# BIOGEOCHEMISTRY OF SILICON IN DIFFERENT RICE ECOSYSTEMS OF KARNATAKA

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### DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY UNIVERSITY OF AGRICULTURAL SCIENCES, BENGALURU – 560 065

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Thesis submitted to the University of Agricultural Sciences, Bengaluru in partial fulfillment of the requirements for the award of the degree of

# **DOCTOR OF PHILOSOPHY**

In

SOIL SCIENCE AND AGRICULTURAL CHEMISTRY

**BENGALURU** 

**DECEMBER, 2016** 

Affectionately dedicated to

My beloved parents Srí. Gangayya, M.K. Smt. Seetha,V.

### UNIVERSITY OF AGRICULTURAL SCIENCES DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY BENGALURU 560 065

### CERTIFICATE

This is to certify that the thesis entitled "BIOGEOCHEMISTRY OF SILICON IN DIFFERENT RICE ECOSYSTEMS OF KARNATAKA" submitted by Ms. SANDHYA, K., ID No. PALB 3090 for the degree of DOCTOR OF PHILOSOPHY in SOIL SCIENCE AND AGRICULTURAL CHEMISTRY to the University of Agricultural Sciences, GKVK, Bengaluru is a bonafide record of research work done by her during the period of her study in this University under my guidance and supervision and the thesis has not previously formed the basis of the award of any other degree, diploma, associate ship, fellowship or similar other titles.

BENGALURU December, 2016

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(Sandhya, K)

### BIOGEOCHEMISTRY OF SILICON IN DIFFERENT RICE ECOSYSTEMS OF KARNATAKA

### SANDHYA, K.

### ABSTRACT

In order to understand biogeochemistry of silicon (Si), plant available Si (PAS) content was analysed in soils of different agro climatic zones of Karnataka besides conducting pot and field experiments to know the efficacy of different sources of Si and its bioavailability in rice ecosystem. Plant available Si content ranged from 1.41-82.89 mg kg<sup>-1</sup> as extracted by calcium chloride (CCSi) and 6.69-370.24 mg kg<sup>-1</sup> as extracted by acetic acid (AASi). Pearson's correlation coefficient worked out for soil analytical data revealed a significant positive correlation between PAS and soil pH, silt, clay, cation exchange capacity and negative correlation with sand content. X-Ray Diffraction analysis of the soil samples revealed the presence of quartz, feldspars, amphibole, phyllosilicates as primary minerals and smectite, kaolinite, illite, vermiculite as clay minerals in various proportions. AASi was positively correlated with Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO and TiO<sub>2</sub> demonstrating the extractant assessed the fraction of Si adsorbed on the surface of oxides or oxy-hydroxides and clays while, CCSi for immediate dissolved Si. Application of diatomite @ 300 kg ha-1 significantly increased the grain yield and numerical increase in other yield attributes in the field experiment. Budgeting of Si in a rice ecosystem revealed that majority of the biogeochemical cycle of Si was controlled by uptake, dissolution and contribution by irrigation water. Bioavailability of Si for rice in acidic, neutral and alkaline soil revealed that application of calcium silicate, diatomite and rice husk biochar significantly increased the yield parameters. Higher Si uptake was noticed in neutral soil followed by acidic and alkaline soil. In acidic and neutral soil, application of calcium silicate significantly increased the nutrient status of soil whereas rice husk biochar in alkaline soil and justifies the variability in reactivity of the sources in different soils rather than total Si content.

December, 2016

Department of Soil Science and Agricultural Chemistry University of Agricultural Sciences GKVK, Bengaluru - 560 065 (**N. B. Prakash**) Major Advisor

### ಕರ್ನಾಟಕದ ವಿವಿಧ ಭತ್ತದ ಪರಿಸರ ವ್ಯವಸ್ಥೆಗಳಲ್ಲಿ ಸಿಲಿಕಾನಿನ ಜೈವ ಭೌಗೋಳಿಕ ರಾಸಾಯನಶಾಸ್ತ್ರ

ಸಂಧ್ಯಾ, ಕೆ.

#### ಪ್ರಬಂಧದ ಸಾರಾಂಶ

ಸಿಲಿಕಾನಿನ ಜೈವ ಭೌಗೋಳಿಕ ರಾಸಾಯನಶಾಸ್ತ್ರ ಅರ್ಥೈಸುವ ಸಲುವಾಗಿ, ಕರ್ನಾಟಕದ ವಿವಿಧ ಕೃಷಿ ಹವಾಮಾನ ವಲಯಗಳಿಗೆ ಸಂಬಂಧಪಟ್ಟ ಭತ್ತದ ಪರಿಸರ ವ್ಯವಸ್ಥೆಗಳ ಮಣ್ಣಿನ ಮಾದರಿಯನ್ನು ಸಸ್ಯ ಲಭ್ಯವಿರುವ ಸಿಲಿಕಾನಿನ ಅಂಶಕ್ಕಾಗಿ ವಿಶ್ಲೇಷಣೆಗೊಳಪಡಿಸುವ ಜೊತೆಗೆ ವಿವಿಧ ಸಿಲಿಕಾನಿನ ಮೂಲಗಳ ದಕ್ಷತೆ ಮತ್ತು ಜೈವಿಕ ಲಭ್ಯತೆಯನ್ನು ತಿಳಿಯಲು ಮಡಕೆ ಮತ್ತು ಕ್ಷೇತ್ರ ಪ್ರಯೋಗಗಳನ್ನು ಹಮ್ಮಿಕೊಳಲಾಗಿತ್ತು. ಸಸ್ಯಕ್ಕೆ ಲಭ್ಯವಿರುವ ಸಿಲಿಕಾನಿನ ಅಂಶವು ೧.೪೧ ರಿಂದ ೮೨.೮೯ ಹಾಗೂ ೬.೬೯ ರಿಂದ ೩೭೦.೨೪ ಮಿ. ಗ್ರಾಂ. ಪ್ರತಿ ಕೆ. ಜಿ. ಮಣ್ಣಿಗೆ ಕ್ರಮವಾಗಿ ಕ್ಯಾಲ್ಸಿಯಂ ಕ್ಲೋರೈಡ್ ಮತ್ತು ಅಸಿಟಿಕ್ ಆಸಿಡ್ ಬಳಸಿದಾಗ ಕಂಡುಬಂದಿದೆ. ಅಂತೆಯೇ, ಈ ಸದರಿ ಅಂಶಗಳು ಧನಾತ್ಮಕವಾಗಿ ಮಣ್ಣಿನ ರಸಸಾರ, ಹೊಳು, ಜೇಡಿ, ಧನ ಅಯಾನಿನ ವಿನಿಮಯ ಸಾಮರ್ಥ್ಯ ಮತ್ತು ಋಣಾತ್ಮಕವಾಗಿ ಮರಳಿನ ಅಂಶದೊಂದಿಗೆ ಪರಸ್ಪರ ಸಂಬಂಧ ಗುಣಾಂಕವನ್ನು ಹೊಂದಿರುತ್ತದೆ. ಕ್ಷ-ಕಿರಣ ವಿವರ್ತನಾ ವಿಶ್ಲೇಷಣೆಯಲ್ಲಿ ಸ್ಪಟಿಕ, ಪಾತಾಳ, ಆಂಫಿಬೋಲ್, ಫಿಲೋಸಿಲಿಕೇಟಗಳು ಪ್ರಾಥಮಿಕ ಖನಿಜಗಳಾಗಿ ಮತ್ತು ಬಿಳಿ ಜೇಡಿ ಮಣ್ಣ. ಕಯೊಲಿನೈಟ್, ಇಲ್ಲೈಟ್ ಮತ್ತು ವರ್ಮಿಕ್ಯುಲೈಟ್ ಜೇಡಿ ಮಣ್ಣಿನ ಖನಿಜಗಳಾಗಿ ವಿವಿಧ ಪ್ರಮಾಣದಲ್ಲಿರುವುದು ಕಂಡುಬಂದಿರುತ್ತದೆ. ಅಸಿಟಿಕ್ ಆಸಿಡ್ ಬಳಸಿ ಪಡೆಯಬಹುದಾದ ಸಿಲಿಕಾನಿನ ಅಂಶವು ಅಲ್ಯೂಮಿನಿಯಂ ಆಕ್ರೈಡ್, ಕಬ್ಬಿಣದ ಆಕ್ಸೈಡ್, ಮ್ಯಾಂಗನೀಸ್ ಆಕ್ಸೈಡ್ ಮತ್ತು ಟೈಟಾನಿಯಂ ಆಕ್ಸೈಡ್ ಗಳ ಜೊತೆಗೆ ಧನಾತ್ಮಕ ಸಂಬಂಧ ಗುಣಾಂಕವನ್ನು ಹೊಂದಿದ್ದು, ಈ ವಿಧಾನವು ಮಣ್ಣಿನ ಮೇಲ್ಮೈ ಮತ್ತು ಜೇಡಿ ಮಣ್ಣಿನ ಜತೆಗೆ ಇರುವ ಸಿಲಿಕಾನಿನ ಅಂಶವನ್ನು ಹೊರತೆಗೆಯುವ ಸಾಮರ್ಥ್ಯವನ್ನು ಪ್ರದರ್ಶಿಸಿದ್ದು ಹಾಗೆಯೇ ಕ್ಯಾಲ್ಸಿಯಂ ಕ್ಲೋರೈಡ್ ನಿಂದ ಹೊರತೆಗೆದ ಅಂಶವು ತಕ್ಷಣವೇ ದೊರೆಯುವ ಕರಗಿದ ರೂಪದಲ್ಲಿರುವ ಸಿಲಿಕಾನಿನ ಅಂಶವೆಂದು ರೂಪಿಸಿದೆ. ಡೈಯಾಟೋಮೈಟ್ ೩೦೦ ಕೆ. ಜಿ. ಪ್ರತಿ ಹೆಕ್ಟೇರಿಗೆ ಹಾಕಿದಾಗ, ಭತ್ತದ ಇಳುವರಿಯಲ್ಲಿ ಗಮನಾರ್ಹವಾಗಿ ಮತ್ತು ಇತರ ಇಳುವರಿಯ ನಿಯತಾಂಕಗಳಲ್ಲಿ ಸಂಖ್ಯಾತ್ಮಕವಾಗಿ ಹೆಚ್ಚುವರಿಯಾಗಿರುವುದು ಕ್ಷೇತ್ರ ಪ್ರಯೋಗದಲ್ಲಿ ಕಂಡು ಬಂದಿದೆ. ಬಹುತೇಕ ಸಿಲಿಕಾನಿನ ಜೈವ ಭೌಗೋಳಿಕ ರಾಸಾಯನಶಾಸ್ತ್ರವು ಜೈವಿಕ ಗ್ರಹಿಸುವಿಕೆ, ಕರಗಿಸುವಿಕೆ ಮತ್ತು ನೀರಾವರಿಯ ಮೂಲಗಳಿಂದ ವ್ಯವಸ್ಥಿತವಾಗಿರುವುದೆಂದು ಭತ್ತದ ಪರಿಸರ ವ್ಯವಸ್ಥೆಯಲ್ಲಿ ಸಿಲಿಕಾನಿನ ಸಮತೋಲನದ ಅಧ್ಯಯನದಲ್ಲಿ ಕಂಡುಬಂದಿದೆ. ಕ್ಯಾಲ್ಫಿಯಂ ಸಿಲಿಕೇಟ್, ಡೈಯಾಟೋಮೈಟ್ ಮತ್ತು ಭತ್ತದ ಹೊಟ್ಟಿನ ಜೈವ ಇದ್ದಿಲಿನ ಬಳಕೆಯು ಜೈವಿಕ ಲಭ್ಯವಿರುವ ಸಿಲಿಕಾನಿನ ಅಂಶವನ್ನು ಅಂತೆಯೇ ಇಳುವರಿಯ ನಿಯತಾಂಕಗಳನ್ನು ಆಮ್ಲೀಯ, ತಟಸ್ಗ ಮತ್ತು ಕ್ಷಾರೀಯ ಮಣ್ಣಿನಲ್ಲಿ ಗಮನಾರ್ಹವಾಗಿ ಹೆಚ್ಚುವರಿ ಮಾಡಿದೆ. ಆಮ್ಲೀಯ ಮತ್ತು ಕ್ಷಾರೀಯ ಮಣ್ಣಿಗೆ ಹೋಲಿಸಿಕೊಂಡರೆ, ತಟಸ್ಥ ಮಣ್ಣಿನಲ್ಲಿ ಸಿಲಿಕಾನಿನ ಜೈವಿಕ ಗ್ರಹಿಸುವಿಕೆಯು ಹೆಚ್ಚಾಗಿ ಕಂಡುಬಂದಿದೆ. ಕ್ಯಾಲ್ಸಿಯಂ ಸಿಲಿಕೇಟ್ ಬಳಕೆಯು ಆಮ್ಲೀಯ ಮತ್ತು ತಟಸ್ಥ ಮಣ್ಣಿಗೆ ಹಾಗೂ ಭತ್ತದ ಹೊಟ್ಟಿನ ಜೈವ ಇದ್ದಿಲಿನ ಬಳಕೆಯು ಕ್ಷಾರೀಯ ಮಣ್ಣಿನಲ್ಲಿ ಪೋಷಕಾಂಶಗಳ ಪ್ರಮಾಣವನ್ನು ಹೆಚ್ಚುವರಿ ಮಾಡಿದ್ದು, ವಿವಿಧ ಸಿಲಿಕಾನಿನ ಮೂಲಗಳು ಮಣ್ಣಿನ ಗುಣಧರ್ಮಗಳ ಮೇಲೆ ಅವಲಂಬನೆಯಾಗಿರುವುದನ್ನು ಸಮರ್ಥಿಸುತ್ತದೆ.

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(ಎನ್. ಬಿ. ಪ್ರಕಾಶ್) ಮುಖ್ಯ ಸಲಹೆಗಾರರು

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### **I** INTRODUCTION

Rice is life for most of the people living in Asia. Rice has shaped the cultures, diets and economics of thousands of millions of people (Gnanamanikam, 2009). Rice is the most important staple food crop in world as well as in India. About 90 per cent of the global rice area is in the Asian continent, where more than 90 per cent of the world's rice is produced and consumed. Total global consumption of milled rice amounted to approximately 485 million metric tons in 2014-15. With over 200 million metric tons, China is the world's leading rice producer, while India has the largest area where rice is harvested. It serves as a major source of calories for about 60 per cent of the world's population and provides 32.59 per cent of the dietary energy and 25-44 per cent of the dietary protein. As population increases, global demand for rice in the next decade is expected to expand at around one percent per year. By 2030, targeted total rice production would be 800 million tonnes, which is 200 million tonnes more than the rice production in 2006 (FAO, 2006). Asia's food security depends largely on irrigated rice fields, which produce three quarters of all rice harvested. It is expected that expansion will mostly stem from intensified production, with marginal increase in area (Calpe, 2001). In India rice is grown in an area of 44 million ha with a production of 107 million tons and productivity of 2424 kg ha<sup>-1</sup>. In Karnataka total area under rice is 11.69 lakh hectares with a production of 28.05 lakh tons (Anon., 2015).

Karnataka state represents a wide variety of geological, climatic, vegetational and physiographic features, which have influenced soil formation and thus has given rise to various types of soils. Accordingly, the different soils have distinct morphological and physico-chemical properties that have a bearing on plant growth and have influenced the cropping pattern, giving Karnataka a unique status. A scientific knowledge of soils is a pre-requisite to understand the local ecology which would be useful in planning for agricultural development (Rajanna, 2013). As per the updated soil survey data, the soils of Karnataka have been broadly classified under nine groups based on soil properties as shallow black soil, medium black soil, deep black soil, red sandy soil, mixed red and black soil, red loamy soil, lateritic soil, laterite gravelly soil and coastal alluvium soil.

In Karnataka rice is grown under a variety of soils and wide range of rainfall and temperature. Only around 44 per cent of the total acreage is under irrigation while the rest is under the regime of monsoon. Rice is cultivated in places where the rains are as heavy as much as 3000 mm and in others where it is just 600 mm. In some areas only one crop is grown and in certain other areas three crops are raised. The unique feature of rice culture in the state is that it is either sown or transplanted during all seasons of the year. The duration of the rice varieties cultivated in the state varies from 100 to 180 days depending on season and agro-climatic location. It is highly challenging for the researchers to work with the problems of diversified rice cultivation. Based on the agro-climatic practices, rice growing ecosystems of the state can be broadly classified into following six categories *viz.*, coastal area, hilly area, transitional area, tank fed area, irrigated maidan area (South) and irrigated maidan area (North) and these soils greatly vary with their nutritional status.

Biogeochemistry of silicon in different rice ecosystems of Karnataka

Silicon is the second most abundant element after oxygen in this earth's crust and in soil. Total Si content of soil ranges normally from 25 to 35 per cent with an average of 28 per cent depending greatly upon soil types. However, in some highly weathered soils such as latosols and latosolic red soils in the tropics where desilification processes are extremely active, Si content can be as low as less than 1 per cent. Generally, Si is absorbed and transported by plants in the form of monosilicic acid (H<sub>4</sub>SiO<sub>4</sub>). However, in monosilicic acid saturated soil solution, H<sub>4</sub>SiO<sub>4</sub> easily polymerises into polymeric Si(OH)<sub>4</sub> which is in dynamic equilibrium with noncrystalline and crystalline silicates, exchangeable silicates and sesquioxides. The main factors influencing soil Si availability or Si supplying power include type of soil and parent material, historical land use change, soil pH, soil texture, soil Eh, organic matter, temperature and accompanying ions (Struyf et al., 2009). Rice is considered as a typical Si accumulator and takes up Si actively. Information on the importance of Si in Indian rice farming system is limited (Prakash, 2002). There is need to identify the nature and magnitude of the Si status in different rice eco-systems and thereby develop suitable Si management agenda to harness the yield potentials of improved rice cultivars.

Knowledge of Si cycling in rice paddies is still scarce. In general, Si cycling is affected by Si inputs, losses, and transformation processes within the soil-plant system (Sommer *et al.*, 2006). It ultimately determines how well the plants are supplied with Si. Studies on inputs suggest that irrigation provides 27– 44 per cent of Si uptake by plants in irrigated lowland rice production (Ma *et al.*, 2001). This implies that the largest part of the Si for plants is provided by soil constituents. Si forms were continuously regenerated during the growing season by dissolved Si (DSi) inputs via irrigation and, more importantly in wet seasons through the dissolution of solid soil particles. Largest portion of DSi that was taken up by plants or lost by drainage and percolation was supplied by soil constituents. The DSi losses in paddy field are mainly influenced by percolation, drainage and extent of evaporation. The situation for higher DSi content during dry season can be expected in flooded condition with irrigation water due to reduced rainfall. Si concentrations in plants as well as the total plant- Si-uptake hardly differ between dry and wet seasons (Klotzbucher *et al.*, 2015). Therefore, it is necessary to study the biogeochemical cycle of Si in cultivated ecosystems (Desplanques *et al.*, 2006).

This is evident from the fact that most of the traditional rice fields of the world are low in plant available Si and addition of Si is reported to improve the rice yield. This emphasize the need for identifying an ideal Si source/ sources for field application, which can improve soil Si status, plant available Si and sustain rice production. Si sources for agricultural use range from chemical products to natural minerals to byproducts of steel and iron industries. All these products are shown to be effective in improving crop growth and yield (Liang *et al.*, 2015). In general, their usefulness depends on the reactivity rather than total Si content (Haynes, 2014). But, for field application an ideal Si source should possess attributes like local availability, cost effectiveness, easy to handle, improve plant available Si and Si bioavailability, environment friendly and improve crop growth and yield. Also, for Si sources to be most effective as a fertilizer, it is essential to acquire knowledge of physical and chemical characteristics of Si sources and to understand the extent of bioavailability from sources for adequate plant uptake (Savant et al., 1997).

There is no national database on Si availability in Indian soils although it is available in other countries of the world. It is apparent from the reviewed literature (Prakash, 2002), that most of the paddy soils studied were deficient in Si. The biogeochemical cycle of Si in the rice ecosystems are affected by many factors and hence there is a need to assess the Si transport and accumulation in rice soil – plant system. Reactivity and bioavailability of Si sources vary based on the soil type and accompanying ions. In view of this, a study entitled "Biogeochemistry of silicon in different rice ecosystems of Karnataka" was conducted with the following objectives:

- To assess the silicon status and their relationship with physico-chemical properties of rice soils of different agro climatic zones of Karnataka.
- To assess the silicon budget in wetland rice ecosystem.
- To assess the bioavailability of different sources of silicon in rice and silicon budgeting in acidic, neutral and alkaline soils.

### **II REVIEW OF LITERATURE**

The present investigation was undertaken to study "Biogeochemistry of silicon in different rice ecosystems of Karnataka". The available reviews related to the present investigation are presented under following headings.

- 2.1. Silicon: Its importance in agriculture with special reference to rice
- **2.2.** Status of silicon in soil
- 2.3. Silicon pools and biogeochemistry in soil
- **2.4.** Dissolution and bioavailability of different sources of silicon
- **2.5.** Dissolved silicon in soil plant system

### 2.1. Silicon: Its importance in agriculture with special reference to rice

There is an established doctrine that plants need 17 essential elements to grow. In reality, plant growth requires far more than 17 elements (Chen *et al.*, 2000). Si is the second most abundant element on the surface of the earth and accounts for up to 41 per cent of the earth's crust. Silicon dioxide comprises 50 - 70 per cent of the soil mass. As a consequence, all plants rooting in soil contain some Si in their tissues. The role of Si in plant growth and development was overlooked until the beginning of the 20<sup>th</sup> century because of the abundance of the element in nature and because visible symptoms of either Si deficiency or toxicity are not apparent. However, repeated cropping and the constant application of chemical fertilizers have depleted the amount of Si that is available to plants in the soil. An awareness of Si deficiency in soil is now recognized as being a limiting factor for crop production, particularly in soils that are deemed to be low or limiting in plant available Si and for known Si-accumulating plants such as rice and sugarcane. Today, Si still is not recognized as an essential element for plant growth but the beneficial effects of this element on the growth, development, yield and disease resistance have been observed in a wide variety of plant species (Ma *et al.*, 2006).

Silicon is taken up by the roots in the form of silicic acid [Si(OH)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 (dry weight). Within the angiosperms, species from the commelinoid monocot orders Poales and Arecales accumulate substantially more Si in their shoots than do species from other monocot clades. Among Poales, species of the Gramineae and Cyperaceae families accumulate high levels of Si. Most plants, particularly dicots, are unable to accumulate high levels of Si in their shoots. The difference in Si accumulation between species has been attributed to differences in the Si uptake ability of the roots (Ma and Takahashi, 2002).

Rice (*Oryza sativa* L.) is a typical silicon accumulating plant requiring large amounts of silicon for vigorous growth and high production. Silicon deposited in the leaves, stem and husk forms a physiological barrier, which mitigates fungal infection and pest attack, alleviates lodging and other abiotic stress, improves the light-interception ability by plants in a community, and minimizes transpiration losses. Soluble silicon in plants also has an active function in enhancing host resistance to plant diseases by stimulating one or more defence reaction mechanisms (Ma, 2007).

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

It has been reported that silicon suppresses insect pests such as stem borers, brown plant hopper, green leaf hopper, white backed plant hopper and non-insect pests such as spider mites (Savant *et al.*, 1997 and Ma and Takahashi, 2002). Most of the plant silicon occurs in the epidermis, which might dislodge young larvae before they can establish in the stem.

The application of silicon to crops is a viable component of an integrated management programme for insect pests and diseases because it leaves no pesticide residue in food or the environment, and relatively cheap and could easily be integrated with other pest management practices (Laing *et al.*, 2006).

Several studies in monocots (rice and wheat) have shown that plants supplied with Si can produce phenolics and phytoalexins in response to fungal infection such as those causing rice blast and powdery mildew (Fawe *et al.*, 1998; Belanger *et al.*, 2003; Rodrigues *et al.*, 2004 and Remus-Borel *et al.*, 2005). The presence of Si in nutrient solutions affects the absorption and translocation of several macro and micro-nutrients (Epstein, 1994). Increased Si fertilisation increases Zinc uptake if deficient, especially if P is excessive (Marschner *et al.*, 1990).

Silicon fertilisation retards the uptake of phosphorous by roots beyond toxic limits, such as in cucumbers, while promoting its translocation to grain in rice and wheat (Lewin and Reimann, 1969). Si fertilisation has been shown to alleviate sodium uptake in rice, wheat and barley (Savant *et al.*, 1997). Si interaction with Na<sup>+</sup>, reduced its uptake and transport to shoots and consequently improved cane yield and juice quality in salt-sensitive and salt-tolerant sugarcane genotypes under salt stress (Ashraf *et al.*, 2010).

Optimization of Si nutrition results in increased weight and volume of roots by 20 to 200 per cent and enhanced drought and salt resistance of cultivated plants (Matichenkov *et al.*, 2001). Silicon priming potentially can induce anatomical changes in cell wall with deposition of silica in the form of polymerized silicon dioxide (SiO<sub>2</sub>) solid particles, alleviating the oxidative damage of functional molecules and improving anti-oxidative defence abilities. Silicon, actually, induces dehydration tolerance at tissue or cellular levels by improving the water status and hence, facilitates the plant to access photosynthates and this modified adaptability mechanism varies among species (Muktar *et al.*, 2013).

Cheng (1982) noted beneficial effects of Si on plant growth in terms of increased number of leaves, tillers and alleviation of disorders like bronzing and Akiochi in rice. Ma *et al.* (1989) observed that addition of 100 mg kg<sup>-1</sup> SiO<sub>2</sub> as silicic acid during the reproductive stage markedly increased straw yield. The maintenance of photosynthetic activity due to Si fertilization could be one of the reasons for increased dry matter production in rice (Agarie *et al.*, 1992). Plant grown with added Si enhanced the photosynthesis, translocation of carbon to panicles or seeds and water use efficiency.

Application of silicon in rice was found to increase the grain yield by increasing spikelets number panicles<sup>-1</sup>, mature grain percentage and 1000 grain weight (Takahashi, 1996 and Singh *et al.*, 2005). Silicon application enhanced more optimal use of nitrogen applied to rice but N may also have decreased acquisition of Si, especially by NH<sub>4</sub>-N applied during early growth compared to NO<sub>3</sub>-N.

With the likely removal of large amounts of plant nutrients including Si from the soil attempts were made to replace these nutrients using conventional fertilizer. However, the potential beneficial role of Si was overlooked. Si-depleted soils have been associated with lower resistance to insect pests and fungal diseases as well as crop lodging (Flinn and De Datta, 1984).

Si supplied rice plants can tolerate Fe, Al and Mn toxicities and the increased mechanical strength of the culm helps to reduce crop lodging. Hossain *et al.* (2001) showed that calcium silicate and rice straw application to rice crop improved silicon concentration in straw which was more than grain silicon concentration.

Foliar sprays of NaSiO<sub>3</sub> at a rate of 150 mg Si L<sup>-1</sup> accumulated higher levels of silicon in leaf, peduncle and flower tissues than non-supplemented controls and leaf concentrations of macronutrients such as N, K, S and Ca and micronutrients such as B, Cu, Fe and Mg were slightly changed in Gerbera plants. Leaf Si concentrations were 1.2–3.3 fold higher in Si-supplemented plants, while the macronutrients N, K, S, Mg and Ca and micronutrients like Al and B concentration increased in KSiO<sub>3</sub> (280 g m<sup>-3</sup>) supplemented Zinnia plants (Kamenidou *et al.*, 2009).

Hayasaka *et al.* (2005) studied the control of rice blast at the nursery stage, using various rice cultivars and soils. In all rice cultivars, the number of lesions was significantly reduced when  $SiO_2$  content increased in the rice seedling; lesions were

Biogeochemistry of silicon in different rice ecosystem of Karnataka

reduced to 5-20 per cent of the number on the seedlings grown in soil without silica gel when the seedling  $SiO_2$  content reached 5 per cent. These results suggest that  $SiO_2$  content of at least 5 per cent in the rice plant can control disease at the nursery stage under any conditions.

Field experiments were conducted in the coastal zone soils of South India with application of calcium silicate as silicon source (Prakash *et al.*, 2011). Application of calcium silicate @ 3 to 4 t ha<sup>-1</sup> as a Si source resulted in a significant increase in grain yield over the control and other treatments (CaCO<sub>3</sub>) in the acid soils of Karnataka, Southern India.

Saigusa *et al.* (2000) studied the effect of porous hydrated calcium silicate (PS) application on the resistance of rice plants (*Oryza sativa* L.) to blast (*Pyriculariaoryzae*). The results imply that PS application is effective in preventing fungal infection through silicification of bulliform cells. The number of silicified bulliform and trichome cells increased exponentially with increasing content of the silicon in the leaf blade, whereas the number of silicified short cells, which are smaller than bulliform cells and trichomes, has no relation to the silicon content in the leaf blade.

A study on recycling of Si rich plant residues such as the use of rice chaffs as soil amendments was conducted by Khandaker *et al.* (2001). In this investigation, powdered rice chaff (Cp) and normal rice chaff (Ch) was mixed in a fertile clay loam soil and less fertile sandy loam soil, with or without a biodecomposer. Calcium silicate was also applied to the soils for comparison. Application of rice chaffs had little effect on plant height, but slightly increased the number of tillers per pot. The total N content of the plants were decreased in the clay loam soil but not in the sandy loam soil, but the Si content in the plants, grown in both soils was increased. The effect of Cp and Ch on the Si content of plants was significantly enhanced by the addition of the biodecomposer. Considering the polluting effect of inorganic fertilizers and the high cost of inorganic Si fertilizers, the use of rice chaff seemed to be important not only as an in situ source of Si but also for its sustainability over a long period of time (Savant *et al.*, 1997; Sistani *et al.*, 1997).

A study was conducted by Sattar *et al.* (2013) to assess the effective source and best level of soil applied Si on the growth of the wheat seedling. Experiment comprised of three silicon sources (sodium silicate, calcium silicate and silicic acid) and four concentrations (0, 50, 100 and 150 mg kg<sup>-1</sup>). Results revealed that soil applied Si improved the growth of wheat plant when compared to control. Significantly higher shoot and root length, fresh and dry weights, shoot: root ratio, total plant biomass was obtained when 100 and 150 mg kg<sup>-1</sup> Si was applied as Ca-silicate. The current results also enabled selection of the most effective (100 mg kg<sup>-1</sup>) levels out of four levels of Si using Ca-silicate.

