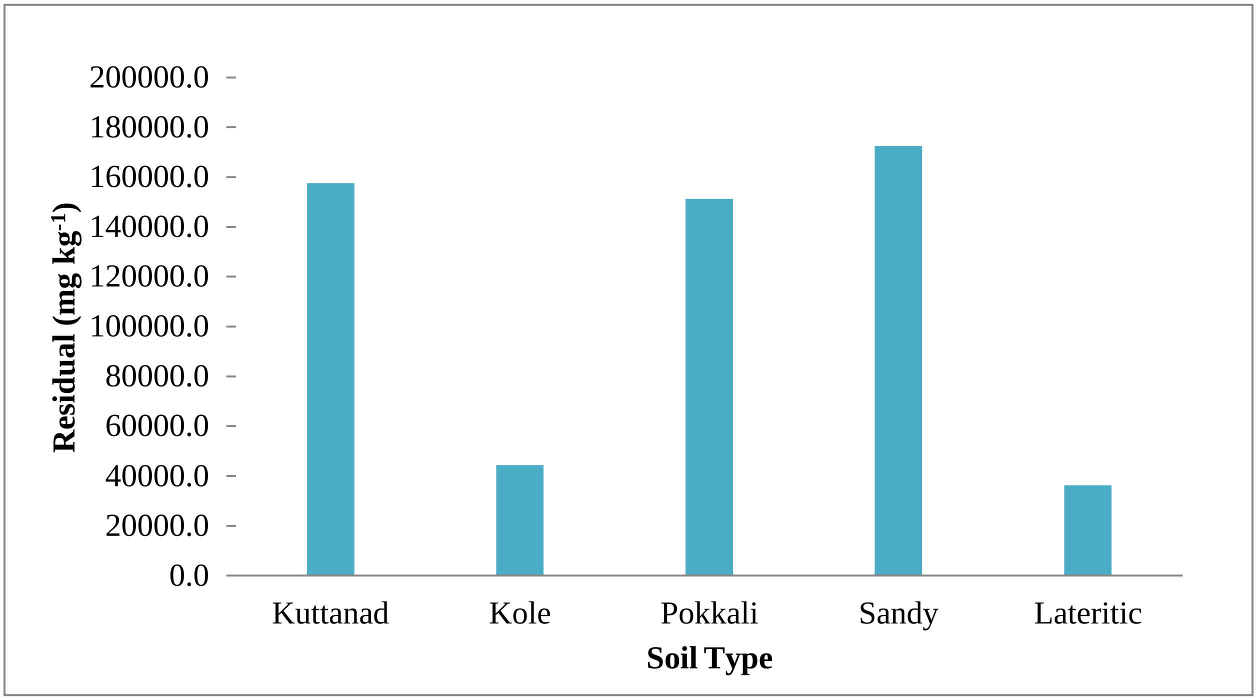


Fig.18 Distribution of residual Si in major rice growing soils of Kerala

A stepwise regression analysis including all the parameters correlated significantly with amorphous Si finally yielded the following equation.

1. Am-Si = 54525.912 – 2834.211** $SiO_2:R_2O_3$ ($R^2 = 0.648$)
2. Am-Si = 37873.301 – 2329.994** $SiO_2:R_2O_3$ + 448.395** Clay ($R^2 = 0.735$)
3. Am-Si = -175959.78 – 6738.5** $SiO_2:R_2O_3$ + 2656.6** Clay + 49551.96**AEC ($R^2 = 0.917$)
4. Am-Si = -127596.17 – 7482.6** $SiO_2:R_2O_3$ + 3475.9** Clay + 45905.6**AEC – 16360.9**Ex. Ca ($R^2 = 0.990$)

The above equations clearly indicated that $SiO_2:R_2O_3$ ratio was the single most important factor in predicting amorphous Si status explaining 64.8 per cent variability.

Residual Si (Res-Si)

The remaining unknown mineral fractions were together known as residual Si. Thehighest value of residual Si was observed in sandy soils and lowest in lateritic soils (fig.18). *Kuttanad* and *Pokkali* soils also showed very high content of residual Si. The residual Si was found to contribute highest percentage of Si to total Si. It was highest (97.65 per cent) in sandy soils of Chalakudy and lowest (36.36 per cent) in lateritic soils of Pattambi.

The residual Si had significant negative correlation with plant available silicon in soil, but a significant positive correlation with AEC and $SiO_2:R_2O_3$. Residual Si had significant negative correlation with available Ca, Mn and exchangeable K.

A stepwise regression analysis including all the parameters significantly correlated with residual Si finally yielded the following equation.

1. Res-Si = 54593.39 + 8382.37** $SiO_2:R_2O_3$ ($R^2 = 0.634$)

The above equation clearly indicated that $SiO_2:R_2O_3$ ratio was the single most important factor in predicting residual Si status explaining 63.4 per cent variability.

The percentage distributions of the different fractions of Si were in the order; residual Si > amorphous Si > occluded Si > oragnic Si > mobile Si > adsorbed Si in *Kuttanad*, *Pokkali* and sandy soils, where as it was in the order amorphous Si > residual Si > occluded Si > oragnic Si >

mobile Si > adsorbed Si in *Kole* land soil and amorphous Si > residual Si > oragnic Si > occluded Si > mobile Si > adsorbed Si in lateritic soil.

The results of fractions of Si in major rice growing soils showed that residual and amorphous Si fractions were the most dominant fractions. Adsorbed Si was the least fraction present in all these soils. The correlation analysis revealed association of fractions of Si with various physico-chemical properties, available and exchangeable nutrients and plant available Si. The mobile Si had high direct positive effect on plant available Si. The exchange and release of these Si fractions are mainly influenced by adsorption of Si on soil particles which in turn affects the availability of Si for plant uptake. For better understanding of adsorption behavior of Si in soil, adsorption study was conducted to know the quantity-intensity relationship. The results of adsorption study are discussed below.

Adsorption study

The adsorption of Si onto soil particles is an important process affecting the plant availability of Si to plants, but little is known about the fate of Si after it is added to the soil. The adsorption of Si at the soil particle-water interface has an important effect on the transport, bioavailability, and fate of Si added to soil (Qiu *et al.*, 2010).

5.1.6 Q-I relationship

Quantity – intensity relationship of five major rice growing soils at two temperatures *viz*. 25 and 40^{0}C were studied. From the data obtained, Q-I curves were plotted with the amount of Si adsorbed on Y axis and the equilibrium concentration of Si in the soil solution on X axis. The Q and I parameters were calculated from the adsorption experiments with increasing concentration of Si added to one gram of soil. The concentration of Si in solution after equilibration for 24 hours was considered as intensity factor. The amount of Si adsorbed on solid phase per unit weight was considered as the quantity factor. The Q/I curves were fitted with these data and intercepts and slopes were computed from the best fit curves using regression analysis. The slopeof the curve is the parameter which explains the buffer power (Si supplying power of the soil). The simple linear equation $\Delta Q = bC + K$ was used to obtain the best curve, where b is the buffer power (slope of the curve) and K is the intercept (fig. 19 - 28).

The intensity factor is a measure of level of Si in soil solution that is immediately available for absorption by the plants and quantity factor is the capacity of the soil to replenish the level of Si in soil solution over a period of time. The slope of Q-I curve is the buffer power which explains how the level of Si in soil solution (quantity) varies with the unit change in intensity factor. Buffer power is the change in quantity factor with respect to unit change in intensity factor ($\Delta Q/\Delta I$). Greater values of buffer power would mean that greater will be the ability of a given soil to release Si from the exchange phase to the solution phase when Si concentration got decreased in soil solution.

The solubility of soil Si is low. Si in soil solution (intensity factor) is largely influenced by its dissolution kinetics, which in turn is influenced by various soil factors such as Al, Fe oxides, organic matter, redox potential and moisture.

The data on values of both b and K at 25^0C and 40^0C are presented in table.16 and 17 respectively. The highest buffer power was indicated by *Kuttanad* soil followed by *Pokkali* and sandy soils at 25^0C. It clearly indicated that these soils have the greater power to retain Si onsolid phase and replenish its concentration in soil solution as and when it is depleted through plant uptake or leaching. At 25^0C, *Pokkali* and sandy soils of Chalakudi showed almost equal buffer power. At 40^0C, the buffer power decreased in all the soils and showed negative values except sandy soils of Chalakudi. The reduced buffer power at 40^0C indicated that the sites of adsorption in these soils are purely organic which might have lost their specificity due to denaturing of specific functional groups at higher temperature. Whereas in sandy soils, the adsorption sites are mainly inorganic oxide and hydroxide surfaces whose specificity might have increased at higher temperature.

At 25^0C, the intercept of Q-I curve was positive for *Kole, Pokkali* and lateritic soils, whereas *Kuttanad* and Sandy soils of Cahalakudi had negative intercepts. The positive intercept indicated the requirement of minimum amount of Si at solid phase below which there will not be any desorption. The negative intercept indicates desorption of Si from the solid phase below equilibrium concentration. At 40^0C, all soils except sandy soils of Chalakudi had positiveintercept which indicated the minimum adsorption of Si at solid phase.

Fig.19 Quantity – intensity curve for *Kuttanau* soil at 25^{0}C

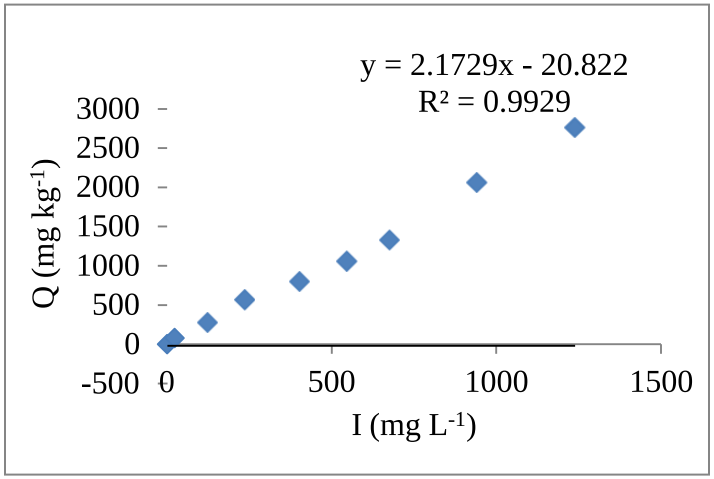


Fig.20 Quantity – intensity curve for *Kuttanau* soil at 40^{0}C

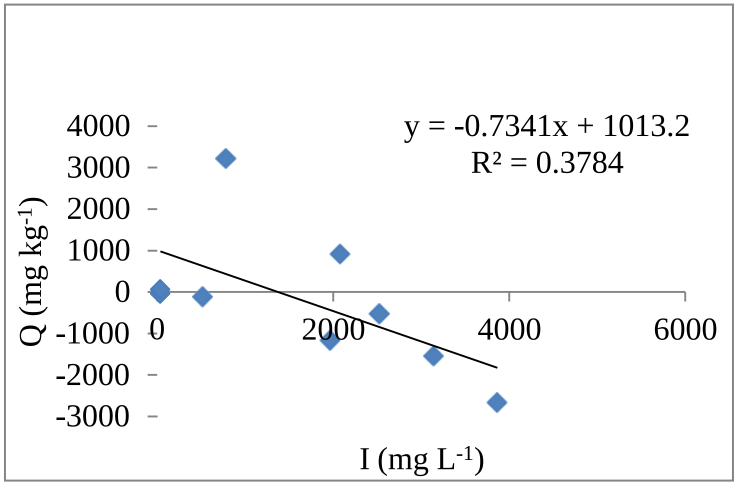


Fig.21 Quantity – intensity curve for *Kole* land soil at 25^{0}C

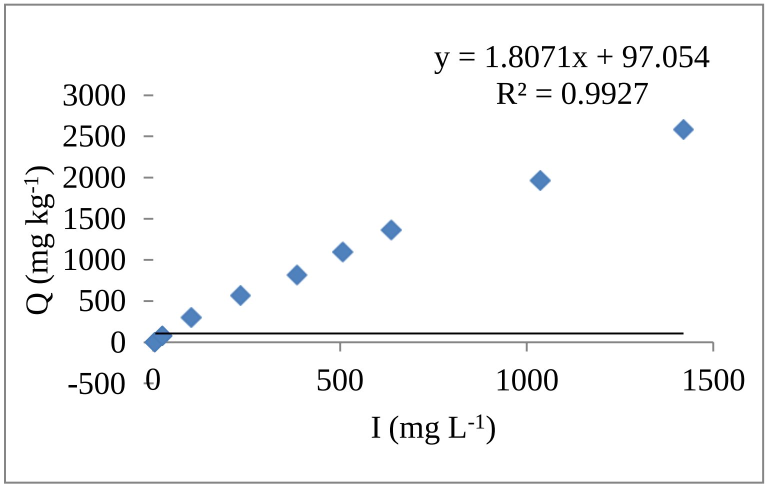


Fig.22 Quantity – intensity curve for *Kole* land soil at 40^{0}C

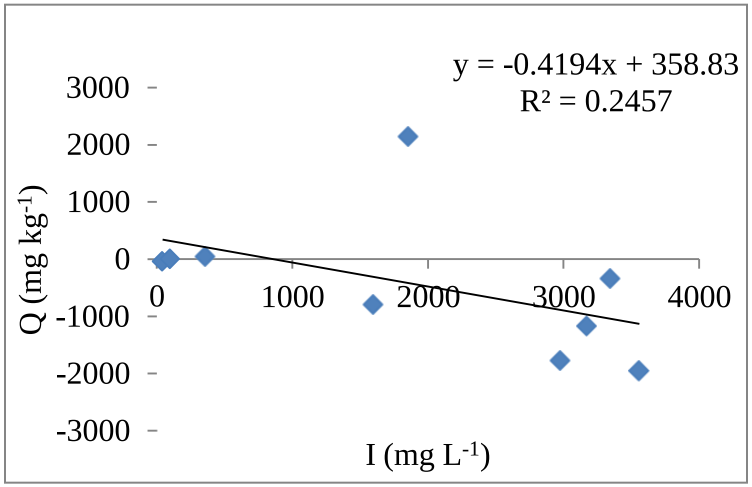


Fig.23 Quantity – intensity curve for *Pokkali* soil at 25^{0}C

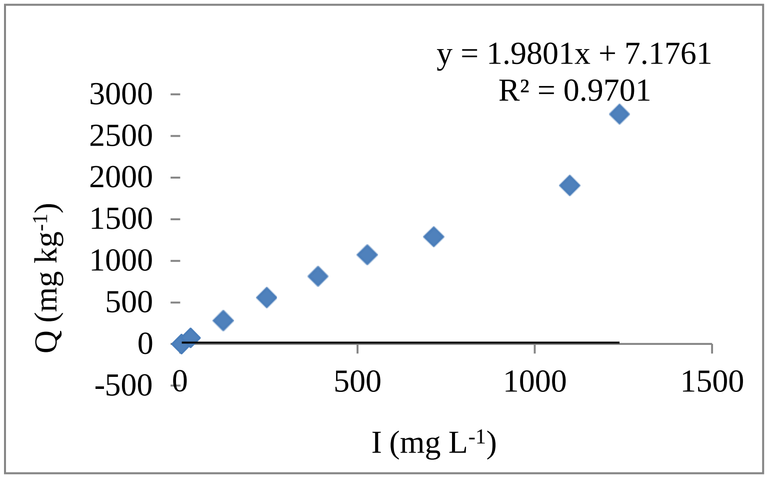


Fig.24 Quantity – intensity curve for *Pokkali* soil at 40^{0}C

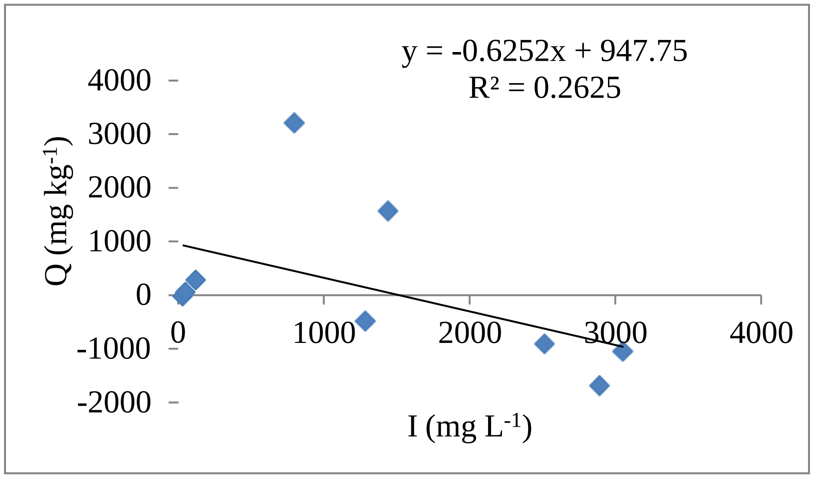


Fig.25 Quantity – intensity curve for sandy soil at 25^{0}C

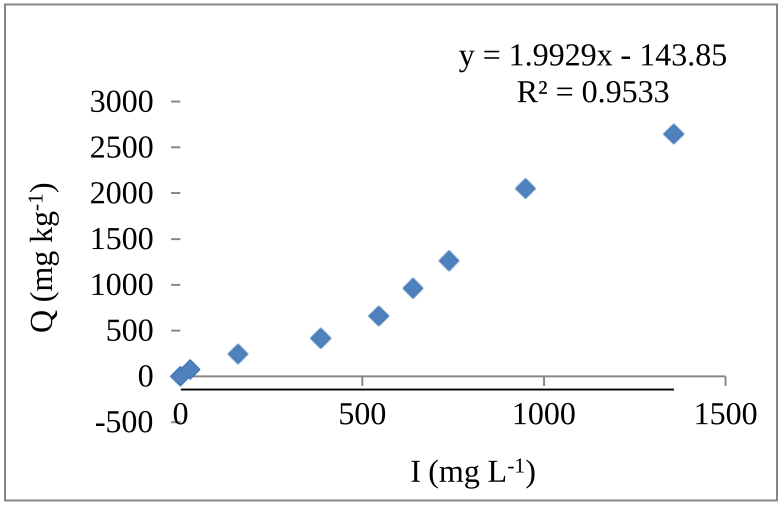


Fig.26 Quantity – intensity curve for sandy soil at 40^{0}C

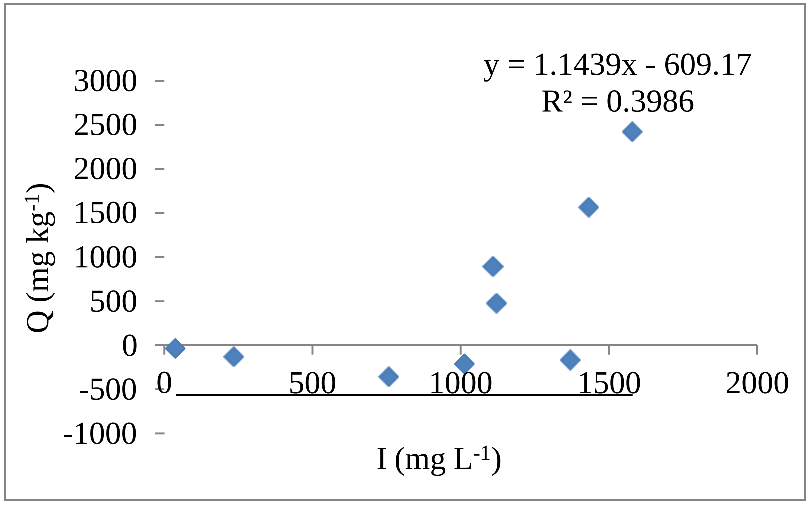


Fig.27 Quantity – intensity curve for lateritic soil at 25⁰C

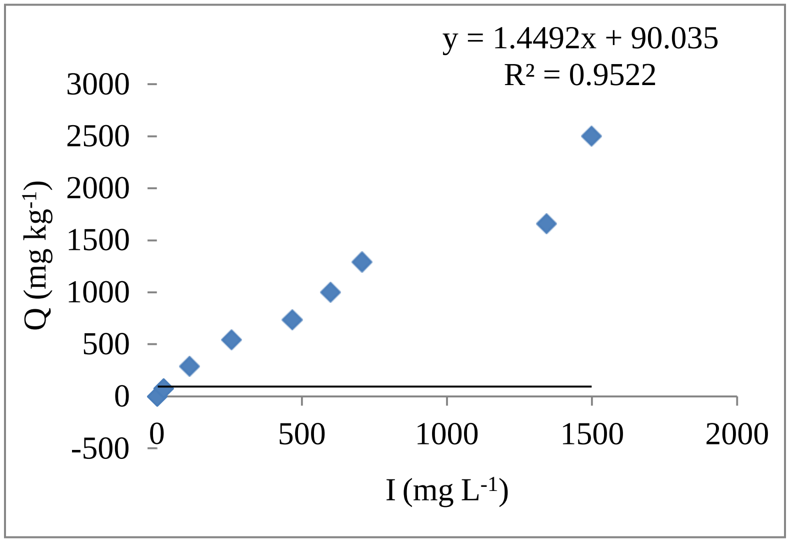
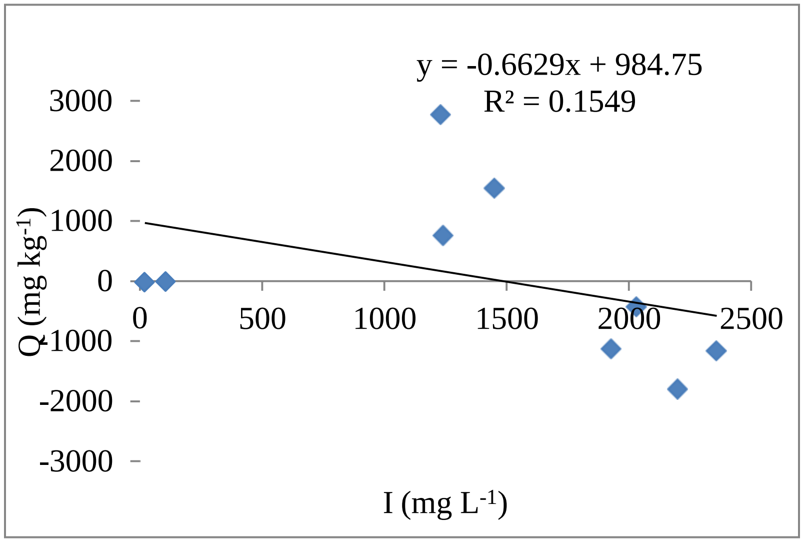


Fig.28 Quantity – intensity curve for lateritic soil at 40⁰C



The adsorption of Si increased greatly as the Si concentration in the equilibrium solution increased. The slopes of the isotherms were very steep when Si concentrations were low but decreased markedly when Si concentrations were higher. This indicated that the adsorption of Si in soils may include multiple adsorption sites.

Kuttanad and *Pokkali* soils adsorbed highest percentage of Si applied to the soil followed by sandy, *Kole* land and lateritic soils at 25^0C. At 40^0C, *Kuttanad* and *Pokkali* soils adsorbed highest percentage of Si applied followed by lateritic, sandy and *Kole* land soils at the highest Si concentration. These results suggested that *Kuttanad* and *Pokkali* soils may not have reached its maximum adsorption potential at the levels of Si added to the soil. Given that the higher removal of Si was associated with the lower level of dissolved iron, it may be deduced that silicic acid in the solution was associated with the iron hydroxides, leading to the formation of silica-iron (III) complexes on pyrite surfaces (Schenk and Weber, 1968; Herbillon and Vinhan, 1969). The silicic acid association with hydrous ferric oxyhydroxides involves both adsorption and polymerization processes and depends on the amount of H_4SiO_4 present at their surfaces, i.e. adsorption as monomeric silicate on the surface, or via siloxane linkages (Si-O-Si) essentially polymerizing to form a separate silica phase (Swedlund and Webster, 1999; Swedlund *et al*., 2011).

With higher CEC, organic matter and iron content, *Kuttanad* and *Pokkali* soils adsorbed more Si than sandy, lateritic and *Kole* land soils. Eventhough *Kole* land soils are rich in organic matter and have high CEC, the reason for less adsorption of Si as compared to *Kuttanad* and *Pokkali* soils need investigations. Meanwhile, soil minerals also exert significant control over Si adsorption. Quartz and feldspar in sandy and lateritic soils contribute to less Si adsorption, while montmorillonite contribute to more adsorption of Si in *Kuttanad* and *Pokkali* soils. Similar results were reported by Qiu *et al.* (2010) in soil samples collected from Anthrosols, Argosols and Cambisols of China.

5.1.7 Adsorption isotherms

The equilibrium Si concentration and the amount of Si adsorbed by each soil were used to test the fitness of data to the adsorption equations *viz*., Langmuir, Freundlich and Temkin adsorption equations. The data obtained from the adsorption experiments could be fitted into

Freundlich and Temkin equations (variance of exploration > 50 per cent) and not fitted to Langmuir equation (variance of exploration < 50 per cent) at 25^0C. The data obtained for equilibrium Si concentration and the amount of Si adsorbed by each soil at 40^0C was not fitted to any adsorption equations. The failure of adsorption data to fit into Langmuir equation could be attributed to the involvement of more than one type of sites with different binding energies at the concentration range selected for the study (Santhosh, 2013). Qiu *et al.* (2010) also reported that Langmuir, Freundlich, and Temkin equations described the adsorption of Si in China soils as a function of Si concentration and their goodness of fit varied according to soil type.

The Freundlich adsorption isotherm equations and constants for the soils at 25^0C aregiven in table.18 and depicted in fig.29-33. The data for all the soils could be described by the linear form of Freundlich equation. All the adsorption isotherms conformed to Freundlich's adsorption equation at and above certain SiO_2 concentrations and suggest that it was primarily related to pH effect (Wada and Inoue, 1974). In this equation, K is defined as the amount of Si adsorbed at unit soil solution concentration of Si. The constant ‗1/n‘ related to adsorption intensity of the soil. This assumes that the affinity for adsorption decreases exponentially withthe increase in surface coverage which is more logical in real situation.

K_F is Freundlich adsorption coefficients, and n is a linearity factor, it is also known as adsorption intensity, 1/n is the slope and logK_F is the intercept of the straight line resulting from the plot of log (x/m) versus log C. The Freundlich exponent, ‗n‘, should have values in the range of 1 and 10 (i.e., 1/n < 1) to be considered as favorable adsorption (Ghorbani *et al.,* 2012). A 1/n value of less than 1 indicates that Si is favorably adsorbed by soil.

The *Kole* land soil showed highest adsorption intensity of Si, whereas sandy soils of Chalakudy and *Pokkali* soils of Vyttila showed lowest adsorption intensity. Si-adsorption behavior varied significantly between soil types (Qiu *et al.,* 2010). The *Kole* land soil showed highest adsorption intensity of Si which was ascribed to high clay content or organic matter of soil or both (Santhosh, 2013).