Response of sugarcane to calcium silicate on yield, gas exchange characteristics, leaf nutrient concentrations, and soil properties in two different soils was studied by Bokhtiar *et al.* (2012). Seven levels of Si (0, 20, 40, 60, 80, 120 and 150 g pot<sup>-1</sup>) were

tested by applying them with traditional fertilizers. Gas exchange characteristics such as photosynthesis, transpiration, and stomatal conductance were significantly greater with the plants fertilized with silicate over unamended control in both soils. Silicate fertilization increased chlorophyll and moisture contents in the top visible dewlap (TVD) leaf tissues. Si-amended treatments significantly increased dry matter and cane yield respectively by 77 and 66 per cent in soil-1 and 41 and 15 per cent in soil-2. With increasing silicate application, iron, copper, zinc, and manganese contents significantly decreased in leaf tissues and in both soils. Soil pH, Si contents, available sulfur, exchangeable Ca and magnesium and cation exchange capacity were increased significantly more or less, whereas aluminum content decreased dramatically in both soils when amended with Ca-silicate. Results indicated that different soil fertility status and rates of Si application were important factors influencing the yield, growth parameters, chlorophyll and nutrient contents of sugarcane leaf as well as soil properties.

A greenhouse experiment was conducted to study the effect of Si of rice hull ash (RHA) on the growth of rice (*Oryza sativa* L.) seedlings by Sistani *et al.* (2008). The RHA-treated seedlings produced (average of all treated seedlings) more dry matter (18%) over the untreated seedlings. The effects of rice cultivar and soils on the seedling growth were not significant. The RHA application to rice nurseries seems to be an efficient way of recycling plant Si and have agronomic and environmental benefits, especially in developing countries.

Mauad *et al.* (2003) evaluated the effects of N and Si fertilization on vegetative and yield components of rice cultivar IAC 202. An experiment was carried out combining three N rates (5, 75 and 150 mg N kg<sup>-1</sup> soil) applied as urea, and four silicon rates (0, 200, 400 and 600 mg SiO<sub>2</sub> kg<sup>-1</sup> soil) applied as calcium silicate. Nitrogen fertilization increased the number of stems and panicles per square meter and the total number of spikelets, reflecting on grain productivity. Excessive tillering caused by inadequate N fertilization reduced the percentage of fertile stalks, spikelet fertility and grain mass. Silicon fertilization reduced the number of blank spikelets per panicles and increased grain mass but did not affect grain productivity.

Studies on the effect of Si application on rice growth and yield in different soil types were carried out using steel slag by Linca *et al.* (2016). Silica availability has been decreased in rice fields of Indonesia and Si deficiency was recognized as a possible limiting factor in rice production. Steel slag, which has a high Si content and is locally available selected as a potential source of Si in the study. A greenhouse experiment was carried out to evaluate the effect of steel slag on rice growth in different soil types. Steel slag was applied at the rates of 0, 20, 50, 100, 200 and 300 kg Si ha<sup>-1</sup>. Steel slag application increased plant height at 300 kg Si ha<sup>-1</sup>. Grain yield of soils that contained low available Si increased with steel slag application. In contrast, some soils with high available Si content did not respond to Si application and other soil properties affected rice growth.

Significantly higher grain weight of rice was recorded with the application of porous hydrated calcium silicate (CS) @ 2.0 per cent and silica gel @ 1.0 per cent in

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Andosol and potassium silicate (PS) @ 0.75 per cent in alluvial soil (Zhongqiu *et al.*, 2005). PS and CaCO<sub>3</sub> treatment significantly increased soil pH, decreased the 1 M NH<sub>4</sub>OAc extractable cadmium and reduced cadmium content in straw and brown rice.

Application of calcium silicate as Si source significantly increased the rice grain and straw yield in the soils of Karnataka (Narayanaswamy and Prakash, 2009). Among the soils studied, crop responded even up to 1448 kg ha<sup>-1</sup> of applied Si in achieving higher yield over the control. However, there was a varied response in rice yield in different soils to the application rates of Si. These varied responses of soil to applied Si may be attributed to variation in native plant available Si content of those soils. Soils having low to medium available Si responded to applied Si fertilizers to greater extent than the soils having higher levels of available Si. The maximum yield obtained due to application of varied levels of Si in different soils ranged from 25.4 to 40.9 g pot<sup>-1</sup> and the increase in yield ranged from 1.1 to 16.0 g pot<sup>-1</sup>. The relative yield ranged from 35.8 to 96.4 per cent and was higher for the soils having higher native Si content and lower yield was associated with soils having a lower native Si.

### 2.2 Status of silicon in soil

Soil Si availability and Si supplying power vary with soil types, depending mainly on the type of parent materials, weathering, elluviation and illuviation.

A major consequence of the chemical weathering of primary silicate minerals is desilication. Weathering releases highly mobile cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup>), moderately mobile Si(OH)<sub>4</sub> and relatively immobile Al and Fe into the soil solution (White and Brantley, 1995). Part of the Si released from the mineral structure reacts with Al to form secondary minerals while the remainder is subjected to leaching. As a consequence, most soils experience a loss of Si and basic cations during weathering. Desilication is most pronounced in humid tropical environments and occurs to a lesser extent in temperate regions. From this point of view, it is important to note that rice and sugarcane are tropical/subtropical crops and the majority of their production is on highly weathered Ultisols and Oxisols which have a characteristically low Si status (Haynes, 2014).

Si depletion in soil due to desilication depend on the stage/duration of soil development, content of weatherable minerals in the parent material and amount of percolating water (assuming steady state of biogenic Si pools at short time scales). Also intensive cultivation and crop removal can reduce the concentration of potentially available Si to the extent that Si fertilization is necessary (Savant *et al.*, 1997; Meunier *et al.*, 2008).

Hoda *et al.* (2016) conducted a study with the objective of understanding Si status in calcareous soils of Egypt by surveying the soil samples from 6 zones. The results revealed that total Si ranged from 311.2 to  $5760 \text{ mg kg}^{-1}$  soil. The highest concentration was found in the coarse textured soils. Also sand, silt and clay contents were more effective in contributing to total Si content. The results of sequential extraction indicated

that most of the Si was mobile which represents 35.69 per cent of the total. The dominant mobile Si class was 1001 to 1500 mg kg<sup>-1</sup> soil covered about 43.7 per cent of the total area followed by the class 800 to 1000 mg kg<sup>-1</sup> soil and covered 31.7 per cent of the total area. The amorphous fraction was the lower level and represented 5.38 per cent of the total Si. The results also indicated that about 11.36 per cent of total Si is bound in primary and secondary silicates.

Soil particles can adsorb silicic acid dissolved from the soil solution (Anna *et al.*, 2010). In addition, silica can be included in sesquioxides or bound to organic matter and amorphous silica exists in the form of biogenic and minerogenic opal. Dissolved silicic acid form is retained in the soil solution and/or adsorbed with many primary and secondary crystalline silicates generally found in soils.

Si distribution in the soils of northern highland of Ethiopia (Fassil, 2009) was studied by collecting survey samples from 5 agro ecological zones. The study revealed that Si contents ranged from 79.8 to 87.5 g Si kg<sup>-1</sup> in the cultivated Vertisols of Adigudom, from 97.7 to 115.2 g Si kg<sup>-1</sup> in Axum, from 113.7 to 117.2 g Si kg<sup>-1</sup> in Maychew, from 130.0 to 133.9 g Si kg<sup>-1</sup> in Shire and from 137.3 to 166.3 g Si kg<sup>-1</sup> in Wukro. The highest concentration was found in Wukro where the sand content amounted to 50 per cent whereas the lowest level was obtained from soils of Adigudom where the clay content exceeded 60 per cent. The Si contents in all the studied soils were lower than the documented ranges of 200 and 300 g Si kg<sup>-1</sup>. Significant correlation was found between silicon status and organic carbon 0.84\*(p<0.05), silt -0.84\*(p<0.05) and clay 0.84\*(p<0.05).

Distribution of available Si was investigated and was discussed with land use types and soil erosion status as estimated by USLE (Universal Soil Loss Equation) in Sumani watershed where main rice producing area is in Sumatra Island by Aflizar (2009). The results showed that available Si levels in sawah (leveled and bounded rice field) soil was less than 300 mg SiO<sub>2</sub> kg<sup>-1</sup> in average, being deficient level for rice growth. Available Si content in river sediments was also determined and was higher than those in sawah or other land uses. This might indicate that available Si was redistributed through soil erosion. Soil erosion rate tended to be negatively correlated with concentration of available Si in soils. Land use types with small values of crop factor in USLE calculation and soil with lower pH showed relatively low available Si values in the soils. It appears that soil erosion and land use types affected the distribution of available Si in the watershed.

Kraska and Brietenbeck (2010) surveyed to assess the Si status of rice plants at mid-tiller (Y-leaf) and at harvest (straw) in 97 rice fields located throughout the rice growing regions of Louisiana. On an average, Y-leaves contained  $30.5 \pm 7.8$  g Si kg<sup>-1</sup>, whereas mature rice straw contained  $54.7 \pm 12.7$  g Si kg<sup>-1</sup>. Low early season Si assimilation occurred in nearly all rice fields, whereas only 36 per cent contained mature straw with <50 g Si kg<sup>-1</sup>, a level commonly used to indicate sufficiency. Late-season deficiencies were limited to fields in extreme southwest Louisiana where soils tend to be strongly acidic and have a long history of rice production.

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Berthelson *et al.* (2003) reported that under high leaching environments common to the wet tropics, soils undergo significant weathering, which when combined with accelerated chemical and physical degradation due to soil perturbation and crop removal results in increased soil acidification and dissolution of the alumino-silicate clay minerals (de-silication). The consequences are both a loss of plant available Si through leaching and a decline in cation exchange capacity and hence an inability to retain essential plant nutrients. Large areas of cane growing soils in North Queensland have sub-optimal levels of plant available Si. Based on the soil test, some 85 per cent of soils that were evaluated in the six mill areas on the wet tropical coast have sub-optimal to marginal levels of available Si. Some of the main factors involved in the short term depletion of plant-available soil Si are (i) many tropical and subtropical rice soils (Alfisols, Ultisols, or Oxisols) are desilicated (weathered) to varying degrees and may therefore contain less sources of soil Si (ii) dissolution kinetics of soil Si are very slow and (iii) Si from soil solution is sorbed by sesquioxides that are present in many tropical soils in relatively large proportions.

A study on silica availability and dynamics in soils of rice fields, other land uses, and also in river and canal water in two watersheds in Citarum and Kaligarang, Java Island, Indonesia (Husnain et al., 2008) revealed that Si content in soils, plants and river water was influenced by parent material and land use. The available Si content in rice fields was found to be deficient at two sites and low at 10 sites out of 16 sites investigated in the Citarum watershed. In the Kaligarang watershed, no rice field site was classified as deficient and nine out of the 15 sites were determined to be low for rice plant growth. A survey of Si content in rice flag leaves in some selected rice fields showed that seven out of 12 samples had contents less than 125 g SiO<sub>2</sub> kg<sup>-1</sup>. In the Citarum watershed, type of land use influenced Si availability in the soils via a large amount of litter accumulation of pine trees in the case of pine plantations and acidification in the soils in the case of tea plantations and maize fields. In general Si content in river and canal water was higher in the Kaligarang watershed than in the Citarum watershed and this appears to be affected by the type of parent material. In addition to the type of parent material, Si depletion occurring in dams might also influenced the Si content in the lower stream of river or canal water in the Citarum watershed.

He (1993) determined available Si content in 64 paddy soil samples collected from Hunan province, South China. Results showed that the available Si content in paddy soil ranged from 26 to 256 mg SiO<sub>2</sub> Kg<sup>-1</sup>. It was estimated that 51.5 per cent of the total area of soils were Si deficient. By determining the available Si content of 410 paddy soil sample collected from China, Ma *et al.* (1993) found that 30 per cent of the areas of paddy soils were Si deficient with the available Si content of less than 100 mg SiO<sub>2</sub> kg<sup>-1</sup> and 50 per cent of those contained available Si less than 150 mg SiO<sub>2</sub> kg<sup>-1</sup>.

Cai *et al.* (1997) collected 179 upland and paddy rice soil samples in Southeast China to analyse their Si supplying power. The results showed that the available Si content extracted by 1M acetate buffer ranged from 6 to 450 mg SiO<sub>2</sub> kg<sup>-1</sup> with an avarage value of 82 mg SiO<sub>2</sub> kg<sup>-1</sup>. More importantly according to the critical value of Si deficiency, 80 per cent of upland and 84 per cent paddy soil samples tested were deficient in Si.

In Anhui province, out of 251 soil samples Si defieciency was established in about 54 per cent with 28 per cent of the samples having severe Si deficiency (Zeng, 1998). By analysing available Si content of 1818 surface soil samples collected from North China, Quan *et al.* (1999) reported that the available Si content deficient in 17.21 per cent of the soils.

The average available Si status of eight different soil types of Kerala (South India) as adjudged by four different extractants revealed that Si extracted by 0.025 M citric acid ranged between 250 to 1500 kg ha<sup>-1</sup> with an average of 700 kg ha<sup>-1</sup> (Nair and Aiyer, 1968). Nayar *et al.* (1982) reported that in 5 out of 9 soils (mostly belonging to red and laterite groups) studied, Si content ranged from 8 to 83 mg kg<sup>-1</sup> and considered to be highly deficient. Subramanian and Gopalaswamy (1991) reported that the plant available Si status of rice growing soils of Kanyakumari, Madurai, Chinnamannur of Tamilnadu were 29, 70 and 40 mg kg<sup>-1</sup>, respectively. The plant available soil Si (mean) extracted by 1N NaOAc (pH 4.0) in soils of Orissa and Andhra Pradesh were 139 and 278 mg kg<sup>-1</sup> respectively (Nayar *et al.*, 1982).

### 2.3 Silicon pools and biogeochemistry in soil

Soils are the main reactor of terrestrial biogeosystems in which chemical processes interact with biological processes. Vertical and lateral translocation as well as temporary or permanent immobilization processes operates at various scales, which lead to vary Si pools in soils.

Silicon pools can be subdivided into mineral and biogenic according to their origin. Mineral Si pools in soils consist of three major phases, which are (1) primary minerals inherited from parent material, (2) secondary minerals (crystalline phases) developed through soil formation mainly clay minerals and (3) secondary microcrystalline (autogenic quartz, Opal CT, chalcedony) to poorly ordered phases (Opal- A, imogolite, allophane) which are also a result of soil formation (Sommer *et al.*, 2006).

Among secondary Si minerals, imogolite and allophone are clay minerals as well as short range order minerals. These products of soil formation are poorly crystalline aluminosilicates with a high specific surface area and variable charge. Poorly ordered aluminosilicates are likely to occur in acid soils showing a molar Si:Al ratio of 0.5–1.0. Imogolite and proto-imogolite are mostly reported from podzols, whereas allophane occurs mainly in volcanic soils (Wada, 1989).

Silicates with low Al-content include crystobalite, secondary quartz, microcrystalline, as well as noncrystalline Si minerals. Crystobalite is a dominant mineral of volcanic rocks and commonly occurs in soils developed from these rocks. Crystobalite

has not been found in other soils. Only in diagenetic processes, opal-A converted to crystoballite and further transformed into secondary quartz. Secondary quartz can also originate from opal (abiotic) in cemented soil profiles (*i.e.*, duripan, Ortstein) or develops directly from siliceous gel (Drees *et al.*, 1989; Monger and Kelly, 2002). Silicon may also be precipitated from soil solution as almost pure and amorphous silica phases on mineral surfaces.

Biogenic Si pools in soils can be subdivided into phytogenic (including phytoliths), microbial and protozoic Si. In general, knowledge about size, properties, and transformation of these pools is very scarce for almost all soils. For bacterial and protozoic Si, only qualitative evidences proved that these pools exist in soils. Microorganisms influence Si transformations in soils by (1) decomposition of plant litter, which releases Si from tissues, roots, etc., and (2) active mineral dissolution, e.g., by fungi hyphae (Sommer *et al.*, 2006).

Cornellis *et al.* (2011) identified the components of the readily soluble Si pool in the Cambisol found below tree species, under homogeneous soil and climate conditions and studied the impact of Si recycling by tree species on the Si pools. The Si<sub>alk</sub> (extracted by alkali) concentration decreased from the humus layer to 15 cm depth and then slightly increased until a depth of 75 cm. Below 7.5cm, the Si<sub>alk</sub> content did not differ significantly between tree species and the Si<sub>ox</sub> (Oxalate extractable) content, increased significantly, mainly comprised of Si adsorbed onto amorphous Fe oxides. These results suggested that (a) tree species can impact the readily soluble Si content in the topsoil through different rates of Si uptake and phytolith restitution by the vegetation and (b) the soils readily soluble Si pool mainly comprised of phytoliths and adsorbed Si. In this study, the readily soluble Si pool is controlled by both the iron dynamics and Si biocycling.

Very little information exists on how land use affects amorphous silica (ASi) storage in soils. Clymans *et al.* (2011) quantified and compared total alkali-extracted (PSia) and easily soluble (PSie) Si pools at four sites along a gradient of anthropogenic disturbance in southern Sweden. Land use clearly affected the ASi pools and their distribution. Total PSia and PSie for a continuous forested site at Siggaboda Nature Reserve (66,900±22 800 kg SiO<sub>2</sub> ha<sup>-1</sup> and 952 ± 16 kg SiO<sub>2</sub> ha<sup>-1</sup>) were significantly higher than disturbed land use types from the Rashult Culture Reserve including arable land (28,800 ± 7200 kg SiO<sub>2</sub> ha<sup>-1</sup> and 239 ± 91 kg SiO<sub>2</sub> ha<sup>-1</sup>), pasture sites (27,300 ± 5980 kg SiO<sub>2</sub> ha<sup>-1</sup> and 370 ±129 kg SiO<sub>2</sub> ha<sup>-1</sup>) and grazed forest (23,600 ± 6,370 kg SiO<sub>2</sub> ha<sup>-1</sup> and 346 ± 123 kg SiO<sub>2</sub> ha<sup>-1</sup>). Vertical PSia and PSie profiles show significant (p <0.05) variation among the sites.

Phytogenic Si is the most active Si pool in the soil–plant system because of its great surface to volume ratio, amorphous structure and high water solubility. Klotzbucher *et al.* (2015) studied the forms and fluxes of Si in paddy fields and resulted Si storage in plants at harvest was  $0.73 \pm 0.12$  Mg ha<sup>-1</sup> (>78 % in straw) and not related to different Si forms in topsoils. Large stocks of carbonate-extractable Si (2–29 Mg ha<sup>-1</sup>) suggested an accumulation of 'phytoliths' (amorphous Si oxides in straw) in topsoil due to irrigation.

Acetate-extractable Si in topsoils hardly changed during plant growth, suggesting dSi and absorded Si was continuously contributed by irrigation and phytolith dissolution.

Phytoliths and clay minerals contribute mainly to the plant available Si in soil, which is released by chemical and biological processes. Alexandre *et al.* (1997) estimated the contribution of plants to the biogeochemical cycle of Si and related weathering processes in an equatorial rainforest ecosystem where the biologic turnover of Si was high (58 to 76 kg<sup>-1</sup>ha<sup>-1</sup>y<sup>-1</sup>). Phytoliths and organic matter had a similar distribution with depth in the soil profile. About 92 per cent biogenic silica input was rapidly recycled while about 8 per cent of the biogenic silica input supplied a stable pool of phytoliths, with a lower turnover. The precipitation of silica was observed at the base of the soil profile, indicating a local geochemical environment that was oversaturated with respect to amorphous silica. A balance in biogeochemical cycle of Si requires that the vegetation absorb dissolved Si released from weathering of minerals, which otherwise would be available for mineral neoformation or export from the profile towards regional drainages. Plant uptake of Si increases the chemical weathering rate without increasing the denudation rate. This study showed that the uptake, storage and release of Si by the vegetation have to be taken into account to describe dissolution of silicates in soil.

Role of sustained and intensive land use and human disturbance impacts on Si pool distribution in soils with similar climatological and bulk mineralogical characteristics (Vandevenne *et al.*, 2015). The land use impacts both biogenic and nonbiogenic Si pools. While biogenic Si strongly decreases along the land use change gradient (from forest to croplands), pedogenic silica fractions (e.g. pedogenic clays) increase in topsoils with a long duration of cultivation and soil disturbance. Study revealed that nonbiogenic Si pools might compensate for the loss of reactive biogenic silicon in temperate zones.

Aluminium hydroxides, iron oxides and carbonates play a major role in the interaction between the solid and dissolved Si pools in the soil (Struyf *et al.*, 2009). Silicon is chemically adsorbed at the surfaces of these secondary minerals. When Fe oxides are present, Si dynamics have been hypothesized to be influenced by redox processes. Reaeration of soils after periods of water-logging was observed to enhance DSi release from silicate minerals.

Gocke *et al.* (2013) investigated the contribution of various soil Si pools to Si uptake by wheat. Wheat was grown on Si free pellets mixed with one the following Si pools: quartz sand (crystalline), anorthite powder (crystalline), or silica gel (amorphous). Plant growth was best on anorthite and highest total Si contents in plant biomass were obtained with silica gel treatment compared to all other treatments with up to 26 mg g<sup>-1</sup> in aboveground biomass and upto 17 mg g<sup>-1</sup> in roots.

A study by Petra *et al.* (2010) on the distribution of biogenic Si in soil, suspended particles and sediment in samples from a small watershed in Southern Finland resulted that biogenic Si content in different parts of the watershed varied and biogenic Si produced by diatom algae in the aquatic part of the watershed appeared to be more

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important than the transformation of dissolved Si into phytoliths by terrestrial plants in the soil. More information on the variability of the biogenic Si (phytolith) content in different types of soil and on the differentiation between diatom and phytolith Si in waters are needed.

The weathering ability of silicate minerals, including phytoliths, depends on environmental factors such as temperature and pH as well as the physico-chemical characteristics of the minerals, which can be evaluated by thermodynamic and kinetic data (White and Brantely, 1995; Fraysse *et al.*, 2009).

During weathering and soil development, Si can be leached out, redistributed, or accumulated in soil. Quantitative analysis on losses and gains of Si during soil development are scarce. For most soils of humid climates, Si losses are reported. This process of "desilication" is well known for (sub) tropical climates (Lucas *et al.*, 1993; Paquet and Clauer, 1997; Stonestrom *et al.*, 1998). Here the rate of Si losses ranges from 20 to 400 mmol Si m<sup>-2</sup> y<sup>-1</sup> which equals 0.2-4 k mol Si m<sup>-2</sup> during Holocene pedogenesis. These numbers are much smaller compared to total desilication of older soils, e.g., 28-70 kmol Si m<sup>-2</sup> from Alfi-and Utisols developed on phyllite, granitic gneiss, and diabase in subtropical climate (Oh and Richerter, 2005) or 96 k mol m<sup>-2</sup> in a Ferralsol of an old craton (Brimhall *et al.*, 1991).

Chronosequence studies coupled with mass balances confirm the general trend of Si losses in freely draining soils of humid climates. Langley-Turnbough and Bockheim (1998) reported total Si losses of 2.3-15.4 k mol m<sup>-2</sup> during pedogenesis in their chronosequence of Inceptisols Spodosols-Ultisols on marine terraces. Similar total Si losses (0.3-19 k mol m<sup>-2</sup>) were observed by Brimhall *et al.* (1991) and Merritts *et al.* (1992) in their study of Mollisols – Inceptisols - Alfisols chronosequence. Ziegler *et al.* (2005) stated increased total Si losses with age in a chronosequence of Inceptisols - Andisols - Ultisols - Oxisols on Hawaiian basalts. However, due to atmospheric inputs of dust or lateral Si influx (Langely-Turnbaugh and Bockheim, 1998) showed Si accumulations in the chronosequences of few soils.

The relationship between the amount of available Si in paddy soils and their mineral properties on the Shounai Plain in Japan, which is formed from several parent materials, was evaluated by Makabe *et al.* (2009). The amount of available Si in the soil and the oxide content of the crystalline minerals differed among four soil groups that were distinguished by their clay mineral composition. There was no difference in the particle size distribution among the soil groups. The amount of available Si was positively related to the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio of clay, the CaO concentration of silt and fine sand, and the amounts of SiO, FeO and AlO in the soil and negatively correlated with the Na<sub>2</sub>O and K<sub>2</sub>O concentrations of silt, the K<sub>2</sub>O concentration of fine sand and the coarse sand content. These results suggested that the amount of available Si in soil was affected by the weathering resistivity of their minerals and that the particle size distribution and mineral composition were related to the available Si of the soils. Mineralogical properties, including the particle size distribution and mineral composition such as the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio, clay fraction content and the amounts of CaO and MgO in silt-sized

particles were positively correlated with the amount of available Si in the soil, but these correlations were not found for fine sand-sized particles. The SiO, FeO and SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio, clay fraction contents contributed approximately 50 per cent to the amount of available Si in the soils.

The reserve of weatherable primary silicates had a great influence on accumulation of biogenic silicon in volcanic ash soils (Henriet *et al.*, 2008). The mineralogical composition of soils was inferred from X-ray diffraction, elemental analysis and selective chemical/mineralogical extractions. With increasing weathering, the content of weatherable primary minerals decreased. Conversely, clay content increased and stable secondary minerals were increasingly dominant: gibbsite, Fe oxides, allophane, halloysite and kaolinite. The contents of biogenic Si in plant and soil were governed by the reserve of weatherable primary minerals. The largest concentrations of biogenic Si in plant ( $6.9 - 7.0 \text{ g kg}^{-1}$ ) and soil ( $50 - 58 \text{ g kg}^{-1}$ ) occurred in the least weathered soils, where total Si content was above 225 g kg<sup>-1</sup>. The lowest contents of biogenic Si in plant ( $2.8 - 4.3 \text{ g kg}^{-1}$ ) and soil ( $8 - 31 \text{ g kg}^{-1}$ ) occurred in the most weathered desilicated soils enriched with secondary oxides and clay minerals. So, data imply that weathering stage directly impacted the soil to plant transfer of silicon and thereby the stock of biogenic Si in a soil plant system involving a Si-accumulating plant.

The soil BSi (biogenic Si) pool can be substantial, particularly in the humid tropics  $(10 - 40 \text{ g kg}^{-1})$  and can be rapidly recycled (Alexandre *et al.*, 1997). The soil–plant Si cycle is significant in comparison with weathering input and hydrologic output, as most of the Si released to water streams can pass through the BSi pool (Derry *et al.*, 2005). The building-up of that pool would primarily depend on the availability of H<sub>4</sub>SiO<sub>4</sub> in the soil solution, which is controlled by silicate dissolution and clay formation in soil (Garrels, 1967; Kittrick, 1969), which both reflect soil constitution and weathering stage. The relationship between the soil mineral composition and Si soil-to-plant transfer was however poorly investigated though plant-BSi has been reported to vary depending on soil type (Schwandes *et al.*, 2001).

Soil itself contains various Si fractions, since weathering and mineral neoformation processes create a great variety of Si fractions in soils. They are developed from rocks or sediment sand and mainly composed of primary crystalline silicates such as quartz, feldspars, mica and secondary silicates, especially clay minerals (Iler, 1979; Conley *et al.*, 2005). They contain Si of biogenic origin *viz.*, phytoliths, diatoms and sponge spicules and pedogenic amorphous silica (Drees *et al.*, 1989). In addition, complexes of Si with Al, Fe, heavy metals and organic matter occur (Matichenkov and Bocharnikova, 2010; Farmer *et al.*, 2005). Silicic acid also dissolved in soil solution, some part adsorbed to soil minerals partially to iron and aluminium oxides/ hydroxides (Beckwith and Reeve, 1964; McKeague and Cline, 1962). Danilova *et al.* (2010) by sequential extraction on a soil catena in the black forest in Germany indicated that most of the Si (98 - 99 %) was bound in primary and secondary silicates. Inroganic materials such as quartz, clays, micas and feldspars although rich in Si, were poor Si fertilizer sources because of the low solubility of the Si (Gascho, 2001).

Drees *et al.*, (1989) reviewed that "soluble silica levels in soil are more likely controlled by kinetics than by thermodynamics". If this were to be the case, in the absence of leaching, Si in soil solution would increase linearly with time, as soil solution concentrations were far below equilibrium with feldspars and micas (Gerard *et al.*, 2002). However, some papers have reported equilibrium levels of Al and Si in 1:1 to 1:10 soil/solution systems. These studies indicated that at least in 1:1 and in some 1:10 systems, Si concentrations in Bs horizon soils approached equilibrium after 15 days, and thereafter increased little up to 35 days (Zysset *et al.*, 1999; Gustafsson *et al.*, 2001). Su *et al.* (1995) found no significant change in Si concentration over 2-6 months.

Acidification can lead to disintegration of clay minerals and release of Si. This phenomenon was observed in very acid soils, e.g., Podzols of temperate or boreal climates and acid topsoils of Luvisols (Veerhoff, 1992; Frank, 1993). Released Si might precipitate at mineral grain surfaces forming amorphous siliceous shells and covers, which have been observed by SEM-EDX (Veerhoff and Brummer, 1993). Silicon is also chemically adsorbed at surfaces of soil constituents, like carbonates, Al hydroxides, and Fe oxides (Beckwith and Reeve, 1964; Iler, 1979; Glasauer, 1995; Dietzel, 2002; 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 (Gallez *et al.*, 1977; Herbillion *et al.*, 1977).

Sorptions on to mineral surfaces were related to the amount, type, size, and crystallinity of Fe oxides and Al hydroxides. From formation as well as dissolution experiments of goethites and ferrihydrites, Glasauer (1995) hypothesized Si inclusions or clusters near the Fe oxide surface with specific Si-O-Fe bonds. Morphological properties as well as crystallinity of goethites and ferrihydrites were related to the Si concentrations and pH of solutions. He also 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, latter of which is the dominant species in soil solutions with pH < 8.