The Freundlich equation described Si adsorption better for sandy soils of Chalakudy and *Pokkali* soils of Vyttila followed by *Kuttanad* soil. Freundlich adsorption isotherms indicate that the amount of Si adsorbed increased linearly with increasing concentration of added Si. Miller *et*

Fig.29 Freundlich adsorption isotherm for *Kuttanad* soil at 25^{0}C

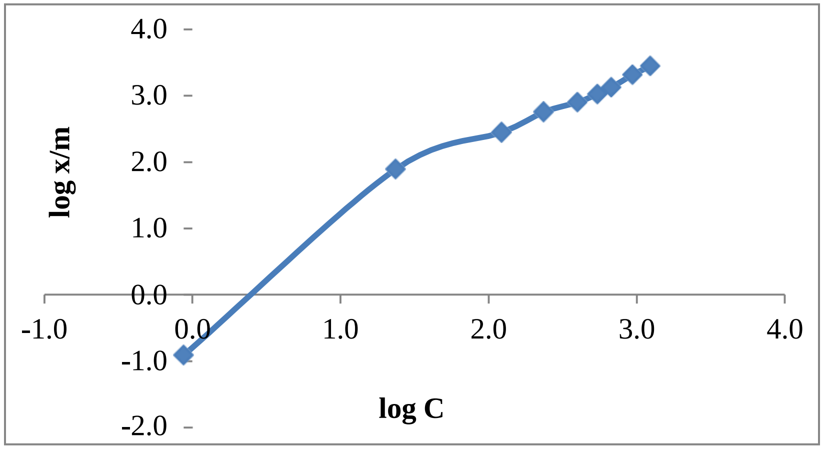


Fig.30 Freundlich adsorption isotherm for *Kole* land soil at 25^{0}C

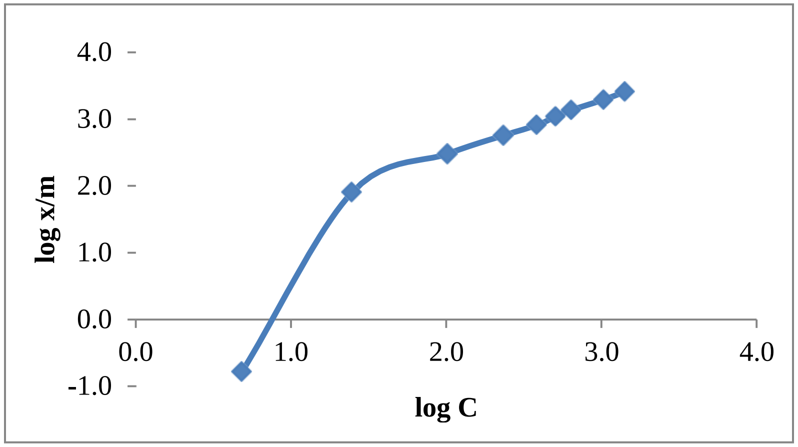


Fig.31 Freundlich adsorption isotherm for *Pokkali* soil at 25^{0}C

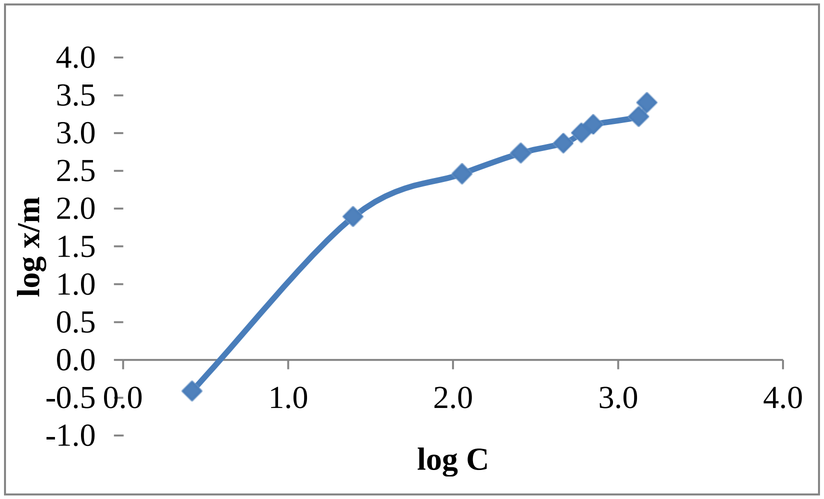


Fig.32 Freundlich adsorption isotherm for sandy soil at 25^{0}C

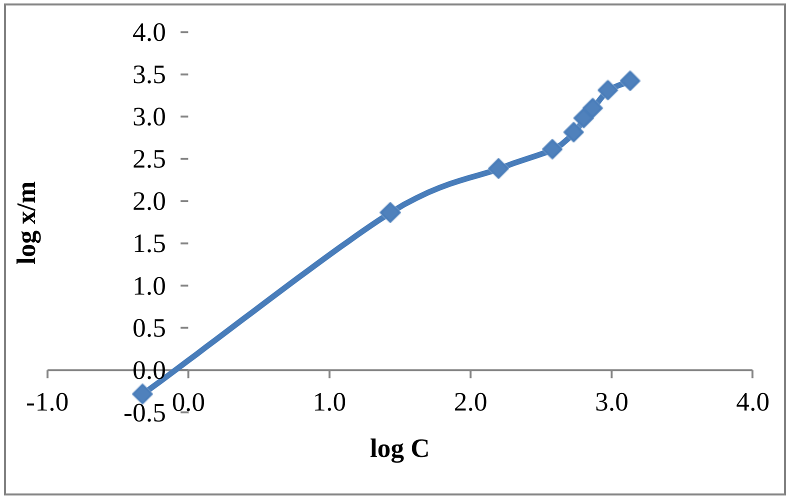
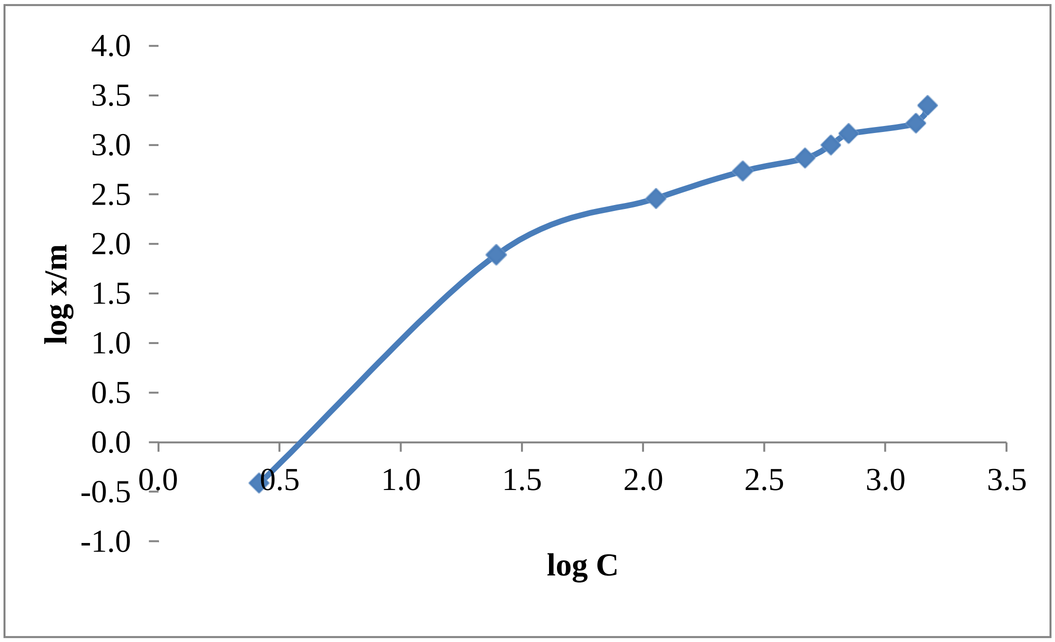


Fig.33 Freundlich adsorption isotherm for lateritic soil at 25^0C



al. (1989) reported that Si adsorption by goethite is a linear type, which implies that adsorption does not approach a fixed value. Hingston *et al.* (1972) reported that the maximum adsorption of Si occurred at about pH 9.2, just below the p*Ka* (9.7) of silicic acid. Multilayer silicate formation at the soil surface is the reason that Si adsorption could not reach a constant value (Iller, 1979).

The equations for Temkin isotherms at 25 and 40^0C are represented in table.19 and depicted in fig.34-37. The Temkin isotherm model is based on the assumption that adsorption energy decreases linearly with the surface coverage due to adsorbent-adsorbate interactions. In this equation, A is the intercept and B is the slope of the equation. A (L g^{-1}) is the Temkin isotherm constant, B (J mol^{-1}) is a constant related to heat of sorption. In the present study, this equation was most accurate in describing Si adsorption in *Kole* land soil followed by lateritic and*Pokkali* soils, whereas data obtained from sandy soils of Chalakudi could not be fitted into Temkin equation. According to Tempkin and Pyozhev (1940), if the adsorption energy B in the Temkin model is positive for Si adsorption, then the adsorption can be considered as exothermic.

As per variance of exploration values (table.18 and 19), the data was better fitted to Freundlich model as compared to Temkin model indicating that adsorption mechanism was related to non-ideal, reversible and multilayer adsorption with non-uniform distribution of ad- sorption heat and affinities over the heterogeneous surface. This result was in close agreement with the findings of Bajeer *et al*. (2012).

5.1.7 Thermodynamics of Si adsorption in soil

The thermodynamic parameters of Si adsorption are presented in the table.20. ΔG is the Gibbs free energy of reaction (J mol^{-1}) that governs the direction of the adsorption reaction. If $\Delta G = 0$, the reaction will be at equilibrium; if $\Delta G > 0$, the reaction will not proceed spontaneously, *ie.*, desorption of Si is favored; if $\Delta G < 0$, the reaction will proceed spontaneously, *ie.*, the adsorption of Si is favored. The free energy change (ΔG^0) values were negative and almost equal for all soils at both temperatures. The negative ΔG° values at both temperatures confirmed the spontaneous nature of the Si adsorption process. With the increase intemperature, ΔG° did not show much variation in all soils except *Kole* land soil. This indicated better desorption was obtained at higher temperature in *Kole* land soil. Enthalpy change (ΔH^0) indicates the nature of heat change associated with the process. Positive values of ΔH^0 indicate

Fig.34 Temkin adsorption isotherm for *Kuttanad* soil at 25⁰C

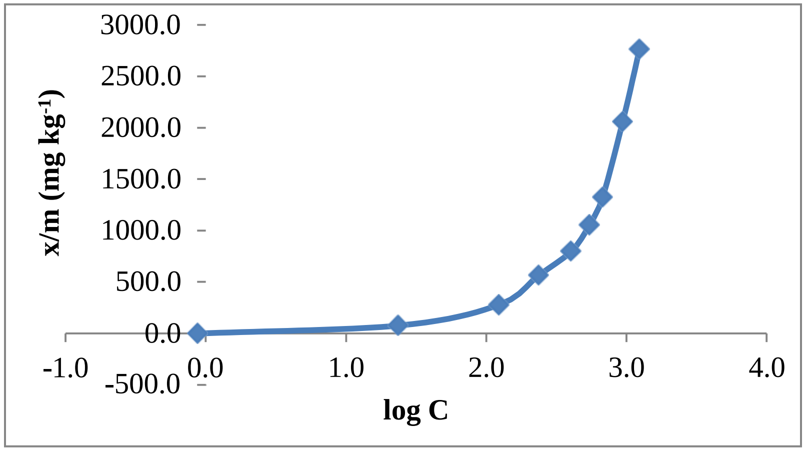


Fig.35 Temkin adsorption isotherm for *Kole* land soil at 25⁰C

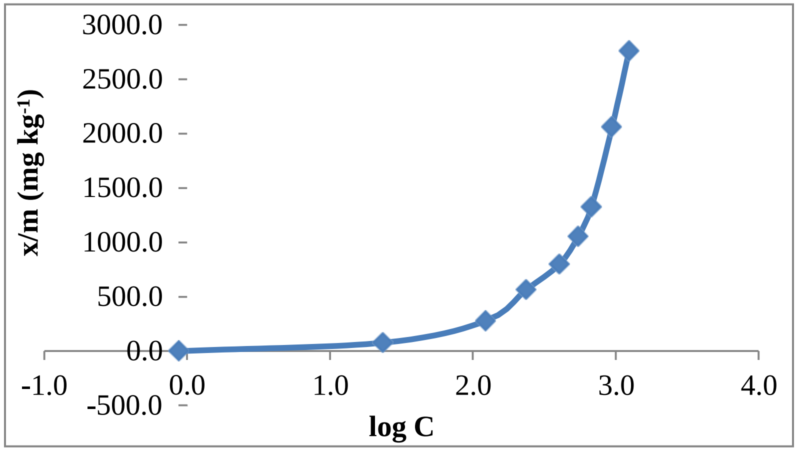


Fig.36 Temkin adsorption isotherm for *Pokkali* soil at 25⁰C

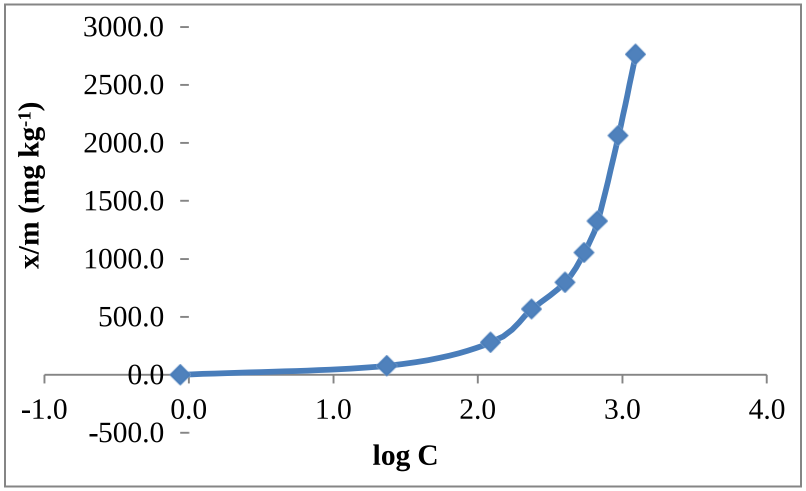
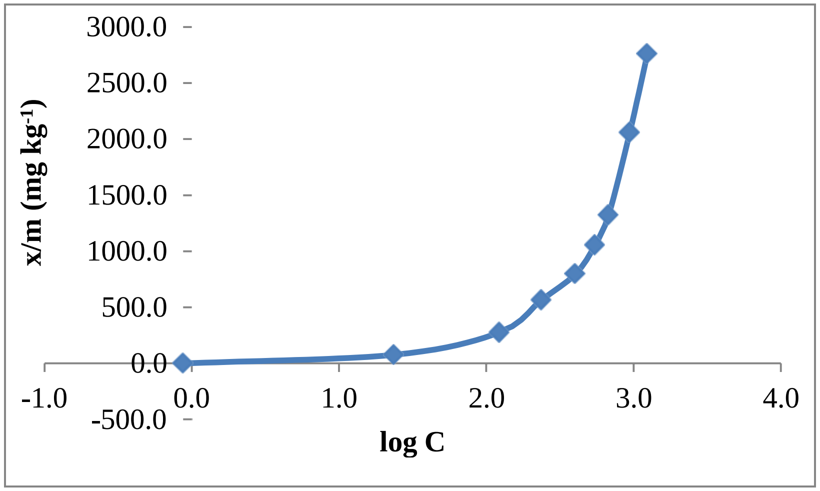


Fig.37 Temkin adsorption isotherm for lateritic soil at 25⁰C



that the adsorption process is endothermic in nature while the negative values indicate that the process is exothermic in nature. The change in enthalpy (ΔH^0) was negative for the all soils. The negative values of ΔH indicated the exothermic behaviors of the reaction and showed that the adsorption process was spontaneous and exothermic in nature and occurred through chemisorption mechanism. Derived enthalpies indicate that hydrogen bonding, charge transfer and ligand-exchange interactions may have a role to play in adsorption mechanism as suggested by Calvet (1989) and Broznic and Milin (2012).

Entropy change (ΔS^0) explains the degree of disorder or spontaneity of the process. The change in entropy (ΔS^0) was negative except for *Kuttanad* and *Pokkali* soils at 25^0C and 40^0C. The negative values of ΔS^0 indicate that the adsorption complexes of soil system are stable. The immobilization of Si as a result of adsorption will decrease the degrees of freedom and that is why ΔS^0 values are negative (Biggar and Cheung, 1973). The small negative values of $\Delta S°$ suggested the decreased randomness on solid/solute interface during the adsorption. The positive values of ΔS^0 are indicators of more disorder or spontaneous nature of adsorption (Santhosh. 2013).

It was seen that major rice growing regions of Kerala were deficient in plant available Si. The studies on distribution of fractions of Si and adsorption behavior of Si in these soils had given a clear picture on influence of these factors on dissolution of Si into soil solution for plant uptake. It clearly indicates the importance of effective management of Si in soil and utilization of Si fertilizers for improving soil fertility and enhancing crop growth and yield.

There are locally available Si rich materials which are under utilized to a certain extent, dumped as waste. Rice husk is such a material which can be effectively used as source of Si for plants. The biodecomposition of rice husk will favour the easy release of Si from this material. An attempt has done to prepare biodecomposed rice husk using a standard method as detailed below.

5.1.8 Preparation of biodecomposed rice husk

The rice husk may become a potentially environmentally friendly source of soil amendment if it is properly processed. It is difficult to compost rice husk due to high C: N ratio, high cellulose and lignin content, waxy surface cover that impedes microbial attack and low capacity to absorb water. Using standard procedures of composting, rice husk degradation can not be considered as total. It is expected that composted rice husk may be able to improve soil properties by increasing soil organic C, releasing various essential and beneficial elements and suppressing toxic elements.

The compost was prepared following the method suggested by Anda *et al*. (2008). After three months of composting, the biodecomposed rice husk compost (BRH) and raw rice husk (RRH) were analyzed for elemental composition (P, K, Ca, Mg, S, Fe, Cu, Mn, Zn and Si), lignin and cellulose. The bio-chemical properties of RRH and BRH are shown in table.21 and depicted in fig 38.

The analytical data showed that the lignin and cellulose content decreased during composting. Govindarao (1980) reported that rice husk contained 22 per cent of lignin and 38 per cent of cellulose. Hwang and Chandra (1997) reported that the chemical composition of rice husk was similar to that of many common organic fibers with a cellulose content of 40-50percent and lignin content of 25-30 percent.

The total carbon content was found to be reduced during composting. Anda *et al*. (2008) reported that during the active composting phase, total organic C achieved a maximum value of 41–43 per cent at days 8 to 20 and then decreased to about 40 per cent at the end of the active composting phase (day 53). This pointed that total C in rice husk was only slightly decreased (2 – 4 per cent) during the composting period, suggesting that rice husk degrades very slowly.

The total N and Si content increased during biodecomposition of rice husk. Demir and Gulser (2015) reported similar findings. The experimental results showed that elemental composition of raw rice husk and rice husk compost are composed mainly of carbon, silicon, sulphur and phosphorus. No other plant part except paddy husk is capable of retaining such a huge proportion of silica in it. The content of other elements was less than one percent. A combined study using back scattered electron and X-ray images of the husk showed that the silica is distributed mostly under the outer surface of husk (Bui *et al.,* 2005). This confirms the general concept of a soluble form of silica transported through the plant and concentrated at the outer surface of straw and husk through evaporation.

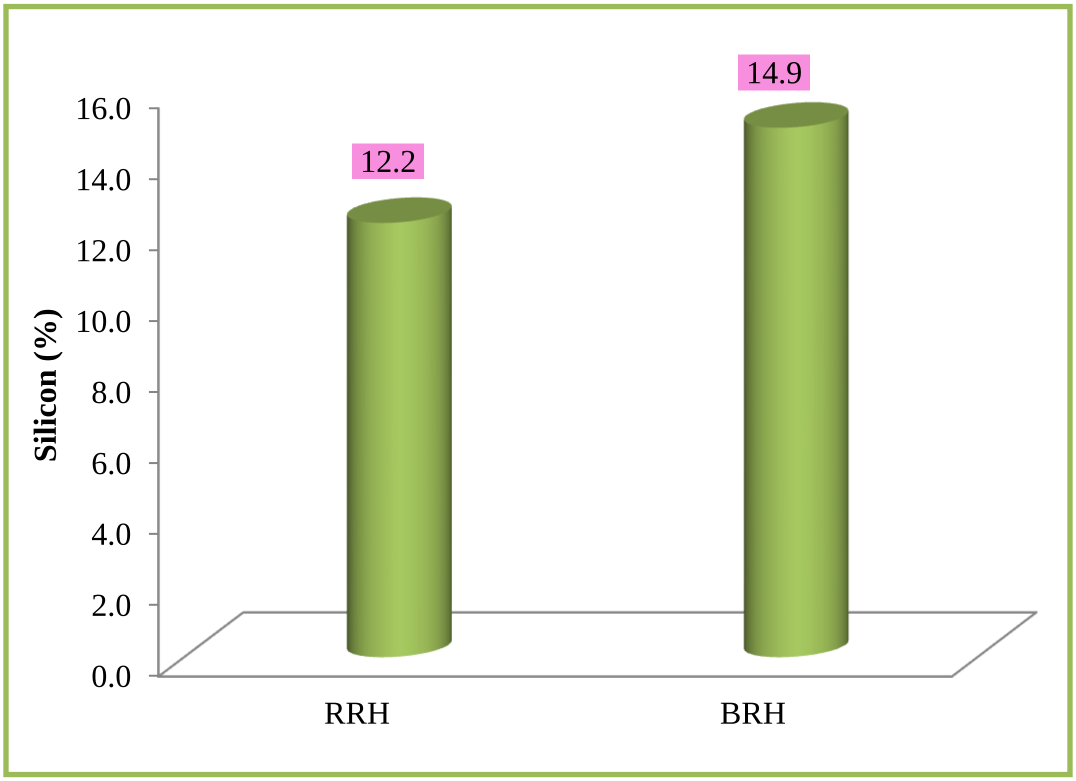


Fig.38 Silicon content in RRH and BRH

Experiment 2

Release of silicon in different rice growing soils with different sources of Si under different water regimes

An incubation experiment was conducted to know the extent of release of Silicon after the addition of different sources of silicon such as rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate in five rice growing soils *viz. Kuttanad* soil (S_1) of Moncombu, *Kole* soil (S_2) of Thrissur, *Pokkali* soil (S_3) of Vyttila, sandy soil (S_4) of Chalakudi, and lateritic soils of Pattambi (S_5) under submerged water regime (SWR) and field capacity water regime (FCWR). The incubated sample was sub-sampled repeatedly at different time intervals to determine the pH, EC, available Si and total Si. The available and total Si were estimated after first, second and third month of incubation. The pH, EC and redox potential of each treatments were analyzed continuously for first two weeks, once in a week for next one month and then at monthly intervals.

5.2.1 Effect of different Si sources and soil type on available and total soil Si under different water regimes during incubation

The data on available and total Si estimated after first, second and third month ofincubation are given in the table.22 – 27 and depicted in fig.39-44.

The addition of Si significantly increased the available Si in all soils. The available Si increased initially and subsequently decreased with passage of time. Subramanian and Gopalswamy (1991) also reported that available Si increased with continuous submergence of soil. The available Si was found to be highest on 30 DAI in all soils except *Kole* land. Sh *et al.* (2015) also reported that in clay loam soil, Si increased during the first 10-20 days, and then decreased. In general, *Kole* land soil showed higher available Si up to 60 days of incubation. In *Kole* land soil, the treatment with rice husk ash, calcium silicate and sodium silicate as Si fertilizer showed higher available Si on 60 DAI both at SWR and FCWR. The soils having the highest content of OM also showed the highest level of soluble silicon (Sh *et al.*, 2015).

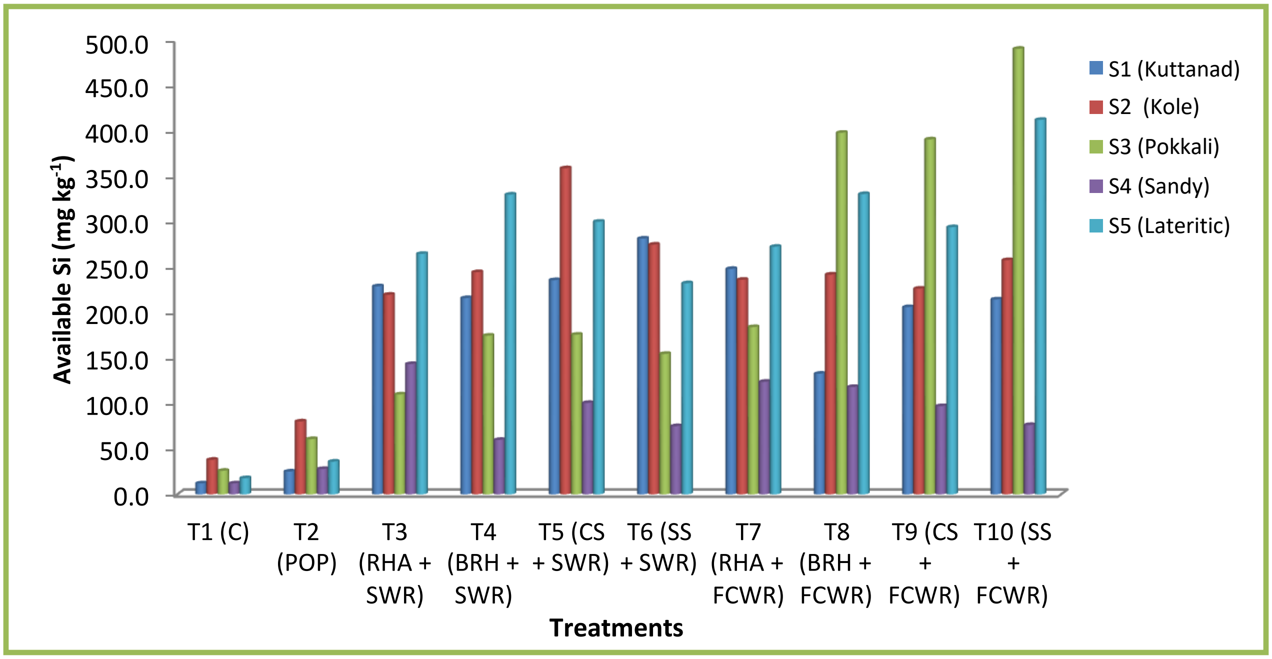


Fig.39 Effect of different Si sources and soil type on available Si under different water regimes after one month of incubation

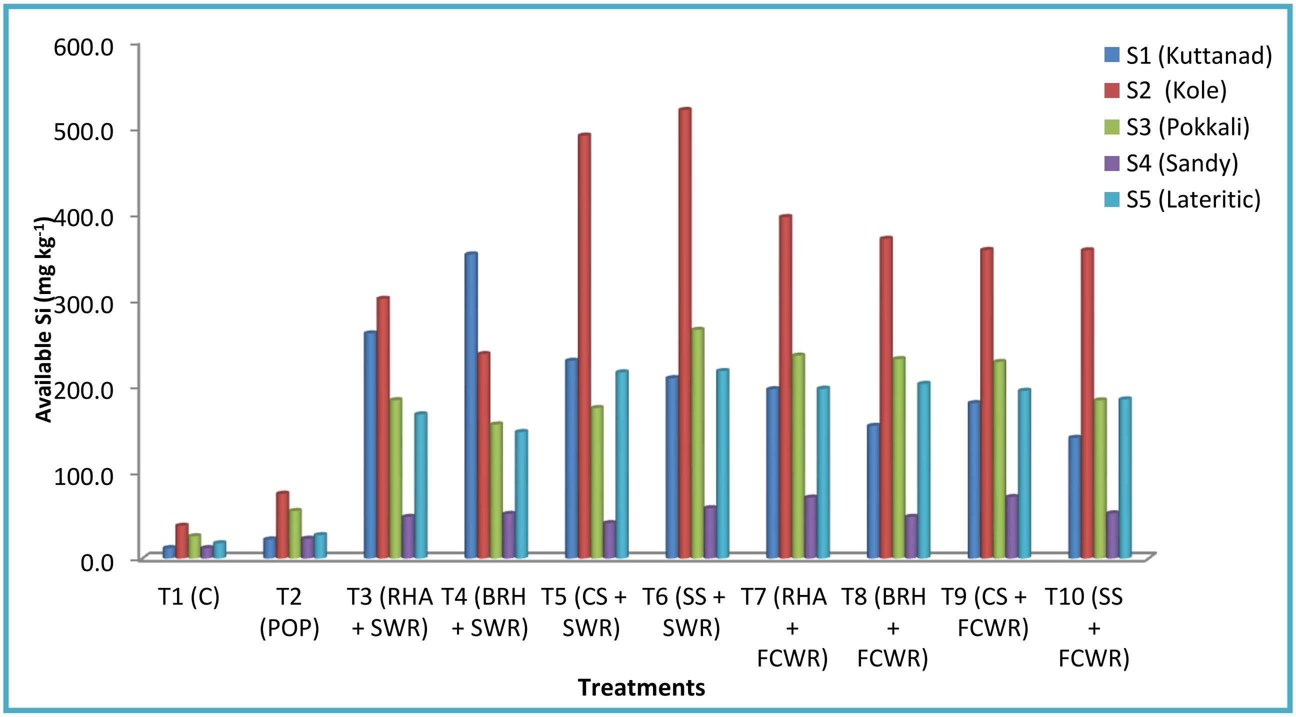


Fig.40 Effect of different Si sources and soil type on available Si under different water regimes after two month of incubation

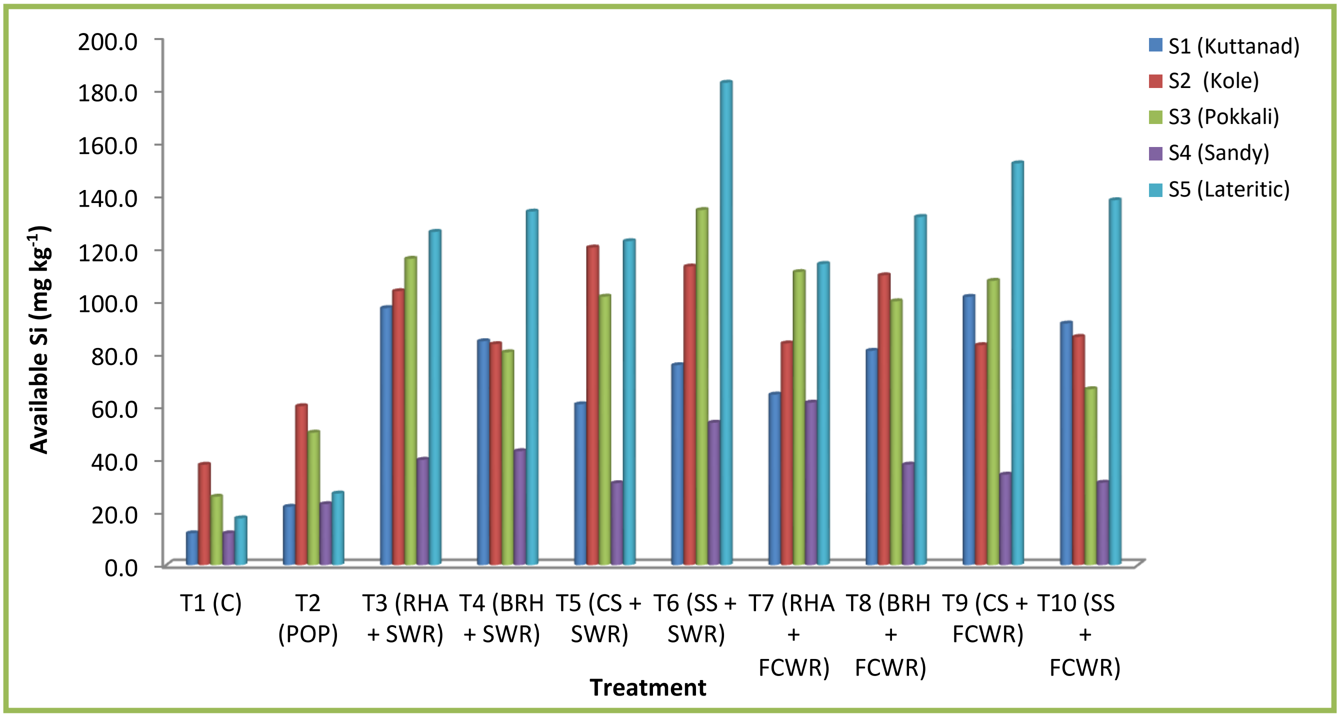


Fig.41 Effect of different Si sources and soil type on available Si under different water regimes after three month of incubation

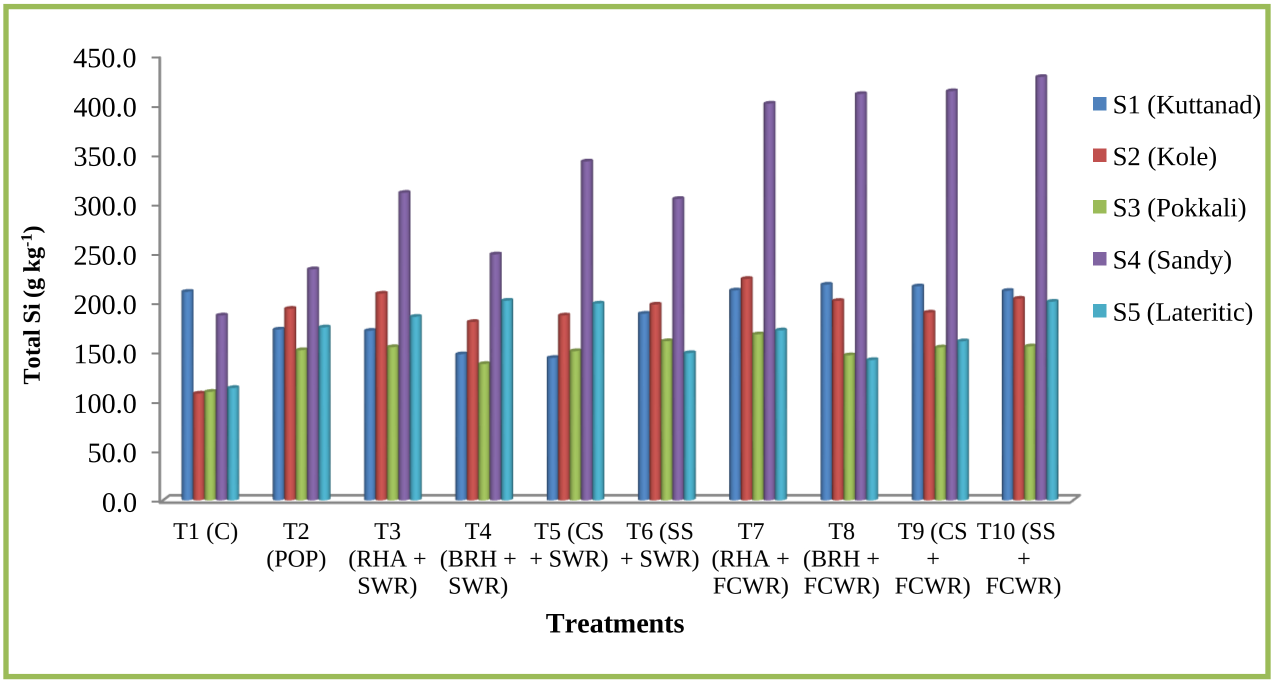


Fig.42 Effect of different Si sources and soil type on total Si under different water regimes after one month of incubation

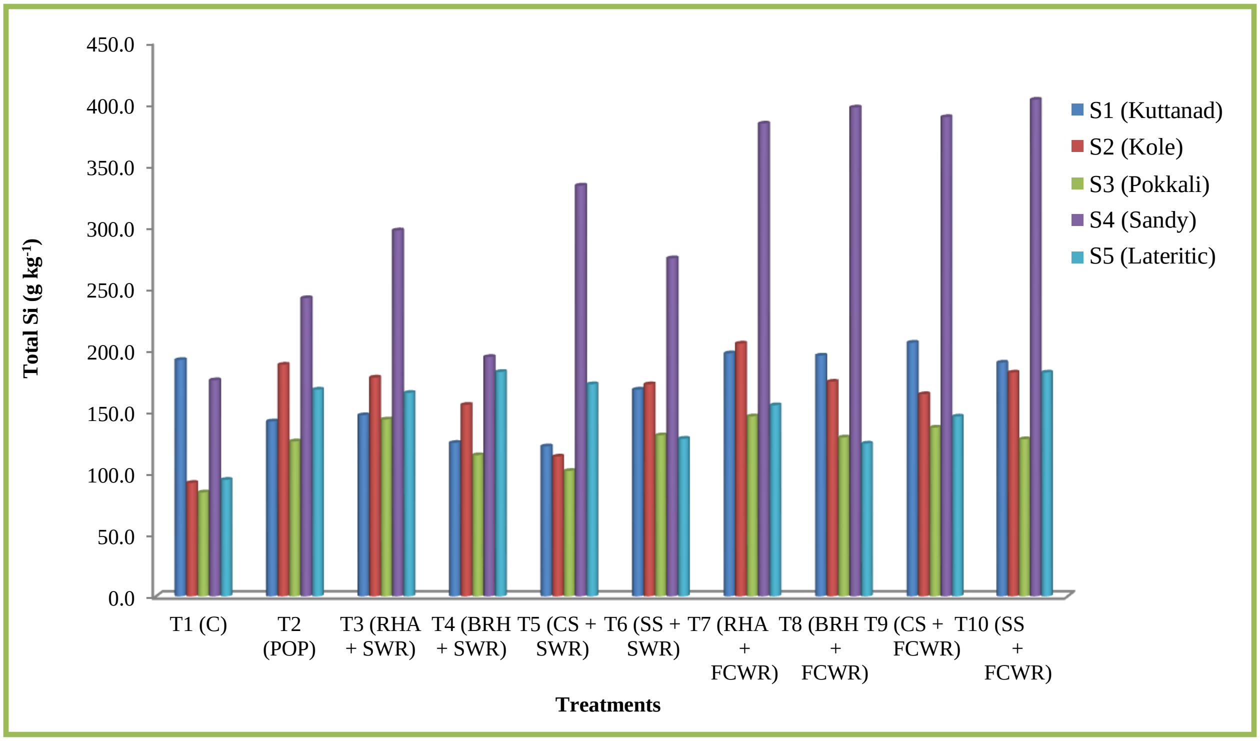


Fig.43 Effect of different Si sources and soil type on total Si under different water regimes after two month of incubation

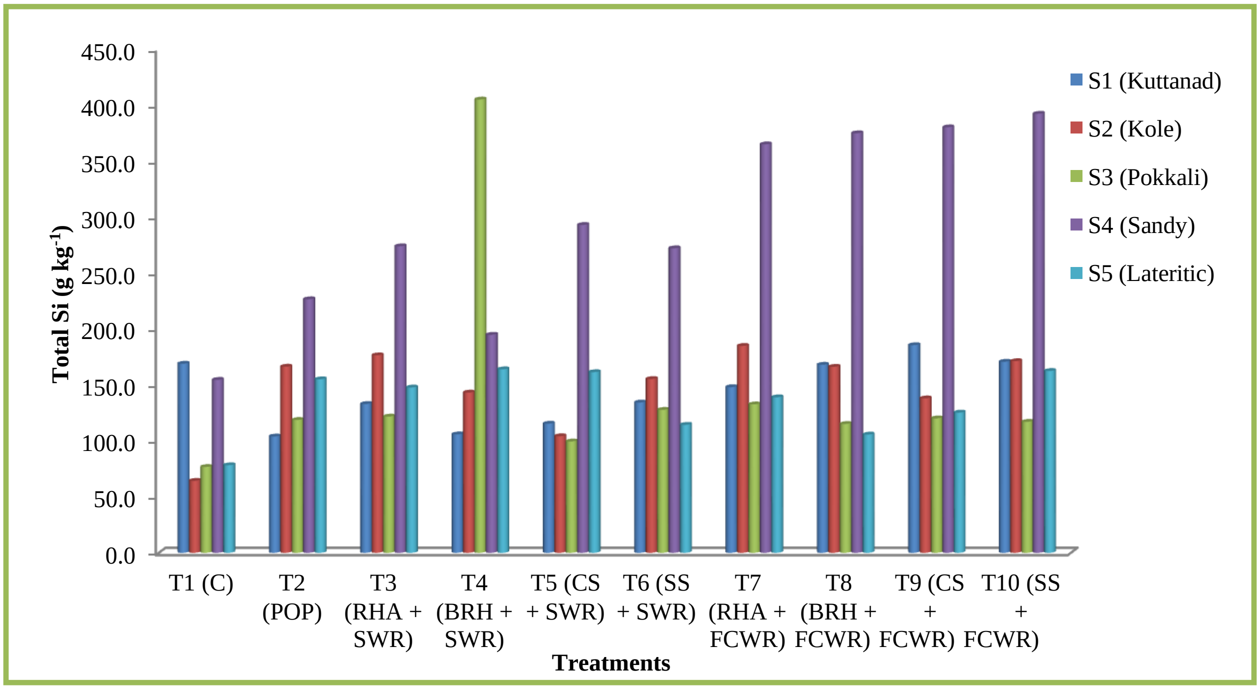


Fig.44 Effect of different Si sources and soil type on total Si under different water regimes after three month of incubation

In case of Pokkali soil, addition of sodium silicate at SWR and rice husk ash at FCWR showed higher available Si on 60 DAI. In general, there was a decreasing trend in availability of Si in soil solution over the period of incubation up to three month. After 30 days of incubation, the highest available Si was recorded in *Kole* land soil in addition with rice husk compost at SWR, where as lowest available Si was estimated in sandy soil with same treatment of Si application. It clearly indicates the importance of organic matter on availability of Si to plants in soil. The available Si was found to be very low in T_1 and T_2 where Si was not applied throughoutthe period of incubation. Till 60 days of incubation, *Kole* land soil recorded higher available Si followed by *Kuttanad* soil. During last period of incubation, lateritic soil showed comparatively higher available Si both at SWR and FCWR. In sandy soil, Si release was found to be maximum up to 30 days of incubation and further reduced and stabilized after 60 days of incubation. The stabilization of available Si over period of incubation could be due to stabilization of pH, EC andORP. Changes in soil pH, EC and oxidation-reduction potential caused by soil water regimes andorganic and inorganic Si fertilizers certainly affected Si solubility and its availability.

The highest release of available Si was at SWR in case of *Kole* land and *Kuttanad* soil, where as *Pokkali*, sandy and lateritic soils showed more release of available Si at FCWR. Irrespective of soils, treatment with sodium silicate showed higher release of available Si.

In general, there was a decreasing trend in total Si in all the soil over the period of incubation up to three month. The total Si was found to be highest on 30 DAI in all soils. The sandy soil of Chalakudi recorded highest Si during all the period of incubation, while *Pokkali* soil of Vyttila recorded the lowest total Si during incubation. There was not much variation in total Si with the addition Si fertilizer at SWR and FCWR. The lowest Si was recorded in T_1 (Absolute control) in all soils except *Kuttanad* soil. The *Pokkali* soil showed strongly acidic pH with weak redox potential during incubation. The acidic pH and weakly redox potential cause strong mobilization and leaching of Si and Fe, concomitantly with high accumulation of Al in soils (Desire *et al.*, 2009). This could be the reason for lower total Si status of *Pokkali* soil.

5.2.2 Effect of different sources of Si on pH, EC and ORP during incubation

The data on effect of different sources of Si at different water regimes on pH, EC and ORP during incubation are presented in table.28 – 32 and depicted in fig.45 – 47.

pH

In general, the pH of all soils increased during initial period of incubation up to 10 days and further reduced and stabilized over the period of incubation in all treatments except T_1 and T_2. The decrease in pH shortly after submergence is probably due to the accumulation of CO_2 produced by respiration of aerobic bacteria, because CO_2 decreases the pH even in acid soils (Siam *et al.* 2015). The decrease in pH was also in very little range and varied with the moisture regimes. The treatments with Si fertilizers at submerged water regime (SWR) showed higher pH than treatments at field capacity water regimes (FCWR). Submerging under 5 cm of water increased soil pH towards neutral.The pH increase was more pronounced in *Kuttanad* soil, from 4.11 in control to 7.27 in submerged water regime with sodium silicate treatment (Fig.45). It might be due to the adsorption of H^+ ions into soil surface and release of basic cations and OH^- ions into soil solution. The increase in pH was maximum in the range of 7 to 7.2 in all soils except *Pokkali* soil, where the higher pH was less than 6.0. This might be due to extreme acid nature of this soil due to the presence of iron pyrite. Pons and vanBreemen (1982) stated that the pH of acid sulfate soils increases slowly on submergence and rarely exceeding 6.0.

The addition of organic Si fertilizers to the soils under submerged water regime clearly decrease pH values after 10 days from submergence, and then they slightly increased on 30 days after incubation. Sh (1989) revealed that OM magnifies the decrease in pH of soil.

Electrical Conductivity

In general, the EC of all soils increased during initial period of incubation up to 5 days and further reduced and stabilized over the period of incubation in all treatments except T_1 and T_2.

The electrical conductivity was found to be higher in treatments at submergence water regimes than field capacity water regimes. It might be due to the release of basic cations into soil solution on addition of water. During incubation, higher EC was noticed in *Pokkali* soil, whereas lateritic soil recorded the lower EC both at SWR and FCWR.

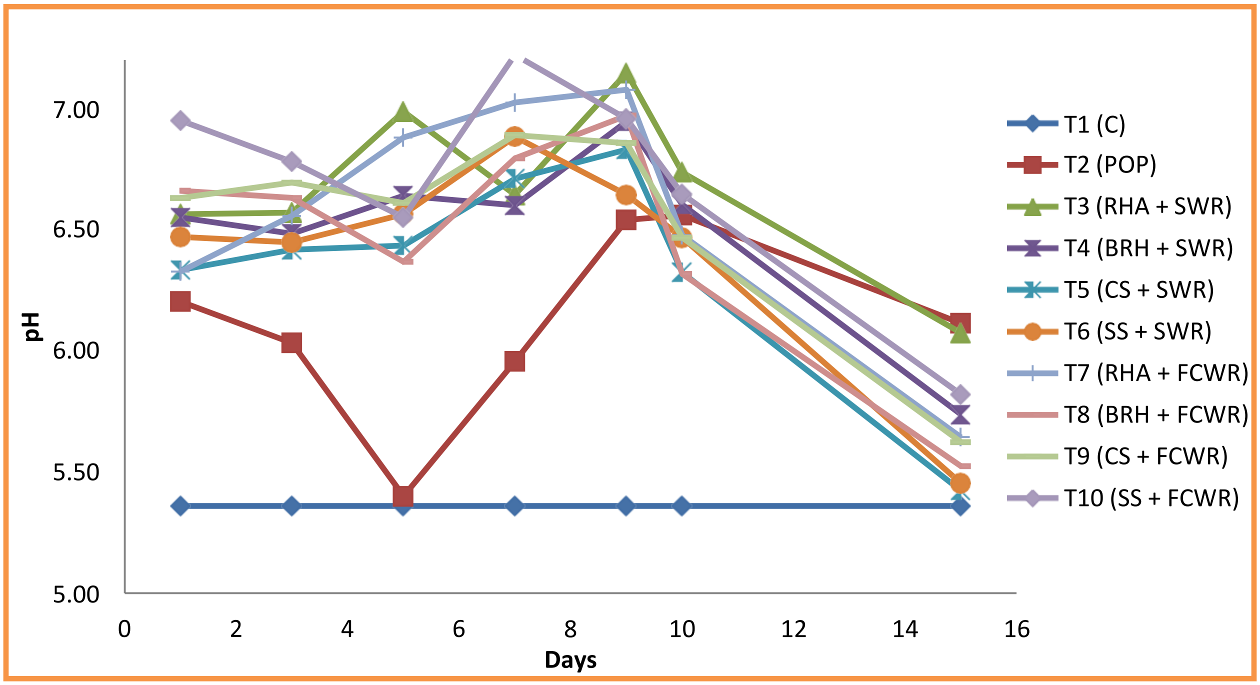


Fig.45 Effect of different Si sources on changes in pH of sandy soil during incubation

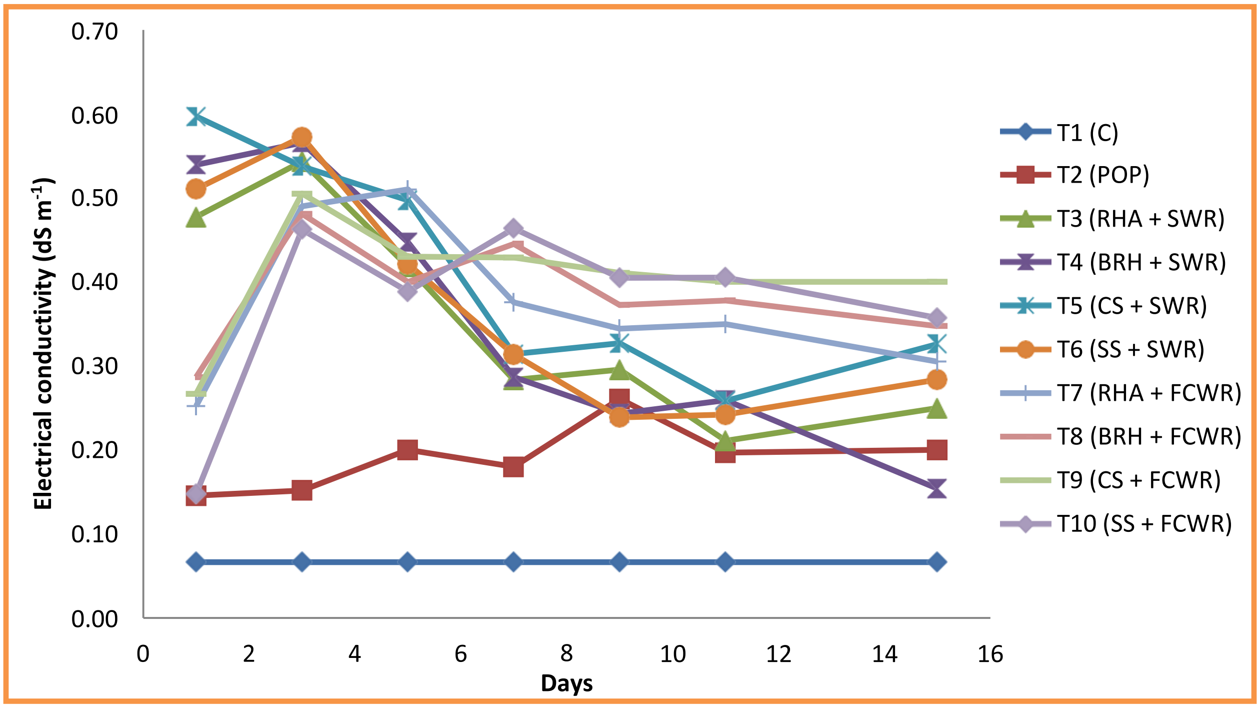


Fig.46 Effect of different Si sources on changes in EC of sandy soil during incubation

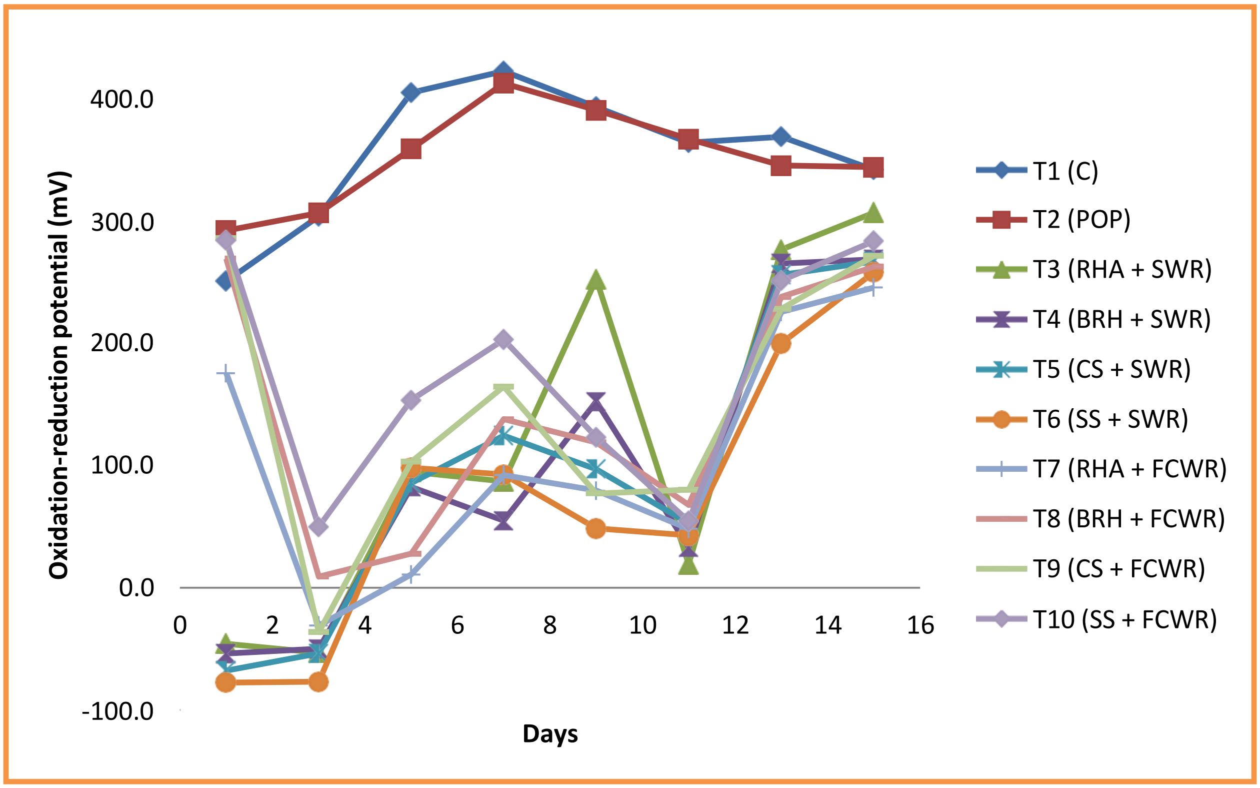


Fig.47 Effect of different Si sources on changes in ORP of sandy soil during incubation

Oxidation-reduction potential (ORP)

In general, the oxidation-reduction potential of all soils decreased during initial days and further increased and stabilized over the period of incubation in all treatments except T_1 and T_2. Generally, 12 – 16 days after incubation exhibited the largest differences in ORP within the treatments. It might be due to depletion of oxygen by submergence or saturation of soil with water. The rapid initial decrease of Eh values was apparently due to the release of reducing substances accompanying oxygen depletion before Mn (IV) and Fe (III) oxide hydrates can mobilize their buffer capacity (Sh *et al.*, 2015).