The properties of amorphous silica surface and the processes of dehydration (the removal of physically absorbed water), dehydroxylation (the removal of silanol groups from the silica surface), and rehydroxylation (the restoration of the hydroxyl covering) on the silica surface was described by Zhuravlev (2000). The results of experimental and theoretical studies lead to the formation of Zhuravlev model-1 and model-2 for describing the surface chemistry of amorphous silica.

Findings from the horizon and pedon scales, respectively, confirmed the importance of redox processes for Si dynamics, when Fe oxides are present. Ruckert (1992) observed an additional Si release during cyclic patterns of water-logging and drying in batch experiment. This phenomenon was explained as a result of H<sup>+</sup> production during oxidation of ferrous to ferric compounds and subsequent acid dissolution of clay minerals- a pedogenic process called "ferrolysis" (Brinkman, 1979). Experimental results confirmed an enhanced release of silicic acid following the oxidation of ferrous-silicate surface coatings, even in Fe-quartz systems (Morris and Fletcher, 1987). The Fe-Si-gels

synthesized in reductive environments were unstable under oxic conditions due to Fe oxidization (Fe<sup>2+</sup>  $\rightarrow$  Fe<sup>3+</sup>) and subsequent Fe oxide crystallization. Nevertheless, a comprehensive analysis of the phenomena observed is still missing (Sommer *et al.*, 2006).

### 2.4 Dissolution and bioavailability of different sources of silicon

#### 2.4.1 Dissolution of native and applied fertilizer silicon

Solubility and bioavailability of native soil Si or applied Si fertilizers mainly depends on the surface properties like pH, soil constituents and type of soil. Struyf *et al.* (2009) reported the influence of pH on the dissolution of silicates can be neglected in the range of pH 2.5 to 8.5. However, in strong alkaline conditions (pH>9), part of the Si monomers transforms to polymers and DSi concentrations in soil solution increased almost exponentially with pH as a result of growing speciation to  $H_3SiO_4^-$  and  $H_2SiO_4^{-2-}$ .

Fraysse *et al.* (2009) studied the surface chemistry and reactivity of plant phytoliths in aqueous solutions. The solubility product of larch, horsetail, elm and fern phytoliths were close to that of amorphous silica and soil bamboo phytoliths. Phytolith dissolution rates exhibit a minimum at pH 3. Mass normalized dissolution rates are similar among all four types of plant species studied and those rates were an order of magnitude higher than those of typical soil clay minerals.

Kato and Owa (1998) reported that at the early growth stage in the pot experiment, in some slag application treatments the Si concentration in the soil solution was lower than in the treatment without slag (control). Also, the Si concentration was negatively correlated with the Al/Si ratio (ratio of alkalinity to 0.5 M HCI-soluble SiO<sub>2</sub> content in the slags). These results were presumably due to increase in the soil ability to adsorb Si which was caused by increase in the soil solution pH. The continuous dissolution of the slags could also be depressed by increase in the pH and Ca concentration in the soil solution. On the other hand, in the treatment with cellulose and at the later growth stage in the pot experiment, the Si concentration in almost all the slag application treatments was higher than in the control.

It was considered that Si dissolution from the slags and/or the soil was enhanced by the neutralization effect of  $CO_2$  gas, which originated from the decomposition of cellulose (+cellulose) or respiration of the plant roots and microorganisms present in the rhizosphere (pot experiment) and by the decrease in Si and Ca concentrations in the soil solution caused by plant uptake and sampling loss. The Si uptake by rice plant measured at the maturing stage was positively correlated with the Si concentration in the soil solution which was sampled after the tillering stage, while no correlation was obtained when the soil solution was collected at the early growth stage. It was suggested that the soil ability to supply silicic acid continuously into the soil solution when Si was removed from the soil solution was more important parameter for a better estimation of available soil Si than the Si concentration in the soil solution at the beginning of cultivation. Theodre Chappex and Karen Scrivener (2012) reported that the main mechanism controlling ASR (alkali silica reaction) in blends was the alkali fixation capacity of silica rich C-S-H, which lowers the pH of the pore solution. Aluminium species, present in the pore solution are adsorbed on the silica surface and limit the dissolution of amorphous silica of the aggregates restricting ASR.

Masahiko Fuji and Fei Chai (2005) reported that biogenic silica ( $bSiO_2$ ) dissolution plays an important role in the marine silicon cycle, diatom production and vertical export production. Diatoms dominate with higher  $bSiO_2$  dissolution rates because of enhanced silicic acid supply for diatom production. Annual  $bSiO_2$  export does not change with  $bSiO_2$  dissolution rate because of less  $bSiO_2$  production with lower rates and greater  $bSiO_2$  dissolution with higher rates.

Wickramasinghe and Rowell (2006) reported that the soils (Alfisols and Ultisols) shaken with 0.1 M NaCl (5 g per 125 mL for 250 days) produced concentrations of 1- 4 mg L<sup>-1</sup> of monosilicic acid-Si. Amorphous silica added to these suspensions (36.5 mg, containing 17 mg Si) raised the concentrations to 20 - 40 mg L<sup>-1</sup> and added rice straw (0.5 g, containing 17 mg Si) gave 10 - 25 mg L<sup>-1</sup>. The rate of release from straw into solution without soil, the release of Si into soil suspensions was increased during the first 20 days by adsorption on the soil but was then reduced probably through the effect of Fe and Al on the phytolith surfaces. The extent of this blocking effect varied between soils and was not simply related to soil pH.

The Si concentration in a soil was controlled by the dissolution of the siliceous materials and by the sorption reactions between soluble silica and reactive soil materials, particularly the iron and aluminium oxides and hydroxides. Other anions and soil pH also influence the reactions (Obihara and Russell, 1972). Soils may contain both crystalline quartz (SiO<sub>2</sub>) and amorphous silica (SiO<sub>2</sub>·nH<sub>2</sub>O), together with opaline silica (SiO<sub>2</sub>·nH<sub>2</sub>O) from plant materials. Mica, feldspar and clay minerals also contain Si. Quartz is the least soluble of the silica minerals, giving 8 mg Si L<sup>-1</sup> when in equilibrium with water (Jones and Handreck, 1963; Sadiq *et al.*, 1980).

A saturated solution of amorphous silica has 56 - 65 mg Si  $L^{-1}$  as monosilicic acid, although initially the concentration may be greater than this, with the decrease to the equilibrium value reflecting polymerization in solution. Opaline silica behaves as amorphous silica, but in soil the phytoliths adsorb Fe and Al and form Fe and Al complexes which reduce their solubility to 10 - 15 mg  $L^{-1}$  (Jones and Handreck, 1963; Wilding *et al.*, 1979 and Bartoli, 1985).

The solubility of pure silica in water is independent of pH (Lindsay, 1979), but in soil, dissolution decreases with increasing pH up to 8 - 9 due to changes in adsorption and then rapidly increases due to the formation of silicate ions (Beckwith and Reeve, 1964). Temperature, redox conditions, other anions and organic matter content also influence dissolution. The Si dissolution from straw was slower than from amorphous silica presumably as a result of the protection of the silica by the plant matrix (Jones and Handreck, 1963) and as a result polymerization occurs later.
Two diatom frustule dissolution experiments were performed on material from Lakes Geneva and Nantua, SE France (Barker *et al.*, 1998). The dissolution of diatom silica from sediments was measured over a 92-day period in six 3 M salt solutions (NaCl, Na<sub>2</sub>CO<sub>3</sub>, KNO<sub>3</sub>, CaCl<sub>2</sub>, LiNO<sub>3</sub> and MgCl<sub>2</sub>) in 0.6 M NaCl and in distilled water. As expected, dissolution was greatest in Na<sub>2</sub>CO<sub>3</sub> where high pH leads to ionic dissociation. A similar process was also apparent in solutions of KNO<sub>3</sub>, and LiNO<sub>3</sub>, which were only slightly alkaline. In contrast, weakly acid solutions of MgCl and CaCl<sub>2</sub> produced were less dissolved than distilled water. Between 0.6 and 3 M NaCl, silica solubility appeared to reach an undetermined optimum which could correspond to minimum values of ion activity coefficients.

A solubility diagram was developed that shows the activity of various ionic and molecular species of Si in equilibrium with amorphous silica as a function of pH. Below pH 8.0 only uncharged Si (OH)<sub>4</sub> contributes significantly to total soluble Si. The solubility of Si was measured on two soils in which equilibrium was approached from both undersaturation and supersaturation over a 50-day period by Elghawary and Lindsay (1972). In this study, 0.02M CaCl<sub>2</sub> was included in all suspensions during their equilibration to flocculate colloidal Si and preclude its inclusion as soluble Si. The acid Paxton soil supported approximately 19 mg kg<sup>-1</sup> of Si in solution while the calcareous soil supported 25 mg kg<sup>-1</sup>. These levels are intermediate between the solubility of quartz (2.8 mg kg<sup>-1</sup> Si) and amorphous silica (51 mg kg<sup>-1</sup> Si) and lie very near the level predicted for equilibrium between kaolinite and montmorillonite.

Dissolution of amorphous silica as monosilicic acid and the establishment of solubility equilibrium with silica gel and colloidal silica have been demonstrated (Krauskopf, 1959). The rate of dissolution and precipitation were slow at normal temperatures. As the temperature increased both solubility and rates of dissolution were much higher. The solubility was hardly by pH between values of 1 and 9, but increased rapidly at pH over 9.

Xin *et al.* (2014) studied transformation and dissolution of Si from Si rich biochar. Biochar was prepared from rice straw at different pyrolysis temperature ranging from 150 °C to 700 °C. The released Si from biochar produced at low temperature increased linearly with dissolution time. On other hand those produced at high temperature released Si non linearly and sharply increased with dissolution time. In other words, silicon dissolving rate and quantity are connected to pyrolysis temperature, which leads to variation in pH, structure, Si form and other properties of biochar. Further, batch extraction studies were conducted to the continuous release of Si from rice straw derived biochar. The highest Si content was recorded at 30 days and then decreased for the biochar produced at higher temperature. While those produced at low temperature showed an increasing trend throughout study period.

Fraysse *et al.* (2006) studied the horsetail and pine litter degradation in acidic, neutral, and alkaline solution. Results revealed that the release of Si was fastest in basic condition and slowest in acidic condition. Both litter showed a higher Si content at 15

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days in alkaline solution and there after Si concentration decreased. On other hand in neutral and acidic solution dissolution continued till end of study period (60 days).

Monosilicic acid (H<sub>4</sub>SiO<sub>4</sub>), behaves as a very weak acid, and even in pH 7, only 2 mg kg<sup>-1</sup> are ionized acid as pH increases the degree of ionization increases (Jones and Handreck, 1963). Monosilicic acid concentration in soil solution is variable, from 1 to 100 mg dm<sup>-3</sup> SiO<sub>2</sub> (Raven, 2003) and depended on clay content (Raij & Camargo 1973), iron and aluminum oxides and pH (Jones & Handreck, 1963; Beckwith & Reeve, 1964). Among these factors, soil pH can be altered with liming materials, modifying the solubility of the monosilicic acid. This is important for rice, once maximum Si absorption occurs within the pH 4.7 to 7.6 (Cheong *et al.*, 1982).

Monomeric silicic acid (H4SiO<sub>4</sub>) dissociates into H<sup>+</sup> + H4SiO<sub>4</sub> above pH and into  $2H^+ + H_4SiO_4$  above pH 11. Oligomeric silicic acid is only stable at high concentrations of silcic acid at pH > 9 (Knight and Kinrade, 2001). It occurs in a transition stage during the dissolution of minerals, which under most natural conditions is only stable for a few hours or days, before it decomposes into mononeric silicic acid occurs (McKeague and Cline, 1962; Dietzel, 2000). Alkaline soils such as solonetzs and solonchalks also contain dissociated monomeric silicic acid.

The influence of four major dissolved solutes found in terrestrial and marine environment on the dissolution kinetics of quartz was quantified by Dove and Nix (1997). Dissolution rates are dependent upon the concentration and identity of alkali and alkaline earth cations in near neutral pH solutions. They determined the effect of alkaline earth cations upon quartz reactivity by measuring dissolution rates in 0.0001-0.2 molal solutions of MgCl<sub>2</sub>, CaCl<sub>2</sub>, BaCl<sub>2</sub>, LiCl, KCl and NaCl at near neutral pH. The results fit to first order rate law, where order: Mg<sup>2+</sup>< Ca<sup>2+</sup>  $\approx$  Li<sup>+</sup> Na<sup>+</sup>  $\approx$  K<sup>+</sup> < Ba<sup>2+</sup>. Alkali and alkaline earth cations indirectly enhanced dissolution rate of quartz modifying rates of solvent motion, exchange or orientation at the mineral solution interface. Rate enhancement was proportional to the concentration of ions at the surface and their salvation character.

A basic tenet of sediment diagenesis, the "Goldich Weathering Sequence" (Goldich, 1938), stated that the most unstable silicate mineral will weather (dissolve) first, with more resistant silicates taking progressively longer to dissolve (from least to most stable), olivine < plagioclase < albite < anorthoclase  $\approx$  microcline < quartz. Organic acid substances can influence feldspar dissolution rates either by decreasing pH, by forming frame work-destabilizing surface complexes or by complexing metals in solution. Many investigators have found that organic acids enhanced the dissolution of aluminosilicate minerals or quartz both in field observations and from laboratory experiments (Bennett *et al.*, 2001).

Welch and Ullman (1993) found that the rates of plagioclase dissolution in solutions containing organic acids were up to 10 times greater than the rates in solutions containing inorganic acids at the acidity. Steady-state rates of dissolution were highest (up to  $1.3 \times 10^{12} \text{ mol}^{-1} \text{ cm}^{-2} \text{ sec}^{-1}$ ) in acidic solutions (pH $\approx$ 3) and decreased (1 x 10<sup>-15</sup> mol

cm<sup>-2</sup> sec<sup>-1</sup>) as acidity decreased towards neutral pH. The polyfunctional acids like oxalic, citric, succinic and 2-ketoglutaric acids were the most effective at promoting dissolution.

High Si concentrations were measured in Histosols of fens or bogs. Komor (1994) observed Si concentrations ranged from 310 to 530  $\mu$ mol L<sup>-1</sup> in a calcareous fen without any trend in depth function. Bennett *et al.* (1991) reported that fen showed no trend in depth function, whereas an increase with depth by factor 5 was observed in the bog. Analyses on mineral phases showed an etching of silicate grain surfaces, including quartz. The authors concluded that organic acids dissolved the solid silicates.

Bennet *et al.* (1991) studied the influence of organic electrolytes on silica mobility, quartz solubility and quartz dissolution kinetics in organic rich aqueous systems. Results revealed that organic acids like citrate and oxalate accelerated quartz dissolution by decreasing the activation energy by approximately 20 per cent. The increase in dissolution rate was accompanied by a 100 per cent increase in apparent quartz solubility at 25°C. Experiments in using inorganic electrolytes, in contrast, increased the rate of quartz dissolution without decreasing the activation energy, and without increasing solubility. Dissolved organic compounds in natural waters at near-neutral pH and low temperatures were capable of accelerating the dissolution of quartz and increasing its solubility.

#### 2.4.2 Bioavailability of silicon

Silicon is taken up in the form of an uncharged molecule, silicic acid. Recent reviews reported that Si accumulation is, in general, higher in monocot than in non-monocot species (Epstein 1999; Richmond and Sussman, 2003). The difference in Si accumulation has been attributed to the ability of the roots to take up Si. Three different modes of Si uptake have been proposed for plants having different degrees of Si accumulation, which is active, passive and rejective uptake. Plants with an active mode of uptake take up Si faster than water, resulting in a depletion of Si in the uptake solution. Plants with a passive mode of uptake take up Si at a rate that is similar to the uptake rate of water; thus, no significant changes in the concentration of Si in the uptake solution are observed. By contrast, plants with a rejective mode of uptake tend to exclude Si, which is demonstrated by the increasing concentration of Si in the uptake solution (Takahashi *et al.*, 1990).

Liang *et al.* (2006) characterized Si uptake and xylem loading in rice, maize, sunflower (*Helianthus annuus*) and ash gourd (*Benincase hispida*) in a series of hydroponic experiments. Both active and passive Si-uptake components co-exist in all the plants tested. The active component was the major mechanism responsible for Si uptake in rice and maize. By contrast, passive uptake prevails in sunflower and ash gourd at a higher external Si concentration (0.85 mM), while the active component constantly exists and contributed to the total Si uptake, especially at a lower external Si concentration (0.85 mM). Silicon accumulation into various plant organs varied among rice genotypes (Winslow *et al.*, 1997). Different parts of the same plant can show large differences in Si accumulation. In rice, this variation can be seen from 0.5 g kg<sup>-1</sup> in polished rice, 50 g kg<sup>-1</sup>

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in rice bran, 130 g kg<sup>-1</sup> in rice straw, 230 g kg<sup>-1</sup> in rice hulls to 350 g kg<sup>-1</sup> in rice joints (found at the base of the grain) (Van Hoest, 2006).

Hodson and Sangster (1988) observed that in case of wheat, Si compounds predominantly deposited in the epidermal cells of the abaxial side of the leaves, while in older leaves incorporated Si compounds are on the adaxial side as well. Mecfel *et al.* (2007) reported significant Si contents in the cell walls suggesting that the enrichment with Si compounds was due to an accumulation of Si within regions that are rich in matrix materials like hemicelluloses and pectins.

Despite an abundance of studies on the site and shape of silica depositions within plants, no molecular mechanism for this deposition has been characterized. Depositions of opal occur throughout the plant in cell walls, cell lumens, tricombs, intracellular spaces, roots, leaves, and reproductive organs. Silica depositions primarily occur through evapotranspiration (Motomura, 2002), a hypothesis based on the fact that the common locations of opal coincide with major evapotranspiration sites. There is, however, some evidence that plant macromolecules participate in forming an organic matrix for silica deposition (Inanaga *et al.*, 1995). Such molecules have already been identified in other organisms that deposit silica (Kroger *et al.*, 2002).

Camargo *et al.* (2013) evaluated the silicon availability, uptake and recovery index of Si from the applied silicate in tropical soils with and without silicate fertilization, in three crops. The experiments in pots (100 L) were performed with specific Si rates (0, 185, 370 and 555 kg ha<sup>-1</sup> Si), three soils (Quartzipsamment-Q, 6 % clay; Rhodic hapludox-RH, 22 % clay; and Rhodic Acrudox-RA, 68 % clay) with four replications. The silicon source was Ca-Mg silicate. The silicon rates increased soil Si availability and Si uptake by sugarcane and had a strong residual effect. The contents of soluble Si were reduced by harvesting and increased with silicate application in the following decreasing order: Q>RH>RA. The silicate rates promoted an increase in soluble acetic acid-Si at harvest for all crops and in all soils, except RA. The amounts of CaCl<sub>2</sub>-Si were not influenced by silicate in the ratoon crops. The plant Si uptake increased according to the Si rates and was highest in RA at all harvests. The recovery index of applied Si of sugarcane increased over time and was highest in RA.

Increasing Si availability in the soil resulted in increased Si uptake by plants by the application of rice straw. Silicon uptake was limited by Si availability in soil. This increase was averaged to 28 per cent (addition of 0.4 Mg Si ha<sup>-1</sup>) and 120 per cent (addition of 17.3 Mg Si ha<sup>-1</sup>) compared to the control, respectively. Likewise, Si concentrations in rice hulls increased by 34 per cent (0.4 Mg Si ha<sup>-1</sup>) and 72 per cent (17.3 Mg Si ha<sup>-1</sup>), respectively. Silicon concentration in rice grains was  $\leq 0.1$  in all treatments. Total Si uptake by rice shoots (including straw, hulls and grains) increased by 37 per cent (application of 0.4 Mg Si ha<sup>-1</sup>) and 126 per cent (application of 17.3 Mg Si ha<sup>-1</sup>) compared to control (Marxen *et al.*, 2016). Phytoliths from fresh rice straw dissolve fast in soil thus recycling of rice straw is an important source of plant-available Si.

Martina et al. (2013) elucidated the contribution of various soil Si pools to Si uptake by wheat. As pH affects dissolution of Si pools and Si uptake by plants, the effect of pH (4.5 and 7) was evaluated. Wheat was grown on Si-free pellets mixed with one of the following Si pools: quartz sand (crystalline), anorthite powder (crystalline), or silica gel (amorphous). Silicon content was measured in aboveground biomass, roots and soil solution 4 times in intervals of 7 day. At pH 4.5, plants grew best on anorthite, but pH did not significantly affect Si-uptake rates. Total Si contents in plant biomass were significantly higher in the silica-gel treatment compared to all other treatments, with up to 26 mg  $g^{-1}$  in above ground biomass and up to 17 mg  $g^{-1}$  in roots. Thus, Si uptake depends on the conversion of Si into plant-available silicic acid. This conversion occurs too slowly for crystalline Si phases, therefore Si uptake from treatments with quartz sand and anorthite did not differ from the control. For plants grown on silica gel, real Si-uptake rates were higher than the theoretical value calculated based on water transpiration. This implies that Si uptake by wheat was driven not only by passive water flux but also by active transporters, depending on Si concentration in the aqueous phase, thus on type of Si pool. These results showed that Si uptake by plants as well as plant growth is significantly affected by the type of Si pool and factors controlling its solubility.

Ma *et al.* (2003) noticed genotypic variation in Si concentration in barley grain. The Si concentration was much lower in hull-less barley than in hulled barley. The Si concentration of two-row barley was similar to that of six-row barley, suggesting that Si concentration was not affected by the number of spike rows. Si concentration also did not differ with the origin of the barley variety. More than 80 per cent of total Si was localized in the hull. The Si concentration of the hull was between 15343 and 27089 mg kg<sup>-1</sup> in the varieties tested. A close correlation was obtained between the Si concentrations of barley grains harvested in different years, suggesting that the variation in Si concentration of barley.

Wheat plants were grown under identical growing conditions, but subjected to fertilization with various Si compounds (pyrolitic fine silica particles [aerosil], sodium silicate, silica gel), and the Si content of the above ground plants was analyzed *via* X-ray microanalysis (EDX) and atomic absorption spectroscopy (AAS). Silicon was predominantly deposited in the epidermis cells of the leaves and their cell walls. The efficiency of the Si compounds used as fertilizers to augment the Si content of the plants increased in the order sodium silicate > silica gel > aerosil and thus seemed to correlate with the ease of formation of orthosilicic acid from these compounds (Joanna *et al.*, 2007).

It was reported that rice, cucumber, and tomato contained 7.3, 2.3, and 0.2 per cent Si in the dry shoot respectively, when they were grown under similar conditions. When the plants were exposed to a solution containing the same Si concentration under the same conditions, the uptake of Si by rice was much higher than that by the other two species at each time point. Si uptake by cucumber was also higher than that by tomato. At 24 hour, the Si uptake by rice was about 6-fold and 12-fold higher than cucumber and tomato, respectively. The Si concentration in the uptake solution for rice decreased markedly with time, but remained constant for cucumber and increased slightly for

tomato. No significant difference was observed in the transpiration rate between the three species (Mitani *et al.*, 2005).

Phytoliths are silica deposits that retain genus or species specific morphological characteristics in higher plants. Recently, phytoliths have received increased attention because of the application of phytolith analysis in archeological research. Unique and specific deposits have been noted in Equisitaceae (horsetails), Coniferophyta (gymnosperms) and Magnoliophyta (angiosperms; including monocots and dicots) (Sangster *et al.*, 2001).

Work by Piperno *et al.* (2002) and Dorweiler and Doebley (1997) examined the genetic basis of silica deposition. In the dicot Cucurbita, phytolith deposition was correlated with the presence of a mutant locus called hard rind (Hr); whereas in the monocot maize, phytolith deposition appeared to be linked to the teosinte glume architecture1 locus. In both plant species, silification appeared to be linked to loci that are involved in lignification. However, silicic acid has a strong affinity to the organic polyhydroxyl compounds, which participate in the synthesis of lignin.

Pereira *et al.* (2004) evaluated the silicon sources in relation to agronomic efficiency and economic viability in rice crops. Silicon was applied at the rate of 125 kg Si ha<sup>-1</sup>. Data were compared to a standard response curve for Si using the standard source wollastonite at rates of 0, 125, 250, 375 and 500 kg Si ha<sup>-1</sup>. Wollastonite had linear response, increasing Si in the soil and plants with increasing application rates. Differences between silicon sources in relation to Si uptake were observed. Phosphate slag provided the highest Si uptake, followed by Wollastonite and electric furnace silicates which however, did not show differences among themselves. The highest Si accumulation in grain was observed for stainless steel slag, which significantly differed from the control, silicate clay, Wollastonite, and AF2 (blast furnace of the company 2) slag. Silicate clay showed the lowest Si accumulation in grain and did not differ from the control, AF2 slag, AF1 slag schist ash, schist and LD4 (furnace steel type LD of the company 4) slag.

Tavakkoli *et al.* (2011) studied the response of rice to Si fertilization in two variably weathered basalt soils adjusted at different pH values (5.5-9.5) with three levels of acidulated wollastonite. Greater biomass was observed at lower pH due to decreased Si sorption and higher solution Si concentrations suggesting a relationship between Si speciation and uptake. In contrast Si uptake and rice shoot dry matter in the less weathered grey vertisols were unaffected by Si fertilization. Solution Si concentration were controlled by precipitation/ polymerization reactions in equilibrium with specific soil pH values rather than adsorption processes.

Sarto *et al.* (2014) reported significant increase in the concentration of Si in the shoots of wheat plant in both stem and leaves with the application of calcium silicate @ 9.6 Mg ha<sup>-1</sup> which indicated reactive and effectiveness of source used in providing Si to soil and plant. The effects of slag silicate fertilizer (SSF) application on the Si concentration in rice plants were investigated by Sasaki *et al.* (2014). The Si

concentration in the shoot and aboveground parts of the rice plants significantly increased by the SSF application in six or more of the fields at two growth stages. Results showed a significant effect on the difference in the Si concentration of rice tissues between treatments in the shoots and above ground parts.

#### 2.5 Dissolved silicon in soil – plant system

Silicon fluxes in soils and terrestrial biogeosystems are mainly mediated through water. Silicic acid (H<sub>4</sub>SiO<sub>4</sub>) is the main component of soil solutions, mostly as monomeric silicic acid (Iler, 1979; Drees *et al.*, 1989; Dove, 1995). Monomeric silicic acid can be transformed into polymeric silicic acid under strongly alkaline conditions (Dietzel, 2000, 2002). Polymeric silicic acid is composed of two or more Si atoms and may occur in different forms, *e.g.*, chains, branching forms, or spherical clusters. Riise *et al.* (2000) separated soil solutions of a Podzol with ultramembrane-filtration techniques. They found more than 90 per cent of Si to be in the smallest-size fraction (<1 kDa).

The concentration of Si in soil solution depends on the solubility of primary and secondary Si compounds in soils. Solubility is a function of temperature, particle size, chemical composition (accessory elements) and the presence of disrupted surface layers (Drees *et al.*, 1989). Quartz has a solubility of 36 to 250  $\mu$ mol L<sup>-1</sup> in water depending on particle size and temperature (Iler, 1979; Bartoli and Wilding, 1980; Dove, 1995). Due to surface coatings on quartz grains (Fe oxides, organic matter), the lower value is more realistic for quartz in soils. Somewhat higher solubility can be observed for biogenic opal (20 to 360  $\mu$ mol L<sup>-1</sup>). Synthetic amorphous silica shows a much higher solubility (1800 to 2100  $\mu$ mol L<sup>-1</sup>). The solubility of amorphous silica and crystalline SiO<sub>2</sub> is also influenced by soil pH, but essentially constant between pH 2.5 and 8.5.

*In-situ* measured Si concentrations of soil solutions ranged from 0.4 to 2000  $\mu$ mol L<sup>-1</sup> (Schwer, 1994; Riise *et al.*, 2000). However, most values lie between 100 and 500  $\mu$ mol L<sup>-1</sup>, which is somewhat higher compared to groundwater or surface waters (150 to 180  $\mu$ mol L<sup>-1</sup>) and oceans (approx. 70  $\mu$ mol L<sup>-1</sup>) (Treguer *et al.*, 1995). Most important factors for Si concentrations in soil solutions seem to be parent material (notably content of weatherable minerals), stage of soil development, temperature (seasonal effects) and residence time of pore water.

The main determinant of concentration of Si in soil solution is the solubility of primary and secondary minerals. Si concentration in soil solution has been reported from 0.01 to 2.0 mM but is commonly in the range of 0.1 to 0.6mm. In general Si concentration in soil solution decreases with increasing soil development, as a result the soluble Si content of tropical soils is generally 5-10 times less than that of most temperate soils. A large group of soils in a region of a country surveyed there was generally a positive relationship between pH and Si solubility and extractability (Miles *et al.*, 2014).

Details of the speciation of silica in soils were provided by Lindsay (1979). At a lower pH, silicic acid (H<sub>4</sub>SiO<sub>4</sub>) is more soluble and less likely to dissociate. Dissolved silicic acid in soil solutions occurs as monomeric or oligomeric silicic acid (Iler, 1979).

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Silicic acid (H<sub>4</sub>SiO<sub>4</sub>) is in equilibrium with soil SiO<sub>2</sub> at pH 3.1. H<sub>4</sub>SiO<sub>4</sub> is in equilibrium with silicate ions that polymerize at pH 9.71, at a concentration of 0.794 mM. A 1 mM solution of H<sub>4</sub>SiO<sub>4</sub> would dissociate into 0.999 mM H<sub>4</sub>SiO<sub>4</sub> and 0.0001 mM H<sub>3</sub>SiO<sub>4</sub> at pH 6. The same solution would dissociate into 0.404 mM H<sub>4</sub>SiO<sub>4</sub> and 0.596 mM H<sub>3</sub>SiO<sub>4</sub> at pH10.

Gerard *et al.* (2002) showed capillary water (600 kPa) of a Cambisol from volcanic tuff to be higher in silicic acid concentration compared to free percolating soil water. Both showed distinct seasonal dynamics with maximum values (185 to 240  $\mu$ mol L<sup>-1</sup>) in capillary water during summer and minimum values during winter time (150 to 200  $\mu$ mol L<sup>-1</sup>). Free percolating water behaved just in the opposite way. The differences were higher in topsoils compared to subsoil horizons.