In all soils, ORP was found to be lower in SWR than FCWR. It might be due to the presence of oxidation layer on surface of soil at field capacity water regime. In sandy soils of Chalakudi, treatment with Si application at SWR showed negative ORP value during initial four days and thereafter increased. In *Kole* land soil, ORP was found to be negative at SWR throughout incubation period. In *Kuttanad* soil, Si application under submerged water regimes recorded ORP with negative values till 30 days of incubation. In *Pokkali* soil of Vyttila, the negative ORP was recorded only on third day of incubation in treatments at SWR.

In general, the addition of organic sources of Si under FCWR decreases ORP as compared with inorganic fertilizer and control in all soils except *Pokkali* soil, where the decreasein ORP was noticed under SWR. The same result was also reported by Siam *et al.* (2015).

It could be seen that the release of Si was highest in *Kole* land soil and lowest in sandy soil on addition of Si fertilizers under SWR and FCWR. With respect to water regimes, the release of available Si was highest at SWR in case of *Kole* land and *Kuttanad* soil, where as *Pokkali*, sandy and lateritic soils showed more release of available Si at FCWR. Irrespective of soils, treatment with sodium silicate released more Si into soil solution for plant uptake. As it was pot experiment without any crop, it would not give clear information about field condition.In order to get a better idea about release of Si under field condition and to reinforce the resultsof pot experiment, a field investigation was conducted with an objective to evaluate the efficacy of different sources of silicon including rice straw in wet land rice ecosystem. The results of field experiment were discussed below.

Experiment 3

Field study to evaluate the efficacy of different sources of silicon in wetland rice

5.3.1 Field experiment 1

Two field experiments were conducted at Agronomic Research Station, Chalakudy to evaluate the efficacy of different sources of silicon including rice straw in wetland rice. The different sources of silicon used in this field experiment were rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate.

5.3.1.1 Biometric observations

The application of different sources of silicon had significant effect on number of tillers at tillering, panicle initiation and harvesting stage and varied significantly with respect to the treatments (table.33). After transplanting, Si fertilization increased the number of tillers. Attillering stage, maximum numbers of tillers were observed in T_6 (T_2 + Sodium silicate) and minimum number of tillers were noticed in T_1 (Absolute control). At panicle initiation and harvest stage, all treatments except T_1 were on par and T_1 was significantly varied from all other treatments. The number of tillers increased from the panicle initiation stage and attained a maximum value at the harvest stage in all groups at the different treatments. At the stage of maximum tiller and harvest, the effect of sodium silicate had an increasing out come on no.of tillers. It might be due to more solubility of sodium silicate. All the silicon sources correspondingly increased no. of tillers significantly over control at tillering, panicle initiation and harvesting stage (fig.48).

The treatments with different sources of Si had significant effect on plant height at tillering, panicle initiation and harvesting stages (fig.49). All the silicon sources correspondingly increased plant height significantly over control. The effect of sodium silicate on the number of tiller has an increasing out come on plant height. Snyder *et al.* (1986) suggested that silicon increases the height of the plant and cause tiller. Ravent (1983) reported that the plant height willbe increased by using materials consisting silicon.

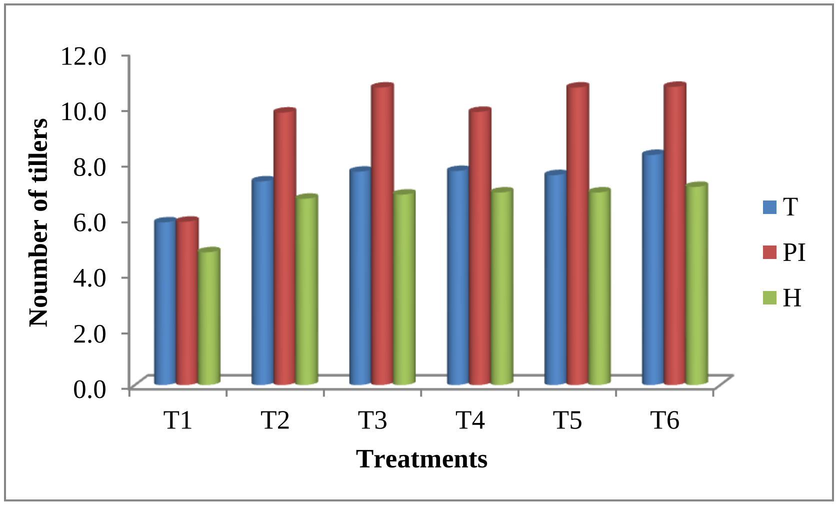


Fig.48 Effect of different sources of Si on no.of tillers of rice

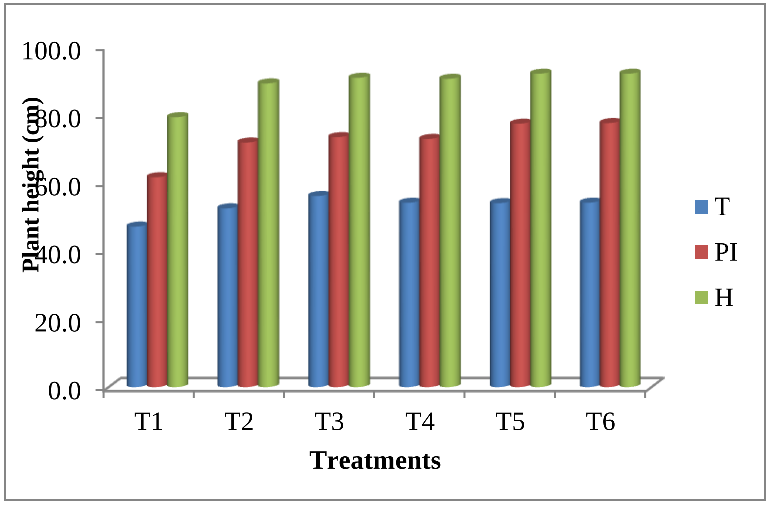


Fig.49 Effect of different sources of Si on plant height of rice

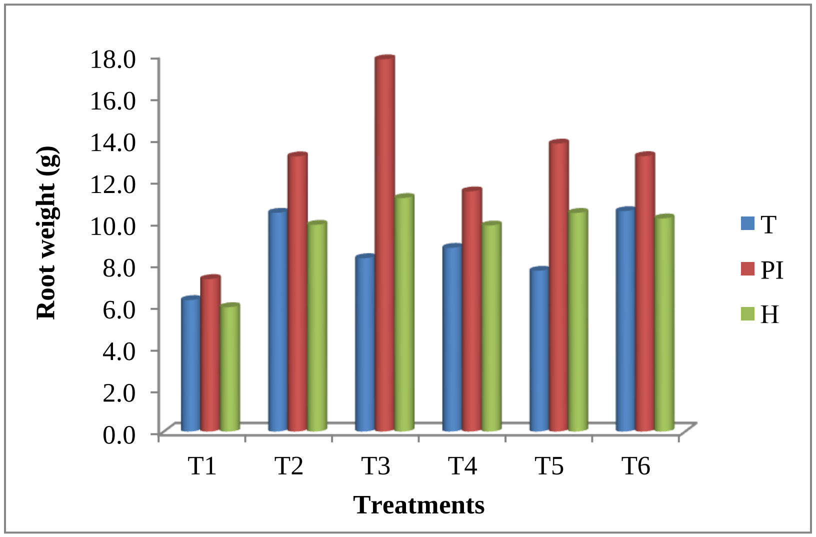


Fig.50 Effect of different sources of Si on root weight of rice

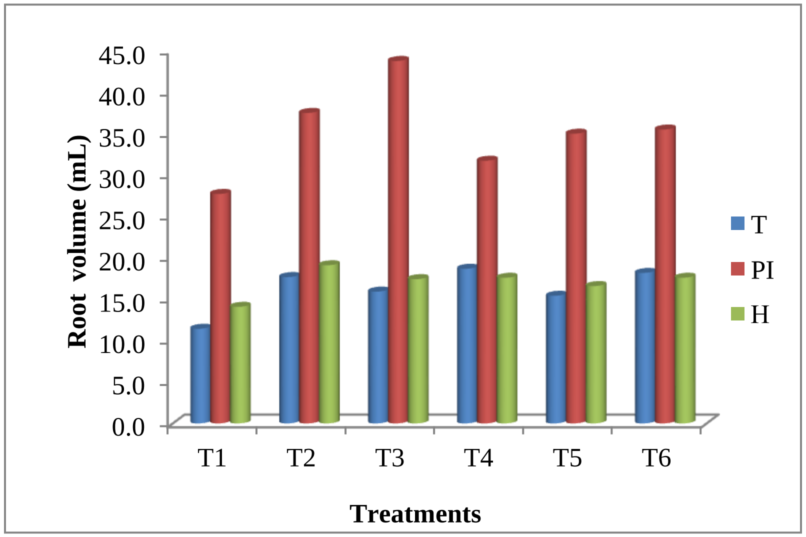


Fig.51 Effect of different sources of Si on root volume of rice

The application of different sources of silicon had significant effect on root weight and root volume only at panicle initiation stage and varied significantly with respect to the treatments (fig.50 and 51). At tillering stage, maximum root weight was recorded in T_6 (T_2 + Sodium silicate) and minimum was noticed in T_1 (Absolute control). Rice husk ash has reasonable quantities of cations Ca, Mg, K, Na, and other essential elements including P and very little N. Paddy husk ash from various locations contains 0.72–3.84% K_2O and 0.23–1.59 MgO (Muthadhi *et al*., 2007). Slow release of these elements from RHA into soil solutionand there by root uptake could be the reason for higher root weight in T_3 at panicle initiation stage. T_3, T_4 and T_5 were on par. It showed that all the treatments with applications of silicon are statistically similar but significantly higher than control. Ali *et al.* (2008) reported that root biomass and root volume were significantly increased by silicate fertilizer at harvesting stage.

There was significant difference between the treatments with respect to the number of panicle per hill. T_5 recorded maximum number of panicles per hill and it was significantly superior to all other treatments (fig.52). All the silicon sources correspondingly increased no. of spikelets per panicle significantly over control (fig.53). Number of unfilled grains per panicle was found maximum in control, whereas this percentage is significantly reduced by silicon application (fig.53). This reduction might be due to balanced nutrition, optimum metabolic activities or nullification of stresses by silicon application. These findings are near to the Mauad *et al.* (2003) and Wang *et al.* (2010), who reported that silicon is not directly evolved in quality enhancement but it control diseases and stresses to maximize the quality.

The maximum thousand grain weight was recorded in T_4 and it was superior to all the treatments. The minimum thousand grain weight was recorded in T_2. The silicon application significantly affects the thousand grain weight. These findings are similar to Malidareh(2011) but against the results of Mobasser *et al.* (2008) who reported that silicon application does not affect thousand grain weights in rice. Sunilkumar and Geethakumari (2002) reportedthat silica application resulted in an increase in the number of spikelets per panicle, filled grains per panicle and panicle weight. Miyoshi and Ishii (1960) reported better translocation of photosynthates from straw to ear head by the application of silica. Better filling of grainsby the application of silica was earlier reported by Vijayakumar (1977) who found anincrease in thousand-grain weight by the application of silica.

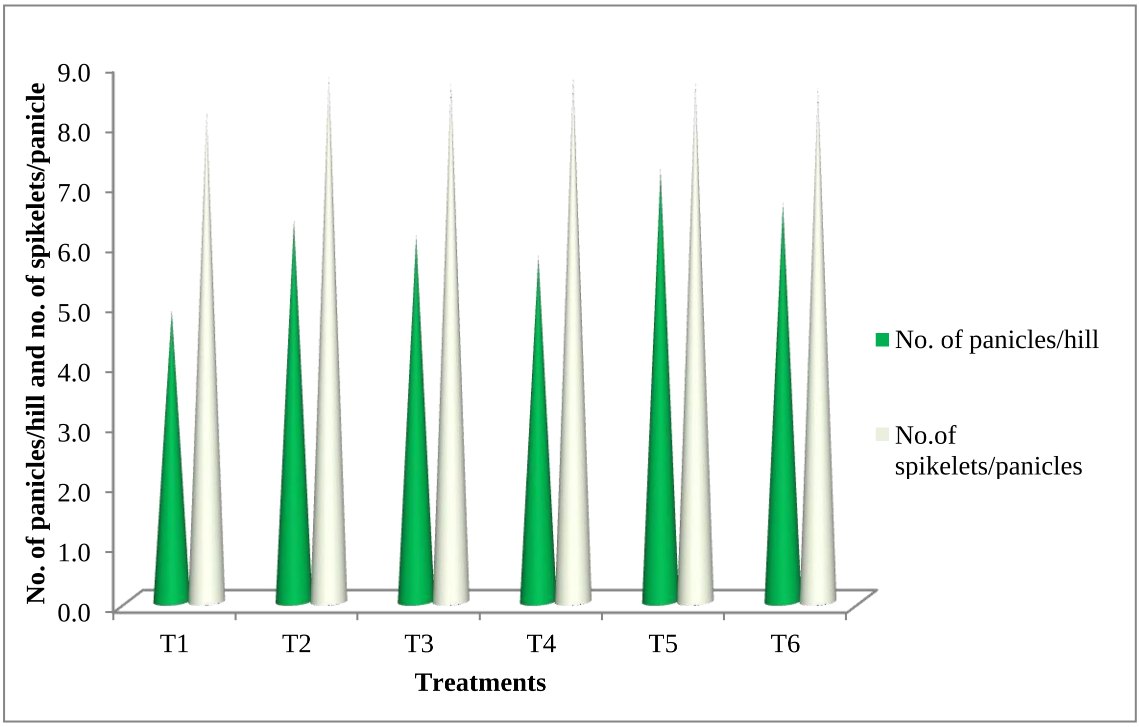


Fig.52 Effect of different sources of Si on no.of panicle/hill and no.of spikelets/panicles of rice

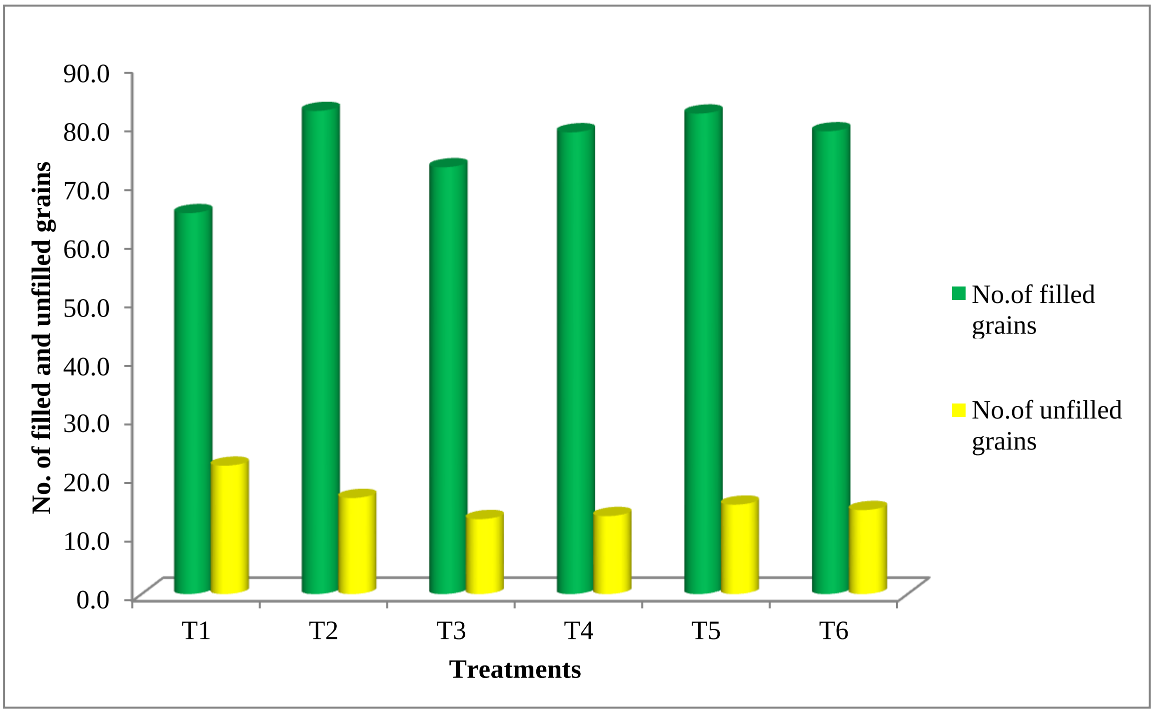


Fig.53 Effect of different sources of Si on no.of filled and unfilled grains/panicle rice crop

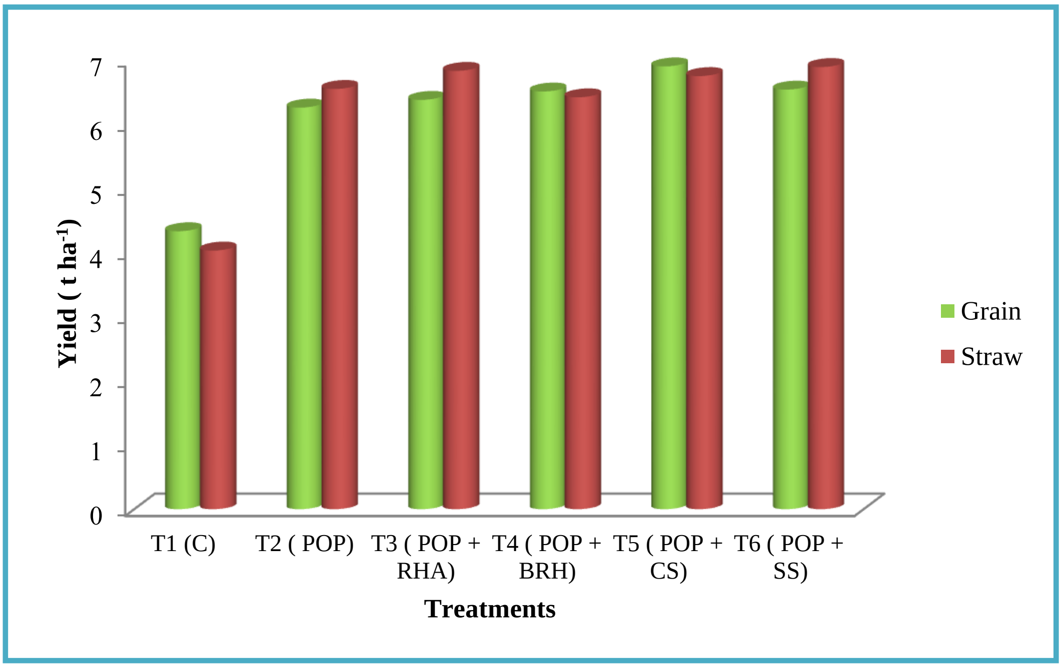


Fig.54 Effect of different sources of Si on grain and straw yield of rice

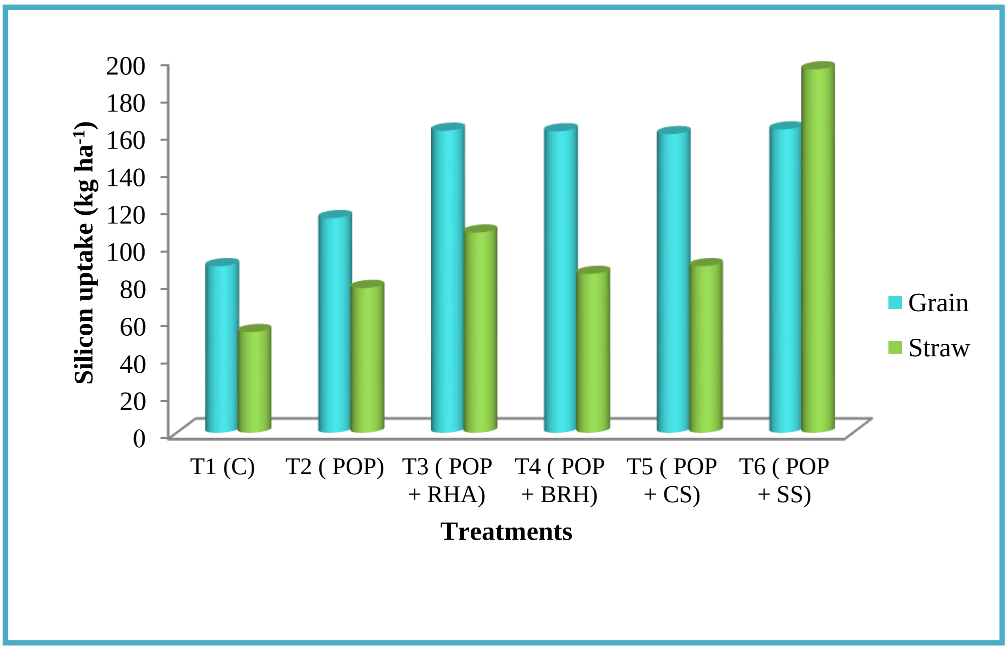


Fig.55 Effect of different sources of Si on Si uptake by grain and straw of rice

The maximum number panicle per hill, number of spikelets per panicle, and thousand grain weights and minimum number of unfilled grains per panicle were recorded in treatment with calcium silicate application. The maximum grain yield of 6.90 t ha^{-1} was recorded in treatment T_5 (T_2 + Calcium silicate) and significantly superior (fig.54) over all other treatments. This increase in yield may be due to the effect of application of Si on soil fertility,nutrient uptake, and plant growth. The direct effect of Si fertilization on increased number panicle per hill, number of spikelets per panicle, and thousand grain weight and decreased number of unfilled grains per panicle might be the reason for increased grain and straw yield in treatment with calcium silicate. The same result was reported by Narayanaswamy and Prakash (2009). Similar results were also noticed for organic soils of Florida (Korndorfer *et al.,* 2001a). RHC was not significantly different from the sodium silicate in case of grain yield indicating that there was no difference RHC and sodium silicate as source of Si for higher yield. The minimum of 4.68 t ha^{-1} was recorded in T_1 (Absolute control). The grain yield significantly varied with respect to treatments. The beneficial effect of Si on yield attributes and dry matter yield was mainly owing to its favourable effect on leaf erectness andbetter penetration of sunlight leading to high photosynthetic activity and reduction in the incidence of pest and diseases. Silicon is responsible to control stomatal activity, photosynthesis and water use efficiency which ultimately results in better vegetative growth and straw yield (Ahmad *et al.* (2007); Surapornpiboom *et al.* (2008); and Elzbieta (2009). In general, sandy soil low in available Si had a high response to applied Si in achieving higher grain yields.

5.3.1.2 Effect of different sources of Si on Si uptake by straw and grain

The uptake of Si by grains varied significantly with respect to the treatments (fig.55). The treatments with Si application were on par and significantly differ from treatments without Si application. The Si uptake by grain and straw were highest in T_6 (T_2 + Sodium silicate) and lowest in T_1 (Absolute control). The effect of Si application indicated that Si uptake by grain significantly increased over control. Since sodium silicate is liquid fertilizer, release of Si from this would be more. The soil analysis also showed that significantly higher available silicon was observed in the treatments receiving sodium silicate at flowering and panicle initiation stage. This could be the reason for higher uptake of Si by grain and straw in treatment with sodium silicate application. Rice requires large amounts of Si for healthy plantgrowth and development. Under warm subhumid tropical conditions of India, Si removed by

12 rice cultivars grown on Inceptisol during the dry season varied from 205 to 611 kg Si ha^{-1} when grain yield ranged from 4.6 to 8.4 t ha^{-1} (Nayar *et al*., 1982).

5.3.1.3 Effect of different sources of Si on soil properties at tillering stage

The data on the electrochemical properties and nutrient contents in the soil at tillering stage are presented in table.41. The application of different sources of Si had significanteffect on pH, plant available Si and available Cu at tillering stage and increased significantly over control. The pH and available Si were significantly higher with the application of RHA. Okon *et al.* (2012) reported that RHA was responsible for ameliorating the soil acidity and thus, improving fertility of the acid sands. Silicon is present in RHA as SiO_2 which can be easily solubilized into soil solution. This might be the reason for higher available Si in this treatment. The plant available Si was increased with calcium silicate and sodium silicate application. As compared to initial Si concentration, Si was low in soils where RHC was applied. It could due to more uptake of Si by plants as evidenced by the higher Si content in shoot at tillering stage in treatment with RHC.

Electrical conductivity, available N, P, K, Ca, Mg, S, Fe, Zn, Mn, B and Al content of the soils of the experimental plots were not significantly influenced by any of the treatment at this stage. The pH, available N, Mg, S and Mn were increased with Si application at this stage, whereas EC, available P, K, Ca, Fe, Cu, Zn, B and Al were decreased at this stage.

The content of available P, Ca, S, Zn and Al were found to be lowest in T_4 where biodecomposed rice husk applied as Si source. The highest values of available K, Fe, Mn and Zn were recorded in control treatment (T_1). Treatments without silicon application showed a low available Si as compared to initial soil Si content due to more uptake of Si by plant during vegetative growth stage.

5.3.1.4 Effect of treatments on soil properties at panicle initiation stage

The results pertaining to the electrochemical properties and nutrient status of soil at panicle initiation stage are presented in table.42. The data showed that pH, available Si and available S found to be significantly varied with respect to treatments and all other parameters remain as non significant. Higher pH was recorded with application of calcium silicate. This might be due to the fact that calcium silicate would have prevailed in soil as monosilicic acid (H_4SiO_4) which increases soil pH. The available Si increased significantly inall treatments from tillering to panicle initiation stage except in treatments with RHC and calcium silicate. It clearly indicates that Si release from RHC and calcium silicate is higher at tillering stage. The available sulphur in soil was significantly increased over control, but decreased from tillering stage and higher S content was recorded with RHC application.

There was no significant difference between the treatments with respect to available N, P, K, Mg, Fe, Zn, B and Al content in soil, but decreased as compared to tillering stage, whereas available Cu and Mn increased as compared to tillering stage. The available Ca in soil increased with RHA, RHC and calcium silicate application, while decreased in remaining treatments as compared to tillering stage.

5.3.1.5 Effect of different sources of Si on soil properties at harvest stage

The data on electrochemical properties and nutrient status of soil at harvest arepresented in table.44 and 45. The pH, EC, CEC, AEC, SiO_2: R_2O_3, available Ca, Mg, Mn, Zn and B were found to be significantly varied with respect to treatment. Silicate fertilization increased soil pH, OC, available N, P, K, Ca, Fe, Al and Si, AEC and SiO_2: R_2O_3 ratio, and decreased EC, available S, Cu, Mn and B. The application of Si fertilizers did not influence the content of Mg and Zn in soil.