Sommer (2002) compiled data from various studies on acid soils in base-poor catchments of the Black Forest (SW Germany). Here, *in-situ* measured Si concentrations of soil solutions in and near Fe-rich redoximorphic soils and horizons were higher compared to non-redoximorphic ones. These data confirmed the importance of redox reactions involving Fe oxides for Si concentrations in soil solutions.

Gerard *et al.* (2003) revealed the evidence of surface-controlled and protonpromoted chemical weathering of primary silicates in a brown acidic soil. Aqueous silica (Si) in soil solutions held at high matric potential (180 to 1600 kPa) are representative of solutions reacting with soil solids. Si concentration was well correlated with H<sup>+</sup> concentration and to a lesser extent with dissolved organic carbon (DOC), which showed a significant affect (P < 0.05) only in the surface layer (0 to 15 cm). Significant negative linear relationships were obtained between log (Si) and pH at the profile scale, at each soil depth and for most sampling dates.

Prasanta and Neue (2009) studied the dynamics of water soluble silica [Si (OH)<sub>4</sub>] in relation to changes in pH, redox potential (Eh), water soluble iron and phosphorus in two Alfisol and Ultisol soils, under intermittent dried and reflooded conditions and their effect on growth and yield of rice. Soil reduction due to flooding increased the soil solution  $Fe^{2+}$  concentration which in turn increased concentration of [Si (OH)<sub>4</sub>] and H<sub>2</sub>PO<sub>4</sub><sup>-</sup>. Grain yield of rice was significantly positively correlated with soil solution Si, P and Fe concentration. While concentrations of Si and P in rice plants during vegetative growth stage significantly influenced rice grain yield but Fe did not. Concentration of P in rice shoots during vegetative growth period was significantly influenced by Si concentration of rice at that stage.

Freshly precipitated hydroxides of polyvalent metal ions were most effective and in some soils iron oxides are moderately effective in adsorbing the dissolved silica (McKeague and Cline, 1962). The adsorption of Si increases throughout the reaction range from 4 to 9 with ferruginous and adsorption decreased after pH 10.

Sasaki *et al.* (2014) evaluated soil factors associated with the effects of slag silicate fertilizer (SSF) application on Si supply in soil solution. Nine Gleysols with a wide range of chemical properties were incubated with (+Fertilizer) or without (-Fertilizer) SSF for 71 days under submerged conditions. The percentage of dissolved Si from 0.5N hydrochloric acid soluble Si in the SSF varied from 15 to 67 per cent among different soils, suggesting that the effect of SSF on Si supply in the soil solution varied among Gleysols. Dissolved Si was negatively correlated with the mean soil solution pH (P < 0.001) and Ca concentration (P < 0.05) for +Fertilizer samples during the incubation experiment, soil pH after incubation under submerged conditions (P < 0.001), soil Si adsorption capacity (P < 0.001), acid oxalate extractable iron (P < 0.001) and acid oxalate extractable manganese (P < 0.005), and indicators of soil Si availability (P < 0.05). These results suggested that the effects of SSF on Si supply in solution were affected by Si dissolution from the applied SSF and the Si adsorption capacity of the soil.

Polysilicic acids are an integral component of the soil solution. They mainly affect soil physical properties. The mechanism of polysilicic acid formation is not clearly understood. Unlike monosilicic acid, polysilicic acid is chemically inert and basically acts as an adsorbent, forming colloidal particles (Hodson and evans, 1995). Polysilicic acids are readily sorbed by minerals and form siloxane bridges (Chadwick *et al.*, 1987). Since polysilicic acids are highly water saturated, they may have effect on the soil water-holding capacity. Polysilicic acids have been found to be important for the formation of soil structure (Matichenkov *et al.*, 1995).

It is given that leaching and capillary solutions have different residence times, different processes may control the amount of dissolved Si, basically capillary solutions are almost immobile, whereas leaching solutions flow through the soil and thus have a much shorter residence time. Therefore, Si concentration in capillary solutions may better reflect interactions (Marques *et al.*, 1996).

Gerard *et al.* (2008) investigated the biogeochemical cycling of silicon (Si) in an acidic brown soil covered by a coniferous forest with respect to biomass data and Siconcentrations in capillary solutions, which were collected monthly over several years by means of suction-cup lysimeters placed at different soil depths. Mass balance calculations indicate that an average of 60 per cent of the biogeochemical cycle of Si was controlled by biological processes (Si-uptake and dissolution of phytoliths). Sensitivity analyses suggest that no more than 55 per cent of the Si-cycle is controlled by weathering of primary silicates. Such a large contribution of biological turnover to Si-cycling may be explained by the combined effects of a relatively large Si-content in the litter fall (specifically in the needles) and high biomass productivity of the coniferous species considered.

A silicon isotope composition of dissolved silicon and suspended matter in the Yangtze River, China was studied by Ding *et al.* (2003). Dissolved silicon tends to decreased from the upper reaches to the lower reaches, with maximum values at Yichang (YZ-08) and Jiujiang (YZ-13). The DSi value in riverine water was controlled by many factors: a) the amount and silicon arriving from upstream and from nearby tributaries; b)

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decomposition of silicon bearing minerals (feldspars, micas and other silicates); c) precipitation of silicon bearing minerals (opal and clay minerals), and d) evaporation of water from the river and addition of meteoric water into the river.

The integration of many studies on the concentration and flux of Si in European forest soils evidenced that phytoliths must be the principal immediate source and sink of silica in soil solution, although mineral weathering is the ultimate source. During the growing season, forest vegetation takes up most of the Si made available by weathering of soil minerals and by phytolith dissolution and converts it into phytoliths. Phytoliths are the principal source of Si leached from the soil during winter rains and spring snowmelt (Farmer *et al.*, 2005). Concentrations of Si observed in laboratory equilibrations of Bs horizon soils, for the maximum Si concentration reported for B horizons in the field, for a deep sink for Si in Bs horizons, and for the fact that the concentrations of Si in soil drainage water and in streams all fall in, or below, the range expected for phytolith solubility. Concentrations of Si in surface horizons can exceed these levels during droughts. The common assumption that the concentration of Si in soil solution is a result of a dynamic balance between Si released by mineral weathering and that lost by leaching is untenable for Bs horizons.

Dissolved reactive silicon was measured at weekly intervals over a 3 year period (1991-94) on a 1.2km reach of a gauged Dorset Mill Stream (House et al., 2000). The results were analysed using a mass balance approach with the loss and gains in nutrients dissolved in the water expressed in terms of areal rates. The residual load data indicate a net loss of dissolved silicon from the stream water from May 1991 to the end of November 1992. The relatively low winterflows in 1991 did lead to periods when the water gained dissolved silicon that coincide with peaks in the stream discharge i.e. when the gradient in the residual load line became positive. However, the major storms in the winter of 1992 led to large gains in silicon during passage through the reach as the streambed was scoured and sediment porewaters entrained in the flow. This was not matched in the following winter, presumably because of the scouring of dissolved silicon from accumulated sediment porewater in the previous year. The growth of benthic diatoms in the stream, combined with low riverflows, lead to the removal of silicon from the water and the accumulation of fine sediments containing diatoms. The subsequent decay of frustules in the sediments leads to relatively high concentrations of silicon in the porewater and diffusion of silicon to the overlying water or biofilm. During highdischarge conditions, sediments are mobilised and the porewater silicon released into the water. The results also show that there are times during higher water discharge when silicon is mobilised within the reach, although the magnitude of this effect depends on the antecedent conditions, i.e. the degree of accumulation of diatomaceous material in the streambed and dissolution of frustules and silicates in sediment.

Conley (1997) studied biological uptake of dissolved silicate (DSi) and formation of biogenic silica (BSi) during diatom growth modifies the form of Si carried from the continents to the world ocean. Significant concentrations of BSi, averaging 28.0  $\mu$ mol L<sup>-1</sup>, are found in all sizes of rivers. The global contribution of BSi carried by rivers was estimated as 1.05 ± 0.20 T mol Si year<sup>-1</sup>. Combined with the global mean riverine DSi

concentration of 150  $\mu$ mol L<sup>-1</sup>, 16 per cent of the gross riverine Si load was delivered to the ocean as BSi. Most of this BSi would be remobilized by dissolution in marine environments. These results demonstrate that the contribution of biogenic silica carried in suspension by rivers is an important component in the world ocean Si budget.

Husnain *et al.* (2010) assessed the nutrient balance under intensive rice-farming systems, and its effects on the sustainability of rice production in Java Island, Indonesia. Silica was mainly derived from irrigation water and the large amount of Si removed through harvest resulted in a deficit of Si in rice soils. The loss of silica through harvest was more than double that of the other major nutrients, including N, P and K. This deficit implies that the enormous amount of Si removed during rice harvest cannot be replenished by a natural Si source such as geological fertilization alone.

In the Broadbalk experiment, a decrease over time in ASi in the topsoil samples is in good agreement with the hypothesis that cropping and exports of straw leads to depletion of soil phytoliths (Guntzer *et al.*, 2012). A decrease in Si concentration in straw samples was observed between 1883 and 1944. From 1944 to the present, Si concentration increased irregularly in the straw, probably as the result of liming, which enhanced the dissolution of the remaining phytoliths through increasing pH. In the reforested Geescroft field, the higher phytolith concentration in the modern topsoil samples was in good agreement with a re-building of phytolith storage from litter input in an acidic environment.

A silica transfers in rice field of Camarague, France was studied by Despalnques *et al.* (2006). The budget of the dissolved silicon (DSi) fluxes given the following results: the atmospheric and irrigation inputs represent 1 per cent and roughly 10 per cent, respectively, of the annual need for rice; the drainage and infiltration outputs represent 17  $\pm$  14 and 12  $\pm$  9 kg Si ha<sup>-1</sup> year<sup>-1</sup>, respectively; the balance of budget shows that at least 170 kg Si ha<sup>-1</sup> year<sup>-1</sup> are exported from the soil. By considering the soil BSi as the only source of dissolved silicon, this stock could be exhausted in 5 years.

Ma and Takahashi (1989) analyzed the release of Si from rice straw under flooded condition by measuring the concentration of silicon in the percolating water. Addition of straw increased the Si concentration in the percolating water by 1.5 to 2 times compared with the control, suggesting the Si in the straw was gradually released. Only about 10 per cent of the Si contained in the straw was released over a study period of 60 days. The small amount of Si released suggested that only low molecular forms of Si in the + Si straw were dissolved while most of the silica gel remained in the soil. The amount of Si released from two sources: from the Si contained in the straw, and from the soil Si liberated by straw decomposition. Similarly, Yoshida *et al.* (1962) indicated that less than 10 per cent of Si in the rice plant present in the form of silicate ion and colloidal silicic acid and 90 per cent or more in the form of silica gel.

Seyfferth *et al.* (2013) monitored seasonal trends of Si in pore-water, plants and soil over a two-year period in rice cropping system where straw was incorporated into the soil during the fallow season. There was a seasonal trend of high pore-water Si

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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. The seasonal change in Ge/Si ratios from low values during the winter fallow to high values (up to 36  $\mu$ mol mol<sup>-1</sup>) during the growing season was due to a greater change in Si concentrations rather than Ge concentrations. These data indicate a low- [Ge], high-[Si] source of Si during the winter fallow, which may be due to incorporation of rice straw (a low-[Ge], high-[Si] source) and subsequent phytolith dissolution. The incorporation of high-[Si] plant material (e.g. straw) released additional Si to soil pore-waters that was available for plant-uptake during the growing season.

A study on soil nutrient balance is essential to ascertain the future sustainability of soil fertility and continued rice farming. This can be conducted by applying a direct measurement approach or through a literature survey. A simplified calculation to determine nutrient balance would be valuable not only for monitoring purposes but also for farmers to gauge the appropriate application of fertilizer.

### **III MATERIAL AND METHODS**

Rice is a silicon accumulating plant. The beneficial role of Si in rice plant in imparting both biotic and abiotic stress resistance and enhancing productivity is highly emphasized in literature. Studies on the Si dynamics and biogeochemistry in rice are lacking. The present investigation was undertaken to understand the "Biogeochemistry of silicon in different rice ecosystems of Karnataka".

In this investigation, soil samples were collected from rice ecosystems which comprise of different agro climatic zones of Karnataka. The field experiment was conducted at V. C. Farm, Mandya to assess the budgeting of silicon in wetland rice system. A pot culture experiment was conducted using acidic, neutral and alkaline soil collected from different locations at the Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bangalore. The details of the soil sampling, field and pot experiment and the laboratory analytical techniques followed for soil and plant sample analysis, as well as the statistical methods adopted in the present investigation are presented in this chapter.

# **3.1** Assessment of silicon status and their relationship with physico-chemical properties of rice soils of different agro climatic zones of Karnataka.

#### 3.1.1 Soil sampling

To assess the silicon status surface soil samples were collected from different agro climatic zones (ACZ) of Karnataka. Based on the rainfall pattern, topography, soil characteristics and climate in general and cropping patterns, Karnataka state has been divided into ten distinct agro-climatic zones. The ten agro climatic zones of the state are North-eastern transition zone, North-eastern dry zone, Northern dry zone, Central dry zone, Eastern dry zone, Southern dry zone, Southern transition zone, Northern transition zone, Hilly zone and coastal zone (Plate 1). Out of ten zones, soil samples were collected from nine ACZ except from north eastern transition zone and the list of ACZ is given in Table 1.

Totally 200 soil samples (Plate 2) were collected based on the availability and area of rice growing ecosystems in each ACZ by recording geographical location (Latitude and longitude) and altitude for each samples using GPS (Global Positioning System). The number of samples collected varied for each zone and the details are presented in Table 1. Basic information such as district, taluk, village and cropping system regarding locations were also recorded and presented in Annexure 1.

| Sl. No. | ACZ Number | Name                     | No. of samples |
|---------|------------|--------------------------|----------------|
| 1.      | II         | North Eastern Dry zone   | 23             |
| 2.      | III        | Northern Dry zone        | 19             |
| 3.      | IV         | Central dry zone         | 16             |
| 4.      | V          | Eastern dry zone         | 17             |
| 5.      | VI         | Southern dry zone        | 41             |
| 6.      | VII        | Southern transition zone | 20             |
| 7.      | VIII       | Northern transition zone | 11             |
| 8.      | IX         | Hilly zone               | 34             |
| 9.      | Х          | Coastal zone             | 19             |

 Table 1: List of agro climatic zones selected for soil sampling and number of samples collected from each zone

Approximately 12 - 15 sub samples were collected from each sampling location by using screw auger and mixed thoroughly to take representative sample. Each representative soil samples filled into a plastic zip lock cover bag separately to avoid the contamination of the samples. Soil samples were shade dried, powdered and sieved through 2mm mesh size sieve and stored in plastic container bottles for further use (Plate 3).

Initially, 200 soil samples were analysed for pH, EC, cation exchange capacity particle size distribution, 0.01M CaCl<sub>2</sub> extractable silicon and 0.5M acetic acid extractable silicon (Annexure II) by using standard procedure given in Table 3. Out of 200 samples, 40 representative samples from nine ACZ with varied pH (acidic, neutral and alkaline) and silicon content were selected for extensive studies such as X-Ray Diffraction (XRD), total elemental analysis by using Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) and organic carbon. Number of samples selected for extensive studies varied according to total number of samples from each zone and details are given in Annexure III.

### 3.1.2 X- Ray diffraction analysis

Mineralogical composition of soil clay fractions was measured using Philips MPD 3710 (Cobalt anti–cathode) X-ray diffractometer at CEREGE, Aix-en Provence, France.

The soil samples were ground to fine powder by using pestle and mortar and stored in plastic container for further use. Mineralogical properties were studied by two methods:



Plate 1: Agro climatic zones of Karnataka



Plate 2: Soil sampling location in different agro climatic zones of Karnataka



Plate 3: Sampling of soil from rice fields of different agro climatic zones of Karnataka

- 1) Powder diffraction for bulk soil samples
- 2) Separation of clay fractions for identifying the secondary clay minerals

#### **3.1.2.1** Powder diffraction for bulk soil samples

The finely powdered soil sample was put into well of the sample holder, tapped gently on the bench to help fill and pack to avoid sample displacement which causes peak shifts and pressed flat. Using a sharp razor, the sample surface was smeared slowly in all directions to prevent distorted orientation, and then leveling was continued while gently removing excess sample powder by scrapping off from the edges of the well of the sample holder. It is very important to have the correct sample level on the well surface since any error in the height of the sample will cause peak displacement. The samples were later run on the diffractometer.

#### 3.1.2.2 Separation of clay fractions for identifying the secondary clay minerals

The procedure followed for separation of clay fractions is described below:

- > Finely powdered soil samples were used for separation of clay fractions.
- A known quantity (10 g) of the sample was treated with 35 per cent hydrogen peroxide overnight to oxidize carbon content of the samples and thereby removing the organic matter.
- Then samples were treated with hydrochloric acid to remove the carbonates and calcite etc. and centrifuged for 5 minutes at 4000 rpm to remove excess of hydrochloric acid.
- ➤ Water was added and allowed to settle.
- By adopting the principle of Stoke's Law, suspension was collected based on the sedimentation technique.
- > The suspension was centrifuged to separate clays.
- Clays were smeared on the glass slides and dried or to evaporate water.
- > Three slides were prepared for each sample for different treatments.
- > One slide was used as reference without any treatments.
- Remaining two sets were treated in a vacuum chamber with ethylene glycol for half an hour and heated at 490 °C for 4 hours respectively. Ethylene glycol was

used because of its tendency to solvate (due to its polar nature) the interlayer regions in bilayer configuration of smectites and monolayer's of vermiculites.

> After respective treatment, samples were subjected to XRD analysis.

### 3.1.2.3 Principle of XRD

A parallel beam of X- rays of a single wavelength impinges on parallel planes of atoms or ions at an angle  $\theta$  (Theta). The beam interacts with the atoms or planes and is diffracted. Some of the diffracted rays will emerge from the crystal at the same angle  $\theta$  as the incident rays. For certain values of  $\theta$ , the path difference will be a whole number (n) of wavelengths.

When this happens the diffracted rays are intensified by constructive interferences and are recorded on the photographic film. By simple trigonometry the wavelength  $\lambda$ (known) and the angle  $\theta$  (measured) are related to the interplanar spacing, d, by the relationship: 2d sin  $\theta = n \lambda$ , known as the Bragg's equation. Schematic representation is given in Fig. 1.

### **3.1.2.4 Identification of minerals**

Primary and secondary minerals of the respective diffractogram of samples were identified by PANalytical X'Pert Highscore tool by comparing the sample peaks with the reference peaks.

### **3.1.3 Total elemental analysis**

Total elemental analysis of soil samples were determined by inductively coupled plasma optical emission spectrometer (ICP-OES Jobin-Yvon, Ultima-C) at CEREGE, Aix-en Provence, France after alkaline fusion (Germanique, 1994).

### 3.2 Assessment of silicon budget in wetland rice ecosystem

In natural ecosystems, plant activity and silicate weathering control the biogeochemical cycle of silicon. The objective of the task was to monitor the inputs, outputs, and the internal transfer of silicon in paddy field in order to estimate the solute mass balance, status of silicon and bioavailable silicon.

### **3.2.1 Experimental location**

A field experiment was carried out at C- Block, ZARS, V. C. Farm, Mandya during *Summer* and *Kharif* 2015. The soil of experimental plot was neutral in reaction with sandy loam in texture. Acetic acid and calcium chloride extractable silicon was medium in range. Available nitrogen and potassium content of the soil was medium in range whereas available phosphorus was very high. Secondary and micronutrients were

higher than the critical limit. Details of the soil physicochemical parameters are presented in Table 4.

# **3.2.2 Experiment details:**

| Test crop                                 | : Rice  |
|---|---|
| Variety                                   | : Tanu  |
| Season                                    | : Summer and Kharif 2015  |
| No. of treatments                         | : 04  |
| No. of replications                       | : 04  |
| Package of practice (POP)                 | : 125: 62.5: 62.5 NPK kg ha <sup>-1</sup> in <i>summer</i> , 100: 50: 50 NPK kg ha <sup>-1</sup> during <i>kharif</i> and zinc sulphate @ 20kg ha <sup>-1</sup> |
| Duration of I experiment                  | : 10 <sup>th</sup> March to 2 <sup>nd</sup> July 2015 (Summer crop)   |
| Duration of II experiment                 | : 22 <sup>nd</sup> August to 16 <sup>th</sup> December 2015 ( <i>Kharif</i> crop)   |
| Level and source of Si                    | : 300 kg DE ha <sup>-1</sup>  |
|   | Diatomite or Diatomaceous earth (DE), Agripower silica,<br>Australia  |
| Design/analysis                           | : Experiment laid out as per (3 X 2) with 2 control and (3 X 2) with 1 control. Statistical analysis performed as per two-way ANOVA with multiple observations  |
| Treatment details:                        |   |
| $T_1$ : Si <sub>0</sub> + RP <sub>0</sub> |   |
| $T_2$ : Si <sub>0</sub> + RP              |   |

# $T_3$ : Si<sub>1</sub>+ RP<sub>0</sub>

 $T_4$  : Si<sub>1</sub>+ RP

 $(Si_0 = without silicon, Si_1 = with silicon, RP_0 = without crop, RP=with crop)$ 

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# 3.2.3 Installation of rhizons and collection of soil solution in the experimental field

Solute silicon budget was estimated for each treatment as the difference between the soil inputs and outputs and assessed by monitoring the soil solution samples during the plant growth period at soil depths of 5cm (considered as input) and 40 cm (considered as output, below the root zone).

### **3.2.3.1** Soil solution sampler (Rhizon sampler)

Soil solution was sampled with permanently installed rhizon samplers (used for repeated and reliable sampling of all dissolved components in the soil solution) that consisted of a 10cm long porous part, with an outside diameter of 4.5 mm and a pore size of 0.1 micron. The samplers were supplied with an extension tube to draw the water itself connected to a 60ml syringe (capacity). Vacuum created in small volume of rhizon (about 0.5 cm<sup>3</sup>) and large volume of syringe allowed an efficient suction of soil pore water (Plate 4).

# 3.2.3.2 Installation of rhizon sampler in the experimental plot

Rhizon samplers were installed in each of the 16 plots at soil depths of 1cm and 40cm by measuring the coordinates for each plot using a suitable benchmark identified at corner of the experimental field. Deeper samplers along with sampling connector were installed horizontally at 40cm depth before ploughing of the experimental plot and buried inside the soil (Plate 5). Land was ploughed twice followed by puddling and leveling under saturated moisture content. Layout of the field was carried out as planned dimensions and ridges, furrows were constructed (Fig. 2). Each plot size was 20 m<sup>2</sup> (4m X 5m) demarcated by 0.5m bunds and 1m furrow to prevent lateral entry of water from one plot to another. Flow of water from one treatment plot to another treatment plot was avoided to a greater extent by irrigating to each plot separately with pipes. After layout of experimental plot, deep sampling connectors which were connected to the rhizons were taken out from the soil and erected at a height of 30cm to the syringe support (PVC pipe) to protect the collection part from dirt and contamination.

Twenty one days old rice seedlings of *var*. Tanu were transplanted with a spacing of 20 cm ×10 cm and standing water was maintained to achieve submergence condition. Recommended dose of fertilizers (125:62.5:62.5 of N:  $P_2O_5$ : K<sub>2</sub>O ha<sup>-1</sup>) were applied as per package of practice. Recommended dose of  $P_2O_5$  (SSP), half dose of the recommended K<sub>2</sub>O (as MOP) and N (as Urea) were applied prior to transplanting. Remaining nitrogen and potash were given as two splits at 30<sup>th</sup> and 60<sup>th</sup> day after transplanting. Diatomaceous earth @ 300 kg ha<sup>-1</sup> was used as silicon source applied as basal dosage along with the fertilizers. Composition of DE is provided in Table 6.

Surface rhizons at 5 cm depth were inserted horizontally after transplanting the rice to each plot (Plate 6). Both surface and deeper rhizons were supported by one PVC pipe and supported with wooden stick. Soil solution was recovered by creating vacuum in



Fig. 1: Schematic representation of XRD by regularly spaced planes of atoms in a crystal



a)Rhizon sampler



b) Extension tubes



c) Syringe (60ml)



d) Plastic blockers



e) A complete set of soil solution sampler

Plate (a-e) 4: Materials used for soil solution sampling



Plate 5: Installation of deeper rhizons in experimental plot



Plate 6: Overview of rhizon sampler installed in experimental plot





syringe by using plastic blockers (to enable suction). Solute samples were collected in Tarsons PP vials and brought to the laboratory for analysis of major anions, cations and silica content. The samples collected during experimental period are referred to as solute samples or soil solution or pore water in the text. Solute samples were collected from all plots at 0, 7, 15, 30, 60, 90 days after transplanting (DAT) and analyzed for Si, PO<sub>4</sub>, Ca, Mg, Na and Cl at the Indo – French Cell for Water Sciences, Indian Institute of Sciences, Bangalore. Anions and cations were measured by ion chromatography (Ion chromatograph Metrohm 861) and dissolved silica by blue method colorimetry (detector UV-visible Knauer).

Five plants were randomly labeled and recorded for plant height and number of tillers at 30, 60, 90 DAT and at harvest. The height was measured from the base of the fully opened leaf or tip of the panicle, whichever is longest. Mean of the height and tillers recorded from five plants were reported.

Following yield parameters were recorded at harvest:

**a. Panicle length (cm):** Five plants were randomly selected in each plot and panicle length was measured from base to tip of the panicle and the mean was reported.

**b. 1000 grain weight (g):** Weight of thousand grains drawn at random from the labeled plants and expressed in grams.

**c.** Grain weight panicle<sup>-1</sup>: Weight of grains per panicle was recorded from the five randomly selected plants and mean was reported.

**d.** Grain weight hill<sup>-1</sup>: Weight of grains per hill was recorded for the five randomly selected plants and mean was reported.

e. Grain yield (t ha<sup>-1</sup>): Grains from corresponding net plot was sundried and the weight of grain per net plot was computed and then transformed as ton per hectare.

**f. Straw yield (t ha<sup>-1</sup>):** Straw of each net plot was sundried, weighed and expressed in ton per hectare.

Grain and straw samples were collected from field after the harvest of crop and washed with deionised water and were dried in an oven at 70 °C, powdered and analysed for total N, P, K, Ca, Mg, Zn, Cu, Fe, Mn, and silicon content by adopting standard procedures as given in Table 3. The nutrient uptake by the crop was computed using respective elemental content and expressed as kg ha<sup>-1</sup> using following formula.

Nutrient uptake (kg ha<sup>-1</sup>) =  $\frac{\text{Nutrient content (\%) X dry weight of crop (kg ha<sup>-1</sup>)}{100}$ 

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After the harvest of the crop, surface soil samples were collected plot wise using screw auger and air dried, powdered, sieved with 2mm sieve and analyzed for parameters such as pH, EC, available N, P & K, Exch. Ca, Mg and Na, DTPA extractable Zn, Cu, Mn and Fe, acetic acid and CaCl<sub>2</sub> extractable Si adopting standard procedures as given in Table 3.

#### 3.2.4 Volume of irrigation water

Borewell water was used for irrigation purpose and irrigation water samples were collected periodically for analyzing the nutrients (Si – 1151; Cl – 3663: Na – 6178  $\mu$ mol L<sup>-1</sup>) and mean of these values were used for calculating nutrients supplied by irrigation. Water was let into each plot from the pipeline drawn exclusively for the experiment.

Volume of water let into each plot was calculated by 'bucket method'. This method is based on the measurement of time taken to fill the volume of bucket which was used for calculation of the flow of water to the plot. The amount of water supplied through irrigation was 675 liters per irrigation per plot during the crop growth period. Irrigation was given to each plot at three days interval except during the rainfall. Accordingly, the volume of irrigated water relates to 574 mm per plot during the crop growth period. The quantity of irrigated water used computed using the formula;

QT = AD Q = Discharge (L sec<sup>-1</sup>) T = Time (second) A = Area (cm)D = Depth (cm)

### 3.2.5 Collection of solute samples by core sampler during kharif, 2015

Evidently, due to shallow water table (about 50cm) in the experimental plot there was similar trend and no significant difference among the treatments and different intervals of the samplings for nutrient content at 40cm depth of soil. As an alternative, core sampling was carried out up to 17.5 cm depth of the soil.

Field experiment was carried out during *kharif*, 2015 without disturbing the layout of the experiment carried out during summer by adopting same set of treatments in same plots. Land ploughing and leveling were carried out manually and were used for collecting the soil solution samples at different intervals of crop growth. Core solute samples were collected from four plots representing the four treatments *viz.*, T<sub>1</sub>: Si<sub>0</sub> + RP<sub>0</sub>; T<sub>2</sub>: Si<sub>0</sub>+ RP; T<sub>3</sub>: Si<sub>1</sub>+ RP<sub>0</sub>; T<sub>4</sub>: Si<sub>1</sub>+ RP. The core samples were collected by inserting sampling device to a maximum depth (17.50 cm) of soil and centrifugation was carried out to obtain clear solute samples (Plate 7). The slicing of core to specified depth permits the sampling of soil pore water. However, it provides only a snapshot of the pore water composition. Core solute samples were analyzed for Si, Cl and Na. Analytical data obtained from core samples were used for calculation of mass balance.

Grain and straw samples were collected from field after the harvest of crop and washed with deionised water and dried in an oven at 70 °C, powdered and analysed for Si content by adopting standard procedures as given in Table 3. The nutrient uptake by the crop was computed from respective elemental content and expressed as kg ha<sup>-1</sup>. Initial properties of the soil are given in Table 5. After the harvest of the crop, surface soil samples were collected plotwise using screw auger, air dried, powdered, sieved with 2 mm sieve and analyzed for pH, acetic acid and CaCl<sub>2</sub> extractable Si by adopting standard procedures given in Table 3.