The available phosphorous content in soil was increased by the application of silicate fertilizer, probably due to the increase in soil pH. Another possible reason is the displacing of phosphate from the ligand exchange sites (Roy *et al.,* 1971; Lee *et al.* 2004), and/or the decrease in phosphate sorption on soil colloids by silicate ion (Shariatmadari and Mermut 1999). Subramanian and Gopalswamy (1991) reported 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. The organic matter content of soil after rice harvesting was slightly increased with silicate fertilizer applications, probably due to the increased shoot and root biomass production.

The available potassium content in soil was increased at harvest. 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 (Nagula *et al.,* 2015).

Sadgrove, (2006) reported that silicon reduced leaching of phosphorous and potassium in soil and increased stability of soil organic matter. The available sulphur, iron, manganese and boron were decreased at harvest stage. The available Mn was significantly differing with respect to Si fertilizers. The higher Mn was estimated in treatments without Si application. Si application could reduced and manganese mobility in soil (Matichenkov and Calvert, 2002).

At flowering and panicle initiation stage, significantly higher available silicon was observed in the treatments receiving sodium silicate and RHA, while at the harvesting stage calcium silicate treatment was superior in available Si content in soil (fig.62). 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 (Singh *et al.* 2006).

The variation in available Si in paddy soil during rice growth stage suggests that the application of Si in later growth stages might be important for rice growth stage. Rice plant absorb large a large amount of available Si from the soil for its vegetative growth in the early growth stage. Thus available Si in soil was much reduced to meet the requirement in the later growth stage. The paddy soil could not accumulate a higher level of available Si during rice growth due to vigorous absorption by the rice plant.

5.3.1.6 Effect of different sources of Si on nutrient content in shoot at tillering stage

The analytical data on nutrient contents in shoot was represented on table.46. The contents of Si, N, P and S in shoot at tillering stage were found to be significantly increased with Si application. Higher content of Si, P and S was found with RHC application. Vavoulidu *et al.* (2004) reported that as a result of organic treatments into the soils, productivity levels of soils increased with the increase of available P amounts and enhance P uptake by plants.

The silicon content in shoot increased significantly in treatments with Si application over control. The silicon content was more in treatment with RHC which was on par with calcium silicate. 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.

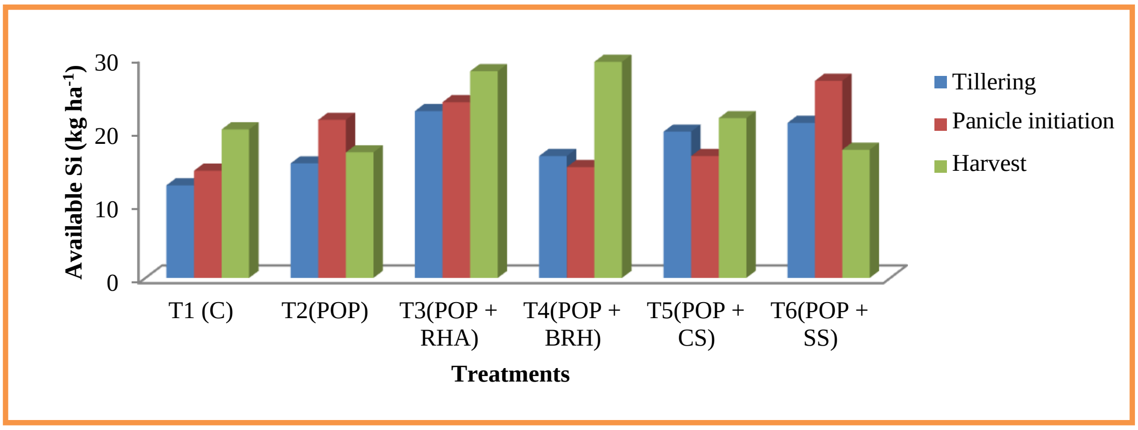


Fig.56 Effect of different sources of Si on available Si in soil during rice cultivation

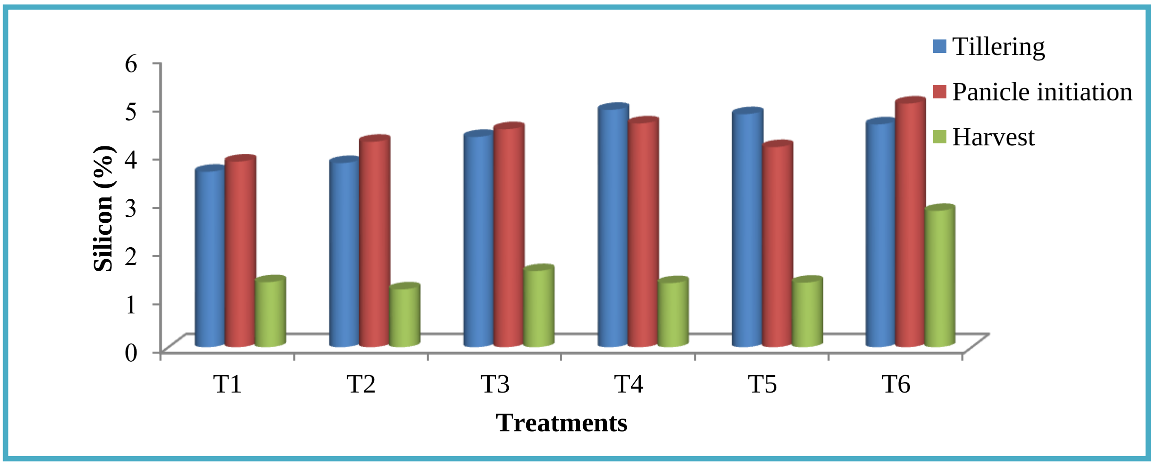


Fig.57 Effect of different sources of Si on Si content in shoot of rice

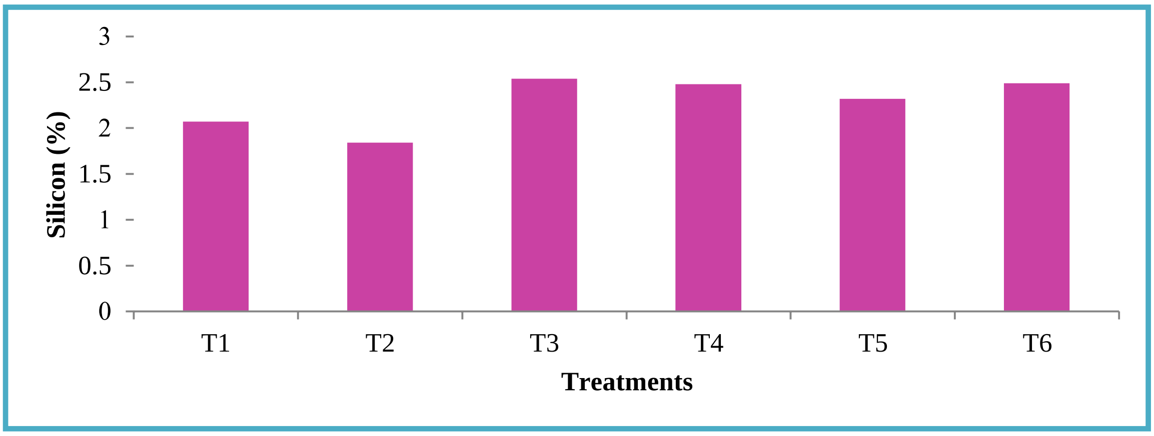


Fig.58 Effect of different sources of Si on Si content in grain of rice

5.3.1.7 Effect of different sources of Si on nutrient content in shoot at panicle initiation stage

The results pertaining to the nutrient content in shoot at panicle initiation stage are presented in table.47. The contents of Si, N, P, Ca, S and Mn in shoot at panicle initiation stage were found to be significantly varied with respect to treatments. Si content in shoot was increased significantly over control with application of Si fertilizers. Due to lower available Si in soil with RHC and calcium silicate application, the Si content in shoot was lower in these treatments as compared to tillering stage. The analytical data showed that the plant requires maximum Si at this reproductive stage. The manganese content in shoot was significantly decreased in treatments with Si fertilizers over control and reduced. As Si was added to the nutrient solution, the concentration of Mn in leaves decreased and increased in roots, thus alleviating the toxic effects of Mn on the plants. (Junior *et al.*, 2010)

Although the active Si absorption by rice seems to start after tillering stage or after stem elongation, the most effective period for Si application for increasing yield seems to be during the reproductive stage in which its uptake and dry matter production are most vigorous(Kato and Owa, 1990; Chen, 1990).

5.3.1.8 Effect of different sources of Si on nutrient content in straw at harvest stage

The results pertaining to the nutrient content in shoot at harvest stage are furnished in table.48. The contents of Si, N and S in shoot at harvest stage were found to be significantly influenced by treatments. Higher Si content in shoot was recorded with the application of sodium silicate followed by RHA (fig.57), whereas higher content of N and S was found in treatment representing calcium silicate as Si source.

The contents of P, Ca, Mg, Fe, Mn, Zn, B and Al in shoot got decreased towards harvest as compared to panicle initiation stage and remained almost a constant in all treatments. The potassium content was found to increase at this stage. It clearly indicated that maximum absorption of plant nutrients except K occurred at panicle initiation stage.

The Si uptake or its content in plants might get increased to some extent by applying silicate material. Similar results were also reported by Snyder *et al.* (1986) and Korndorfer *et al.* (2001b) in some soils of Florida and Takahashi *et al.* (1990) in soils of Sri Lanka, Singh *et al.* (2006) in soils of India. The lower straw Si concentrations were associated with lower relative yield (Korndorfer *et al.*, 2001b). The physiological mobility of Si was very low in rice plants; the reutilization of Si is unlikely to occur once. This fact indicated that a continuous supply of Si is necessary through entire growth period of rice plant.

The analytical data showed Si as the highest dominant element in rice straw followed by potassium, nitrogen, calcium and magnesium.

5.3.1.9 Effect of treatments on nutrient content in grain at harvest stage

The results related to the nutrient content in grain at harvest stage are presented in table.49. The treatments had significant effect on Si, N and P contents alone in grain at harvest stage. The Si content in grain increased significantly following Si fertilizer application over control and highest Si in grain was associated with application of RHA. All Si sources were on par with respect to Si content in grain (fig.58). Nitrogen content in grain significantly increased over control and the highest N content was observed with the application of sodium silicate. The contents of K, Ca, Mg, S, Fe, Mn, Zn, B and Al remained almost constant in grain at harvest stage. Silicon remained as the dominant element in rice grain followed by nitrogen, potassium and phosphorous.

5.3.1.10 Effect of silicon fertilizers on electrolyte leakage, catalase and peroxidase activity

To keep the levels of active oxygen species under control, plants have non-enzymatic and enzymatic antioxidant systems to protect cells from oxidative damage. Catalase and peroxidase are enzymes that catalyze the conversion of H_2O_2 to water and O_2. Cell membranes are one of the first targets of many plant stresses. The degree of cell membrane injury may be easily estimated through measurements of electrolyte leakage from the cells. Electrolyte leakage is used to assess membrane permeability.

The data on effect of treatments on electrolyte leakage in leaf of rice plant at different growth stages are shown in table.50 and fig.59. The analytical data showed that EL increased during vegetative and reproductive stages and decreased during harvesting stage. At 90 DAT, highest EL was recorded with the application of RHA. EL increased significantly over control except with calcium silicate application. Calcium silicate significantly decreased ELat 90 DAT. Increased EL leakages at harvesting stage might be due to lower Si content in straw at this stage.

The data on effect of treatments on catalase activity in leaf of rice plant at different growth stages are provided in table.51 and fig.60. At 45 and 60 DAT, treatments had significant effect on catalase activity, but no significant effect was seen at 90 DAT. Si applications significantly reduced catalase activity over control at 45 and 90 DAT. It might be due to absence of any type of stress in the present experiment. Ali *et al.* (2013) reported that the lower concentrations of CAT, indicating lower levels of reactive oxygen species (ROS), would be a sign of lower oxidative damage. Zhu *et al.* (2004) also reported a reduced catalase activity with Si addition in cucumber. He stated that the antioxidant enzymes arevery complex and their activity depends on the stress condition, treatment time, plant species and genotypes. The catalase activity was found to be highest at reproductive stage (60 DAT).

The results pertaining to the effect of treatments on peroxidase activity in rice leaf at different growth stages are presented in table.52 and fig.61. The treatments had significant effect on peroxidase activity at 45, 60 and 90 DAT. Peroxidase activity significantly decreased over control with Si application. It showed an increasing trend throughout the growth stages of rice plant. Gong *et al.* (2005) reported the same result in wheat. The increasein the activity of POD at different growth stage might be an adaptive response. In barley, it was found that added Si increased POD activity of salt stressed plants (Liang *et al*. 2001).

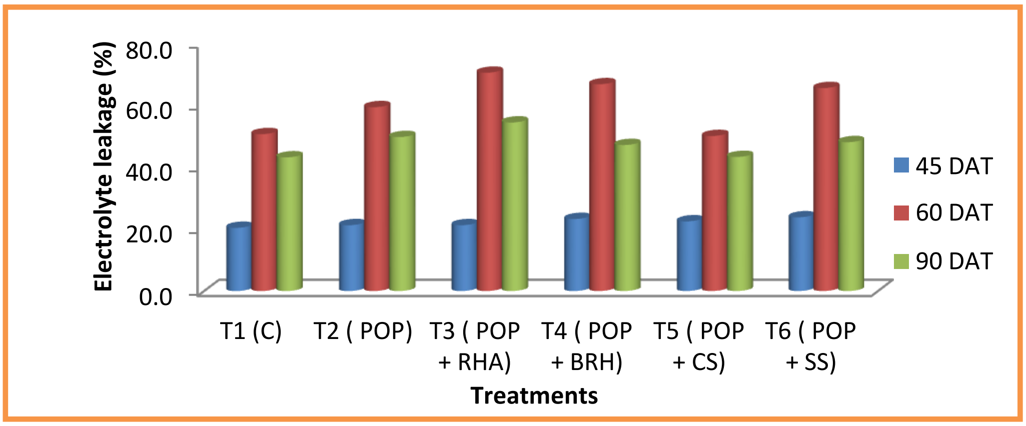


Fig.59 Effect of different sources of Si on electrolyte leakage from rice leaf

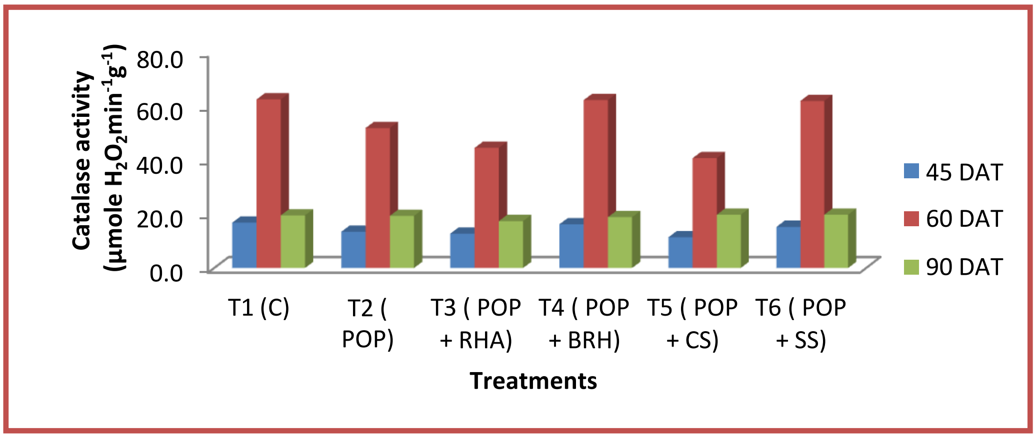


Fig.60 Effect of different sources of Si on catalase activity from rice leaf

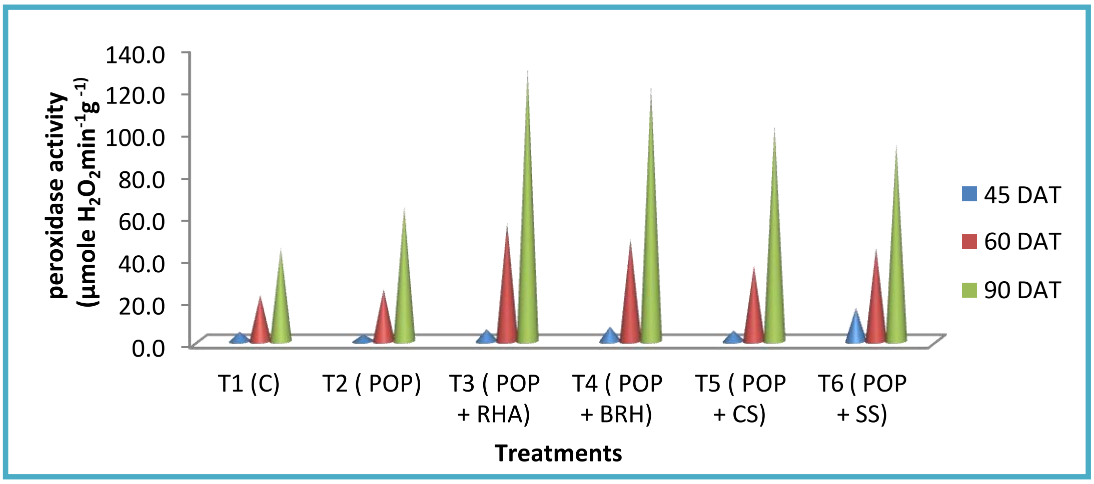


Fig.61 Effect of different sources of Si on peroxidase activity from rice leaf

Residual effect of rice straw incorporation on growth and yield of succeeding crop of rice

5.3.2 Field experiment 2

Incorporation of the remaining stubble and straw of first crop into the soil returns most of the nutrients and helps to conserve soil nutrient reserves in the long term. Short-term effects on grain yield are often small (compared with straw removal or burning) but long- term benefits are significant. When mineral fertilizers are used and straw is incorporated, reserves of soil N, P, K, and Si are maintained and may even be increased (Dobermann and Fairhurst, 2002).

Rice is a Si accumulator; therefore, adequate attention should be given to the beneficial role that Si nutrition and its management can play in a balanced integrated nutrient management system for increasing and sustaining rice yields. Large amounts of Si as monosilicic acid [H_4SiO_4, or $Si(OH)_4$] are absorbed by the rice plant. Subsequently, Si is deposited as amorphous SiO, and is mainly associated with cellulose and hemicellulose in therice plant tops (leaves and hulls) in the form of *cuticle-Si double layer*. Rice straw has been shown to keep silicon in an available form so thatwith its decay during the following crop,the silicon becomes available for uptake by the rice plant. Incorporation of straw and stubble into wet soil (during plowing) resulted in a temporary immobilizationof N (Dobermann and Fairhurst, 2002).

5.3.2.1 Biometric observations

The results pertaining to biometric observations of second crop of rice are given in table.53. the data on number of tillers per hill, plant height, root weight, root volume, number of unfilled grains per panicle, thousand grain weights did not vary significantly with respect to treatments in succeeding rice crop, whereas number of panicles per hill, number of spikelet per panicle and number of filled grains per panicle varied significantly due to residual effect of Si in succeeding crop.

Number of panicles per hill and number of filled grains per panicle were significantly higher in plots where calcium silicate was applied as Si source in first crop. Number of filled grains per panicle significantly increased over control due to residual action of Si fertilizers except RHA. In the second rice crop, control plot showed significantly higher number of spikelet per panicle.

5.3.2.2 Residual effect of rice straw in corporation on grain and straw yield

Grain and straw yield recorded are presented in table.56 and depicted in fig.62. In the succeeding rice crop, the residual effect of Si sources had no significant effect on grain and straw yield. It might be due to very slow release of Si and inadequate supply of other essential elements for growth and development. Even though the rice straw was incorporated into the field itself, the temporary immobilization of nutrients due to the presence of undecomposed organic manure or the wider C: N ratio would have reduced the nutrient release. There was no residual effect of Si on rice grain yield of succeeding crop. This is confirmed with the findings of Yadvinder-Singh *et al.* (2005).

5.3.2.3 Effect of rice straw in corporation on Si uptake by straw, grain and total uptake

Si uptake by straw as well as grain and the total uptake are given in table.57 and fig.63. The Si uptake by grain and total Si uptake by plant did not vary significantly due to residual action of Si, while Si uptake by straw revealed significant variation with respect to treatments. Si uptake by straw was significantly higher in treatment where calcium silicate was applied as a Si fertilizer to first crop. It clearly indicated that Si accumulation was morein straw than grain in rice plant. Anderson *et al.* (1990) reported that with calcium silicate slag application, yields decreased as much as 28 per cent in cane and 29 per cent in sugar in a ratoon crop of sugarcane. The reduced yields in ratoon crops were associated with lower Si levels.

5.3.2.4 Residual effect of rice straw in corporation on soil properties beforetransplanting of rice

The organic carbon content of soil varied significantly and highest OC content was recorded with the application of calcium silicate to the preceding crop. The incorporation of rice straw helped in improving soil organic carbon content (Xionghui *et al.*, 2012). The available Ca in soil was significantly increased over control and was on par with all other treatments. Both organic carbon and Ca might have influenced the cation exchange capacity of soil as it varied significantly with respect to treatments. This is confirmed with the findings of El Sharkawi *et al*., (2006). Added rice straw in submerged soils enhanced slower, incomplete and inefficient decomposition (Sahrawat, 2006). It is necessary to make compost or lower the C/N ratio for rice straw before using.

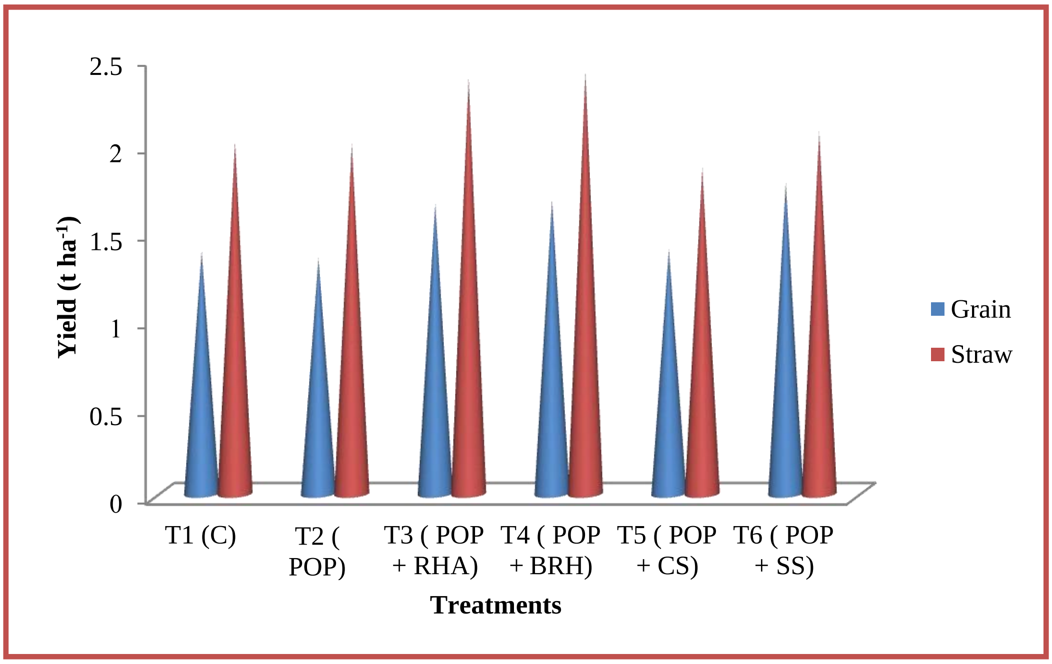


Fig.62 Residual effect of rice straw incorporation on grain and straw yield of succeeding rice crop

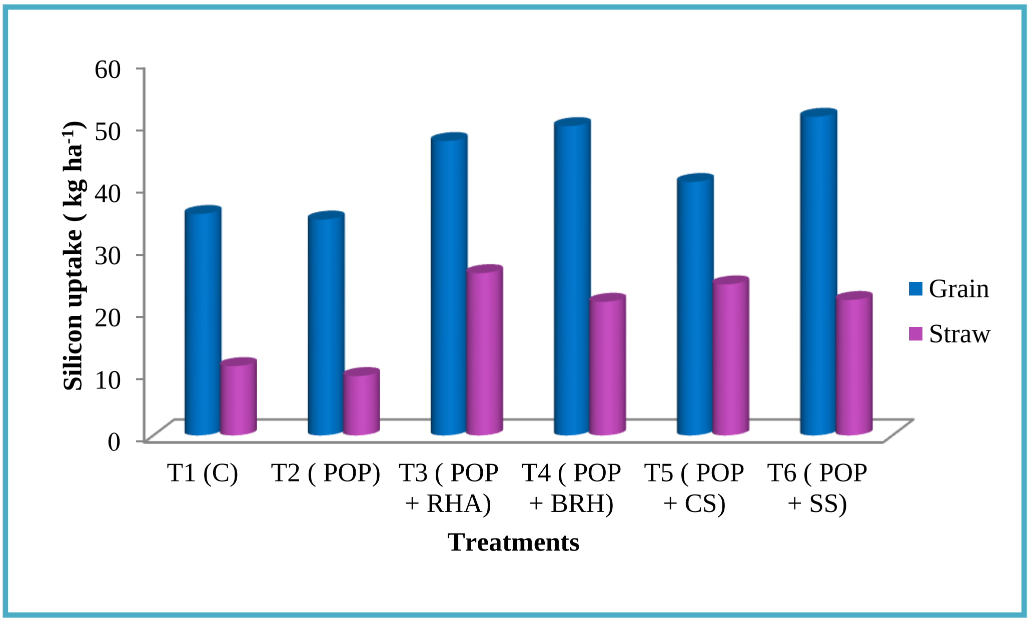


Fig.63 Residual effect of rice straw incorporation on Si uptake by grain and straw of succeeding rice crop

The analytical data of soil before transplanting of rice revealed that pH, available N, P, Ca, Mg and Cu decreased, while OC, S, Fe, Mn, Zn, B and Al increased due to rice straw incorporation as compared to electro-chemical properties of soil after harvest of preceding rice crop. The decrease in availability of major nutrients might be due to temporary immobilization of these nutrients with the addition of undecomposed organic matter (Yadvinder-Singh *et al.,* 2005). At the same time, due to chelation, availability of micronutrients increased with organic matter addition. But copper with its ability to establish very tight bonds with organic matter than any other micronutrient might have reduced its availability (Angelova *et al*., 2010).