#### **3.2.6** Weather parameters

Rainfall and potential evapotranspiration (PET) data were collected from Karnataka State Natural Disaster Monitoring Centre (KSNDMC) for the crop growth period (Table 2). Total amount of rainfall and PET during the *summer* (from 10<sup>th</sup> March to 2<sup>nd</sup> July 2015) and *kharif* (from 22<sup>nd</sup> august to 16<sup>th</sup> December 2015) crop was 245mm,411mm and 455mm, 459mm respectively (Table 2 and Fig. 3). The chemical composition of the rain water (Si – 3; Cl – 27; Na – 22 µmol L<sup>-1</sup>) was considered by referring to Riotte *et al.* (2014).

| Duration  | Rainfall (mm) | PET (mm) |
|-----------|---------------|----------|
| March     | 0             | 89       |
| April     | 40            | 129      |
| May       | 153           | 117      |
| June      | 53            | 113      |
| July      | 0.05          | 7        |
| August    | 16            | 62       |
| September | 80            | 119      |
| October   | 97            | 132      |
| November  | 216           | 83       |
| December  | 1             | 64       |

Table 2: Rainfall and PET data for the crop growth period

#### 3.2.7 Principle of solute mass balance at soil-plant scale

The solute mass balance relies on the water balance at soil-plant scale, of which main unknown is the water flux leached from the soil layer. In the case of a paddy field, because of submergence, another difficulty arises; the input chemical flux due to borewell, rainfall (and MOP for K and Cl) may be affected by evaporation and/or algae blooms above the ground surface. This may be particularly important in the case of silicon because of potential diatom blooms. Hence, three kinds of water/chemical fluxes will be considered in the mass balance (Plate 8): The above ground flux, the soil input flux and the soil output flux.

The above ground flux (F *above ground*) includes, irrigation + rainfall fluxes for water; irrigation + rainfall fluxes + KCl (MOP) for chemical elements. KCl is highly soluble and accounts for the K and Cl balance. The above ground flux of an element X,  $F_{X above ground}$ , can be described as:

 $F_{X above ground} = Fw_{borewell water}$ . [X]<sub>borewell water</sub> +  $Fw_{rain}$ . [X]<sub>rain</sub> +  $F_{KCl}$ 

Where,

Fw refers to the fluxes of water (measured)

[X] is the concentration of element X in borewell water (measured) and the rain (according to Riotte *et al.*, 2014)

F<sub>KCl</sub> flux of Cl and K associated to the MOP application (measured).

The soil input and output fluxes were further estimated from the above ground flux according to two methods:

a) The "chloride mass balance", a method initially developed for estimating groundwater recharge in watersheds (Dettinger, 1989) and more recently for determining fluxes beneath KCl fertilized crops (Tyner *et al.*, 2000). It relies on the hypothesis that Cl is conservative in the soil profile (no interaction with soil mineral, limited uptake by vegetation) and therefore, Cl soil input is equal to the Cl soil output. Then according to the mass conservation principle.

The soil input flux of water (Fw<sub>Cl input</sub>) can be estimated from the relationship:

Fwcl input = Fwaboveground. [C1] above ground / [C1] input

The soil output flux of water (Fw<sub>Cl output</sub>) can be estimated from the relationship:

Fw<sub>Cloutput</sub> = Fw<sub>Clinput</sub> . [C1]<sub>input</sub> / [C1]<sub>output</sub>

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Plate 7: Collection of core solute sample



Fig. 3: Pattern of rainfall and PET during crop growth period

Where, F is the water flux for the period of cultivation and [Cl] the average concentration of chloride above ground and in the input / output fluxes. Since a small fraction of Cl might be taken up by the plant, another potential conservative candidate was tested i.e., sodium. For this element it was considered that the Na-plagioclase weathering, usually susceptible to release Na in the soil layer, was negligible and Na-adsorption on clays as well. Since the Cl and Na concentrations in the borewell water were quite high i.e., 130 ppm and 140 ppm respectively, the processes susceptible to affect the conservative behavior of these elements marginally affect the chemical balance.

b) A simplified water balance considering the PET as the maximum water loss in the soil layer can also be adopted. Then a minimum\_flux of water (Min.  $Fw_{Cl output}$ ) leached from the soil can be estimated from the simple equation:

Min. Fw<sub>Cl output</sub> = Fw above ground – PET

Once the soil input/output fluxes of water is estimated, the associated solute fluxes was estimated by multiplying the water fluxes by the average concentrations measured in the input flux (rhizon sampler at 5cm depth) and in the output flux (Core samples at 17.50cm depth). Due to Shallow water table in the experimental field, soil core samples were collected from 1cm to 17.50 cm and the mass balance as described was calculated.

# **3.3** Assessment of bioavailability of different sources of silicon in rice and silicon budgeting in acidic, neutral and alkaline soils

A pot experiment was conducted at greenhouse, Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bangalore to assess the bioavailability Si from different sources and budgeting in three types of soil.

#### 3.3.1 Soil

Three soils with contrasting pH were used in this study. Acidic soil with pH 5.86 was collected from Hassan representing southern dry zone and taxonomically classified as *Rhodic Paleustalfs*. Neutral soil was collected from the field experimental plot with pH of 7.10 from C block, ZARS, V. C. Farm, Mandya representing southern dry zone and taxonomically classified *as Typic Rhodustalfs*. Alkaline soil with pH of 9.38 was collected from Hiriyur representing central dry zone and taxonomically classified as *Chromic haplusterts*. The texture of acidic and neutral soil was sandy loam and that of alkaline soil was clay loam. Bulk soil was collected from each location and soils were air dried, sieved through two mm sieve and used for pot culture studies. The soils were analysed for initial properties by following standard procedures as given in Table 3 and the data are presented in Table 7.

# 3.3.2 Silicon sources

Three types of silicon sources used for the experiment were calcium silicate  $(CaSiO_3)$ , diatomaceous earth or diatomite (DE) and rice husk biochar (RHB). Calcium silicate is industrial slag by-product which contains around 12 per cent of Si, DE is a sedimentary rock which was used for field experiment having 30 per cent Si and RHB was produced at relatively lower temperature at around 400°C and contains 31per cent Si. All these sources were passed through 0.2 mm sieve and used for the greenhouse experiment. Compositions of Si sources are presented in Table 6.

# 3.3.3 Experiment details:-

| 1) Crop               | : Rice  |
|-----------------------|---|
| 2) Variety            | : Tanu  |
| 3) Types of soil      | : Three   |
|                       | 1. Acidic soil (Hassan) - ( <i>Rhodic Paleustalfs</i> )                               |
|                       | 2. Neutral soil (Mandya) - ( <i>Typic Rhodustalfs</i> )                               |
|                       | 3. Alkaline soil (Hiriyur) - ( <i>Chromic haplusterts</i> )                           |
| 4) Moisture level     | : Submergence   |
| 5) Sources of silicon | : Three   |
|                       | 1. Calcium silicate (CaSiO <sub>3</sub> )   |
|                       | 2. Diatomaceous earth (DE)  |
|                       | 3. Rice hull biochar (RHB)  |
| 6) Levels of silicon  | : 02 (250 and 500 kg Si ha <sup>-1</sup> )  |
| 7) RDF                | : 100:50:50 (N: P <sub>2</sub> O <sub>5</sub> :K <sub>2</sub> O kg ha <sup>-1</sup> ) |
| 8) Treatments         | : 14  |
| 9) Replication        | : 03  |
| 10) Total number of J | pots: 42 pots per soil = $126$ pots for three soils                                   |
| 11) Design            | : CRD   |

| $T_1$                 | : Ck – without plant  |
|-----------------------|---|
| $T_2$                 | : Ck – with plant   |
|                       | Without plant   |
| <b>T</b> <sub>3</sub> | : Si <sub>1</sub> + RP <sub>0</sub> - CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> |
| $T_4$                 | : Si <sub>1</sub> + RP <sub>0</sub> - CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> |
| T <sub>5</sub>        | : Si <sub>1</sub> + RP <sub>0</sub> - DE @ 250 kg Si ha <sup>-1</sup>                 |
| T <sub>6</sub>        | : Si <sub>1</sub> + RP <sub>0</sub> - DE @ 500 kg Si ha <sup>-1</sup>                 |
| <b>T</b> <sub>7</sub> | : Si <sub>1</sub> + RP <sub>0</sub> - RHB @ 250 kg Si ha <sup>-1</sup>                |
| $T_8$                 | : Si <sub>1</sub> + RP <sub>0</sub> - RHB @ 500 kg Si ha <sup>-1</sup>                |
|                       | With plant  |
| <b>T</b> 9            | : Si <sub>1</sub> + RP - CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup>              |
| T <sub>10</sub>       | : Si <sub>1</sub> + RP - CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup>              |
| T <sub>11</sub>       | : Si <sub>1</sub> + RP - DE @ 250 kg Si ha <sup>-1</sup>                              |
| T <sub>12</sub>       | : Si <sub>1</sub> + RP - DE @ 500 kg Si ha <sup>-1</sup>                              |
| T <sub>13</sub>       | : Si <sub>1</sub> + RP - RHB @ 250 kg Si ha <sup>-1</sup>                             |
| $T_{14}$              | : Si <sub>1</sub> + RP - RHB @ 500 kg Si ha <sup>-1</sup>                             |

 $(Si_0 - without silicon, Si_1 - with silicon, RP_0 - without crop, RP - with crop)$ 

Ck - Check or control

# 3.3.4 Experimental set up

Study was undertaken by taking 5 kg of each soil per pot and thoroughly mixed with graded levels Si sources. After filling 2/3<sup>rd</sup> of the pot with soil to each pot, soil solution sampler (Rhizon) was placed horizontally at 10cm depth of the pot and

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remaining 1/3<sup>rd</sup> of soil was filled and kept undisturbed. Rhizon sampler consisted of a 5cm long porous part, with an outside diameter of 2.5 mm with pore size of 0.15 micron.

The samplers were supplied with coextruded tubing (PE inside / PVC outside) 1 mm internal diameter with connector and protective cap (Supplier – *Eijkelkamp* Agrisearch equipment- www. Eijelkamp.com). Sampler end was connected with extension tube to draw the water and connected to a syringe (20ml capacity) (Plate 9). Water samples were extracted by creating vacuum through syringe and samples were collected in Tarsons plastic vials (Plate 10).

One seedling of twenty one days old paddy was transplanted to each pot and moisture was maintained at submergence. Recommended dose of  $P_2O_5$  (SSP), half dose of the recommended K<sub>2</sub>O (as MOP) and N (as Urea) were applied as basal dosage. Remaining nitrogen and potash were applied as two splits at 30<sup>th</sup> and 60<sup>th</sup> day after transplanting.

Water samples were collected at 0, 7, 15, 30, 60, 90 and 120 days after transplanting (DAT) and analysed for pH and dissolved silicon (DSi) content by adopting standard procedure. Biometric observations such as plant height and number of tillers were recorded at critical growth stages. The straw and grain samples were collected at harvest and yield was recorded. Straw and grain samples were analysed for nutrient content including silicon by following standard procedures (Table 3). Soil samples after completion of the experiment was collected and analysed for parameters such as pH, EC, available P, & K, Exch. Ca, Mg and Na, DTPA extractable Zn, Cu, Mn, Fe, Acetic acid and CaCl<sub>2</sub> extractable Si by adopting standard procedures as given in Table 3.

### 3.3.5 Si budgeting

Elemental Si budget was estimated for each treatments as the difference between the inputs (irrigation water and fertilizer) and outputs (straw and grain Si uptake, plant available Si stock in soil after completion of the experiment).

### 3.4. Statistical analysis

Data generated were statistically analysed using Pearson's correlation and oneway ANOVA at 5 per cent level of significance as per the procedures outlined by Rangaswamy (2010).

### **3.5.** Analytical methods for soil and plant samples

The physico - chemical properties of the initial soil and soil after completion of the experiment and plant nutrient content were analysed as per the methodology presented in Table 3.



Plate 8: Kinds of fluxes considered in mass balance





Plate 10: Overview of pots installed with rhizon sampler

| Sl.<br>No. | Parameter   | Procedure   | Method &<br>Reference                                |
|------------|---|---|--|
| 1          | Particle size<br>analysis   | Soil was treated with $H_2O_2$ , dispersed<br>with sodium hexa metaphosphate, sand<br>with decantation procedure, silt and<br>clay in the suspension was quantified<br>after pipetting with Robinson pipette. | International<br>pipette method,<br>Jackson (1973)   |
| 2          | Cation<br>exchange<br>capacity of the<br>soil (pH less<br>than 8.2) | Sample was leached with 1N (pH 7)<br>ammonium acetate followed by<br>washing with alcohol and ammonium<br>in the leachate was determined by<br>distillation method.   | Distillation<br>method<br>Page <i>et al</i> . (1982) |
| 3          | Cation<br>exchange<br>capacity of the<br>soil (pH more<br>than 8.2) | Sample was leached with 1 <i>N</i> Sodium acetate followed by washing with alcohol and KCl and sodium concentration was estimated with flame photometer.  | Flame photometry,<br>Jackson (1973)                  |
| 4          | Soil reaction   | Soil: water suspension (1:2.5) was used<br>for pH measurement using<br>potentiometer after standardising with<br>appropriate buffers.   | Potentiometry,<br>Jackson (1973)                     |
| 5          | Electrical conductivity   | Soil: water extract (1:2.5) was used for<br>measuring EC using conductivity<br>bridge.  | Conductometry<br>Jackson (1973)                      |
| 6          | Organic carbon  | Soil was treated with $K_2Cr_2O_7$ and<br>Conc. $H_2SO_4$ , the unutilized $K_2Cr_2O_7$<br>was back titrated against ferrous<br>ammonium sulphate using diphenyl<br>amine indicator.                          | Wet oxidation,<br>Walkley and Black<br>(1934)        |
| 7          | Available<br>phosphorus in<br>acidic soil                           | Soil was extracted with Brays - I and<br>estimated by chloromolybdate acid<br>method using spectrophotometer and<br>intensity of blue color measured at 660<br>nm.  | Bray & Kurtz<br>(1945)                               |
| 8          | Available<br>phosphorus in<br>neutral and<br>alkaline soil          | Soil was extracted with sodium bicarbonate $(0.05 N)$ and estimated by chloromolybdate acid method using spectrophotometer and intensity of blue color measured at 660 nm.                                    | Olsen (1954)   |

# Table 3: Methods of soil and plant analysis

| 9  | Available<br>nitrogen                   | Soil was oxidized and distilled with<br>alkaline potassium permanganate and<br>then titrated against standard acid using<br>mixed indicator. | Subbiah and Asija<br>(1949)   |
|----|---|--|---|
| 10 | Available<br>potassium                  | The soil was extracted with 1 N (pH 7) ammonium acetate and K was estimated with flame photometer.   | Flame photometry,<br>Jackson (1973)                                   |
| 11 | Available<br>silicon                    | Soil was extracted with 0.1M Calcium<br>chloride, the Si was determined by<br>using UV- visible spectrophotometer at<br>820nm.               | Haysom and<br>Chapman (1975)  |
|    |   | Soil was extracted with 0.5 <i>M</i> Acetic acid, the<br>Si was determined by using UV- visible spectrophotometer at 630nm.                  | Korndorfer <i>et al.</i><br>(2001)                                    |
| 12 | Available<br>Calcium and<br>Magnesium   | The soil was extracted with 1 N (pH 7)<br>ammonium acetate and Ca and Mg<br>were estimated by complexometric<br>titration method.            | Complexometric<br>titration method,<br>Baruah and<br>Barthakur (1997) |
| 13 | DTPA<br>extractable<br>micronutrients   | Soil was extracted with DTPA and<br>micronutrients were determined by<br>using Graphite furnace-Atomic<br>Absorption Spectrophotometer       | Lindsay and<br>Norvell (1978)   |
| 14 | Total plant<br>nitrogen                 | Plant samples were digested in block<br>digester and total nitrogen was<br>quantified using continuous flow<br>analyser (CFA).               | CFA, Krom<br>(1980)   |
| 15 | Total plant<br>potassium                | Potassium in diacid digested plant<br>sample was estimated with flame<br>photometer  | Flame photometry,<br>Jackson (1973)                                   |
| 16 | Total plant<br>calcium and<br>magnesium | Calcium and magnesium in diacid<br>digested plant sample was estimated by<br>complexometric titration method using<br>EDTA                   | Complexometric<br>titration method,<br>Baruah and<br>Barthakur (1997) |
| 17 | Total plant<br>micronutrients           | Micronutrients in di acid digested plant<br>samples was determined using Graphite<br>furnace-Atomic Absorption<br>Spectrophotometer          | Lindsay and<br>Norvell (1978)   |

# 3.5.1. Extraction of plant available silicon in soils using 0.01M CaCl<sub>2</sub> extractant (CCSi).

Two grams of soil was taken in a 50 ml centrifuge tube and 20 ml of 0.01M CaCl<sub>2</sub> was added. After continuous end to end shaking in a mechanical shaker for sixteen hour, the solution was centrifuged at 2000 rpm for 10 minutes and then filtered.

#### 3.5.2. Estimation of plant available silicon in soils

Silicon in the extracting solution was determined by transferring 1 ml of filtrate into plastic centrifuge tube and then 2.5 ml of 0.5 M sulfuric acid and 2.5 ml of ammonium molybdate solution (pH 7) was added. After vortex stirring for 5 minutes, 1.25 ml of tartaric acid solution was added. After allowing for additional two minutes, 0.25 ml reducing agent (ANSA) was added. After 5 minutes, but not later than 30 minutes following addition of the reducing agent, absorbance was measured at 820nm using UV visible spectrophotometer (Shimadzu). Simultaneously Si standards (0, 0.5, 1, 2, 3, 4, 5 and 6 mg L<sup>-1</sup>) prepared in the same matrix were also measured using UV visible spectrophotometer (Haysom and Chapmen, 1975).

# 3.5.3 Extraction and estimation of plant available Si in soils using 0.5 M acetic acid extractant (AASi)

Available silicon in soil was extracted using 0.5 M acetic acid with the soil to extractant ratio of 1:2.5 as outlined by Korndorfer *et al.* (2001). After shaking continuously for a period of one hour, solution was centrifuged at 3000 rpm for 3 minutes and then filtered. The filtrate was then used for silicon determination. Silicon in the extracting solution was determined by adopting the procedure of Narayanaswamy and Prakash (2009).

An aliquot of 0.25 ml filtrate was taken into a plastic centrifuge tube and then added with 10.5 ml of distilled water, plus 0.25 ml of 1:1 hydrochloric acid, and 0.5 ml of 10 per cent ammonium molybdate solution. After allowing for 5 minutes, 0.5 ml of 20 per cent tartaric acid solution was added. After allowing for additional two minutes, 0.5 ml reducing agent (1-amino-2-napthol-4-sulfonic acid - ANSA) was added. After 5 minute, but not later than 30 minutes following addition of the reducing agent, absorbance was measured at 630nm using UV-visible spectrophotometer (SHIMADZU Pharma spec, UV-1700 series) with auto sample changer (ASC-5). Simultaneously Si standards (0.2, 0.4, 0.8, 1.2 and 1.6 mg  $L^{-1}$ ) prepared in the same matrix were also measured using UV-visible spectrophotometer.

#### **3.5.4 Determination of silicon in plant samples**

#### **3.5.4.1** Plant sample digestion

The powdered grain and straw samples were dried in an oven at 70°C for 2-3 hrs prior to analysis. The sample (0.1g) was digested in a mixture of 7 ml of HNO<sub>3</sub> (70 %), 2

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ml of  $H_2O_2$  (30 %) and 1 ml of HF (40 %) using microwave digestion system (Milestonestart D) with following steps: 1000 watt for 17 minutes, 1000 watt for 10 minutes and venting for 10 minutes. The digested samples were diluted to 50 ml with 4 per cent boric acid (Ma and Takahashi, 2002).

#### **3.5.4.2 Estimation of silicon in plant samples**

The Si concentration in the digested solution was determined as described below: 0.5 ml of digested aliquot was transferred to a plastic centrifuge tube, to this 3.75 ml of 0.2 N HCl, 0.5 ml of 10 per cent ammonium molybdate ( $(NH_4)_6Mo_7O_2$ ) and 0.5 ml of 20 per cent tartaric acid and 0.5 ml of reducing agent (Amino naphtholsulphonic acid - ANSA) was added and the volume was made up to 12.5 ml with distilled water. After one hour, the absorbance was measured at 600 nm with a UV-visible spectrophotometer (Shimadzu) (Ma *et al.*, 2002). Similarly, standards (0, 0.2, 0.4, 0.8 and 1.2 ppm) were prepared by following the same procedure.

| Parameters   | 5          | Content |
|--|------------|---------|
| pH (1:2.5 water)   |            | 7.10    |
| EC ( dSm <sup>-1</sup> ) (1:2.5 water)                         | 0.22       |         |
| Organic carbon (g kg <sup>-1</sup> )                           | 11.70      |         |
|  | Sand       | 76.54   |
| Particle size distribution                                     | Silt       | 6.56    |
|  | Clay       | 16.90   |
| Textural class   | Sandy loam |         |
| $0.01M\ CaCl_2-Si\ (mg\ kg^{\text{-}1})$                       | 41.98      |         |
| 0.5M Acetic acid – Si (mg kg <sup>-1</sup> )                   | 73.82      |         |
| Available N (kg ha <sup>-1</sup> )                             |            | 340.48  |
| Available P <sub>2</sub> O <sub>5</sub> (kg ha <sup>-1</sup> ) |            | 203.31  |
| Available K <sub>2</sub> O (kg ha <sup>-1</sup> )              |            | 348.09  |
| Exch.Ca (cmol $(p^+)$ kg <sup>-1</sup> )                       |            | 4.75    |
| Exch. Mg (cmol $(p^+)$ kg <sup>-1</sup> )                      |            | 2.25    |
| Micronutrients (mg kg <sup>-1</sup> )                          |            |         |
| Zn   |            | 3.18    |
| Mn   |            | 20.40   |
| Fe   | 89.52      |         |
| Cu   |            | 3.75    |

| Table 4: | <b>Physico-chemical</b> | properties of se | oil of V. C. | Farm, | Mandya | during | summer |
|----------|-------------------------|------------------|--------------|-------|--------|--------|--------|
|          | season                  |                  |              |       |        |        |        |

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| Parameters  | Value  |
|---|--------|
| pH (1:2.5 water)                                    | 8.06   |
| EC ( dSm <sup>-1</sup> ) (1:2.5 water)              | 0.61   |
| 0.01M CaCl <sub>2</sub> - Si (mg kg <sup>-1</sup> ) | 41.52  |
| 0.5M Acetic acid – Si (mg kg <sup>-1</sup> )        | 162.29 |

| Table 5: Initial soil pH, | EC and Si | i content | of soil a | nt V. | C. Farm, | , Mandya | during |
|---------------------------|-----------|-----------|-----------|-------|----------|----------|--------|
| kharif season             |           |           |           |       |          |          |        |

## Table 6: Composition of Si sources

| Properties   | CaSiO <sub>3</sub> | DE    | RHB   |
|--|--------------------|-------|-------|
| pH (1:2.5 water)   | 12.45              | 9.21  | 7.39  |
| EC (dSm <sup>-1</sup> ) (1:2.5 water)                              | n.d                | 0.72  | 1.62  |
| Cation exchange capacity (cmol(p <sup>+</sup> ) kg <sup>-1</sup> ) | n.d                | 52.00 | 38.63 |
| per cent   |                    |       |       |
| N  | n.d                | 0.03  | 0.78  |
| Р  | n.d                | 0.02  | 0.24  |
| K  | 0.076              | 0.40  | 0.96  |
| Si   | 12                 | 30.00 | 31.00 |
| Ca   | 5.33               | 2.70  | 0.36  |
| Mg   | 0.82               | 3.25  | 0.31  |
| S  | 0.05               | 0.17  | 0.05  |
| Al <sub>2</sub> O <sub>3</sub>                                     | n.d                | 15.30 | n.d   |
| mg kg <sup>-1</sup>  |                    |       |       |
| Fe   | 2.3                | 2.00  | 0.077 |
| Mn   | n.d                | 0.02  | 0.055 |
| В  | 7.7                | 6.00  | 8.36  |
| Zn   | 1.10               | 19.00 | 63.00 |
| Cu   | 0.10               | 20.00 | 31.00 |
| Мо   | 0.40               | 0.10  | n.d   |
| Se   | n.d                | 1.30  | n.d   |
| Cd   | < 0.01             | 0.50  | n.d   |

CaSiO<sub>3</sub> - Calcium silicate; DE - Diatomite; RHB - Rice hush biochar

n.d – not determined

| Param                                      | eters                               | Acidic soil | Neutral soil     | Alkaline soil |  |
|--|-------------------------------------|-------------|------------------|---------------|--|
| pH (1:2.5 water)                           |                                     | 5.86        | 7.10             | 9.38          |  |
| Location                                   |                                     | Hassan      | V.C. Farm Mandya | Hiriyur       |  |
| EC ( dSm <sup>-1</sup> ) (1:2.             | 5 water)                            | 0.16        | 0.22             | 0.33          |  |
| Organic Carbon (g kg <sup>-1</sup> )       |                                     | 8.40        | 11.70            | 8.10          |  |
| Particle size                              | Sand                                | 68.98       | 76.54            | 41.45         |  |
| distribution                               | Silt                                | 8.60        | 6.56             | 30.40         |  |
| (%)  | Clay                                | 22.42       | 16.90            | 28.15         |  |
| Textural class                             |                                     | Sandy loam  | Sandy loam       | Clay loam     |  |
| 0.01M CaCl <sub>2</sub> – S                | i (mg kg <sup>-1</sup> )            | 30.58       | 41.98            | 46.18         |  |
| 0.5M Acetic acid                           | - Si(mg kg <sup>-1</sup> )          | 43.10       | 73.82            | 109.47        |  |
| Available N (kg l                          | na <sup>-1</sup> )                  | 239.68      | 340.48           | 170.24        |  |
| Available P <sub>2</sub> O <sub>5</sub> (1 | kg ha <sup>-1</sup> )               | 53.73       | 203.66           | 21.16         |  |
| Available K <sub>2</sub> O (k              | ag ha <sup>-1</sup> )               | 141.79      | 348.09           | 247.29        |  |
| Exch.Ca (cmol (p                           | 0 <sup>+</sup> ) kg <sup>-1</sup> ) | 2.82        | 4.75             | 23.62         |  |
| Exch. Mg (cmol                             | (p+) kg-1)                          | 1.18        | 2.25             | 9.50          |  |
| Micronutrients (r                          | ng kg <sup>-1</sup> )               |             |                  |               |  |
| Zn   | l                                   | 0.99        | 3.18             | 0.18          |  |
| Mr   | 1                                   | 8.00        | 89.52            | 9.02          |  |
| Fe   |                                     | 27.94       | 20.40            | 4.09          |  |
| Cu   | l                                   | 2.11        | 3.75             | 1.77          |  |

Table 7: Physico chemical properties of acidic, neutral and alkaline soil used for pot experiment

## **IV RESULTS AND DISCUSSION**

The present investigation was undertaken to understand the "Biogeochemistry of silicon in different rice ecosystems of Karnataka". In this investigation, soil samples were collected from rice ecosystems from different agro climatic zones of Karnataka. The field experiment was conducted at V. C. Farm, Mandya to assess the budgeting of silicon in wetland rice system. A pot culture experiment was conducted using acidic, neutral and alkaline soil collected from different locations at Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bangalore, Karnataka. The results and discussion of the investigation are presented in this chapter.

## 4.1 Silicon status and other physico-chemical properties of the soil samples collected from different agro climatic zones of Karnataka.

Soil samples (n = 200) were collected from the major rice ecosystems of nine agro climatic zones of Karnataka to assess the status of the silicon (Si) and other parameters. The soil samples were collected from North Eastern Dry Zone (NEDZ), Northern Dry Zone (NDZ), Central Dry Zone (CDZ), Eastern Dry Zone (EDZ), Southern Dry Zone (SDZ), Southern Transition Zone (STZ), Northern Transition Zone (NTZ), Hilly Zone (HZ) and Coastal Zone (CZ) were 23, 19, 16, 17, 41, 20, 11, 34 and 19 respectively. These samples were analysed for pH, EC, cation exchange capacity, mechanical analysis (sand, silt, clay) and plant available silicon (0.1M calcium chloride extractable Si - CCSi, 0.5M acetic acid extractable Si - AASi). Analytical data pertaining to 200 samples varied greatly. The maximum, minimum and mean for each zone have been indicated (Table 8). Details of zone wise soil sampling geographical location and analytical data of each soil samples (n = 200) are presented in Annexure I and III.

#### 4.1.1 Soil pH (1: 2.5 water) and Electrical Conductivity (dS m<sup>-1</sup>)

The results revealed that pH and EC of the soil samples were higher in all the agro climatic zones except soils of hilly and coastal zones of the state with few exceptions (Table 8). The pH of NEDZ, NDZ, CDZ, EDZ, SDZ, STZ, NTZ, HZ and CZ soil samples varied from 6.17 - 9.54, 7.12 - 8.85, 4.88 - 9.12, 5.07 - 8.48, 4.96 - 9.10, 4.99 - 8.49, 5.62 - 8.49, 4.95 - 8.40 and 4.93 - 6.21 respectively with mean of 8.21, 8.33, 7.14, 7.04, 7.63, 6.43, 7.73, 5.83 and 5.37 respectively. A very low and high pH range was recorded in soil samples collected from CDZ and NEDZ, respectively. The EC of NEDZ, NDZ, CDZ, EDZ, SDZ, STZ, NTZ, HZ and CZ soil samples varied from 0.10 - 0.35, 0.19 - 1.00, 0.05 - 0.71, 0.05 - 0.73, 0.05 - 1.07, 0.04 - 0.37, 0.05 - 0.78, 0.03 - 0.46 and 0.02 - 0.37 dSm<sup>-1</sup> respectively with mean of 0.39, 0.40, 0.22, 0.21, 0.27, 0.14, 0.37, 0.09 and 0.06 dSm<sup>-1</sup> respectively.

Analysis of soil samples representing nine agro climatic zones of Karnataka revealed that 40 per cent were acidic, 46 per cent were alkaline and 14 per cent were neutral in pH (Fig. 4). Whereas 98 per cent of the soil samples recorded in normal range of EC, only 2 per cent were slightly saline in nature (Fig. 4). Among the nine agro

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climatic zones of Karnataka, highest soil pH and EC was recorded in NEDZ soil samples and lowest in HZ and CZ. The soils of northern zones of Karnataka recorded high pH and EC which may be attributed to dominance of basaltic - black soils. These soils are rich in basic cations and other salts which contribute to higher soil pH and EC. Pulakeshi *et al.* (2012) studied the fertility status of the northern transition zone soils and found that pH of the soil samples were slightly acidic to alkaline. Pulakeshi *et al.* (2014) characterized northern part of the soils and noticed that soils were silty clay in texture, alkaline in reaction with low salt content. Calcium and magnesium were the dominant cations followed by sodium and potassium.

Hilly and coastal zones were characterized with very high rainfall, due to which most of basic cations or salts are leached out from soil and therefore are low in soil pH and EC. Badrinath *et al.* (1995) reported that southern parts (coastal and hilly zone) of Karnataka were distributed with acidic soil which affects crop yields. Dhananjaya and Ananthanarayana (2009) studied the soils of southern Karnataka and found that soils were sandy loam to sandy clay loam in texture with low pH, CEC and base saturation.

## 4.1.2 Cation exchange capacity (CEC) (cmol (p+) kg<sup>-1</sup>)

The results revealed that CEC of 200 soil samples ranged from 8.20 - 122.83 cmol (p+) kg<sup>-1</sup>, lower CEC was recorded in HZ whereas higher CEC found in SDZ soil sample (Table 8). The soil samples collected from NEDZ recorded CEC which ranged from 15.65 - 108.04 cmol (p+) kg<sup>-1</sup> with mean of 57.29 cmol (p+) kg<sup>-1</sup> whereas NDZ soils recorded a minimum and maximum of 12.17 - 98.48 cmol (p+) kg<sup>-1</sup> with mean value of 38.09 cmol (p+) kg<sup>-1</sup>. The CDZ soil samples recorded the CEC ranging from 14.20 – 70.00 cmol (p+) kg<sup>-1</sup> with mean of 27.86 cmol (p+) kg<sup>-1</sup>. Low CEC was noticed in EDZ soil samples, and ranged from  $10.30 - 22.60 \text{ cmol} (p+) \text{ kg}^{-1}$  with mean value of 15.30 cmol (p+) kg<sup>-1</sup>. A very high range in CEC was noticed in SDZ soil samples from 9.20 - 122.83 cmol (p+) kg<sup>-1</sup> with mean value of 35.48 cmol (p+) kg<sup>-1</sup>. STZ and NTZ soil samples recorded minimum CEC of 9.80 and 25.80 cmol (p+) kg<sup>-1</sup> respectively and a maximum of 63.04 and 64.78 cmol(p+) kg<sup>-1</sup> and mean of 22.73 and 48.24 cmol (p+) kg<sup>-1</sup> respectively. The CEC of HZ soil samples ranged from  $8.20 - 73.70 \text{ cmol} (p+) \text{ kg}^{-1}$  with mean value of 25.54 cmol (p+) kg<sup>-1</sup>. CEC values ranged from 12.80 – 28.80 cmol (p+) kg<sup>-1</sup> with mean value of 22.61 cmol (p+) kg<sup>-1</sup> in CZ soil samples. In general, soils with higher clay content recorded higher CEC. Relatively very low CEC was noticed in HZ and CZ due poor clay content in those soils. Soils of northern Karnataka recorded higher CEC due to presence of high silt and clay content. Northern and midland regions of Karnataka were rich in clay content due to dominance of black soils which are characterized by 2:1 clay minerals and hence high CEC.

## 4.1.3 Mechanical analysis (sand, silt and clay)

Perusal of data presented in Annexure II and Table 8 revealed that the textural class of the soil samples greatly varied from sandy to clay. Analytical data on sand, silt and clay content categorized on zone wise is presented in Table 8.

| Sl. No. | Zone | No. of  |          | pH<br>(1:25 water) | <b>E.C.</b>                  | CEC *  | Sand           | Silt              | Clay  | CCSi**        | AASi***                                       |
|---------|------|---------|----------|--------------------|------------------------------|--|----------------|-------------------|-------|---------------|---|
| 1       | NEDZ | samples | Minimum  | (1:2.5 water)      | ( <b>usin</b> <sup>-</sup> ) | $(\operatorname{cmol}(\mathbf{p}+) \operatorname{Kg}^2)$ | 35.23          | <u>per cent</u> - | 1.00  | $(mg kg^{-})$ | $(\operatorname{IIIg} \operatorname{Kg}^{-})$ |
| 1       | NEDZ | 25      | Maximum  | 0.17               | 1.35                         | 108.04   | 33.23<br>83.35 | 50.41             | 62.30 | 12.77         | 26.02   |
|         |      |         | Meen     | 9.04               | 0.30                         | 57 20  | 56.05          | 31.04             | 12.01 | 26.11         | 251.41  |
|         |      |         |          | 0.21               | 0.39                         | 27.29<br>28 77   | 14.04          | 10.41             | 12.01 | 20.11         | 48.08   |
| 2       | ND7  | 10      | Minimum  | 7.12               | 0.28                         | 12.17  | 34.01          | 0.77              | 14.14 | 10.27         | 40.00   |
| 2       | NDL  | 19      | maximum  | 7.12<br>8.85       | 1.00                         | 12.17  | 90.45          | 60.08             | 22.84 | 62.02         | 125 21  |
|         |      |         | Mean     | 8.33               | 0.40                         | 38.00  | 68.08          | 24.01             | 22.84 | 34.97         | 88.15   |
|         |      |         | + SD     | 0.33               | 0.40                         | 23 74  | 14.06          | 24.01             | 5.84  | 15.18         | 28.33   |
| 3       | CDZ  | 16      | Minimum  | 1.99               | 0.19                         | 14.20  | 30.11          | 3.40              | 4.62  | 13.10         | 13.84   |
| 3       | CDL  | 10      | maximum  | 4.00               | 0.05                         | 70.00  | 39.11<br>82.11 | 42.25             | 4.02  | 54.40         | 280.04  |
|         |      |         | Mean     | 9.12<br>7.14       | 0.71                         | 70.00  | 65.83          | 42.23             | 41.19 | 26.79         | 280.04  |
|         |      |         | + SD     | 1 38               | 0.22                         | 14 22  | 14.18          | 9.52              | 10.94 | 9.61          | 67.97   |
| 4       | FDZ  | 17      | Minimum  | 5.07               | 0.15                         | 10.30  | 54.10          | 0.29              | 5 10  | 14 55         | 19.41   |
| -       | EDL  | 17      | maximum  | 8.48               | 0.03                         | 22.60  | 03.04          | 20.95             | 40.42 | 56.18         | 166.04  |
|         |      |         | Mean     | 7.04               | 0.73                         | 15 30  | 75 58          | 7.80              | 16.63 | 34 69         | 79 19   |
|         |      |         | + SD     | 0.96               | 0.17                         | 3.62   | 9 54           | 7.00<br>5.64      | 8 60  | 11.81         | 41.09   |
| 5       | SD7  | /1      | Minimum  | 4.96               | 0.05                         | 9.02   | 32.04          | 0.53              | 0.00  | 12.23         | 20.69   |
| 5       | SDL  | 41      | maximum  | 9.10               | 1.07                         | 122.83   | 86.15          | 40.72             | 48.49 | 79.66         | 162.43  |
|         |      |         | Mean     | 7.63               | 0.27                         | 35.48  | 68.92          | 12.76             | 18 32 | 32.51         | 86.67   |
|         |      |         | + SD     | 1.03               | 0.21                         | 32.97  | 11.76          | 9.81              | 10.52 | 14 51         | 30.96   |
| 6       | STZ  | 20      | Minimum  | 4 99               | 0.21                         | 9.80   | 15.99          | 1.67              | 2.96  | 9.28          | 20.40   |
| 0       | 512  | 20      | maximum  | 8 49               | 0.37                         | 63.04  | 86.10          | 41.67             | 52.04 | 47.83         | 203 35  |
|         |      |         | Mean     | 6.43               | 0.14                         | 22.73  | 61 37          | 14 46             | 24.17 | 24 39         | 69.22   |
|         |      |         | $\pm$ SD | 1.05               | 0.10                         | 13.76  | 20.69          | 11.60             | 12.01 | 9.89          | 52.63   |
| 7       | NTZ  | 11      | Minimum  | 5.62               | 0.05                         | 25.80  | 22.47          | 17.21             | 1.55  | 20.68         | 130.19  |
|         | 1112 |         | maximum  | 8.49               | 0.78                         | 64.78  | 63.00          | 56.01             | 50.95 | 82.89         | 370.24  |
|         |      |         | Mean     | 7.73               | 0.37                         | 48.24  | 48.25          | 33.99             | 17.76 | 37.11         | 198.85  |
|         |      |         | ± SD     | 0.91               | 0.24                         | 11.24  | 13.84          | 11.67             | 17.88 | 17.68         | 76.96   |
| 8       | HZ   | 34      | Minimum  | 4.95               | 0.03                         | 8.20   | 34.80          | 0.53              | 2.65  | 1.41          | 6.69  |
|         |      |         | maximum  | 8.40               | 0.46                         | 73.70  | 87.69          | 57.45             | 43.44 | 55.06         | 276.32  |
|         |      |         | Mean     | 5.83               | 0.09                         | 25.54  | 63.24          | 18.14             | 18.62 | 25.17         | 52.19   |
|         |      |         | ± SD     | 0.71               | 0.10                         | 15.22  | 14.28          | 11.60             | 10.50 | 13.91         | 59.13   |
| 9       | CZ   | 19      | Minimum  | 4.93               | 0.02                         | 12.80  | 51.30          | 3.04              | 9.63  | 5.27          | 6.99  |
|         |      |         | maximum  | 6.21               | 0.37                         | 28.80  | 84.16          | 27.57             | 30.02 | 26.79         | 32.89   |
|         |      |         | Mean     | 5.37               | 0.06                         | 22.61  | 72.23          | 11.52             | 16.24 | 13.68         | 17.74   |
|         |      |         | ± SD     | 0.36               | 0.08                         | 5.00   | 10.03          | 6.26              | 5.60  | 7.24          | 6.96  |

Table 8: Physico-chemical properties of soil samples collected from different agro climatic zones of Karnataka

NEDZ – North Eastern Dry Zone; NDZ – Northern Dry Zone; CDZ - Central Dry Zone; EDZ - Eastern Dry Zone; SDZ - Southern Dry Zone; STZ - Southern Transition Zone; NTZ - Northern Transition Zone; HZ - Hilly Zone; CZ - Costal Zone; SD – Standard Deviation; \* CEC – Cation exchange capacity; \*\* 0.01M Calcium Chloride extractable Silicon; \*\*\*0.5M Acetic acid extractable Silicon;

The results revealed that sand, silt and clay content of NEDZ soil samples varied from 35.23 - 83.35; 0 - 59.41; 1.90 - 62.30 per cent with mean of 56.95, 31.04 and 12.01 per cent, respectively. The soil samples of NDZ recorded 34.01 – 90.45 per cent of sand, 0.77 - 60.08 per cent of silt, 0.00 - 22.84 per cent of clay with mean of 68.98, 24.01 and 7.01 per cent respectively. The sand, silt and clay content of CDZ soil samples ranged from 39.11 - 82.11, 3.40 - 42.25 and 4.62 - 41.19 per cent with mean of 65.83, 11.47 and 22.70 per cent respectively. The soil samples of SDZ recorded 32.04 - 86.15 per cent of sand, 0.53 - 40.72 per cent of silt and 0.26 - 48.49 per cent of clay with mean of 68.92, 12.76 and 18.32 per cent respectively. Whereas, STZ soil samples recorded 15.99 -86.10, 1.67-41.67 and 2.96 - 52.04 per cent of sand, silt and clay content respectively with mean of 61.37, 14.46 and 24.17 per cent respectively. The sand content in NTZ soil samples ranged from 22.47 - 63.00 per cent with mean value of 48.25 per cent, silt content ranged from 17.21 - 56.01 per cent with mean value of 33.99 per cent and clay content ranged from 1.55 – 50.95 per cent with mean value of 17.76 per cent. The sand content of HZ and CZ soil samples ranged from 34.80 - 87.69 per cent with mean of 63.24 per cent and 51.30 – 84.16 per cent with mean value of 72.23 per cent respectively. The silt content of HZ and CZ soil samples ranged from 0.53 - 57.45 per cent with mean of 18.40 per cent and 3.04 - 27.57 per cent with mean value of 11.52 per cent respectively. The clay content of HZ and CZ soil samples ranged from 2.65 - 43.44 per cent with mean of 18.62 per cent and 9.63 – 30.02 per cent with mean value of 16.24 per cent respectively. The soils dominated with sand fraction are mainly formed *in situ* under conditions of high rainfall in CZ or HZ with alternate dry and wet periods. On account of heavy rainfall there was an excessive leaching of soil colloids and silica hence the soils are porous and sandy in nature.

## 4.1.4 Plant available silicon (PAS)

Plant available silicon (PAS) content of the soil samples were estimated by extracting with 0.01M calcium chloride (CCSi) and 0.5 M acetic acid (AASi) (Table 8). The concentration of CCSi ranged from  $12.77 - 44.63 \text{ mg kg}^{-1}$  with mean of 26.11mg kg<sup>-1</sup> in NEDZ soil samples. NDZ soil samples recorded the CCSi content from 10.27 - 62.92 mg kg<sup>-1</sup> with mean of 34.97 mg kg<sup>-1</sup>. The soil samples of CDZ recorded the CCSi content ranged from  $13.58 - 54.40 \text{ mg kg}^{-1}$  with mean of 26.79 mg kg<sup>-1</sup>. CCSi content in EDZ soils ranged from  $14.55 - 56.18 \text{ mg kg}^{-1}$  with mean of  $34.69 \text{ mg kg}^{-1}$ . STZ soil samples recorded the CCSi content in EDZ soils, it ranged from  $12.23 - 79.66 \text{ mg kg}^{-1}$  with mean of  $32.51 \text{ mg kg}^{-1}$ . STZ soil samples recorded the CCSi content ranged from  $9.28 - 47.83 \text{ mg kg}^{-1}$  with mean of  $24.39 \text{ mg kg}^{-1}$  whereas in NTZ soils it ranged from  $20.68 - 82.89 \text{ mg kg}^{-1}$  with mean of  $37.11 \text{ mg kg}^{-1}$ . Soil samples collected from HZ and CZ had relatively lower CCSi content and ranged from  $1.41 - 55.06 \text{ mg kg}^{-1}$  with mean of  $25.17 \text{ mg kg}^{-1}$  and  $5.27 - 26.79 \text{ mg kg}^{-1}$  with mean of  $13.68 \text{ mg kg}^{-1}$  respectively.

Acetic acid extractable Si concentration (Table 8) of soil samples collected from NEDZ ranged from  $28.02 - 251.41 \text{ mg kg}^{-1}$  with mean of  $95.69 \text{ mg kg}^{-1}$ . In NDZ soil samples, the content of AASi ranged from  $44.61 - 135.21 \text{ mg kg}^{-1}$  with mean of  $88.15 \text{ mg kg}^{-1}$ . In soil samples collected from CDZ the AASi content ranged from  $13.84 - 280.04 \text{ mg kg}^{-1}$  with mean of  $92.62 \text{ mg kg}^{-1}$ . AASi content in EDZ soils ranged from

 $19.41 - 166.04 \text{ mg kg}^{-1}$  with mean of 79.19 mg kg<sup>-1</sup> whereas in SDZ soils it ranged from 20.69 - 162.43 mg kg<sup>-1</sup> with mean of 86.67 mg kg<sup>-1</sup>. The AASi content of STZ soil samples ranged from 20.40 - 203.35 mg kg<sup>-1</sup> with mean of 69.22 mg kg<sup>-1</sup> whereas in NTZ soils it ranged from 130.19 - 370.24 mg kg<sup>-1</sup> with mean of 198.85 mg kg<sup>-1</sup>. Soil samples collected from HZ and CZ recorded relatively lower AASi content and ranged from 6.69 - 276.32 mg kg<sup>-1</sup> with mean of 52.19 mg kg<sup>-1</sup> and 6.99 - 32.89 mg kg<sup>-1</sup> with mean of 17.74 mg kg<sup>-1</sup> respectively.

Among the soils of nine agro climatic zones of Karnataka, 30 to 50 per cent (Fig. 5) of soils were low to medium in plant available Si as extracted by both extractants. Relatively, higher Si content was noticed in soil samples of northern part of Karnataka whereas lower Si was in hilly and coastal zone samples. This may be due to the dominance of black soils with 2:1 type of clay minerals in northern zones of Karnataka.

Plant available Si content in soil mainly depends on the parent material from which soil is formed and extent of clay minerals. Most of this Si present in the form of amorphous or crystalline clay minerals and primary minerals and therefore are high in PAS content. Soil itself contains various Si fractions. Since, weathering and mineral neoformation processes create a great variety of Si fractions in soils they are developed from rocks or sediment sand and mainly composed of primary crystalline silicates such as quartz, feldspars, mica and secondary silicates, especially clay minerals (Iler, 1979; Conley *et al.*, 2005).

In hilly and coastal zones due to high rainfall most of the Si is leached from the soil by the process called desilication and hence resulted in low PAS. Low Si soils are typically highly weathered, leached, acidic and low in base saturation. Thus Oxisols and Ultisols can be quite low in soluble Si (Foy, 1992). Soils comprised mainly of quartz sand (SiO<sub>2</sub>), such as in sandy Entisols, were also very low in PAS (Datnoff et al., 1997). Berthelson et al. (2003) reported that high leaching environment common to the wet tropics, soils undergo significant weathering which, when combined with accelerated chemical and physical degradation due to soil perturbation and crop removal, results in increased soil acidification and dissolution of the aluminosilicate clay minerals which leads to desilication. Weathering releases highly mobile basic cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup>), moderately mobile monosilicic acid [Si(OH)<sub>4</sub>], and relatively immobile Al and Fe into soil solution (Karathanasis, 1989). Part of the Si released from the mineral structure reacts with Al (and to a lesser extent with Fe and Mg) to form secondary clay minerals, while the remainder is subjected to leaching. As a consequence, most soils experience a loss of Si and basic cations during weathering (White and Brantley, 1995). The severe and frequent soil erosion and sediment transportation mainly in hilly and coastal zones owing to high rainfall and coarse texture of soil could lead to desilication and relatively low soil Si. Si depletion in soil due to desilication depend on the stage/duration of soil development, content of weatherable minerals in the parent material, and amount of percolating water. Also intensive cultivation and crop removal can reduce the concentration of potentially available Si to an extent that Si fertilization is necessary (Meunier et al., 2008; Savant et al., 1997).

The variation among the available Si and Si supplying power of the soil can be attributed to cultivation practices followed, cropping system, organic carbon content of the soils, soil reaction, rainfall, parent materials, topography of the land, soil type and nature of the crop residues incorporated (He and Li, 1995; Cai et al., 1997; Korndofer et al., 2001). Land use impacts both biogenic and nonbiogenic Si pools. While biogenic Si strongly decreases along the land use change gradient (from forest to croplands); pedogenic silica fractions (e.g. pedogenic clays) increase in top soils with a long duration of cultivation and soil disturbance. The nonbiogenic Si pools might compensate for the loss of reactive biogenic silicon in temperate zones (Vandevenne et al., 2015). The deficiency or depletion of Si could also be due to continuous rice cultivation, low solubility and / or slow dissolution kinetics of the soil Si (Lindsay, 1979; Drees et al., 1989), high uptake of Si by rice crops (Savant et al., 1997), limited attempts by farmers to recycle Si in crop residues and / or application of balanced fertilizer that include Si sources. Nayar et al. (1982) reported 5 out of 9 soils were deficient in Si content mostly belonging to red and lateritic groups. At present, there is no national database on Si availability in Indian soils although it is available in other countries of the world. It is apparent from the reviewed literature (Prakash, 2002) that most of the paddy soils studied was deficient in Si.

In general, AASi was found to be higher than that of CCSi. This was mainly attributed to the extracting power of the individual extractant, soil to solution ratio used for analysis, pH of the extractant and forms of Si, which they extract (Nayar *et al.*, 1977). It has been reported that acid extractants can remove very large amount of Si (Haynes *et al.*, 2013). When acid extractants are used, they remove OH<sup>-</sup> ions from solution and can extract unrealistically large amount of Si (Haynes, 2014; Kato and Owa, 1996). Near neutral extractants such as 0.01M CaCl<sub>2</sub> solution was used by many workers to estimate readily soluble fraction of Si (Fox *et al.*, 1967; Khalid *et al.*, 1978; Haysom and Chapman, 1975). A large group of soils studied in a region of a South Africa, generally had a positive relationship between pH and Si solubility and extractability (Miles *et al.*, 2014).

# 4.1.2 Relationship between physico-chemical properties and Si content of soils of different agro climatic zones of Karnataka

Pearson's correlation coefficient (r) were worked out for soil analytical data such as pH, EC, plant available silicon (0.1M Calcium chloride extractable Si - CCSi, 0.5M Acetic acid extractable Si - AASi), mechanical analysis (sand, silt, clay) and cation exchange capacity and are presented in Table 9 to 17.

Perusal of data revealed that there was both significant and nonsignificant relationship between the soil properties of different agro climatic zones. Soil pH had positive and significant correlation with EC of SDZ (r = 0.570), STZ (r = 0.770), HZ (r = 0.606) soil samples, CCSi of HZ (r = 0.580) soil samples and AASi content of majority of soil samples representing CDZ (r = 0.640), EDZ (r = 0.707), SDZ (r = 0.573), STZ (r = 0.664), HZ (r = 0.893) and CZ (r = 0.496). There was also positive and significant correlation between pH and silt in EDZ (r = 0.531), SDZ (r = 0.440) and HZ (r = 0.382)



Fig 4: Status of pH and EC of soil samples of different agro climatic zones



Fig. 5: Status of plant available Si in soil samples of different agro climatic zones

soil samples and CEC of STZ (r = 0.825) and HZ (r = 0.679) soil samples. The relationship between pH and sand content was found to be significant and negatively correlated. Most of the soil sample collected from different agro climatic zones of Karnataka recorded significantly positive correlation for soil pH, Si content, silt and CEC and negatively correlated with sand content. This might be due to influence of one property on the behavior of other soil properties. For example, soil samples with higher soil pH contain relatively higher Si content, clay and CEC whereas soils with lower pH had lower Si content and higher sand content. In most of the zones soil pH was significantly correlated with Si concentration in soil was affected by the Si solubility and environmental conditions such as pH, redox potential and temperature. Dietzel (2000) reported that dissolution of silicates could be neglected in the range of pH 2.5 to 8.5. However, in strong alkaline conditions (pH>9), part of the Si monomers transforms to polymers, and dissolved Si (DSi) concentrations in soil solution increased almost exponentially with pH as a result of growing speciation to H<sub>3</sub>SiO<sub>4</sub><sup>-</sup>and H<sub>2</sub>SiO<sub>4</sub><sup>2-</sup>.

In a large group of soils studied, there exists generally a positive relationship between pH and Si solubility and extractability (Fox *et al.*, 1967; Cheong *et al.*, 1968; Oya and Kina, 1989; Oya *et al.*, 1989; Miles *et al.*, 2014). Oliveira *et al.* (2007), Korndorfer *et al.* (2005) and Camargo *et al.* (2007) further explained that the concentration of available soil Si (whether native Si or added as an amendment) decreased with increasing soil acidity due to decreased dissolution of Si in soil. According to Oliveira *et al.* (2005), increase in soil pH from 4.5 to 6.0 promoted release of colloid-adsorbed Si to the soil solution and there was an increase in available Si. Solubility and bioavailability of native soil Si or applied Si fertilizers mainly depends on the surface properties like pH, soil constituents and type of soil. The solubility of pure silica in water is independent of pH (Lindsay, 1979), but in soil, dissolution decreases with increasing pH up to 8 - 9 due to changes in adsorption and then rapidly increases due to the formation of silicate ions (Beckwith and Reeve, 1964). Temperature, redox conditions, other anions and organic matter content also influence dissolution.

Plant available Si extracted by calcium chloride (CCSi) had positive and significant correlation with clay content of NTZ (r = 0.645) and CZ (r = 0.571) soil samples, CEC of CDZ (r = 0.650) HZ (r = 0.630) soil samples. Whereas AASi content had positive and significant correlation with CEC of CDZ (r = 0.611), SDZ (r = 0.388), STZ (r = 0.585) and HZ (r = 0.775) soil samples, silt content of EDZ (r = 0.638), SDZ (r = 0.361), HZ (r = 0.462) soil samples. Irrespective of the soil samples representing different zones, CCSi had positive correlation with AASi. Si content analysed by both methods had significant and negative correlation with sand content of the soil samples. There was good correlation between Si content with clay and CEC. This may be due to the fact that majority of the clay minerals or clays can act as major source of Si in the soil besides influencing CEC of the soil. The major Si phases in soil are primary minerals inherited from parent material and secondary minerals resulting from soil formation.

| Ducucation                       |        | E.C.                         | CCSi                   | AASi                   | Sand    | Silt    | Clay    | CEC                           |
|----------------------------------|--------|------------------------------|------------------------|------------------------|---------|---------|---------|-------------------------------|
| Properues                        | рп     | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (%)     | (%)     | (%)     | (cmol (p+) kg <sup>-1</sup> ) |
| рН                               | 1      |                              |                        |                        |         |         |         |                               |
| E.C. (dSm <sup>-1</sup> )        | 0.273  | 1                            |                        |                        |         |         |         |                               |
| CCSi (mg kg <sup>-1</sup> )      | 0.098  | -0.283                       | 1                      |                        |         |         |         |                               |
| AASi (mg kg <sup>-1</sup> )      | 0.357  | 0.291                        | -0.167                 | 1                      |         |         |         |                               |
| Sand (%)                         | 0.538* | -0.210                       | 0.004                  | -0.146                 | 1       |         |         |                               |
| Silt (%)                         | 0.244  | 0.197                        | -0.082                 | 0.127                  | -0.690* | 1       |         |                               |
| <b>Clay</b> (%)                  | 0.234  | -0.049                       | 0.108                  | -0.021                 | -0.110  | -0.644* | 1       |                               |
| CEC (cmol(p+) kg <sup>-1</sup> ) | 0.390  | 0.054                        | -0.083                 | -0.033                 | -0.363  | 0.642*  | -0.498* | 1                             |

 Table 9: Pearson's correlation coefficient for pH, EC, plant available silicon, particle size distribution and CEC of north eastern dry zone soil samples

\*Significant at p≤0.05; CCSi- 0.01M Calcium Chloride extractable Silicon; AASi- 0.5M Acetic acid extractable Silicon; CEC –Cation exchange capacity

|   | Biogeochemistry |
|---|-----------------|
|   | Q               |
|   | silicon         |
|   | Ħ.              |
|   | different       |
|   | nice            |
| • | ecosyst         |
|   | ems             |
|   | of              |
|   | Karnataka       |

| Properties                               | TT      | E.C.                         | CCSi                   | AASi                   | Sand    | Silt   | Clay  | CEC                          |
|--|---------|------------------------------|------------------------|------------------------|---------|--------|-------|------------------------------|
|  | рп      | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (%)     | (%)    | (%)   | (cmol(p+) kg <sup>-1</sup> ) |
| рН                                       | 1       |                              |                        |                        |         |        |       |                              |
| <b>E.C.</b> ( <b>dSm</b> <sup>-1</sup> ) | 0.252   | 1                            |                        |                        |         |        |       |                              |
| CCSi (mg kg <sup>-1</sup> )              | -0.312  | -0.279                       | 1                      |                        |         |        |       |                              |
| AASi (mg kg <sup>-1</sup> )              | -0.260  | 0.035                        | 0.144                  | 1                      |         |        |       |                              |
| Sand (%)                                 | -0.475* | 0.028                        | 0.439                  | 0.098                  | 1       |        |       |                              |
| <b>Silt</b> (%)                          | 0.397   | -0.038                       | -0.385                 | 0.100                  | -0.923* | 1      |       |                              |
| <b>Clay</b> (%)                          | 0.110   | 0.031                        | -0.054                 | -0.497*                | -0.003  | -0.382 | 1     |                              |
| CEC (cmol(p+) kg <sup>-1</sup> )         | 0.148   | -0.119                       | 0.179                  | -0.109                 | -0.156  | 0.041  | 0.268 | 1                            |

 Table 10: Pearson's correlation coefficient for pH, EC, plant available silicon, particle size distribution and CEC of northern dry zone soil samples

\* Significant at p $\leq$ 0.05; CCSi- 0.01M Calcium Chloride extractable Silicon; AASi- 0.5M Acetic acid extractable Silicon; CEC – Cation exchange capacity

| Dronarties                               | ъЦ     | E.C.                         | CCSi                   | AASi                   | Sand    | Silt   | Clay   | CEC                          |
|--|--------|------------------------------|------------------------|------------------------|---------|--------|--------|------------------------------|
| rioperues                                | рп     | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (%)     | (%)    | (%)    | (cmol(p+) kg <sup>-1</sup> ) |
| pH                                       | 1      |                              |                        |                        |         |        |        |                              |
| <b>E.C.</b> ( <b>dSm</b> <sup>-1</sup> ) | 0.557* | 1                            |                        |                        |         |        |        |                              |
| CCSi (mg kg <sup>-1</sup> )              | 0.411  | 0.148                        | 1                      |                        |         |        |        |                              |
| AASi (mg kg <sup>-1</sup> )              | 0.640* | 0.074                        | 0.770*                 | 1                      |         |        |        |                              |
| Sand (%)                                 | -0.163 | 0.058                        | -0.460                 | -0.416                 | 1       |        |        |                              |
| Silt (%)                                 | 0.021  | 0.244                        | 0.284                  | 0.088                  | -0.637* | 1      |        |                              |
| <b>Clay</b> (%)                          | 0.193  | -0.288                       | 0.349                  | 0.463                  | -0.741* | -0.045 | 1      |                              |
| CEC (cmol(p+) kg <sup>-1</sup> )         | 0.415  | 0.043                        | 0.650*                 | 0.611*                 | -0.691* | 0.431  | 0.520* | 1                            |