5.3.2.5 Residual effect of rice straw in corporation on soil properties at at tillering stage

The data on soil properties at tillering stage are presented in table.60. The residual effect of treatments had no significant effect soil properties except available Ca at tillering stage. pH and EC increased as compared to initial value. The submergence of soil after transplanting of rice could be the reason for increased pH and EC. The available Si, K, Mg, S,Cu, Mn, Zn, B and Al showed an increase over the initial. It clearly indicated that decomposition of rice straw under submergence enhanced the availability of these nutrients insoil solution and made them available for plant absorption (Marxen *et al*., 2015). Sidhu *et al.* (1995) reported that soil treated with crop residue held 5 – 10 times more aerobic bacteria and1.5- 11 times more furngi. Due to increase in microbial population, the activity of soil enzymes responsible for conversion of unavailable to available form of nutrients also increased. At the same time, available N and P got decreased due to more uptakes of these nutrients by plants during vegetative growth stage.

5.3.2.6. Residual effect of rice straw in corporation on soil properties at panicle initiation stage

The results pertaining to soil properties at panicle initiation stage are presented in table.61. The data showed that pH, EC available Ca and available B showed significant variation, while all other parameters remained non significant with respect to treatments. The pH and EC revealed a significant increase over control, but then decreased as compared to tillering stage. Application of rice straw significantly increased the pH value. Soil pH can be increased due to the decarboxylation of organic anions on decomposition by microorganisms (Saha *et al.,* 2009). The available Ca content significantly increased over control and the highest value of Ca was noticed consequent to calcium silicate application to the first crop. The residual effect of calcium silicate in soil is well reflected in the result. The available B also increased significantly over control. The available B status of soil was found highest with application of calcium silicate and RHA to the preceding crop. It is emphasizing the significant residual effect of Si on availability of B in soil. It can also be well stated that the residual effect of Si on availability of Ca and B in soil will be expressed after long time of fertilizer application. The content of available Si, N, Cu and Mn were low in soil at panicle initiation stage as compared to tillering stage. It could be due to more uptakes of Si and N by plants in the absence of fertilizer application, adsorption of Cu by organic matter and Mn by silicate minerals. Available P, K, Ca, Mg, S and Al content in soil showed an increase at panicle initiation stage as compared to tillering stage.

5.3.2.7 Residual effect of rice straw in corporation on soil properties at harvest stage

The data on soil properties at harvest are presented in table.62 and table.63. The AEC, SiO_2: R_2O_3, available S and B were found to be varying significantly with respect to treatment. The highest AEC was noticed with the application of calcium silicate and sodium silicate to the first crop. SiO_2: R_2O_3 ratio was highest in the treatment that supplied Si as sodium silicate to the first crop. Available S and B increased significantly over control and both were found highest after the first crop in calcium silicate applied plots in first crop. It clearly indicated that the residual effect of Si application towards the availability of B in soil will last for long as evidenced from the content at tillering stage.

The analytical data showed that all elements analyzed got decreased at harvesting stage. It might be due to vigorous uptake of these nutrients from soil solution in absence of fertilizer application. The results indicated that the available Si in soil during second crop season was much lower than first crop season (fig.64). There are several potential mechanisms that may be responsible for the trend observed in case of Si levels in soil solution, but several findings suggest that biocycling has a large influence on the pore-water Si dynamics in the rice agroecosystem (Seyferth *et al.*, 2013).

5.3.2.8 Residual effect of rice straw incorporation on nutrient content in shoot at tillering stage

The analytical data on nutrient contents in shoot are represented on table.64. On comparing the effect of treatments on nutrient content, only N showed a significant effect.

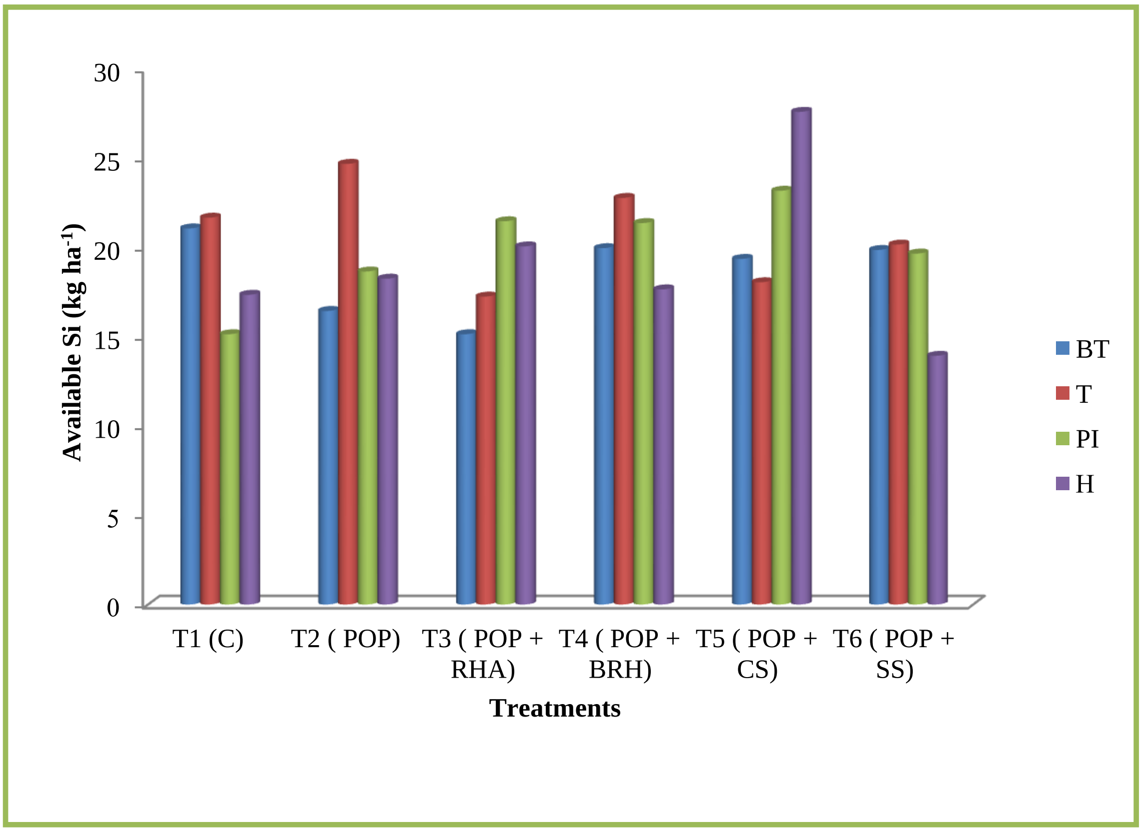


Fig.64 Residual effect of straw incorporation on Si content in soil during cultivation of succeeding rice crop

As against first crop, N, K and Al content showed an increase, while Si, P, Ca, Mg and Fe decreased in succeeding crop. S, Mn, Zn and B did not show much variation as compared to previous crop. The dominant elements present in rice straw of preceding crop were Si, K and N. During decomposition of straw, these elements will be released into soil solution and made available for plant uptake. This could be the reason for higher content of Kand N in second crop as compared to first crop. This is confirmed with the findings of Ghoneim and Ebid (2015). The higher content of Al in shoots of second crop clearly indicatesthat Si application can alleviate Al toxicity by reducing Al uptake by plants. It is adequately evidenced by the lower content of Al in first crop with higher dose of Si application (Ma and Takahashi, 2002).

The Si content in shoot decreased as compared to first crop. Zhang (1984) found that straw incorporation did not affect plant-Si. The fate of Si in soil solution released from plant residues was affected by adsorption onto Fe and Al hydroxides (and other soil minerals), plant-uptake, and rates of mineral dissolution and precipitation (Wickramasinghe and Rowell,2006). Thus, to understand the role of rice straw incorporation into soil on plant-availability of Si, there is a need to examine the relative contribution of different Si pools on pore-water concentrations under the complexity of field conditions.

5.3.2.9 Residual effect of rice straw incorporation on nutrient content in shoot at panicle initiation stage

The results pertaining to the nutrient content in shoot at panicle initiation stage are presented in table.65. The N content varied significantly with respect to treatments. The highest N content in shoot was recorded with the application of RHA to the preceding crop. Except N, P and K, the content of all other nutrients in shoot were found to be less at this stage as compared to tillering stage. Inadequacy of essential nutrients in soil solution due to the absence of fertilizer application in soil might be the reason for fewer up take of these elements by plants at panicle initiation stage.

5.3.2.10 Effect of rice straw incorporation on nutrient content in straw at harvest stage

The results pertaining to the nutrient content in shoot at harvest stage are presented in table.66 and fig.65. The contents of Si and N in shoot at harvest stage were found to vary significantly with respect to treatments. Si content in straw increased significantly overcontrol and the highest value was registered with the application of calcium silicate to the preceding crop. The Si content in straw was lower in all treatments after second crop against first crop at harvesting stage. This suggested that rice accumulates Si on addition of Si fertilizers. The residual effect of Si fertilizers will be expressed after long time of fertilizer application due to slow release of Si from rice straw during decomposition or adsorption onto Fe and Al hydroxides in soil. N content in straw varied significantly over control and highest N content was observed with the application of RHA to the preceding crop. The contents of all other elements except S and Mn in straw remained the same as preceding crop at this stage. It clearly indicated that Si has significant effect on absorption of S and Mn by plants. Itis further evidenced by the lower content of S and Mn in preceding crop with application ofSi fertilizers.

5.3.2.11 Effect of rice straw incorporation on nutrient content in grain at harvest stage

The results pertaining to the nutrient content in grain at harvest stage are presented in table.67 and fig.66. The treatments had significant effect on Si, N, Ca, S and Fe content in grain at harvest stage and others remained non-significant with respect to treatments. Si content of grain increased significantly over control. The highest Si content in grain was recorded with the application RHC which was on par with other treatments of Si application to the first crop. The first crop and second crop showed almost similar Si content in grain. These data suggested that soil incorporation of plant material rich in Si released Si to soil solution, which was available for plant uptake during the growing season.

The highest Ca, S and Fe content were noticed with application of sodium silicate to the preceding crop. P and K content in grain increased, whereas N, Ca and Al content showed a reduction as compared to first crop.

5.3.2.12 Effect of rice straw incorporation on electrolyte leakage, catalase and peroxidase activity

The data on effect of treatments on electrolyte leakage from rice leaf at different growth stages are presented in table.68. The treatments had no significant effect on EL at any stages of rice growth. The EL at three stages was almost similar. On comparison with preceding crop, higher EL was noticed in second crop. It might be due to less availability ofSi in soil.

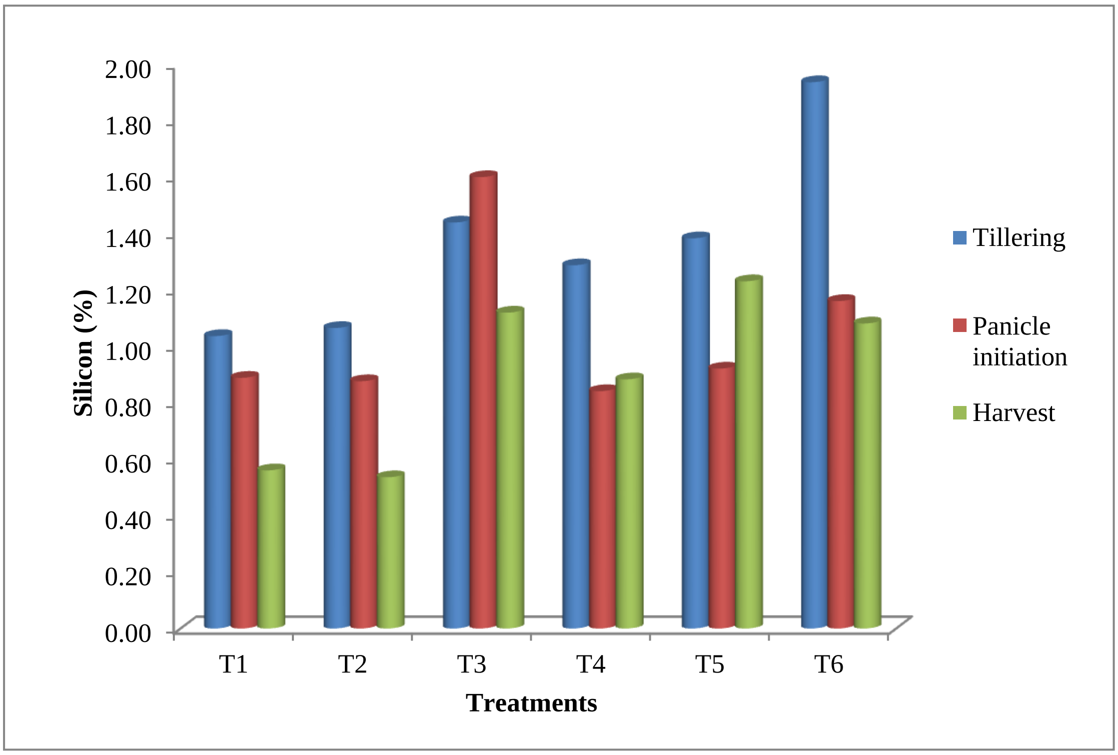


Fig.65 Residual effect of straw incorporation on Si content in shoot of succeeding rice crop

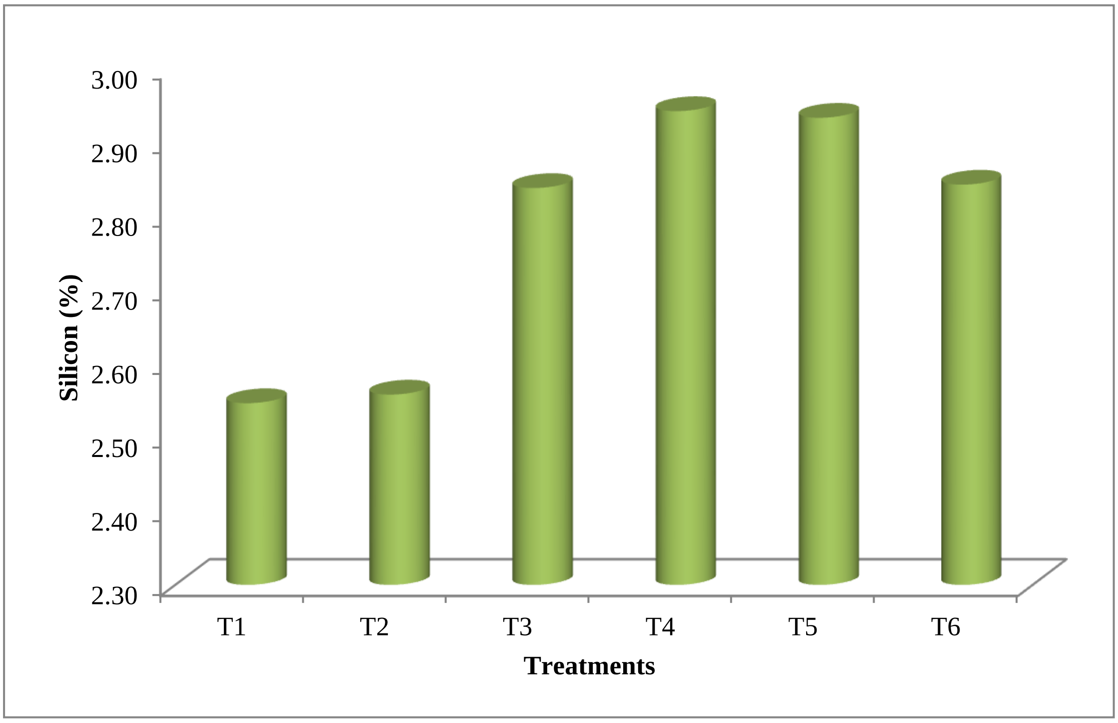


Fig.66 Residual effect of straw incorporation on Si content in grain succeeding rice crop

The data on effect of treatments on catalase activity in leaf of rice plant at different growth stages are furnished in table.69. The treatments had no significant effect on catalase activity at different growth stages. The catalase activity increased from 45 DAT to 60 DAT and then decreased at harvesting stage. As compared to first crop, catalase activity was found to be lower in second crop.

The results pertaining to the effect of treatments on peroxidase activity in rice leaf at different growth stages are presented in table.70. The treatments had a significant effect on peroxidase activity only at 90 DAT. The highest peroxidase activity was recorded in samples collected from plot supplied with RHA to the preceding crop. This may be due to slow release of N leading to nutrient deficiency. At this time, antioxidant enzyme support plant to become more tolerant against the disturbances in the different physiological processes (Siavoshi and Laware, 2011). There was an increasing trend in peroxidase activity from 45 DAT to 90 DAT. During vegetative and reproductive stage, peroxidase activity was almost similar, whereas at harvesting stage, peroxidase activity was found to be increased nearly three times as compared to initial growth stage. On comparison with first crop, the peroxidase activity was very high in second crop at all the three stages of growth. Peroxidase enzyme is repeated to be involved in several physiological and biochemical processes such as cell growth and expansion, differentiation and development. At harvesting stage, the level of degradation enzymes in the plant will be higher which accounts for the higher peroxidase activity at this stage. Greater increase in peroxidase activity might be due to induction of enzyme in response to increasing temperature during second crop season (Almeselmani *et al.,* 2006).

Summary

6. Summary

The project entitled "Silicon availability of tropical soils with respect to rice nutrition" was conducted in the Department of Soil Science and Agricultural Chemisrty, College of Horticulture, Kerala Agricultural University during 2011-2014. This project included both incubation study and field experiments. The incubation study was conducted to assess the release of silicon in different rice growing soils under different water regimes and to ascertain silicon adsorption capacity of different rice growing soils of Kerala. The field experiments to to evaluate the efficacy of different sources of silicon in wet land rice and also the residual effect of rice straw incorporation on growth and yield of succeeding crop of rice were conducted at Agronomic Research Station, Chalakudy.

Representative soil samples were collected from five different locations representing the major rice growing soils of Kerala *viz.,Kuttanadu* soil (S_1) of Moncombu, *Kole* land soil (S_2) of Adat, *Pokkali* soil (S_3) of Vyttila, sandy soil (S_4) of Chalakudi and lateritic soil (S_5) of Pattambi. The soil samples were analyzed for physico-chemical properties like texture, pH, EC, AEC, CEC, organic carbon, available major nutrients (N, P and K), secondary nutrients (Ca, Mg and S), micronutrients (Fe, Cu, Mn, Zn and B), available and total Si. Then these major rice growing tracts were categorized according to plant available silicon. To know the pools and dynamics of Si in soil and its adsorption behavior, fractionation and adsorption studies of these soils were carried out. The major fractions of Si were mobile, adsorbed, organic, occluded, amorphous and residual Si. Quantity – intensity relationship of five major rice growing soils at two temperatures *viz.* 25 and 40^0C were studied. The equilibrium Si concentration and the amount of Si adsorbed by each soil were used to test the fitness of data to the adsorption equations *viz.,* Langmuir, Freundlich and Temkin adsorption equations. The salient results of the study are summarised and listed below.

- The available Si ranged from 7.70 mg kg^{-1} (sandy soil) to 34.91 mg kg^{-1} (*Kole* land soil) in the order *Kole* land > *Pokkali* > lateritic > *Kuttanad* > sandy soil
- All the soils under study were categorized as low in available Si.
- The available Si had positive correlation with organic carbon, available N, Ca, Mg, Fe, Mn, Zn, exchangeable K, Ca, Mg and CEC and negative correlation with available boron, AEC and silica-sesquioxide ratio.
- Total Si in major rice growing soils ranged from 91.8 to191.2 g kg^{-1} Total
- Si status – *Kuttanad* > *Pokkali* > sandy > lateritic > *Kole* land soils

- Available Si constituted only 0.004 to 0.04 percent of total Si
- Residual and amorphous Si were the most dominant fractions
- Adsorbed Si was the least fraction
- The percentage distributions of the different fractions of Si were in the order; residual Si > amorphous Si > occluded Si > oragnic Si > mobile Si > adsorbed Si in *Kuttanad, Pokkali* and sandy soils,
- It was in the order amorphous Si > residual Si > occluded Si > oragnic Si > mobile Si > adsorbed Si in *Kole* land soil
- Amorphous Si > residual Si > oragnic Si > occluded Si > mobile Si > adsorbed Si in lateritic soil.
- Mobile, occluded and residual Si fractions were most contributing fractions towards availability of Si in soil solution
- The direct effect of residual Si on available Si was very high and positive (1.305).
- The mobile Si had high direct positive effect (0.693) on plant available Si.
- The occluded Si had moderate direct effect (0.231) on plant available Si.
- The direct effect of adsorbed Si on plant available Si was low (0.192).
- The highest buffer power was indicated by *Kuttanad* soil followed by *Pokkali* and sandy soils at 25^0C.
- At 40^0C, the buffer power was highest in sandy (1.14 L kg^{-1}) soil and lowest in *Kuttanad* (-0.73 L kg^{-1}) soil.
- The intercept of soils (K) varied from -143.80 mg kg^{-1} (sandy soil) to 97.05 mg kg^{-1} (*Kole*) at 25^0C. The lowest and highest values of K were found as -609.10 and1013.00 mg kg^{-1} in sandy and *Kuttanad* soils respectively at 40^0C.
- The data obtained from the adsorption experiments fitted into Freundlich and Temkin equations, but not to Langmuir equation at 25^0C.
- At 40^0C no adsorption equations were obtained for any soil.
- The *Kole* land soil showed highest adsorption intensity of Si, whereas sandy soils of Chalakudy and *Pokkali* soils of Vyttila showed lowest adsorption intensity.
- The free energy change (ΔG^0) values were negative for all the soils. The maximum of -1.07 kcal mol^{-1} was recorded for ΔG^0 at 25^0C in *Pokkali* soils of Vyttila and minimum of -1.37 kcal mol^{-1} in sandy soils of Chalakudi,
- *Kole* land (-0.98 kcal mol^{-1}) soils recorded maximum and sandy (-1.36 kcal mol^{-1}) soils of Chalakudy recorded minimum ΔG^0 at 40^0C.

- The change in entropy (ΔS^0) was negative except for *Kuttanad* and *Pokkali* soils at 25^0C and 40^0C.

An incubation study was conducted to know the extent of release of Si on addition of different sources of silicon such as rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate in five rice growing soils under submerged water regime (SWR) and field capacity water regime (FCWR). Quantity of silicon sources were calculated to provide 45 kg ha^{-1}. The incubated samples were subsampled at specified intervals for estimating pH, EC, ORP, available and total Si. During incubation study, the pH, EC and redox potential of soil under each treatment were analysed continuously for first two weeks, once in a week for next one month and then at monthly intervals with the use of pH meter, conductivity meter and redox meter respectively. Available Si and total Si in the soil was analysed by drawing samples at 1, 2 and 3 months during the period of incubation.

- During incubation study, addition of Si significantly increased the release of available Si in all soils except *Kole* land soil after a month.
- *Kole* land soil showed higher release of available Si after two months.
- The highest release of available Si was at SWR in case of *Kole* land and *Kuttanad* soil, where as *Pokkali*, sandy and lateritic soils showed more release of available Si at FCWR.
- Irrespective of soils, treatment with sodium silicate showed higher release of available Si.
- Total Si showed a decreasing trend over the period of incubation for three months in all the soils.

A field experiment was conducted at Agronomic Research Station, Chalakudy to evaluate the efficacy of different sources of silicon including rice straw in wetland rice. Rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate were used as source of Si along with fertilizers as per package of practice recommendation (POP) to the quantity required to supply 45 kg of Si ha^{-1}. The experiment was laid out in a randomised block design with six treatments in four replications. The plot size was 20 m^2. The rice variety used was Uma. Soil and plant samples were collected at tillering, panicle initiation (PI) and harvest stage and analysed for nutrient content. The soil samples were analyzed for physico-chemical properties like texture, pH, EC, AEC, CEC, organic carbon, available major nutrients (N, P and K), secondary nutrients (Ca, Mg and S), micronutrients (Fe, Cu, Mn, Zn and B), available

Al and Si. The plant samples were analysed for N, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn, B, Al and Si. The observations on number of tillers per hill, plant height, root weight and root volume were recorded at tillering, panicle initiation and harvest. In addition to this, number of panicles per hill, number of spikelets per panicle, filled grains per panicles, unfilled grains per panicles and thousand grain weight and the weight of grain and straw were recorded after harvest.

- The maximum number of panicle per hill, number of spikelets per panicle, andthousand grain weights and minimum number of unfilled grains per panicle were recorded in treatment with calcium silicate application.
- During first field experiment, the maximum grain yield of 6.90 t ha^{-1} was recorded in treatment with POP + calcium silicate and it was significantly superior over all other treatments.
- The treatment with POP + sodium silicate showed the highest uptake of Si by grain and straw.
- The maximum grain yield of 1.78 t ha^{-1} was recorded in treatment T_6 (T_2 + sodium silicate) during second crop
- In general, sandy soil low in available Si had a high response to applied Si inachieving higher grain yield.

Incorporation of the remaining stubble and straw of first crop into the soil returns most of the nutrients and helps to conserve soil nutrient reserves in the longterm. It may be a low cost method to increase the availability of Si to soil solution and thereby decreasing depletion of Si from leading to accumulation on above ground plant part. After first field experiment, the straw obtained from each plot under particular treatment was cut into small pieces and incorporated into the same plot. No fertilizers or manures were applied additionally.

- The sources of Si had no residual effect on grain and straw yield of succeeding rice crop.
- It might be due to very slow residual effect of Si and inadequate supply of other essential elements for growth and development.

The categorization of major rice growing soils Kerala showed that the amount of plant available Si present in these soils had good correlation with various physico-chemical properties and available and exchangeable nutrients. Even though the concentration of total Si was very high in all these soils, plant available Si concentration was very much low. It finger out that the dissolved or plant available Si in soil is a part of dynamic system. A large variety of Si fraction may occur in the soil. The amount of available Si for plant uptake depends on pools and fluxes of these Si fractions present in soil. The exchange and release of these Si fractions are mainly influenced by adsorption of Si on soil particles which in turn affects the availability of Si for plant uptake. It clearly indicates the importance of application of Si fertilizers in these soils. The incubation study revealed that the release of added Si was highest in *Kole* land soil and lowest in sandy soil. Irrespective of soils, treatment with sodium silicate released more Si into soil solution for plant uptake. The field experiment conducted with different sources of silicon showed that the maximum number panicle per hill, number of spikelets per panicle, thousand grain weights and minimum number of unfilled grains per panicle were recorded in treatment with calcium silicate application. The maximum grain yield of 6.90 t ha^{-1} was recorded calcium silicate application which was significantly superior over all other treatments. This increase in yield might be due to the effect of application of Si on soil fertility, nutrient uptake, and plant growth. The direct effect of Si fertilization on increased number panicle per hill, number of spikelets per panicle, and thousand grain weight and decreased number of unfilled grains per panicle might be the reason for increased grain and straw yield in treatment with calcium silicate. The incorporation of rice straw into soil after harvest of first crop revealed that Si had no residual effect on grain and straw yield of succeeding rice crop. In general, sandy soil low in available Si had a high response to applied Si in achieving higher grain yield.

Practical utilities of this work are categorization of major rice growing soils according to plant available Si status, effective management Si in soil based on its adsorption behaviour and use of calcium silicate as a good source of Si for rice crop to enhance crop growth and yield.