 Table 11: Pearson's correlation coefficient for pH, EC, plant available silicon, particle size distribution and CEC of central dry zone soil samples

\* Significant at p $\leq$ 0.05; CCSi- 0.01M Calcium Chloride extractable Silicon; AASi- 0.5M Acetic acid extractable Silicon; CEC – Cation exchange capacity

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| Properties                       | лЦ     | E.C.                         | CCSi                   | AASi                   | Sand    | Silt   | Clay   | CEC                          |
|----------------------------------|--------|------------------------------|------------------------|------------------------|---------|--------|--------|------------------------------|
| rioperties                       | pm     | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (%)     | (%)    | (%)    | (cmol(p+) kg <sup>-1</sup> ) |
| рН                               | 1      |                              |                        |                        |         |        |        |                              |
| E.C. (dSm <sup>-1</sup> )        | 0.468  | 1                            |                        |                        |         |        |        |                              |
| CCSi (mg kg <sup>-1</sup> )      | 0.434  | 0.112                        | 1                      |                        |         |        |        |                              |
| AASi (mg kg <sup>-1</sup> )      | 0.707* | 0.301                        | 0.741*                 | 1                      |         |        |        |                              |
| Sand (%)                         | -0.285 | -0.092                       | -0.435                 | -0.592*                | 1       |        |        |                              |
| Silt (%)                         | 0.531* | 0.233                        | 0.368                  | 0.638*                 | -0.455  | 1      |        |                              |
| <b>Clay</b> (%)                  | -0.032 | -0.050                       | 0.242                  | 0.239                  | -0.812* | -0.151 | 1      |                              |
| CEC (cmol(p+) kg <sup>-1</sup> ) | 0.479  | 0.043                        | 0.049                  | 0.411                  | -0.640* | 0.320  | 0.500* | 1                            |

 Table 12: Pearson's correlation coefficient for pH, EC, plant available silicon, particle size distribution and CEC of eastern dry zone soil samples

\* Significant at p $\leq$ 0.05; CCSi- 0.01M Calcium Chloride extractable Silicon; AASi- 0.5M Acetic acid extractable Silicon; CEC – Cation exchange capacity

| Dronaution                               | лU     | E.C.                         | CCSi                   | AASi                   | Sand    | Silt    | Clay  | CEC                          |
|--|--------|------------------------------|------------------------|------------------------|---------|---------|-------|------------------------------|
| rioperties                               | рп     | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (%)     | (%)     | (%)   | (cmol(p+) kg <sup>-1</sup> ) |
| рН                                       | 1      |                              |                        |                        |         |         |       |                              |
| <b>E.C.</b> ( <b>dSm</b> <sup>-1</sup> ) | 0.570* | 1                            |                        |                        |         |         |       |                              |
| CCSi (mg kg <sup>-1</sup> )              | -0.051 | 0.048                        | 1                      |                        |         |         |       |                              |
| AASi (mg kg <sup>-1</sup> )              | 0.573* | 0.291                        | 0.256                  | 1                      |         |         |       |                              |
| <b>Sand</b> (%)                          | -0.264 | -0.235                       | 0.189                  | -0.460*                | 1       |         |       |                              |
| Silt (%)                                 | 0.440* | 0.220                        | -0.113                 | 0.361*                 | -0.529* | 1       |       |                              |
| <b>Clay</b> (%)                          | -0.114 | 0.058                        | -0.105                 | 0.176                  | -0.619* | -0.339* | 1     |                              |
| CEC (cmol(p+) kg <sup>-1</sup> )         | 0.535  | 0.372*                       | -0.013                 | 0.388*                 | -0.349* | 0.308   | 0.102 | 1                            |

 Table 13: Pearson's correlation coefficient for pH, EC, plant available silicon, particle size distribution and CEC of southern dry zone soil samples

\* Significant at p $\leq$ 0.05; CCSi- 0.01M Calcium Chloride extractable Silicon; AASi- 0.5M Acetic acid extractable Silicon; CEC – Cation exchange capacity

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|  |        | E.C.                         | CCSi                   | AASi                   | Sand    | Silt   | Clay  | CEC                          |
|--|--------|------------------------------|------------------------|------------------------|---------|--------|-------|------------------------------|
| Properties                               | pН     | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (%)     | (%)    | (%)   | (cmol(p+) kg <sup>-1</sup> ) |
| рН                                       | 1      |                              |                        |                        |         |        |       |                              |
| <b>E.C.</b> ( <b>dSm</b> <sup>-1</sup> ) | 0.770* | 1                            |                        |                        |         |        |       |                              |
| CCSi (mg kg <sup>-1</sup> )              | -0.025 | -0.286                       | 1                      |                        |         |        |       |                              |
| AASi (mg kg <sup>-1</sup> )              | 0.664* | 0.585*                       | 0.228                  | 1                      |         |        |       |                              |
| Sand (%)                                 | -0.103 | -0.197                       | -0.058                 | -0.153                 | 1       |        |       |                              |
| Silt (%)                                 | -0.079 | 0.207                        | -0.145                 | -0.043                 | -0.871* | 1      |       |                              |
| <b>Clay</b> (%)                          | 0.253  | 0.139                        | 0.241                  | 0.305                  | -0.881* | 0.535* | 1     |                              |
| CEC (cmol(p+) kg <sup>-1</sup> )         | 0.825* | 0.716*                       | -0.172                 | 0.585*                 | -0.217  | 0.041  | 0.334 | 1                            |

 Table 14: Pearson's correlation coefficient for pH, EC, plant available silicon, particle size distribution and CEC of southern transition zone soil samples

\* Significant at p≤0.05; CCSi- 0.01M Calcium Chloride extractable Silicon; AASi- 0.5M Acetic acid extractable Silicon; CEC – Cation exchange capacity

| Duonoution                               | "IJ     | E.C.                         | CCSi                   | AASi                   | Sand    | Silt    | Clay   | CEC                          |
|--|---------|------------------------------|------------------------|------------------------|---------|---------|--------|------------------------------|
| Properues                                | рп      | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (%)     | (%)     | (%)    | (cmol(p+) kg <sup>-1</sup> ) |
| рН                                       | 1       |                              |                        |                        |         |         |        |                              |
| <b>E.C.</b> ( <b>dSm</b> <sup>-1</sup> ) | 0.568   | 1                            |                        |                        |         |         |        |                              |
| CCSi (mg kg <sup>-1</sup> )              | -0.934* | -0.614*                      | 1                      |                        |         |         |        |                              |
| AASi (mg kg <sup>-1</sup> )              | -0.021  | 0.291                        | -0.063                 | 1                      |         |         |        |                              |
| Sand (%)                                 | 0.534   | 0.471                        | -0.511                 | 0.543                  | 1       |         |        |                              |
| Silt (%)                                 | 0.566   | 0.466                        | -0.382                 | -0.351                 | -0.026  | 1       |        |                              |
| <b>Clay</b> (%)                          | -0.783* | -0.669*                      | 0.645*                 | -0.192                 | -0.758* | -0.633* | 1      |                              |
| CEC (cmol(p+) kg <sup>-1</sup> )         | 0.376   | -0.016                       | -0.342                 | 0.182                  | 0.028   | 0.030   | -0.042 | 1                            |

 Table 15: Pearson's correlation coefficient for pH, EC, plant available silicon, particle size distribution and CEC of northern transition zone soil samples

\* Significant at p $\leq$ 0.05; CCSi- 0.01M Calcium Chloride extractable Silicon; AASi- 0.5M Acetic acid extractable Silicon; CEC – Cation exchange capacity

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| Duonoution                       | nII     | E.C.                         | CCSi                   | AASi                   | Sand    | Silt   | Clay  | CEC<br>(cmol(p+) kg <sup>-1</sup> ) |  |
|----------------------------------|---------|------------------------------|------------------------|------------------------|---------|--------|-------|-------------------------------------|--|
| Properties                       | рп      | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (%)     | (%)    | (%)   |                                     |  |
| рН                               | 1       |                              |                        |                        |         |        |       |                                     |  |
| E.C. (dSm <sup>-1</sup> )        | 0.606*  | 1                            |                        |                        |         |        |       |                                     |  |
| CCSi (mg kg <sup>-1</sup> )      | 0.580*  | 0.497*                       | 1                      |                        |         |        |       |                                     |  |
| AASi (mg kg <sup>-1</sup> )      | 0.893*  | 0.751*                       | 0.682*                 | 1                      |         |        |       |                                     |  |
| <b>Sand</b> (%)                  | -0.342* | -0.219                       | -0.328                 | -0.381*                | 1       |        |       |                                     |  |
| Silt (%)                         | 0.382*  | 0.369*                       | 0.549*                 | 0.462*                 | -0.689* | 1      |       |                                     |  |
| <b>Clay</b> (%)                  | 0.043   | -0.111                       | -0.160                 | 0.009                  | -0.599* | -0.168 | 1     |                                     |  |
| CEC (cmol(p+) kg <sup>-1</sup> ) | 0.679*  | 0.497*                       | 0.630*                 | 0.775*                 | -0.299  | 0.334  | 0.037 | 1                                   |  |

 Table 16: Pearson's correlation coefficient for pH, EC, plant available silicon, particle size distribution and CEC of hilly zone soil samples

\* Significant at p≤0.05; CCSi- 0.01M Calcium Chloride extractable Silicon; AASi- 0.5M Acetic acid extractable Silicon; CEC – Cation exchange capacity

| Duanautias                       | TT     | E.C.                         | CCSi                   | AASi                   | Sand    | Silt  | Clay  | CEC                          |  |
|----------------------------------|--------|------------------------------|------------------------|------------------------|---------|-------|-------|------------------------------|--|
| Properues                        | рп     | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) | (%)     | (%)   | (%)   | (cmol(p+) kg <sup>-1</sup> ) |  |
| рН                               | 1      |                              |                        |                        |         |       |       |                              |  |
| E.C. (dSm <sup>-1</sup> )        | 0.005  | 1                            |                        |                        |         |       |       |                              |  |
| CCSi (mg kg <sup>-1</sup> )      | 0.197  | -0.259                       | 1                      |                        |         |       |       |                              |  |
| AASi (mg kg <sup>-1</sup> )      | 0.496* | -0.240                       | 0.664*                 | 1                      |         |       |       |                              |  |
| <b>Sand</b> (%)                  | 0.185  | 0.320                        | -0.610*                | -0.322                 | 1       |       |       |                              |  |
| <b>Silt</b> (%)                  | -0.318 | -0.249                       | 0.467*                 | 0.244                  | -0.864* | 1     |       |                              |  |
| <b>Clay</b> (%)                  | 0.023  | -0.296                       | 0.571*                 | 0.304                  | -0.827* | 0.432 | 1     |                              |  |
| CEC (cmol(p+) kg <sup>-1</sup> ) | 0.097  | -0.198                       | 0.260                  | 0.368                  | -0.201  | 0.185 | 0.153 | 1                            |  |

 Table 17: Pearson's correlation coefficient for pH, EC, plant available silicon, particle size distribution and CEC of coastal zone soil samples

\* Significant at p $\leq$ 0.05; CCSi- 0.01M Calcium Chloride extractable Silicon; AASi- 0.5M Acetic acid extractable Silicon; CEC – Cation exchange capacity

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Transformation between crystalline phases (mainly clay minerals) and microcrystalline to poorly ordered phases (Drees *et al.*, 1989; Monger and Kelly, 2002) controlled by pH, temperature, presence of cations, and organic compounds, with water as the main medium for Si fluxes in terrestrial biogeosystems. There are also reports that the amount of available Si in soils was affected by the clay content (Schwandes *et al.*, 2001; Takahashi and Sato, 2000) and by the parent material of the soil (Imaizumi and Yoshida, 1958), suggesting that the amount of available Si could be influenced by the mineral composition and particle size. Takahashi and Sato (2000) reported that the amount of available Si in paddy soils in the Hachirogata Reclaimed Land area of Japan was positively correlated with the amount of clay when the clay fraction was <290 g kg<sup>-1</sup>. Schwandes *et al.* (2001) reported that the amount of available Si in soils of Ultisols in Florida, USA, was affected by the size of the clay fraction if the clay fraction was <150 g kg<sup>-1</sup>. These reports indicate that the size of the clay fraction was also related to the amount of available Si in the soil.

In the present investigation, Si content of the soil samples of all zones were negatively correlated with the sand content. The amount of available Si in the soil decreased with increase in the sand fraction. Sand consists basically of quartz minerals and in spite of having high SiO<sub>2</sub> content in its composition, has a low Si release potential in the short and medium term. Thus sand fraction of a soil is practically inert. Sandy soils normally have good drainage, which prevents Si accumulation. Gontijo (2000) studied soils of different locations and with different textures, and observed that soil Si values decreased as sand values increased. He (1993) reported that soils derived from red earth with lower pH and lighter soil texture were deficient in available Si, while paddy soil with higher pH and heavier soil texture contains high amount of Si. Quartz has a solubility of 36 - 250  $\mu$  molL<sup>-1</sup> in water depending on particle size and temperature. Due to surface coatings on quartz grains (Fe oxides, organic matter); the lower value is more realistic for quartz in soils (Sommer *et al.*, 2006).

## 4.1.3 Total elemental composition and mineralogical properties of selected soil samples (n=40) of different agro climatic zones of Karnataka

Among 200 soil samples collected from nine agro climatic zones of Karnataka, 40 samples were selected for detailed studies such as analysis of total elemental composition and mineralogical properties by XRD analysis. The number of soil samples selected from North Eastern Dry Zone (NEDZ), Northern Dry Zone (NDZ), Central Dry Zone (CDZ), Eastern Dry Zone (EDZ), Southern Dry Zone (SDZ), Southern Transition Zone (STZ), Northern Transition Zone (NTZ), Hilly Zone (HZ) and Coastal Zone (CZ) were 4, 3, 3, 3, 6, 4, 3, 9 and 5 respectively. Details of the soil samples selected and their physico-chemical properties (for pH, EC, plant available silicon (0.1M Calcium chloride extractable Si - CCSi, 0.5M Acetic acid extractable Si - AASi), mechanical analysis (Sand, silt, clay), cation exchange capacity and organic carbon) are given in Annexure III. The total elemental composition (Table 18) and mineralogical properties (Table 19 and Fig. 6 to 16) varied among the soil samples selected from nine agro climatic zones are described below:

#### 4.1.3.1 North Eastern Dry Zone (NEDZ)

The elemental composition of NEDZ soil samples was in the order of SiO<sub>2</sub> (59.31 – 74.66 %) > Al<sub>2</sub>O<sub>3</sub> (10.72 – 13.79 %) > Fe<sub>2</sub>O<sub>3</sub> (1.97 – 6.23 %) > CaO (0.98 – 5.76 %) > K<sub>2</sub>O (1.54 – 4.21 %) > Na<sub>2</sub>O (0.77 – 3.17 %) > TiO<sub>2</sub> (0.26 – 2.71 %) > MgO (0.46 – 2.21 %) > P<sub>2</sub>O<sub>5</sub> (0.05 – 0.19 %) > BaO (0.04 – 0.16 %) > MnO (0.01-0.16 %) > SrO ( 0.02 – 0.08 %) > SO<sub>3</sub> (0.03 – 0.07 %) > Cr<sub>2</sub>O<sub>3</sub> ( <0.01 – 0.01 %).

There was almost similar mineralogical composition found among the soil samples of NEDZ (Table 19 and Fig. 6). The dominant primary minerals were quartz > feldspar > muscovite followed by amphibole and among the secondary clay minerals kaolinite was dominated followed by vermiculite and smectite as revealed by XRD analysis.

#### 4.1.3.2 Northern Dry Zone (NDZ)

The soil samples collected from NDZ recorded elemental composition in the order of SiO<sub>2</sub> (70.71 –77.19 %) > Al<sub>2</sub>O<sub>3</sub> (9.55 – 10.48 %) > K<sub>2</sub>O (1.62 - 4.08 %) > CaO (0.83 – 3.26 %) > Fe<sub>2</sub>O<sub>3</sub> (1.87 – 3.21 %) > Na<sub>2</sub>O (0.70 – 2.47 %) > MgO (0.35 – 1.32 %) > TiO<sub>2</sub> (0.19 – 0.43 %) > BaO (0.03 – 0.07 %) > SO<sub>3</sub> (0.04 – 0.07 %) > P<sub>2</sub>O<sub>5</sub> (0.04 – 0.06 %) > MnO (0.02 – 0.05 %) > SrO (0.02 %) > Cr<sub>2</sub>O<sub>3</sub> (<0.01 – 0.01 %).

X-ray diffraction revealed that primary minerals such as quartz, feldspars dominated followed by muscovite and amphibole (Table 19 and Fig. 7). Secondary clay minerals such as kaolinite / smectite / vermiculite were dominated in NDZ - 1 and 3 soil samples, whereas no secondary clay mineral was found in NDZ – 2 soil sample.

## 4.1.3.3 Central Dry Zone (CDZ)

 $\begin{array}{l} \mbox{The soil samples representing CDZ recorded elemental composition in the order} \\ \mbox{of } SiO_2\,(54.50-87.60~\%) > Al_2O_3\,(5.38-9.75~\%) > Fe_2O_3\,(2.71-9.17~\%) > CaO\,(0.45-8.83~\%) > MgO\,(0.31-2.93~\%) > Na_2O\,(0.44-0.78~\%) > K_2O\,(0.43-0.72~\%) > TiO_2\,(0.34-0.58~\%) > P_2O_5\,(0.06-0.18~\%) > MnO\,(0.04-0.13~\%) > SO_3\,(0.02-0.05~\%) > Cr_2O_3\,(<0.02-0.03~\%) > SrO\,(<0.01-0.02~\%) > BaO\,(<0.01-0.02~\%). \end{array}$ 

Quartz and feldspars were dominated in three soils whereas CDZ - 1 soil recorded presence of amphibole (Table 19 and Fig. 8). Among the secondary clay minerals, kaolinite was present in all soils followed by smectite/ vermiculite whereas CDZ-3 soil recorded presence of chlorite and mica/illite.

## 4.1.3.4 Eastern Dry Zone (EDZ)

Eastern dry zone soil samples noticed elemental composition in the order of SiO<sub>2</sub> (70.5 –77.30 %) > Al<sub>2</sub>O<sub>3</sub> (11.25 – 14.70 %) > K<sub>2</sub>O (2.21 – 5.00 %) > Fe<sub>2</sub>O<sub>3</sub> (1.43 – 3.26 %) > Na<sub>2</sub>O (1.20 – 2.34 %) > CaO (0.49 – 2.55 %) > TiO<sub>2</sub> (0.17 – 0.68 %) > MgO (0.16 –

 $0.63 \ \%$  > P<sub>2</sub>O<sub>5</sub> (0.04 - 0.12 %) > BaO (0.06 - 0.09 %) > MnO (0.02 - 0.06 %) > SO<sub>3</sub> (0.01 - 0.05 %) > SrO (< 0.01 - 0.02 %) > Cr<sub>2</sub>O<sub>3</sub> (<0.01 - 0.01 %).

The primary minerals such as quartz, feldspars were found in all the soil samples, whereas muscovite and amphibole were present in EDZ - 2 and 3 soils respectively (Table 19 and Fig. 9). All the three samples had koilinite clay mineral, whereas 10Å phyllosilicates in EDZ - 1, chlorite in EDZ - 2 and illite and smectite in EDZ - 3 soil samples.

#### 4.1.3.5 Southern Dry Zone (SDZ)

The elemental composition of SDZ soil samples was in the order of SiO<sub>2</sub> (65.10 – 73.30 %) > Al<sub>2</sub>O<sub>3</sub> (10.75 – 13.35 %) > Fe<sub>2</sub>O<sub>3</sub> (2.44 – 6.33 %) > K<sub>2</sub>O (0.52 – 3.97 %) > CaO (1.02 – 3.11 %) > Na<sub>2</sub>O (1.09 – 2.44 %) > MgO (0.52 – 2.14 %) > TiO<sub>2</sub> (0.25 – 1.09 %) > P<sub>2</sub>O<sub>5</sub> (0.07 – 0.14 %) > BaO (<0.01 – 0.07 %) > MnO (0.02 – 0.10 %) > SO<sub>3</sub> (0.02 – 0.06 %) > SrO ( 0.01 - 0.03 %) > Cr<sub>2</sub>O<sub>3</sub> ( 0.01 – 0.04 %).

Among the primary minerals, quartz and feldspars were dominant in all the six soil samples, whereas amphibole in SDZ - 1, 2, 3 and 4; muscovite in SDZ - 1 soil sample (Table 19 and Fig. 10 & 11). Among the secondary clay minerals, smectite (SDZ - 1 and 2) followed by kaolinite (SDZ - 1, 2 and 3) and vermiculite (SDZ - 4, 5) recorded in respective soil samples. 10 Å and 14Å phyllosilicates was found in SDZ - 2, whereas only 14Å phyllosilicates was found in SDZ - 4 and 5. Illite and gibbsite were found in SDZ - 3 and 6 soil samples respectively.

#### 4.1.3.6 Southern Transition Zone (STZ)

The total elemental composition of the soils representing STZ was in the order of SiO<sub>2</sub> (55.00 -82.70 %) > Al<sub>2</sub>O<sub>3</sub> (8.16 - 12.90 %) > CaO (0.58 - 9.39 %) > Fe<sub>2</sub>O<sub>3</sub> (2.42 - 9.20 %) > K<sub>2</sub>O (0.77 - 2.60 %) > Na<sub>2</sub>O (0.40 - 1.42 %) > MgO (0.21 - 1.06 %) > TiO<sub>2</sub> (0.39 - 0.84 %) > MnO (0.03 - 0.19 %) > P<sub>2</sub>O<sub>5</sub> (0.05 - 0.09 %) > BaO (<0.02 - 0.07 %) > SO<sub>3</sub> (0.03 - 0.11 %) > Cr<sub>2</sub>O<sub>3</sub> (0.01 - 0.04 %) > SrO (<0.01 - 0.02 %).

Quartz and feldspars were found in all the soil samples whereas amphibole was present only in STZ - 1 soil sample (Table 19 and Fig. 12). Among the secondary clay minerals kaolinite was found in STZ - 2, 3, 4 samples; 10 Å phyllosilicates in STZ - 1 and 2; smectite in STZ - 3 and 4; vermiculite in STZ - 2 soil sample.

#### 4.1.3.7 Northern Transition Zone (NTZ)

The NTZ soil samples recorded the elemental composition in the order of SiO<sub>2</sub> (45.71 – 66.60 %) > Al<sub>2</sub>O<sub>3</sub> (13.00 – 18.21 %) > Fe<sub>2</sub>O<sub>3</sub> (7.30 – 16.62 %) > TiO<sub>2</sub> (0.72 – 3.23 %) > CaO (0.56 – 1.87 %) > MgO (0.66 – 1.67 %) > K<sub>2</sub>O (0.30 – 1.16 %) > Na<sub>2</sub>O (0.09– 1.08 %) > MnO (0.06 – 0.18 %) > P<sub>2</sub>O<sub>5</sub> (0.14 – 0.17 %) > SO<sub>3</sub> (0.04 – 0.09 %) > BaO (0.01 – 0.03 %) > Cr<sub>2</sub>O<sub>3</sub> (0.02 – 0.04 %) > SrO (<0.01 - 0.02 %).

| SI. | Sl- ID    | Al <sub>2</sub> O <sub>3</sub> | BaO    | CaO  | Cr <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | MgO  | MnO  | Na <sub>2</sub> O | P <sub>2</sub> O <sub>5</sub> | SO <sub>3</sub> | SiO <sub>2</sub> | SrO    | TiO <sub>2</sub> | Total | LOI*  |
|-----|-----------|--------------------------------|--------|------|--------------------------------|--------------------------------|------------------|------|------|-------------------|-------------------------------|-----------------|------------------|--------|------------------|-------|-------|
| No. | Sample ID |                                |        |      |                                |                                |                  |      |      | per cent          |                               |                 |                  |        |                  |       |       |
| 1   | NEDZ-1    | 13.79                          | 0.08   | 4.45 | 0.01                           | 3.33                           | 2.75             | 1.55 | 0.05 | 3.17              | 0.05                          | 0.04            | 64.22            | 0.08   | 0.40             | 93.97 | 6.03  |
| 2   | NEDZ -2   | 12.19                          | 0.16   | 1.38 | < 0.01                         | 6.23                           | 3.81             | 0.49 | 0.15 | 1.54              | 0.19                          | 0.03            | 66.23            | 0.03   | 2.71             | 95.14 | 4.86  |
| 3   | NEDZ-3    | 10.72                          | 0.06   | 0.98 | 0.01                           | 1.97                           | 4.21             | 0.46 | 0.01 | 1.08              | 0.17                          | 0.06            | 74.66            | 0.02   | 0.26             | 94.67 | 5.33  |
| 4   | NEDZ-4    | 12.93                          | 0.04   | 5.76 | 0.01                           | 5.63                           | 1.54             | 2.21 | 0.16 | 0.77              | 0.12                          | 0.07            | 59.31            | 0.02   | 0.84             | 89.41 | 10.59 |
| 5   | NDZ -1    | 13.8                           | 0.05   | 1.69 | < 0.01                         | 2.35                           | 2.32             | 0.35 | 0.02 | 2.47              | 0.06                          | 0.04            | 70.71            | 0.02   | 0.26             | 94.14 | 5.86  |
| 6   | NDZ -2    | 10.48                          | 0.07   | 0.83 | < 0.01                         | 1.87                           | 4.08             | 0.42 | 0.04 | 1.55              | 0.04                          | 0.06            | 77.19            | 0.02   | 0.19             | 96.84 | 3.16  |
| 7   | NDZ -3    | 9.55                           | 0.03   | 3.26 | 0.01                           | 3.21                           | 1.62             | 1.32 | 0.05 | 0.70              | 0.04                          | 0.07            | 72.56            | 0.02   | 0.43             | 92.87 | 7.13  |
| 8   | CDZ -1    | 5.38                           | < 0.01 | 0.45 | 0.03                           | 2.71                           | 0.43             | 0.31 | 0.04 | 0.44              | 0.06                          | 0.02            | 87.60            | < 0.01 | 0.34             | 97.81 | 2.19  |
| 9   | CDZ -2    | 8.25                           | 0.01   | 0.65 | 0.02                           | 4.30                           | 0.55             | 0.46 | 0.06 | 0.60              | 0.18                          | 0.04            | 79.80            | 0.01   | 0.46             | 95.39 | 4.61  |
| 10  | CDZ -3    | 9.75                           | 0.02   | 8.83 | 0.02                           | 9.17                           | 0.72             | 2.93 | 0.13 | 0.78              | 0.06                          | 0.05            | 54.50            | 0.02   | 0.58             | 87.56 | 12.44 |
| 11  | EDZ -1    | 11.25                          | 0.09   | 0.49 | < 0.01                         | 1.43                           | 4.49             | 0.16 | 0.02 | 1.20              | 0.04                          | 0.01            | 77.30            | 0.02   | 0.17             | 96.67 | 3.33  |
| 12  | EDZ -2    | 14.70                          | 0.09   | 0.85 | < 0.01                         | 2.70                           | 5.00             | 0.46 | 0.04 | 2.34              | 0.05                          | 0.02            | 70.50            | 0.01   | 0.41             | 97.17 | 2.83  |
| 13  | EDZ -3    | 11.40                          | 0.06   | 2.55 | 0.01                           | 3.26                           | 2.21             | 0.63 | 0.06 | 2.04              | 0.12                          | 0.05            | 72.20            | 0.02   | 0.68             | 95.29 | 4.71  |
| 14  | SDZ -1    | 11.95                          | 0.05   | 1.14 | 0.01                           | 4.33                           | 2.22             | 0.52 | 0.05 | 1.28              | 0.08                          | 0.02            | 73.30            | 0.01   | 0.48             | 95.44 | 4.56  |
| 15  | SDZ -2    | 13.35                          | 0.07   | 1.02 | 0.01                           | 3.13                           | 3.97             | 0.53 | 0.02 | 1.59              | 0.10                          | 0.03            | 71.80            | 0.02   | 0.37             | 96.01 | 3.99  |
| 16  | SDZ -3    | 10.75                          | 0.04   | 2.07 | 0.01                           | 2.44                           | 1.41             | 0.61 | 0.04 | 2.02              | 0.07                          | 0.04            | 74.10            | 0.03   | 0.25             | 93.88 | 6.12  |
| 17  | SDZ -4    | 13.10                          | 0.01   | 3.11 | 0.04                           | 6.33                           | 0.52             | 2.14 | 0.07 | 2.44              | 0.14                          | 0.04            | 65.10            | 0.03   | 1.09             | 94.16 | 5.84  |
| 18  | SDZ -5    | 11.95                          | 0.02   | 1.33 | 0.02                           | 3.59                           | 1.64             | 0.76 | 0.04 | 1.09              | 0.07                          | 0.03            | 72.90            | 0.01   | 0.42             | 93.87 | 6.13  |
| 19  | SDZ -6    | 11.38                          | 0.03   | 2.51 | 0.02                           | 3.75                           | 1.32             | 1.26 | 0.10 | 2.23              | 0.10                          | 0.06            | 70.86            | 0.03   | 0.67             | 94.32 | 5.68  |
| 20  | STZ -1    | 8.16                           | 0.02   | 0.58 | 0.01                           | 2.42                           | 0.77             | 0.21 | 0.03 | 1.42              | 0.07                          | 0.03            | 82.7             | 0.02   | 0.39             | 96.83 | 3.17  |
| 21  | STZ -2    | 12.65                          | 0.02   | 0.61 | 0.04                           | 9.20                           | 0.81             | 0.94 | 0.19 | 0.40              | 0.08                          | 0.04            | 67.30            | < 0.01 | 0.84             | 93.12 | 6.88  |
| 22  | STZ -3    | 12.90                          | 0.03   | 9.39 | 0.01                           | 4.37                           | 2.14             | 1.06 | 0.08 | 0.95              | 0.09                          | 0.11            | 55.00            | 0.02   | 0.67             | 86.82 | 13.18 |
| 23  | STZ -4    | 11.04                          | 0.07   | 0.94 | 0.02                           | 2.99                           | 2.60             | 0.76 | 0.04 | 1.32              | 0.05                          | 0.06            | 75.13            | 0.02   | 0.41             | 95.45 | 4.55  |
| 24  | NTZ-1     | 13.00                          | 0.03   | 1.42 | 0.02                           | 7.30                           | 1.16             | 1.67 | 0.10 | 1.08              | 0.14                          | 0.04            | 66.6             | 0.02   | 0.72             | 93.30 | 6.70  |
| 25  | NTZ-2     | 18.21                          | 0.01   | 0.56 | 0.04                           | 16.44                          | 0.30             | 0.66 | 0.06 | 0.09              | 0.16                          | 0.06            | 47.69            | < 0.01 | 3.23             | 87.51 | 12.49 |
| 26  | NTZ-3     | 17.06                          | 0.02   | 1.87 | 0.03                           | 16.62                          | 0.38             | 1.46 | 0.18 | 0.20              | 0.17                          | 0.09            | 45.71            | 0.01   | 3.14             | 86.94 | 13.06 |
| 27  | HZ -1     | 6.77                           | 0.01   | 0.25 | 0.05                           | 3.34                           | 0.41             | 0.94 | 0.02 | 1.00              | 0.03                          | 0.02            | 82.70            | < 0.01 | 0.44             | 95.98 | 4.02  |
| 28  | HZ -2     | 6.67                           | 0.03   | 0.38 | < 0.01                         | 2.64                           | 1.52             | 0.17 | 0.02 | 0.40              | 0.03                          | 0.03            | 84.20            | 0.01   | 0.63             | 96.73 | 3.27  |
| 29  | HZ -3     | 13.05                          | 0.02   | 1.00 | 0.02                           | 7.03                           | 0.35             | 1.28 | 0.09 | 0.32              | 0.11                          | 0.04            | 66.60            | 0.01   | 0.95             | 90.87 | 9.13  |
| 30  | HZ -4     | 9.59                           | 0.01   | 0.22 | < 0.01                         | 2.07                           | 0.69             | 0.21 | 0.01 | 0.19              | 0.04                          | 0.05            | 78.96            | < 0.01 | 0.35             | 92.39 | 7.61  |
| 31  | HZ -5     | 9.60                           | 0.03   | 0.23 | 0.01                           | 5.30                           | 1.28             | 0.64 | 0.07 | 1.40              | 0.05                          | 0.03            | 75.30            | 0.01   | 0.95             | 94.90 | 5.10  |
| 32  | HZ – 6    | 12.96                          | 0.02   | 0.19 | 0.03                           | 13.11                          | 0.86             | 0.41 | 0.15 | 0.23              | 0.11                          | 0.09            | 61.11            | < 0.01 | 0.88             | 90.15 | 9.85  |
| 33  | HZ – 7    | 7.25                           | 0.03   | 0.10 | < 0.01                         | 1.03                           | 3.39             | 0.13 | 0.01 | 0.49              | 0.02                          | 0.02            | 84.10            | < 0.01 | 0.26             | 96.83 | 3.17  |
| 34  | HZ – 8    | 14.84                          | 0.02   | 0.51 | 0.02                           | 16.16                          | 0.14             | 0.55 | 0.22 | 0.23              | 0.27                          | 0.04            | 51.22            | 0.01   | 7.86             | 92.09 | 7.91  |
| 35  | HZ – 9    | 11.06                          | 0.05   | 0.83 | 0.02                           | 1.54                           | 3.07             | 0.40 | 0.01 | 1.75              | 0.07                          | 0.04            | 77.72            | 0.02   | 0.37             | 96.95 | 3.05  |
| 36  | CZ – 1    | 10.76                          | 0.01   | 0.38 | 0.08                           | 8.61                           | 0.62             | 0.38 | 0.09 | 0.35              | 0.14                          | 0.10            | 68.87            | 0.01   | 2.36             | 92.76 | 7.24  |
| 37  | CZ – 2    | 12.67                          | 0.01   | 0.08 | 0.02                           | 4.55                           | 0.73             | 0.22 | 0.01 | 0.09              | 0.13                          | 0.11            | 71.55            | < 0.01 | 0.42             | 90.59 | 9.41  |
| 38  | CZ – 3    | 15.42                          | 0.01   | 0.11 | 0.05                           | 10.75                          | 0.77             | 0.43 | 0.02 | 0.10              | 0.26                          | 0.08            | 58.18            | < 0.01 | 0.74             | 86.92 | 13.08 |
| 39  | CZ – 4    | 13.82                          | 0.03   | 0.87 | 0.01                           | 3.84                           | 0.87             | 0.66 | 0.02 | 0.98              | 0.10                          | 0.05            | 70.68            | 0.01   | 0.46             | 92.40 | 7.60  |
| 40  | CZ - 5    | 15.79                          | 0.02   | 0.38 | 0.02                           | 5.14                           | 1.41             | 0.43 | 0.02 | 0.40              | 0.07                          | 0.08            | 66.84            | 0.01   | 0.47             | 91.08 | 8.92  |