Future line of work

- Collection and characterization of soils from all agro-ecological units of Kerala for plant available Si.
- The exact relation between soil properties and different fractions of Si needs to be established
- Application of higher doses to different crops to know the direct effect as well as residual effect.
- Chemistry and transformation of Si fertilizers in soil. Effective composting method to decompose rice husk at the shortest interval.

References

REFERENCES

Adebisi, N. O., Adeyemi, G. O., Oluwafemi, O. S. and Songca, S. P. 2013. Important properties of clay content of lateritic soils for engineering project. *J. Geogr. Geo.* 5(2): 99 – 115.

Agarie, S., Hanaoka, N., Ueno, O., Miyazaki, A., Kubota, F., Agata, W., and Kaufman, P. B. 1998. Effect of silicon on tolerance to water deficit and heat stress in rice plant (*Oryza sativa* L.) monitored by electrolyte leakage. *Plant Prod. Sci*. 1(2): 96-103.

Ahmad F., Rahmatullah, T., Aziz, M. A., Maqsood, M. A., Tahir, S., and Kanwal. 2007. Effect of silicon application on wheat (*Triticum aestivum* L.) growth under water deficiency stress. *Emir. J. Food Agric*. 19(2):01-07.

Ahmad, S. T. and Haddad, R. 2011. Study of silicon effects on antioxidant enzyme activities and osmotic adjustment of wheat under drought stress. *Czech J. Genet. Plant Breed.* 47(1): 17–27.

Alexandre, A., Meunier, J. D., Colin, F., and Koud, J. M. 1997. Plant impact on the biogeochemical cycle of silicon and related weathering problems. *Geo.Cosmo. Acta*. 61(3):677–682.

Ali, M. A., Lee, C. H., and Kim, P. J. 2008. Effect of silicate fertilizer on reducing methane emission during rice cultivation. *Biol Fertil Soils*. 44:597–604.

Ali, M. A. M., Ramezani, A., Far, S. M., Asilan, K. S., Moradi-Ghahderijani, M., and Jamian, S. S. 2013. Application of silicon ameliorates salinity stress in sunflower (*Helianthus annuus* L.) plants. *Intl J Agri Crop Sci*. 6(20): 1367-1372.

Almeselmani, M., Deshmukh, P. S., Sairam, R. K., Kushwaha, S. R. and Singh. T. P. 2006. Protective role of antioxidant enzymes under high temperature stress. *Plant Sci.* 171:382–388.

Alvarez, R., Cramer, R. E. and Silva, J. A. 1976. Laser Raman spectroscopy: A technique for studying adsorption on aluminum sesquioxide, gibbsite. *Soi1 Sci. Soc. Am. J.* 40:317-319.

Amin, M., Ahmad, R., Shahzad M. A. B., and Murtaza, G. 2014. Silicon induced improvement in morpho-physiological traits of maize (*Zea mays* l.) under waterdeficit. *Pak. J. Agri. Sci.*, 51(1):187-196.

Anda, M., Omar, S. R. S., Shamshuddin, J., and Fauziah, C. I. 2008. Changes in properties of composting rice husk and their effects on soil and cocoa growth. *Commun. Soil Sci. Plant Analy.* 39: 2221–2249.

Anderson, D. L., Synder, G. H. and Martin, F. G. 1990. Multi-Year Response of Sugarcane to Calcium Silicate Slag on Everglades Histosols. *Agron. J.* 83 (5): 870-874.

Angelova, V., Ivanova, R., Pevicharova, G. and Ivanov, K. 2010. Effect of organic amendments on heavy metals uptake by potato plants. In: *19th World Congress of Soil Science, Soil Solutions for a Changing World*, 1 – 6 August 2010, Brisbane, Australia.

Avakyan, Z. A., Pavavarova, T. A, and Karavako, G. I. 1986. Properties of a new species, Bacillus *mucilaginous*. *Microbiol* 55:477–482.

Bajeer M. A., Nizamani S.M., Sherazi S. T. H., Bhanger M. I. (2012): Adsorption and leaching potential of imidacloprid pesticide through alluvial soil. *Am. J. Analyt. Chem.*, 3: 604–611.

Barber J. M. (1980): Catalase and peroxidase in primary leaves during development and senescence. *Z. Pfl.- Physiol*. 97: 135–144.

Baruah, T. C., Borthakur, H. P. 1997. *A Text Book of Soil Analysis*. Vikas publishing, India, 220p.

Bell, G. R. 1994. Behaviour of dissolved silica, and estuarine/coastal mixing and exchange processes at Tairua Harbour, New Zealand. *New Zealand J. Marine Freshwater Res.* 28: 55-68.

Belanger, R. R., Benhamou, N., and Menzies, J. G. 2003. Cytological evidence of an active role of silicon in wheat resistance to powdery mildew (*Blumeria graminis* f. sp *tritici*). *Phytopathol.* 93(4): 402–412.

Berger, K. C. and Troug, E. 1939. Boron determination in soils and plants. *Indian Eng. Chem. Anal. Ed*. 11: 540-542.

Berthelsen, S., Noble, A. D., Kingston, G., Hurney, A., Rudd, A., and Garside, A. 2003. *Improving yield and ccs in sugarcane through the application of silicon based amendments*. Sugar Research and Development Corporation, Brisbane, Australia.

Biggar, J. W. and Cheung, M. W. 1973. Adsorption of Picloram (4-amino 3,5,6 – trichloropicolinic acid) on Panoche, Ephrata, and Palouse soils : A thermodynamic approach to the adsorption mechanism. *Soil Sci. Soc. Am. Proc.* 77: 863 - 868.

Bocharnikova, E. A. and Matichenkov, V. V. 2012. Influence of plant associations on the silicon cycle in the soil-plant ecosystem. *Appl. Eco. Environ. Res.* 10(4): 547-560.

Bokhtiar, S. M., Huang, H. R., and Ruili, Y. 2012. Response of sugarcane to calcium silicate on yield, gas exchange characteristics, leaf nutrient concentrations, and soil properties in two different soils. *Commun. Soil Sci.Plant Anal*. 43:1363–1381.

Borrelli, N., Alvarez, M. F., Osterrieth, M. L. and Marcovecchio, J. E. 2010. Silica content in soil solution and its relation with phytolith weathering and silica biogeochemical cycle in Typical Argiudolls of the Pampean Plain, Argentina—a preliminary study. *J Soils Sediment.* 10:983–994.

Bray, R. H. and Kurtz, L. T. 1945. Determining total, organic and available forms of phosphate in soils. *Soil Sci*. 59: 39-45.

Bridgit, T. K. and Potty, N. N. 2007. Nutrient management for productivity improvement of rice in laterite soils of Kerala. In*: 19th Science Congress*. 29-31 January 2007, Kannur. pp 469-471.

Broznic D. and Milin C. 2012. Effects of temperature on sorption-desorption processes of imidacloprid in soils of Croatian coastal regions. *J. Environ. Sci. Health*. 47: 779–794.

Bui, D.D. Hu, J. and Stroeven, P. 2005. Particle size effect on the strength of rice husk ash blended gap-graded Portland cement concrete. *Cem. Concr. Composites*. 27(3): 357-366.

Calvet R. 1989. Adsorption of organic chemicals in soils. *Environ. Health Perspect*. 83: 145–177.

Carter, D. L., Heilman, M. D. and Gonzalez, C. L. 1965. Ethylene glycol monoethyl ether for determining surface area of silicate minerals. *Soil Sci.*100: 356 – 360.

Casey, W. H. 2004. Aqueous silicate complexes in wheat, *Triticum aestivum* L. *Plant Cell Environ*. 27: 51–54

Chang, S. J., Tzeng, D. D. and Li, C. C. 2002. Effect of silicon nutrient on bacterial blight resistance of rice (Oryza sativa L.). In: *Abstract of second silicon in agriculture conference*, pp 31–33.

Chen, Y. 1990. Characteristics of silicon uptaking and accumulation in rice. *J. Guizhou Agric. Sci.* 6: 37-40.

Cornelis, J. T., Delvaux, B., Cardinal, D., Andre, L., Ranger, J., and Opferge, S. 2010. Tracing mechanisms controlling the release of dissolved silicon in forest soil solutionsusing Si isotopes and Ge/Si ratios. *Geochimica et Cosmochimica Acta* 74 :3913–3924.

Cornelis, J. T., Delvaux, B., Georg, R. B., Lucas, Y., Ranger, J., and Opfergelt, S. 2011. Tracing the origin of dissolved silicon transferred from various soil-plant systems towards rivers: a review. *Biogeosciences,* 8: 89–112.

Cox, F. R. 1987. Micronutrient soil tests. Correlation and calibration. In: Brown, J.R. (Ed.). *Soil Testing: Sampling, Correlation, Calibration and Interpretations*. SSSA, Madison, pp. 97-117.

Danilova, A. A., Sauer, A. D., Breuer, B. J., Herrmann, A. L., Zarei, A. M., and Stahr, K. 2010. Development of a method for sequential extraction of Si-pools from soils. *19th World Congress of Soil Science, Soil Solutions for a Changing World*, 1 – 6 August 2010, Brisbane, Australia.

Datnoff, L. E., Snyder, G. H. and Deren, C. W. 1992. Influence of silicon fertilizer grades on blast and brown spot development on grain yield. *Plant Dis.* 76: 1011-1013.

de Camargo, M. S., Korndorfer, G. H. and Pereira, H. S. 2007. Solubility of silicon in soils: effect of lime and silicic acid applied. *Bragantia,* 66 (4): 637-647.

Dean, L. A. and Rubins, E. J. 1947. Anion exchange in soils: I- exchangeable phosphorus and the anion-exchange capacity. *Soil Sci.* 63 (5): 377-388.

de Datta, S. K. 1981. *Principles and Practices of Rice Production*. Wiley, New York. 230p.

Dematte, J. L. I., Paggiaro, C. M., Beltrame, J. A. and Ribeiro, S. S. 2011. Uso de silicatos em cana-de-açúcar. *Informacoes Agronomicas*, 133 : 7-12.

Demir, Z. and Gulser, C. 2015. Effects of rice husk compost application on soil quality parameters in greenhouse conditions. *Eurasian J. Soil Sci*. 4 (3): 185 – 190.

Derry, L. A., Kurtz A. C., Ziegler, K. and Chadwick, O. A. 2005. Biological control of terrestrial silica cycling and export fluxes to watersheds. *Nature*. 433:728–731.

Desire, T., Dieudonne, B., and Yves, L. 2009. Biogeochemistry of Iron, Aluminium and Silicon in Humid Tropical Mountainous Soils (Bambouto Mountain, West Cameroon). *The Open Geo. J.* 3: 70-81.

de Sousa and Korndorfer. 2010. Slag efficacy as a lime and silicon source for rice crops through the biological method. *J. Plant Nutri.*, 33:1103–1111.

Dietzel, M. 2002. Interaction of polysilicic and monosilicic acid with mineral surfaces, In: *Water-Rock Interaction*, Kluwer Academic Publishers, 207–235.

Dobermann, A. and Fairhurst, T. H. 2002. Rice Straw Management. *Better Crops*, 16: 7-11.

Ebaid, R. A. and El-Refaee, I. S. 2007. Utilization of rice husk as an organic fertilizer to improve productivity and water use efficiency in rice fields. *African Crop Science Conference Proceedings*. Vol. 8. pp. 1923-1928.

El Sharkawi, H., Yamamoto, S., and Honna, T. 2006. Rice yield and nutrient uptake as affected by cyanobacteria and soil amendments - a pot experiment. *J. Plant Nutr. Soil Sci.*169:809–815.

Elzbieta, S. 2009. Role of silicon in plant resistance to water stress. *J. Elementol*. 14 (3):619-630.

Epstein, E. 1994. The anomaly of silicon in plant biology. *Proc. Natl. Acad. Sci*. 91: 11–17.

Epstein, E. 1999, Silicon. *Annu. Rev. Plant. Physiol. Plant Mol. Biol.*, 50:641-664.

Epstein, E. 2009. Silicon: its manifold roles in plants. *Ann. Appl. Biol.*155–160.

Fageria, N. K., Carvalho, G. D., Santos, A. B., Ferreira, E. P. B., and Knupp, A. M. 2011. Chemistry of lowland rice soils and nutrient availability. *Communi. Soil Sci. Plant Analy.*, 42:1913–1933.

Fallah A. 2012. Silicon effect on lodging parameters of rice plants under hydroponic culture. *Intl. J. Agri. Sci*. 2(7): 630-634.

Farmer, V. C. and Lumsdon, D. G. 1994. An assessment of complex formation between aluminum and silicic acid in acidic solutions. *Geochim. Cosmochim. Acta* 58, 3331–3334.

Fassil K. 2009. Silicon Status and Its Relationship with Major Physico-Chemical Properties of Vertisols of Northern Highlands of Ethiopia.

Fertilizer control order [FCO]. 1985. Government of India, New Delhi.

Fox, R. L., Silva, J. A., Plucknett, D. L. and Ternanish, D. Y. 1969. Soluble and total silicon in sugarcane. *Plant Soil*. 30:81-92.

Fraysse, F., Pokrovsky, O. S., Schott, J., and Meunier, J. D. 2009. Surface chemistry and reactivity of plant phytoliths in aqueous solutions. *Chem. Geol*., 258, 197–206.

Friesen, D. K., Sanz, J. I, Correa, F. J., Winslow, M. D., Okada, K., Dantoff, L. E., and Snyder, G. H. 1994. *Silicon Deficiency of Upland Rice on Highly Weathered Savanna Soils in Colombia*.I. Evidence of major rice yield. IX Conferencia Internaciaonal America Latina, Castro‘s park hotel. 21-25 Marco. Brazil.

Gao, D., Cai, K., Chen, J., Luo, S., Zeng, R., Yang, J., and Zhu, X. 2011. Silicon enhances photochemical efficiency and adjusts mineral nutrient absorption in *Magnaporthe oryzae* infected rice plants. *Acta Physiol. Plant*. 33:675–682.

Gascho, G. J. 2001. Silicon sources for Agriculture: In *Silicon in Agriculture* (Eds Datnoff, L. E.,Snyder, G. H. and Korndorfer, G. H.), Elsevier Science, Amsterdam, The Netherland, 345p.

Georgiadis, A., Sauer, D., Herrmann, L., Breuer, J., Zarei, M. and Stahr, K. 2013. Development of a method for sequential Si extraction from soils. *Geoderma.* 209– 210: 251–261.

Ghoneim and Ebid, A. I. 2015. Combined Effects of Soil Water Regimes and Rice Straw Incorporation into the soil on N, P, K uptake, rice yield and selected soil properties. *Internl. J. Plant Soil Sci*. 5(6): 339-349.

Ghorbani, M. Eisazadeh, H. and Ghoreyshi, A. A. 2012. Removal of zinc ions from aqueous solution using polyaniline nanocomposite coated on rice husk. *Iranica J. Energy Environ.*3: 66-71.

Glasauer, S. M. 1995. *Silicate Sssocited With Fe(Hydr)oxides*. PhD thesis, Munich University of Technology.

Goldberg, S. and Glaubig, R. A. 1988. Boron and silicon adsorption on an aluminum oxide. *Soil Sci. Soc. Am. J.* 52:87-91.

Gong, H., Zhu, X., Chen, K., Wang, S. and Zhang, C. Silicon alleviates oxidative damage of wheat plants in pots under drought. *Plant Sci*.169 (2): 313-321.

Gontijo, I. 2000. Characteristics fisicas e quimicas dos solos detemlination da disponibiIidade do silicio para as plantas. Monografia- Insticuto de CienciasAgrarias da universidade federal de Uberlanda.

Govindarao, V. M. H. 1980. Utilization of rice husk — a preliminary analysis. *J. Sci. Ind. Res.* 39:495.

Gu, H., Qiu, H., Tian, T., Zhan, S., Deng, T., Chaney, R. L., Wanga, S., Tang, Y., Morel, J., and Qiu, R. 2011. Mitigation effects of silicon rich amendments on heavy metal accumulation in rice (*Oryza sativa* L.) planted on multi-metal contaminated acidic soil. *Chemosphere* 83:1234–1240.

Guo, W., Hou, Y. L., Wang, S. G., and Zhu, Y. G. 2005. Effect of silicate on the growth and arsenate uptake by rice (Oryza sativa L.) seedlings in solution culture. *Plant Soil*. 272:173–181.

Gupta, U.C. 1972. Effects of boron and limestone on cereal yields and on B and N concentrations of plant tissue. *Commun. Soil Sci. Plant Anal*. 6: 439-450.

He, L. Y. and Li, X. L. 1996. Distribution of Si deficient rice soil in Hubei Province. *Chinese Rice Res. Newsletter* 4: 6-7.

Heckman, J. 2013. Silicon: A Beneficial Substance. *Better Crops*. 97 (4): 14-16.

Heinai, H. and Saigusa, M. 2006. Silicon availability of the nursery bed soils and effects of silicon fertilizer applied on the growth and silicon uptake of rice Oryza sativa L. seedlings, *Soil Sci. Plant Nutri.* 52(2): 253-253.

Hendershot, W. H. and Duquette, M. 1986. A simplified Barium chloride method for determining cation exchange capacity and exchangeable cations. *Soil Sci. Soc. Am. J.* 50:605-608.

Herbillion, A. J., and Vinhan, J. T. 1969. Heterogeneity in silicon-iron mixed hydroxides. *J. Soil Sci.*, 20, 223 - 235.

Herbillon, A. J., Gallez, A., and Juo, A. S. R. 1977. Characteristics of silica sorption and solubility as parameters to evaluate the surface properties of tropical soils: I. The index of silica saturation. *Soil Sci Soc. Am. J.* 41: 1151–1154.

Hingston, F. J., Posnec, A. M. and Quirk, J. P. 1972. Anion adsoption by goethite and gibbsite. *J. Soil Sci.* 23: 177-192.

Hossain, K. A., Horiuchi, T. and Miyagawa, S. 2001. Effects of silicate materials on growth and grain yield of rice plants grown in clay loam and sandy loam soils. *J. Plant Nutri.* 24(1), 1–13.

Hiemstra, T., Barnett, M. O., and van Riemsdijk, W. H. 2007. Interaction of silicic acid with goethite, *J. Colloid. Interf. Sci.*, 310(1):8–17.

Hosseini, S. Z., Babaeian J. N. A., and Bagheri, N. A. 2011. Effect of silica on morphological traits and resistance of rice to stripedstem borer (*Chilo suppressalis* Walker). *Plant Ecophysio.* 3: 95-100.

Houben, D., Sonnet, P., and Cornelis, J. T. 2013. Biochar from Miscanthus: a potential silicon fertilizer. *Plant. Soil.* 374(1):871-882.

Husnain, Wakatsuki, T., Setyorini, D., Hermansah, Sato, K. and Masunaga, T. 2008. Silica availability in soils and river water in two watersheds on Java Island, *Indonesia. Soil Sci. Plant Nutr.* 54:916-927.

Hwang, C.L and Chandra, S. 1997. The Use of Rice Husk Ash in Concrete: In *Waste Materials Used in Concrete Manufacturing.* Edited: Chandra, S., Noyes Publications, USA, p. 198.

Iller, R. K.1979. *The chemistry of silica*. Wiley-Interscience, New York.

Imaizumi, K and Yoshida, S. 1958. Edaphological studies on silicon supplying power of paddy field. *Bull. Natl. Inst. Agric. Sci.* 8: 261-304.

Jackson, M. L. 1958. *Soil Chemical Analysis*. Prentice Hall of India Private Ltd., New Delhi, 498p.

Jacobs, S., Muller, F., Teuchies, J., Oosterlee, L., Struyf, E., and Meire, P. 2013. The vegetation silica pool in a developing tidal freshwater marsh. *Silicon*. 5:91–100.

Jaiswal, P.C. 2003. *Soil, Plant and Water Analysis*. Kalyani publishers, New Delhi, 450p.

Jawahar, S. and Vaiyapuri, V. 2014. Effect of sulphur and silicon fertilization on yield, nutrient uptake and economics of rice. *Internl Res. J. Chem.*. 34-43.

Jones, L. H. P. and Handreck, K. A. 1967. Silica in soils, plants, and animals, *Adv. Agron.*, 19, 107–149.

Joseph, C. 2014. *Quality assessment of pokkali soils under different land uses* . M.Sc (Agri) thesis, Kerala Agricultural University, Thrissur, 120 p.

Junior, L. A. Z, Fontes, R. L. F., Neves, J. C. L., Korndorfer, G. H. and de Avilar, V. T. 2010. Rice grown in nutrient solution with doses of Manganese and silicon. *R. Bras. Ci. Solo,* 34:1629-1639.

Juo, A. S. R and Sanchez, P. A. 1986. Soil nutritional aspects with a view to characterize upland rice environrnents, p, 85-91. *In* Progress in upland rice research. *Proceedings of the 1985 Jakarta conference.* The International Rice Research Institute, Los Banos, Philippines.

Karunakaran, G., Suriyaprabha, R., Manivasakan, P., Yuvakkumar, R., Rajendran, V., Prabu, P., and Kannan, N. 2013. Effect of nanosilica and silicon sources on plant growth promoting rhizobacteria, soil nutrients and maize seed germination. *Nanobiotechnol.*1–8.

Kato, N. and Owa, N. 1990. Dissolution mechanism of silicate slag fertilizers in paddy soils. *XIV Int. Congr. Soil Sci.* 4: 609-610.

KAU [Kerala Agricultural University]. 2011. *Package of Practice Recommendation: Crops* (14th Ed.). Kerala Agricultural University, Thrissur, 360p.

Keller, C., Guntzer, F., Barboni, D., Labreuche, J., Meunier, J. D. 2012. Impact of agriculture on the Si biogeochemical cycle: Input from phytolith studies. *Geoscience,* 344: 739–746.

Khalid, R. A., Silva, J. A. and Fox. R. L. 1978. Residual effects of calcium silicate in tropical soils: 1. Fate of applied silícon during five years cropping. *Soil Sci. Soc. Am. J.* 42:89-94.

Kim, A. M., Kim, A. Y. and Yang, E. J. 2010. Changes of Organic Matter and Available Silica in Paddy Soils from Fifty-six Years Fertilization Experiments. *19th World Congress of Soil Science, Soil Solutions for a Changing World,* 1 – 6 August 2010, Brisbane, Australia

Klason, P. 1923. The determination of lignin. Chapter 6, p 151. *In: The Chemistry of Lignin*. Academic Press, New York.

Klotzbucher, T., Marxenb, A., Vetterleinb, D., Schneikerc, J., Turkec, M., Sinhd, N., Manhd, N. H., Chiene, H., Marquezf, L., Villarealg, S., Bustamanteh, J. V., and Jahn, R. 2014. Plant-available silicon in paddy soils as a key factor forsustainable rice production in Southeast Asia. *Basic Appl. Eco.*, 1-9.

Knight, C. T. G. and Kinrade, S. D. 2001 . A primer on the aqueous chemistry of silicon, In: *Silicon in agriculture*, Elsevier, The Netherlands, 57–84.

Korndorfer, G. H. and Lepsch, I. 2001a. Effect of silicon on plant growth and crop yield, In: *Silicon in agriculture*, Elsevier, The Netherlands, 133–147.

Korndorfer, G. H., Snyder, G. H., Ulloa, M. and Datnoff. L. E. 2001b. Calibration of soil and plant Silicon for rice production. *J. Plant Nutri.* 24: 1071–1084.

Kuruvila, V. O. 1974. *Chemistry of low productive acid sulphate soils of Kerala and amelioration for growing rice.* PhD thesis, Utkal, Bhuvaneswar, 156p.

Laing, M. D., Gatarayiha, M. C. and Adandonon, A. 2006. Silicon use for pest control in Agriculture: A Review. *Proc. S. Afr. Sug. Technol. Ass.* 278-286.

Lalljee, B. 2008. Relationship Between Available Silicon In Soils Of Mauritius, Soil Properties And Plant Silicon Concentration. *IV Silicon in Agriculture Conference,* Wild Coast Sun, KwaZulu-Natal, South Africa, 26 - 31 October 2008. Pp61.

Lee, Y. B., Lee, C. H., Hawng, J. Y., Lee, I. B., and Kim, P. J. 2004. Enhancement of phosphate desorption by silicate in soils with salt accumulation. *Soil Sci Plant Nutri* 50:493–499.

Lewin, J. and Reimann, B. E. F. 1969. Silicon and Plant Growth. *Annual Review Plant Physiol*, 20: 289-304.

Li, C. H., Chu, T. D., Liu, X. B. and Yang, Q. 1999. Silicon nutrition effects and its study and application development in China. In: *Proceedings of Symposium of Plant Nutrition*, Shaanxi Science and Technology Press, China. Pp. 329-333.

Liang, Y. C., Ma, T. S., Li, F. J., and Feng, Y. J. 1994. Silicon availability and response of rice and wheat to silicon in calcareous soils. *Commun. Soil Sci. Plant Anal*. 25:2285– 2297.

Liang, Y. C., Yang, C. G., and Shi, H. H. 2001. Effects of silicon on growth and mineral composition of barley grown under toxic levels of aluminium, *J. Plant. Nutr.*, 24, 229–243.

Liang, Y., Hua, H., Zhu, Y., Zhang, J., Cheng, C. and Romheld, V. 2006. Importance of plant species and external siliconconcentration to active silicon uptake and transport. *New Phytologist.* 172: 63–72.

Lotse, E. G., Datta, N. P., Tomar, K. P., and Motsara, M. R. 1975. Minerological composition of some red and black soils of India. Bull. *India Nat. Acad*, 50:216-226.

Lutts S, Kinet J. M, Bouharmont J. 1996. Effects of salt stress on growth, mineral nutrition and proline accumulation in relation to osmotic adjustment in rice (*Oryza sativa*) cultivars differing in salinity resistance. *Plant Growth Regul.* 19: 207-218.

Ma, J. F., Goto, S., Tamai, K., and Ichii, M. 2001. Role of Root Hairs and Lateral Roots in Silicon uptake by rice. *Plant Physio.* 127:. 1773–1780.

Ma, J. F. and Takahashi, E. 2002. *Soil, fertilizer and plant silicon research in Japan*,Elsevier, The Netherlands.

Ma, J. F., M. Tamai, M. Ichii, and K. Wu. 2002. A rice mutant defective in active silicon uptake. *J. Plant Physiol.* 130: 2111–2117.

Ma, J. F. and Yamaji, N. 2006. Silicon uptake and accumulation in higher plants. *Trends in Plant Sci*.11:8.

Malidareh, A. G. 2011. Silicon application and nitrogen on yield and yield components in rice (*Oryza sativa*) in two irrigation systems. *World Academy of Sci. Engr. and Tech*. 78:88-95.

Marschner, H. 1995. *Mineral Nutrition of Higher Plants*. Academic Press, 2nd edn., London.

Marschner, H., Oberle, H., Cakmak, I. and Romheld, 1990. Growth enhancement bysilicon in cucumber plants depends on imbalance in phosphorous and zinc supply. *Plant. Soil,* 124: 211-219.

Marxen, A. 2015. Interaction between silicon cycling and straw decomposition in a silicon deficient rice production system. *Plant. Soil.*

Matichenkov, V. V., and Bocharnikova, E. A. 2008. New generation of silicon fertilizers. pp. 71. In Malcolm Keeping (ed.) *Silicon in Agriculture Conference South Africa 2008,* 4th International Conference Abstracts. University of Kwazulu-Natal, Wild Coast Sun, Port Edward, KwaZulu-Natal, South Africa.

Matichenkov, V. V and Calvert. 2002. Silicon as a beneficial element for sugarcane. *J. Am. Soc. Sugarcane Techno.* 22: 21-30.

Matichenkov, V. V., Bocharnikova, E. A., Calvert, D. V., Snyder, G. H. 2000. Comparison study of soil silicon status in sandy soils of south Florida. *Soil Crop Sci. Florida Proc*. 59: 132-137.

Matichenkov, V. V., Pinsky, D. L., Bocharnikova, E. A. 1996. Influence of mechanical compaction of soils on the state and forms of available Si. *Eurasian Soil Sci.* 27: 58-67.

Mauad, M., Cruscio, C. A. C., Filho, H. G., and Correa, J. C. 2003. Nitrogen and silicon fertilization of upland rice. *Scientia Agricola*. 60 (4):761-765.

McKeague, J. A. and Cline, M. G. 1963a. Silica in soils, *Adv. Agron.*, 15: 339–396.

McKeague, J. A. and Cline, M. G. 1963b. The form and concentration of dissolved silica in aqueous extracts of some soils. *Can. J. Soil. Sci.* 43: 70-82.

Medina-Gonzales, O.A., Fox, R.I. and Bosshart, R.P. 1988. Solubility and availability to sugarcane of two silicate materials. *Ferti. Res.* 16:3-13.

Meena, V. D., Dotaniya, M. L., Coumar S. V., Rajendiran, Ajay , Kundu, S. and Rao, A. S. 2014. A Case for Silicon Fertilization to Improve Crop Yields in Tropical Soils. *Proc. Natl. Acad. Sci., India, Sect. B Biol. Sci.* 84(3):505–518.

Miller, D. M., Sumner, M. E., and Miller, W. P. 1989. A comparison of batch- and flow-generated anion adsorption isotherms. *Soil Sci. Soc. Am. J.* 53:373-380.

Miyoshi, H. and Ishii, H. 1960. Effect of silicic acid and silicic slag on paddy rice: IV. Effect of silicic acid on P metabolism of paddy rice. *J. Sci. Soil Tokyo* 31: 146-148.

Mobasser, H. R., Malidarh, G. A. and Sedghi, H. 2008. Effects of silicon application to nitrogen rate and splitting on agronomic characteristics of rice (*Oryza sativa*). *Silicon in Agriculture: 4th International Conference*, 26-31 October, South Africa: 76.

Monger, H. C. and Kelly, E. F. 2002. Silica minerals, In: *Soil Mineralogy with environmental applications.* Soil Science Society of America, Madison, USA, 611–636.

Mongia, A. D. and Chhabra, R. 2000. Silica and phosphates of alkali soils following reclamation. *J. Indian. Soc. Soil Sci*. 48(1):33-37.

Morsy, M. A. 2008. Status of silicon in soils of Middle Egypt. *IV Silicon in Agriculture Conference* Wild Coast Sun, KwaZulu-Natal, South Africa, 26 - 31 October 2008. Pp79.

Moulton, K. L.,West, J., and Berner, R. A. 2000. Solute flux and mineral mass balance approaches to the quantification of plant effects on silicate weathering, *Am. J. Sci.* 300:539–570.

Muller, F., Struyf, E., Hartmann, J., Weiss, A., and Jensen, K. 2013. Impact of grazing management on silica export dynamics of Wadden Sea saltmarshes. *Estuarine, Coastal and Shelf Science* 127 :1-11.

Muralikannan, N. and Anthomiraj, S. 1998. Occurrence of silicate solublising bacteria in rice ecosystem. *Madras Agric J.* 85(1):47–50.

Muthadhi, M., Anitha, R. and Kothandaraman S..2007. Rice husk ash properties and its uses - A review. *J. Inst. Eng (India)*. 88: 50-55.

Nagula, S., Joseph, B. and Gladis, R. 2015. Effect of silicon and boron on nutrient status and yield of rice in laterite soils. *Ann. of Plant. Soil Res.* 17(3): 299-302.

Nair, P. K. and Aiyer, R. S. 1968. Status of available silica in the rice soils of Kerala state (India). II. Silicon uptake by different varieties of rice in relation to available silica contributed by soil and irrigation water. *Agric. Res. J. Kerala*, 6, 88-94.

Narayanaswamy, C. and Prakash. N. B. 2009. Calibration and categorization of plant available silicon in rice soils of south India. *J. of Plant Nutri.* 32: 1237–1254.

Narayanaswamy, C. and Prakash, N. B. 2010. Evaluation of Selected Extractants for Plant-Available Silicon in Rice Soils of Southern India. *Comm. Soil Sci. Plant Anal.*,41:977–989.

Nayar, P. K., Misra, A. K., and Patnaik, S. 1977. Evaluation of silica supplying power of soils for growing rice. *Plant Soil* 47:487–494.

Nayar, P. K., Mirsa, A. K., and Patnaik, S. 1982. Silica in rice and flooded rice soils. *Oryza*, 19: 82-92.

Ning, D., Song, A., Fan, F., Li Z., and Liang, Y. 2014. Effects of slag-based silicon fertilizer on rice growth and brown-spot resistance. *J. Pone*.9 (7): 134-137.

Okon, K. O., Osundi, S., Dibal, J., Ngbale, T., Bello, M., Akuhwa, R. T., Balogun, S. T. and Uba, A. 2012. Bacterial contamination of operating theatre and other specialized care unit in a tertiary hospital in Northeastern Nigeria . *African J. Micro. Res*. 6 (13): 3092-3096.

Okuda, A. and Takahashi, E. 1961. Studies on the physiological role of silicon in crop plants: 1. Discussion on the silicon deficient culture method. *J. Sci. Soil Manure Jpn.* 32: 475–480.

Opfergelt, S., de Bournonville, G., Cardinal, D., Andr´e, L., Delstanche, S., and Delvaux, B. 2009. Impact of soil weathering degree on silicon isotopic fractionation during adsorption onto iron oxides in basaltic ash soils, Cameroon, *Geochim. Cosmochim. Ac*., 73, 7226–7240.

Panse, V.G. and Sukatme, P.V. 1978. *Statistical Methods for Agricultural Workers*. ICAR, New Delhi, 347p.

Patra, P. K. and Neue, H. U. 2010. Dynamics of water soluble silica and silicon nutrition of rice in relation to changes in iron and phosphorus in soil solution due to soil drying and reflooding. *Archives Agron. Soil Sci.* 56 (6): 605 – 622.

Peera, P. G. S. K., Balasubramaniam, P., and Mahendran, P. P. 2014. Silicon release characteristics of graded levels of fly ash with silicate solubilizing bacteria and farm yard manure in soil under submergence. *Indian J. Hill Farming,* 27(2):29-30.

Phonde, D. B., Deshmukh, P. S., Banerjee, K., and Adsule, P. G. 2014. Plant available silicon in sugarcane soils and its relationship with soil properties, leaf silicon and cane yield. *Asian J. Soil Sci.* 9(2): 176-180.

Piper, C. S. 1966. *Soil and Plant Analysis*. Hans publishers, Mumbai, 365p.

Pokrovsky, G. S., Schott, J., Garges, F., and Hazemann, J. L. 2003. Iron (III)-silica interactions in aqueous solution: Insights from X-ray absorption fine structure spectroscopy, *Geochim. Cosmochim. Ac*. 67(19), 3559–3573,

Ponnamperumma, F. N. 1965. Dynamic aspects of flooded soils and the nutrition of rice plant. In *The mineral nutrition of the rice plant*. Pp 295-328. John hopkins press, baltimore.

Pons, L. J. and vanBreemen, N. 1982. Factors influencing the formation of potential acidity in tidal swamps. In: *Proc. Bangkok Symp. A. S. Soils*. pp 37-51.

Prakash, N. B., Narayanaswamy, C., Hanumantharaju, T. H., Shashidhar, H. E., Patil, S. U., Thippeshappa, G. N., Datnoff, L. E. 2010. Effect of calcium silicate as a silicon source on growth and yield of rice in different acid soils of Karnataka, southern India. *Internl. Rice Res. Notes.* 4184-4185.

Qiu, L. P., Zhang, X. C., Cheng, J. M. and Han, X. N. 2010. Isotherms and kinetics of Si adsorption in soils, *Acta Agri. Scandinavica, Section B – Soil. Plant Sci.*, 60:2, 157- 165

Rafi, M. M., Zemetra, R. S. and Quisenberry, S. S. 1997. Feeding damage of Russian wheat aphid on resistant and susceptible wheat genotypes. *Cereal Res. Comm*. 25: 63–68.

Rajan, S. V. G. and Rao, H. G. G. 1978. *Studies on Soils of India*, Vikas Pub. House Pvt Ltd, New Delhi.

Ravent, J. A. 1983. The transport and function of silicon in plants. *Biol. Rev*., 58, 179–207.

Robinson, G.W. 1922. A new method for the mechanical analysis of soils and other dispersions. *J. Agri. Sci*. 12:306-321.

Rodrigues, L. L, Daroub, S. H., Rice, R. W. and Snyder, G. H. 2003. Comparison of three soil test methods for estimating plant available silicon. *Comm. Soil Sci. Plant Anal*., 34:15-16:2059-2071.

Roy, A. C., Ali, M.Y., Fox, R. L and Silva, J.A. 1971. Influence of calcium silicate on phosphate solubility and availability in Hawaiian latosols. In: *Proceedings of International Symposium on Soil Fertility Evaluation* - 1. New Delhi, pp 757–765.

Sadasivam, S. and Manickam, A. 1996. *Biochemical Methods for Agricultural Sciences*. Pp12-13.

Sadgrove, N. 2006. Nutrient and moisture economics in diatomaceous earth amended growth media. Southern Cross University.

Saha, P. K., Miah, A. M., Hossain, T. M. S., Rahman, and Saleque, A. 2009. Contribution of rice straw to potassium supply in ricefallow-rice cropping patternbangladesh. *J. Agril. Res*. 34(4) : 633-643.

Sahrawat, K. L. 2006. Organic matter and mineralizable nitrogen relationships in wetland rice soils. *Comm. Soil Sci. Plant Anal*. 37:787-796.

Samuels A. L., Glass A. D. M., Ehret D. L. and Menzies J. G. 1991. Mobility and deposition of silicon in cucumber plants. *Plant Cell Environ.* 14: 485-492.

Santhosh, C. 2013. *Chemistry and Transformation of Boron in Soils of Kerala*. PhD thesis, Kerala Agricultural University, Thrissur, 187 p.

Sauer, D. and Burghardt, W. 2006. The occurrence and distribution of various forms of silica and zeolites in soils developed from wastes of iron production. *Catena*. 65:247 – 257.

Sauer, D., Saccone, L., Conley, D.J., Herrmann, L., Sommer, M., 2006. Review of methodologies for extracting plant-available and amorphous Si from soils and aquatic sediments. *Biogeochemistry*. 80 (1): 89–108.

Savant, N. K., Snyder, G. H., and Datnoff, L. E. 1997. Silicon management and sustainable rice production. *Adv. Agron.* 58: 151-199.

Schenk, J. E. and Weber Jr., W. J. 1968. Chemical Interactions of Dissolved Silica with Iron (II) and (III). *J. Am. Water Works Associ.* 1: 199-212.

Seyfferth A. L., Kocar, B. D., Lee, J. A., and Fendorf, S. 2013. Seasonal dynamics of dissolved silicon in a rice cropping system after straw incorporation. *Geochimica et Cosmochimica Acta* 123 :120–133.

Sh, S. H. 1989. Effect of silicon on the chemical composition of rice plants. *J. Agric. Sci. Mansoura Univ.*. 14(2): 923-934.

Sh, H. S., Zeid S. T. A., Siam, H. S., and Hady, A. M. 2015. Effect of waterlogging and organic matter addition on water soluble Si, pH and Eh values. *Int.J. ChemTech Res*. 8(4):1557-1562.

Shariatmadari, H., Mermut, A. R. 1999. Magnesium and silicon induced phosphate in smectite, palygorskite, and sepiolite-calcite systems. *Soil Sci. Soc. Am. J.* 63:1167– 1173.

Siam, S. H., Saleh, A. L., el-Moez, A. M. R., Sh- Sh, H., and Zeid. S. T. A. 2015. Influence of different moisture regimes and N-fertilization on electrochemical changes andsome nutrients in the leachate solution growing period of rice plants. *Interntl. J. of Basic and applied Sci.* 4 (3):303-309.

Siavoshi, M and Laware, S.L. 2011. Effect of organic fertilizers on yield and its components in rice (Oryza sativa L.) In*: Proceedings of The International conference on the Effect* *of Science on Globalization* held at Yashwantrao Chavan, Academy of Development Administration Pune. pp126-137.

Sidhu, B. S, Beri, V and Gossel, S. K. 1995. Soil microbial health as affected by crop residue management. In: *Proceedings of National Symposium on Development in Soil Science,* Ludhiana, 2-5 November.

Siever, R. and Woodford, N. 1973. Sorption of silica by clay minerals, *Geochim. Cosmochim. Ac.*, 37 :1851–1880.

Sims, J. R. and Johnson, G. V. 1991. Micronutrient soil tests. In: Mortvedt, J.J., Cox, F.R., Shuman, L.M. and Welch, R.M. *Micronutrient in Agriculture* (2nd ed.), SSSA, Madison, USA, pp 427-476.

Singh, K., Singh, R., Singh, J.P., Singh, Y. and Singh, K.K. 2006. Effect of level and time of silicon application on growth, yield and its uptake by rice. *Indian J. Agric. Sci.* 76(7): 410-413.

Snyder G.H, Jones D.B, Gascho G.J. 1986. Silicon fertilization of rice on every ladeshistology, *Soil Sci.,* 50:1259-1263.

Sommer, A. L. 1926. *Studies concerning the essential nature of aluminum and silicon for plant growth.* California University Publications, pp 57.

Sommer, M., Kaczorek, D., Kuzyakov, Y., and Breuer, J. 2006. Silicon pools and fluxes in soils and landscapes-a review. *J. Plant Nutr. Soil Sci.*169:310–329.

Srivastava, P., Prakash, B. Sehgal, J. L., and Kumar, S. 1994. Role of neotectonics and climate in development of Holocene geomorphology and soils of the Gangetic Plains between the Ramganga and Rapti rivers. *Sedimen. Geology*. 94: 129-151.

Subbiah, B. V. and Asija, G. L. 1956. A rapid procedure for the estimation of available nitrogen in soils. *Curr. Sci*. 25:259.

Subramanian, S. and Gopalswamy, A., 1991. Effect of moisture organic matter phosphate and silicate on availability of silicon and phosphorus in rice soils.*J. Indian Soc. Soil Sci*. 39(1): 99-103.

Sudhakar, P. C., Singh, J. P., and Singh, K. 2004. Effect of silicon sources and fertility levels on transplanted rice. *IRRN* 29(2): 61-63.

Sunilkumar, B. and Geethakumari, V. L. 2002. Shade Response of Upland Rice Cultivars *(Oryza Sativa* L.) As Influenced By Silica Application. *J. Tropical Agric*., 40: 67-70.

Surapornpiboom P., Julsrigival, S., Senthong, C. Karladee, D 2008. Effect of silicon on upland rice under drought condition. *J. Nat. Sci.* 7(1):163-171.

Swedlund, P. J. and Webster, J. G. 1999. Adsorption and Polymerization of Silicic Acid on Ferrihydrite, and Its Effect on Arsenic Adsorption. *Water Res.* 33:3413-3422.

Swedlund, P. J., Sivaloganathan, S., Miskelly, G. M., and Waterhouse, G. I. N. 2011. Assessing the Role of Silicate Polymerization on Metal Oxyhydroxide Surfaces Using X-Ray Photoelectron Spectroscopy. *Chemical Geo.* 285: 62-69.

Tabana, B., Babu, T. and Datnoff, L. E. 2013. Silicon Dynamics in Soils under Different Cropping Systems in Louisiana, In: *Water, Food, Energy and Innovation for Sustainable World,* ASA, CSSA and SSSA International Annual Meetings, November 3 – 6, 2013, Tamba, Florida.

Takahashi, E. 1995. Uptake mode and physiological functions of silica. *Sci. Rice Plant* 2:58-71.

Takahashi, E., Ma, J. F. and Miyake. Y. 1990. The possibility of silicon as an essential element for higher plants. *Comments Agric. Food Chem*. 2:99-122.

Tallberg, P., Lehtimaki, M., and Siipola, V. 2010. Distribution of silicon in soils andsediments of a small catchment area: similarities and differences. *19th World Congress of Soil Science, Soil Solutions for a Changing World* 1 – 6 August 2010, Brisbane, Australia.

Tan, K. T. 2000. *Soil Sampling, Preparation and Analysis*. Taylor and Francis. p245.

Tempkin, M. J. and Pyozhev, V. 1940. *Acta Physicochim.*12:327-352.

Thampati, K. C. M. 1997. *Morphological, Physical and Chemical Characterisation of The Soils of North Kuttanad.* PhD thesis, Kerala Agricultural University, Thrissur,

Thampati, K. C. M. and Jose, A. I. 2000. Characterization of acid saline rice based wetland ecosystems of Kuttanad, Kerala, and their salinity protection by Thanneermukkom regulator. *Agroped.,* 10:108-115.

Tomasic, M., Zgorelec, T., Jurisic, A and Kisic, I. 2013. Cation Exchange Capacity of Dominant Soil Types in the Republic of Croatia. *J. Cent. Eur. Agric*., 2013, 14(3):937-951.

Upadhyaya, H., Khan, M. H. and Panda, S. K. 2007. Hydrogen peroxide induces oxidative stress in detached leaves of *Oryza Sativa* L. hydrogen peroxide induces oxidative stress in detached leaves. *Gen. Appl. Plant Physiol.* 33 (1-2): 83-95.

Vasanthi, N., Lilly, Saleena, M. and Raj, S. A. 2012. Concurrent Release of Secondary and Micronutrient by a *Bacillus* sp. *American-Eurasian J. Agric. Environ. Sci.,* 12(8): 1061-1064.

Vavoulidu, E., Dimirkou, A., Papadopoulos, P., Avramides, E.J., and Arapakis, D. 2004. A comparative study for the control of organic agriculture in a region of Greece. *17th Word Congress of Soil Science,* Bangkok, Thailand.

Vijayakumar, K. 1977. *Use of Indigenous Source of Magnesium Silicate as A Soil Amendment.* M.Sc. (Ag.) thesis, Kerala Agricultural University, Thrissur, p. 78.

Wada, K. and Inoue, A. 1974. Adsorption of monomeric silica by volcanic ash soils. *Soil Sci. Plant Nutri.* 20(1):5-15.

Walkley, A. J. and Black, I. A. 1934. Estimation of soil organic carbon by chromic acid Titration method. *Soil Sci*. 31: 29-38.

Wang, H., Li, C., and Liang, Y. 2001. Agricultural Utilization of silicon in China. In:*Silicon in Agriculture.* Datnoff, L. E., Snyder, G. H., Korndorfer, G. H. Elsevier Science, Amsterrdam. Pp 343-358.

Wang S. Q, Gu, C. M., Zhao, H. H., Zhao, L. M., Wang, L. P. H. and Wang. 2010. *Research and Application Prospects of Micro-silicon Fertilizer on Rice Production.* Rice Research Institute of Heilongjiang Academy of Land Reclamation Sciences, Jiamusi Heilongjiang, China.

Watanab F. S. and Olsen, S. R. 1965. Test of an ascorbic acid method for determining phosphorus in water and sodium bicarbonate extracts from soil. *Soil Sci. Soc. Am. Proc*. 29: 39-45.

Wedepohl, K. H.1995. The composition of the continental crust Geochim. *Cosmochim. Ac.* 59:1217–1232.

White, A. F., Vivit, D. V., Schulz, M. S., Bullen, T. D., Evett, R. R., and Aagarwal, J. 2012. Biogenic and pedogenic controls on Si distributions and cycling in grasslands of the Santa Cruz soil chronosequence, California. *Geochimica et Cosmochimica Acta* 94 :72–94.

Wickramasinghe, D. B. and Rowell, D. L. 2006. The release of silicon from amorphous silica and rice straw in Sri Lankan soils. *Biol. Fertil. Soils.* 42:231–240.

Williams, D. E. and Vlamis, J., 1957. Manganese toxicity in standard culture solutions. *Plant Soil*. 8:183-193.

Williams, C. H. and Steinbergs, A. 1959. Soil sulphur fractions as chemical indices ofavailable sulphur in some Australian soils. *Australian J. Agric.Res.*10: 340-353.

Xionghui, J., Jiamei, W., Hua, P., Lihong, S., Zhenhua, Z., Zhaobing, L., Faxiang,T., Liangjie, H., and Jian, Z. 2012. The effect of rice straw incorporation into paddy soil on carbon sequestration and emissions in the double cropping rice system. *J. Sci. Food Agric.* 92(5):1038-1045.

Yadvinder-Singh, Bijay-Singh and Timsina, J. 2005. Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. *Adv. Agron*. 85: 269-407.

Yogendra, N. D., Kumara1, B. H., Chandrashekar, N., Prakash, N. B., Anantha M. S., and Jeyadeva, H. M. 2014. Effect of silicon on real time nitrogen management in a rice ecosystem. *Fr. J. Agric. Res.* 9(9): 831-840.

Yoshida, S. 1965. Chemical aspects of role of silicon in physiology of the rice plant. *Bull. Natl. Inst. Agr. Sci. (Jpn.) Ser. B* 15:1-58.

Yoshida, S. 1981. *Fundamentals of Rice Crop Research*. IRRI, Manila, Philippines. 251p.

Zhang H. L. 1984. Studies on Soil Silica. In Studies on Calcium and Silicon Fertilizer. In Nanjing Institute of Soil Science, pp. 86–96. Nanjing Institute of Soil Science. Academia Sinica Press, Nanjing.

Zhu. Y., Wang, Y., Xia, C., Li, D., Li, Y., Zeng, W., Yuan, W., and Liu, M .2004. WDR26: a novel Gbeta-like protein, suppresses MAPK signaling pathway. *J. Cell Biochem.* 93(3):579-87.

Zuccarini, P. 2008. Effects of silicon on photosynthesis, water relations and nutrient uptake of *Phaseolus vulgaris* under NaCl stress. *Biologia Plantarum.* 52 (1): 157-160.

SILICON AVAILABILITY OF TROPICAL SOILS WITH RESPECT TO RICE NUTRITION

By

ARYA LEKSHMI, V.

ABSTRACT OF THESIS

Submitted in partial fulfillment of the

Requirement for the degree of

Doctor of philosophy in Agriculture

Faculty of Agriculture
Kerala Agricultural University

Department of Soil Science and Agricultural Chemistry
COLLEGE OF HORTICULTURE
KERALA AGRICULTURAL UNIVERSITY
THRISSUR 680 656
KERALA, INDIA

2016

Abstract

Silicon (Si) is the second most abundant element in soil. The amount of silicon in soil depends on parent material, soil type, pedogenic process and landscape. In soil solution, Si is present as monosilicic acid which is the only form that the plant can absorb from soil. The productivity of rice is comparatively low in soils of Kerala. As a _Si – accumulator', rice can benefit from Si nutrition. The application of Si can enhance growth and yield of rice. With this background, studies were conducted to categorize major rice growing soils of Kerala according to plant available silicon and to evaluate the efficacy of different sources of silicon including rice straw in wetland rice. The release of silicon from different soils added with various silicon sources under different water regimes was also monitored.

Soil samples were collected from five different locations representing major rice growing regions of Kerala viz., *Kuttanad, Kole* land, *Pokkali*, sandy and lateritic to categorize them according to plant available silicon. The available Si ranged from 7.70 mg kg^{-1} (sandy soil) to 34.91 mg kg^{-1} (*Kole* land soil) in the order *Kole* land > *Pokkali* > lateritic > *Kuttanad* > sandy soil. All the soils under study were categorized as low in available Si. The available Si had positive correlation with organic carbon, available N, Ca, Mg, Fe, Mn, Zn, exchangeable K, Ca, Mg and CEC and negative correlation with available boron, AEC and silica-sesquioxide ratio. These soils were subjected to fractionation of silicon. The major fractions of Si were mobile, adsorbed, organic, occluded, amorphous and residual Si. The percentage distribution of fractions of Si in these soils were in the order; residual Si > amorphous Si > occluded Si > organic Si > mobile Si > adsorbed Si.

Quantity – intensity relationship of five major rice growing soils at two temperatures *viz*. 25^{0}C and 40^{0}C were studied. The highest buffer power was indicated by *Kuttanad* soil followed by *Pokkali* and sandy soils at 25^{0}C. It clearly indicated that these soils have a higher power to retain Si on solid phase and replenish its concentration in soil solution as and when it is depleted through plant uptake or leaching. The equilibrium Si concentration and the amount of Si adsorbed by each soil were used to test the fitness of data to the adsorption isotherms *viz*., Langmuir, Freundlich and Temkin. The data obtained from the adsorption experiments fitted into Freundlich and Temkin equations, but not to Langmuir equation at 25^{0}C. At 40^{0}C no adsorption equations were obtained for any soil.

An incubation study was conducted to know the extent of release of Si on addition of different sources of silicon such as rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate in five rice growing soils under submerged water regime (SWR) and field capacity water regime (FCWR). Addition of Si significantly increased the release of available Si in all soils except *Kole* land soil after a month. *Kole* land soil showed higher release of available Si after two months. The highest release of available Si was at SWR in case of *Kole* land and *Kuttanad* soil, where as *Pokkali,* sandy and lateritic soils showed more release of available Si at FCWR. Irrespective of soils, treatment with sodium silicate showed higher release of available Si. Total Si showed a decreasing trend over the period of incubation for three months in all the soils.

A field experiment was conducted at Agronomic Research Station, Chalakudy to evaluate the efficacy of different sources of silicon including rice straw in wetland rice. Rice husk ash, biodecomposed rice husk, calcium silicate and sodium silicate were used as source of Si along with fertilizers as per package of practice recommendation (NPK alone). The maximum number of panicles per hill, number of spikelets per panicle, thousand grainweights and minimum number of unfilled grains per panicle were recorded in treatment with calcium silicate application. The maximum grain yield of 6.90 t ha^{-1} was recorded in treatment T_5 (T_2 + Calcium silicate) and significantly superior (fig.54) over all other treatments. This increase in yield may be due to the effect of application of Si on soil fertility,nutrient uptake, and plant growth. The direct effect of Si fertilization on increased number panicle per hill, number of spikelets per panicle, and thousand grain weight and decreased number of unfilled grains per panicle might be the reason for increased grain and straw yield in treatment with calcium silicate. The treatment with POP + sodium silicate showed the highest uptake of Si by grain and straw of rice. The sources of Si had no residual effect on grain and straw yield of succeeding rice crop. In general, sandy soil low in available Si had a high response to applied Si in achieving higher grain yield.