Table 18: Total elemental composition of selected soil samples (n = 40) of different agro climatic zones of Karnataka

NEDZ – North Eastern Dry Zone; NDZ – Northern Dry Zone; CDZ - Central Dry Zone; EDZ - Eastern Dry Zone; SDZ - Southern Dry Zone; STZ - Southern Transition Zone; NTZ - Northern Transition Zone; HZ - Hilly Zone; CZ - Costal Zone; \* Loss on ignition

The NTZ soil samples recorded the presence of quartz and feldspars in all three samples whereas biotite and titanium containing minerals were found in NTZ - 1 and 2 soil samples respectively (Table 19 and Fig.13). Among the secondary clay minerals kaolinite in NTZ - 1 and 2; goethite and vermiculite in NTZ 2 and 3 smectite in NTZ - 1 were dominated in soil samples.

#### 4.1.3.8 Hilly Zone (HZ)

The elemental composition of the HZ soil samples was in the order of SiO<sub>2</sub> (51.22 –84.20 %) > Al<sub>2</sub>O<sub>3</sub> (6.67 – 14.84 %) > Fe<sub>2</sub>O<sub>3</sub> (1.03 – 13.11 %) > TiO<sub>2</sub> (0.26 – 7.86 %) > K<sub>2</sub>O (0.14 – 3.39 %) > Na<sub>2</sub>O (0.23 – 1.75 %) > MgO (0.13 – 1.28%) > CaO (0.19 – 0.83 %) > P<sub>2</sub>O<sub>5</sub> (0.02 – 0.27 %) > SO<sub>3</sub> (0.02 – 0.09 %) > MnO (0.01 – 0.22 %) > BaO (0.01 – 0.05 %) > Cr<sub>2</sub>O<sub>3</sub> (<0.01 – 0.05%) > SrO (<0.01 - 0.02 %).

The primary minerals such as quartz and feldspar were found in all the soil samples representing HZ followed by muscovite (HZ - 1, 2, 4, 5, and 5), amphibole (HZ - 2, 3, 4, 7 and 8) in respective soil samples. 14Å phyllosilicates and biotite were found in some of the soil samples (Table 19 and Fig. 14 & 15). Among the secondary clay minerals kaolinite, goethite and gibbsite were observed in majority of the soil samples followed by vermiculite in some of the soil samples.

#### 4.1.3.9 Coastal Zone (CZ)

The total elemental composition in the soil samples representing CZ recorded was in the order of SiO<sub>2</sub> (58.18 –71.55 %) > Al<sub>2</sub>O<sub>3</sub> (10.76 – 15.79 %) > Fe<sub>2</sub>O<sub>3</sub> (3.84 – 10.75 %) > TiO<sub>2</sub> (0.42 – 2.36 %) > K<sub>2</sub>O (0.62 – 1.41 %) > CaO (0.08 – 0.87 %) > MgO (0.22 – 0.66 %) > Na<sub>2</sub>O (0.09 – 0.98 %) > P<sub>2</sub>O<sub>5</sub> (0.07 – 0.26 %) > MnO (0.01 – 0.09 %) > SO<sub>3</sub> (0.05 – 0.11 %) > Cr<sub>2</sub>O<sub>3</sub> (0.01 – 0.08 %) > BaO (0.01 – 0.03 %) > SrO (<0.01 - 0.01 %).

Quartz, feldspars and amphiboles were found in all the soil samples except in CZ - 3, whereas muscovite was found in CZ - 1 and 2 (Table 19 and Fig. 16). All the soils were dominated with kaolinite, gibbsite and vermiculite clay minerals followed by chlorite and  $10\text{\AA}$  phyllosilicates in CZ - 1 and CZ - 4 soil samples, respectively.

## 4.1.4 Relationship between physicochemical properties and total elemental analysis of selected soil samples (n=40) of different agro climatic zones of Karnataka.

Results presented in the Table 20 represent the correlation coefficient values for physicochemical properties and total elemental analysis of selected soil samples collected from different agro climatic zones of Karnataka.

It was found that there was significant and positive correlation of pH with other parameters such as EC (r = 0.776, p<0.05), AASi (r = 0.499, p<0.05), CEC (r = 0.644, p<0.05), Na<sub>2</sub>O (r = 0.369, p<0.05), CaO (r = 0.627, p<0.05), MgO (r = 0.613, p<0.05), SrO (r = 0.491, p<0.05), whereas negatively correlated with O.C. (r = -0.377, p<0.05).

| SI.<br>No. | Sample<br>ID  | Primary and secondary minerals   |
|------------|---------------|--|
| 1          | NEDZ-1        | Ouartz, Feldspar, Amphibole, Muscovite, Kaolinite, Smectite                        |
| 2          | NEDZ -2       | Quartz, Feldspar, Amphibole, Muscovite, Chlorite, Kaolinite                        |
| 3          | NEDZ-3        | Quartz, Feldspar, Muscovite, Vermiculite   |
| 4          | NEDZ-4        | Quartz, Feldspar, Muscovite, Amphibole, Vermiculite                                |
| 5          | NDZ -1        | Quartz, feldspar, Muscovite, Kaolinite, Smectite                                   |
| 6          | NDZ -2        | Quartz, Feldspar, Muscovite, Amphibole   |
| 7          | NDZ -3        | Quartz, Feldspar, Smectite/Vermiculite   |
| 8          | CDZ -1        | Quartz, Feldspar, Amphibole, Kaolinite, Smectite                                   |
| 9          | <b>CDZ -2</b> | Quartz, Feldspar, Vermiculite/Smectite, Kaolinite                                  |
| 10         | CDZ -3        | Quartz, Feldpsar, Smectite; Chlorite/Kaolinite, Micas/Illite                       |
| 11         | EDZ -1        | Quartz, Feldspar, 10Å Phyllosilicates, Kaolinite                                   |
| 12         | EDZ -2        | Quartz, Feldspar, Muscovite, Chlorite, Kaolinite                                   |
| 13         | EDZ -3        | Quartz, Feldspar, Amphibole, Kaolinite, Illite, Smectite                           |
| 14         | SDZ -1        | Quartz, Feldspar, Muscovite, Amphibole, Smectite, Kaolinite                        |
| 15         | SDZ -2        | Quartz, Feldspar, Amphibole, 10Å and 14Å Phyllosilicates, Smectite / Kaolinite     |
| 16         | SDZ -3        | Quartz, Feldspar, Amphibole, Illite  |
| 17         | SDZ -4        | Quratz, Feldspar, Amphibole, 14Å Phyllosilicates, Vermiculite,                     |
| 18         | SDZ -5        | Quartz, Feldspar, 14Å Phyllosilicates, Vermiculite                                 |
| 19         | SDZ -6        | Quartz, Feldspar, Kaolinite, Gibbsite  |
| 20         | STZ -1        | Quartz, Feldspar, Amphibole, 10Å Phyllosilicates                                   |
| 21         | STZ -2        | Quartz, Feldspar, 10Å Phyllosilicates, Vermiculite, Kaolinite                      |
| 22         | STZ-3         | Quartz, Feldspar, Chlorite, Smectite, Kaolinite                                    |
| 23         | STZ -4        | Quartz, Feldspar, Muscovite, Smectite, Kaolinite                                   |
| 24         | NTZ-1         | Quartz, Feldspar, Biotite, Kaolinite, Smectite                                     |
| 25         | NTZ-2         | Quartz, Fedspar, TiO <sub>2</sub> mineral, Kaolinite, Goethite, Vermiculite        |
| 26         | NTZ-3         | Quartz, Feldspar, Vermiculite, Goethite  |
| 27         | HZ -1         | Quartz, Feldspar, Muscovite, Kaolinite, Vermiculite                                |
| 28         | HZ -2         | Quartz, Feldspar, Muscovite, Amphibole, Kaolinite, Vermiculite, Gibbsite           |
| 29         | HZ -3         | Quartz, Feldspar, Amphibole, Kaolinite, Vermiculite                                |
| 30         | HZ -4         | Quartz, Feldspar, Amphibole, Muscovite, Kaolinite, Gibbsite                        |
| 31         | HZ -5         | Quartz, Feldspar, Chlorite, Muscovite, Goethite                                    |
| 32         | HZ – 6        | Quartz, Feldspar, Muscovite, 14A Phyllosilicates, Kaolinite, Gibbsite, Goethite    |
| 33         | HZ – 7        | Quartz, Feldspar, Amphibole, Goethite  |
| 34         | HZ – 8        | Quartz, Feldspar, Amphibole, Kaolinite, 14A Phyllosilicates                        |
| 35         | HZ – 9        | Quartz, Feldspar, Biotite, Kaolinite, 14A Phyllosilicates                          |
| 36         | CZ – 1        | Quartz, Feldspar, Chlorite, Amphibole, Muscovite, Gibbsite, Kaolinite              |
| 37         | CZ - 2        | Quartz, Feldspar, Muscovite, Kaolinite, Vermiculite, Gibbsite                      |
| 38         | CZ - 3        | Quartz, Muscovite, Gibbsite, Kaolinite, Vermiculite                                |
| 39         | CZ - 4        | Quartz, Feldspar, Amphibole, 10A Phyllosilicates, Vermiculite, Gibbsite            |
| 40         | CZ - 5        | Quartz, Feldspar, Amphibole, Vermiculite, Kaolinite, 10A Phyllosilicates, Gibbsite |

Table 19: Mineralogy\* of selected soil samples (n=40) of different agro climatic zones of Karnataka

\* XRD analysis



Fig. 6: XRD - Diffractogram of soils representing north eastern dry zone



Fig. 7: XRD - Diffractogram of soils representing northern dry zone



Fig. 8: XRD - Diffractogram of soils representing central dry zone



Fig. 9: XRD - Diffractogram of soils representing eastern dry zone



Fig. 10: XRD - Diffractogram of soils representing southern dry zone



Fig. 11: XRD - Diffractogram of soils representing southern dry zone



Fig. 12: XRD - Diffractogram of soils representing southern transition zone



Fig. 13: XRD - Diffractogram of soils representing northern transition zone



Fig. 14: XRD - Diffractogram of soils representing hilly zone


Fig. 15: XRD - Diffractogram of soils representing hilly zone

(Q- Quartz; Fl – Feldspar; Mu – Muscovite; Am – Amphibole; Cl – Chlorite; K – Kaolinite; Sm – Smectitic group; V – Vermiculite; Gb – Gibbsite; Go – Goethite; 10Å or 14Å – Phyllosilicates; B – Biotite; Ti – Titanium; Cal – Calcite; I – Illite; () – Low quantity)



Fig. 16: XRD - Diffractogram of soils representing coastal zone

(Q- Quartz; Fl – Feldspar; Mu – Muscovite; Am – Amphibole; Cl – Chlorite; K – Kaolinite; Sm – Smectitic group; V – Vermiculite; Gb – Gibbsite; Go – Goethite; 10Å or 14Å – Phyllosilicates; B – Biotite; Ti – Titanium; Cal – Calcite; I – Illite; () – Low quantity)

Soil EC correlated significantly positive with CCSi (r = 0.0.312, p<0.05), AASi (r = 0.591, p<0.05), CEC (r = 0.583, p<0.05), CaO (r = 0.514, p<0.05), MgO (r = 0.553, p<0.05), MnO (r = 0.320, p<0.05), SrO (r = 0.381, p<0.05) and negatively correlated with O.C. (r = -0.423, p<0.05).

Silicon extracted using 0.01M calcium chloride (CCSi) had positive and significant correlation with AASi (r = 0.467, p<0.05), clay (r = 0.385, p<0.05), CEC (r = 0.371, p<0.05), Al<sub>2</sub>O<sub>3</sub> (r = 0.337, p<0.05) and negative correlation with sand (r = -0.360, p<0.05). 0.5 M acetic acid extractable Si noticed significant and positive correlation with silt (r = 0.406, p<0.05), CEC (r = 0.481, p<0.05), Al<sub>2</sub>O<sub>3</sub> (r = 0.407, p<0.05), Fe<sub>2</sub>O<sub>3</sub> (r = 0.415, p<0.05), MgO (r = 0.380, p<0.05), MnO (r = 0.440, p<0.05) and negative correlation with SiO<sub>2</sub> (r = -0.409, p<0.05).

Sand content of the soil was poorly correlated with many of the parameters *viz.*, silt (r = -0.705, p<0.05), clay (r = -0.791, p<0.05), Fe<sub>2</sub>O<sub>3</sub> (r = -0.422, p<0.05), MgO (r = -0.401, p<0.05), Cr<sub>2</sub>O<sub>3</sub> (r = -0.376, p<0.05) however, positively correlated with K<sub>2</sub>O (r = 0.428, p<0.05), SiO<sub>2</sub> (r = 0.416, p<0.05), BaO (r = 0.314, p<0.05). Soil silt content correlated significantly and positively with Fe<sub>2</sub>O<sub>3</sub> (r = -0.407, p<0.05) whereas significantly and negatively correlated with K<sub>2</sub>O (r = -0.400, p<0.05), SiO<sub>2</sub> (r = -0.387, p<0.05) and BaO (r = -0.350, p<0.05). Clay content didnot show significant correlation with any of the parameters except with MgO (r = 0.347, p<0.05).

There was a significant correlation between CEC and other parameters such as CaO (r = 0.360, p<0.05), MgO (r = 0.509, p<0.05) and SrO (r = 0.394, p<0.05) whereas significant but negative correlation with SiO<sub>2</sub> (r = -0.400, p<0.05).

Organic carbon was positively correlated with  $Al_2O_3$  (r = 0.325, p<0.05), P<sub>2</sub>O<sub>5</sub> (r = 0.380, p<0.05), SO<sub>3</sub> (r = 0.562, p<0.05) and negatively correlated with remaining properties. The organic carbon content of the soil samples of present investigation was negatively correlated with Si content. Contrasting results on the effects of organic matter on Si availability have been reported. There were contradictory reports as many researchers observed that available Si positively correlated with soil organic matter content (Lian, 1976; Shen *et al.*, 1994; Yu *et al.*, 1998; Qin *et al.*, 2012), while others believe that little or even negative relationship existed between Si and organic matter content (Zhang, 1987; Wan *et al.*, 1993).

Aluminum and iron oxides were significantly correlated with P<sub>2</sub>O<sub>5</sub> (r = 0.500, r = 0.657, p<0.05), MnO (r = 0.316, 0.711, p<0.05), SO<sub>3</sub> (r = 0.388, 0.383, p<0.05) and TiO<sub>2</sub> (r = 0.398, 0.740, p<0.05) whereas strong and negative correlations with SiO<sub>2</sub> (r = -0.808, -0.823, p<0.05), respectively. Potassium and sodium oxide correlated significantly and positively with BaO (r = 0.823, 0.547, p<0.05) and SrO (r = 0.341, 0.760, p<0.05) respectively. There was significant positive correlation between P<sub>2</sub>O<sub>5</sub> with other parameters such as MnO (r = 0.457, p<0.05), SO<sub>3</sub> (r = 0.335, p<0.05), Cr<sub>2</sub>O<sub>3</sub> (r = 0.379, p<0.05) and TiO<sub>2</sub> (r = 0.650, p<0.05) whereas negatively correlated with SiO<sub>2</sub> (r = -0.582. p<0.05). There was no significant correlation between SiO<sub>2</sub> and any of the soil parameters but negatively correlated with Many of the oxides. Calcium and magnesium oxides recorded significant correlation with SrO (r = 0.453, 0.380, p<0.05). There was a significant correlation with SrO (r = 0.453, 0.380, p<0.05). There was a significant correlation between MnO and TiO<sub>2</sub> (r = 0.650, p<0.05); SO<sub>3</sub> and Cr<sub>2</sub>O<sub>3</sub> (r = 0.360, p<0.05); BaO and SrO (r = 0.508, p<0.05).

The mineralogical pool of Si can be subdivided into primary minerals, secondary crystalline minerals (mainly clay minerals) and secondary poorly to non-crystalline (amorphous) phases (Drees *et al.*, 1989). The first group can be indicated as parent material; the other two groups find their origin during processes of ecosystem soil formation. The reserve of weathering primary silicates had a greater influence on the accumulation of biogenic silicon in volcanic ash soils (Henriet *et al.*, 2008). The mineralogical compositions of soils were inferred from X-ray diffraction, elemental analysis and selective chemical/mineralogical extractions. With increasing weathering, the content of weatherable primary minerals decreased. Conversely, clay content increased and stable secondary minerals were increasingly dominant: gibbsite, Fe oxides, allophone, halloysite and kaolinite. The contents of biogenic Si in plant and soil were governed by the reserve of weatherable primary minerals.

Results of the XRD analysis (Table 19, Fig. 6 to 16) indicated that quartz, Na and K feldspars, amphibole, and phyllosilicates (chlorite, muscovite) are the major primary minerals identified in most of the soil samples. The composition of clay minerals includes smectite, kaolinite, illite and vermiculite in various proportions. Although quartz is a major source of Si in many soils, the rate of dissolution of this mineral is very slow and therefore does not contribute significantly to the labile pool of soluble Si. For plant growth the important forms of soil Si are the soluble forms, mainly monosilicic acid  $(Si(OH)_4)$ , various polymers and silica gels, Si adsorbed onto sesquioxide surfaces, and that present in crystalline and amorphous soil minerals. The quantity present in each of these forms was largely controlled by the dominant soil mineral and the amount of Si lost (desilication) through weathering (Berthelson *et al.*, 2003). These minerals release Si to the soil solution through chemical weathering. The rate of chemical weathering of minerals was affected by the type and particle size of the minerals (Jackson *et al.*, 1948,

1952; Carroll, 1974; Drever and Zobrist, 1992). The weathering resistivity of 1:1-type clay minerals is higher than that of 2:1-type clay minerals.

The weathering resistivity of primary minerals, such as alkaline feldspar and biotite, in which the potassium (K) and sodium (Na) contents are relatively high which is greater than that of other primary minerals such as plagioclases, amphibole and pyroxene, which contain calcium (Ca) and/or magnesium (Mg) (Carroll, 1974). A basic tenet of sediment diagenesis, the "Goldich Weathering Sequence" (Goldich, 1938), states that the most unstable silicate mineral will weather (dissolve) first, with more resistant silicates taking progressively longer to dissolve (from least to most stable), olivine < plagioclase < albite < anorthoclase  $\approx$  microcline < quartz. However, the presence of organic acid substances can influence feldspar dissolution rates either by decreasing pH, by forming frame work-destabilizing surface complexes, or by complexing metals in solution. Many investigators have found that organic acids enhance the dissolution of aluminosilicate minerals or quartz both in field observations and from laboratory experiments (Bennett et al., 2001). Soils may contain both crystalline quartz (SiO<sub>2</sub>) and amorphous silica (SiO<sub>2</sub>·nH<sub>2</sub>O), together with opaline silica (SiO<sub>2</sub>·nH<sub>2</sub>O) from plant materials. Mica, feldspar and clay minerals also contain Si. Quartz is the least soluble of the silica minerals, giving 8 mg Si  $L^{-1}$  when in equilibrium with water (Jones and Handreck, 1963; Sadiq et al., 1980).

| Variable                       | pН     | EC.    | CCSi   | AASi   | Sand   | Silt   | Clay   | CEC    | <b>O.C.</b> | AbO3   | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | NaO    | P <sub>2</sub> O <sub>5</sub> | SiO <sub>2</sub> | CaO    | MgO    | MnO    | SO3    | BaO   | Cr <sub>2</sub> O <sub>3</sub> | SrO   | TiO <sub>2</sub> |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|-------------|--------|--------------------------------|------------------|--------|-------------------------------|------------------|--------|--------|--------|--------|-------|--------------------------------|-------|------------------|
| pН                             | 1      |        |        |        |        |        |        |        |             |        |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| EC.                            | 0.776  | 1      |        |        |        |        |        |        |             |        |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| CCSi                           | 0300   | 0312   | 1      |        |        |        |        |        |             |        |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| AASi                           | 0.499  | 0591   | 0.467  | 1      |        |        |        |        |             |        |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| Sand                           | -0.112 | -0.003 | -0360  | -0.214 | 1      |        |        |        |             |        |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| Silt                           | 0.117  | 0.098  | 0.137  | 0.406  | -0.705 | 1      |        |        |             |        |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| Clay                           | 0.055  | -0.081 | 0.385  | -0.051 | -0.791 | 0.124  | 1      |        |             |        |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| ŒĊ                             | 0.644  | 0.583  | 0.371  | 0.481  | -0242  | 0259   | 0.115  | 1      |             |        |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| O.C.                           | -0.377 | -0.423 | -0.121 | -0274  | -0.221 | 0.189  | 0.146  | -0.105 | 1           |        |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| AbO3                           | 0.181  | 0.171  | 0.337  | 0407   | -0.268 | 0312   | 0.106  | 0291   | 0.325       | 1      |                                |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| Fe <sub>2</sub> O <sub>3</sub> | -0.030 | 0.041  | 0.287  | 0415   | -0.422 | 0.447  | 0205   | 0221   | 0.198       | 0595   | 1                              |                  |        |                               |                  |        |        |        |        |       |                                |       |                  |
| K <sub>2</sub> O               | 0.065  | 0.136  | -0.008 | -0.183 | 0.428  | -0400  | -0.253 | -0203  | -0306       | -0.018 | -0535                          | 1                |        |                               |                  |        |        |        |        |       |                                |       |                  |
| NaO                            | 0369   | 0.281  | 0.117  | -0.080 | 0256   | -0276  | -0.119 | 0.089  | -0403       | 0010   | -0.486                         | 0.502            | 1      |                               |                  |        |        |        |        |       |                                |       |                  |
| POs                            | -0.053 | -0.124 | 0.117  | 0.173  | -0.111 | 0.226  | -0.039 | 0.114  | 0.380       | 0500   | 0.657                          | -0291            | -0.287 | 1                             |                  |        |        |        |        |       |                                |       |                  |
| SiO <sub>2</sub>               | -0304  | -0303  | -0302  | -0.409 | 0416   | -0.387 | -0.248 | -0400  | -0212       | -0808  | -0.823                         | 0272             | 0.186  | -0582                         | 1                |        |        |        |        |       |                                |       |                  |
| CaO                            | 0.627  | 0514   | 0.019  | 0.050  | -0.178 | 0.015  | 0236   | 0.360  | -0.145      | 0.078  | 0.012                          | 0.000            | 0232   | -0.077                        | -0436            | 1      |        |        |        |       |                                |       |                  |
| MgO                            | 0.613  | 0553   | 0.258  | 0.380  | -0.401 | 0.248  | 0.347  | 0509   | -0.181      | 0.181  | 0265                           | -0266            | 0.159  | 0.054                         | -0504            | 0.728  | 1      |        |        |       |                                |       |                  |
| MnO                            | 0292   | 0.320  | 0.183  | 0.440  | -0207  | 0.169  | 0.144  | 0264   | -0259       | 0316   | 0.711                          | -0.330           | -0213  | 0.457                         | -0644            | 0277   | 0.466  | 1      |        |       |                                |       |                  |
| SO <sub>3</sub>                | 0.063  | 0.133  | -0.036 | 0.041  | -0.162 | 0.168  | 0.082  | 0259   | 0562        | 0388   | 0383                           | -0290            | -0.374 | 0335                          | -0513            | 0271   | 0.124  | 0.197  | 1      |       |                                |       |                  |
| BaO                            | 0.130  | 0.152  | 0.077  | -0.083 | 0314   | -0350  | -0.137 | -0.111 | -0314       | 0.104  | -0.318                         | 0.823            | 0547   | -0.083                        | 0.075            | 0.050  | -0.122 | -0.020 | -0301  | 1     |                                |       |                  |
| Cr <sub>2</sub> O <sub>3</sub> | -0.205 | -0218  | 0.095  | 0.094  | -0.376 | 0303   | 0264   | 0.072  | 0293        | 0.140  | 0526                           | -0577            | -0.350 | 0.379                         | -0282            | -0.132 | 0.153  | 0234   | 0.360  | -0537 | 1                              |       |                  |
| StO                            | 0491   | 0.381  | 0.182  | 0.016  | 0.187  | -0227  | -0.065 | 0.394  | -0316       | 0.097  | -0.261                         | 0341             | 0.760  | -0.101                        | -0.084           | 0453   | 0380   | 0.011  | -0.103 | 0508  | -0284                          | 1     |                  |
| TiO                            | -0.138 | -0086  | 0.152  | 0141   | -0143  | 0.188  | 0038   | 0043   | -0037       | 0.398  | 0.740                          | -0312            | -0295  | 0650                          | -0581            | -0081  | 0032   | 0650   | 0116   | -0063 | 0256                           | -0103 | 1                |

 Table 20: Pearson's correlation coefficient between physico-chemical properties and total elemental analysis of selected samples (n=40) of different agro climatic zones of Karnataka

• Values in bold are significant level at  $p \le 0.05$ 

E.C. represents electrical conductivity expressed in dSm<sup>-1</sup>

\* CCSi represents 0.01M Calcium Chloride extractable silicon expressed in mg kg-1

\* AASi represents 0.5M Acetic acid extractable silicon expressed in mg kg-1

CEC represents Cation Exchange Capacity expressed in cmol (p+) kg<sup>-1</sup>

✤ O.C. represents Organic Carbon expressed in per cent

Al2O3, Fe2O3, K2O, Na2O, P2O5, SiO2, CaO, MgO, MnO, SO2, BaO, Cr2O3, SrO and TiO2 expressed in per cent

The total elemental composition (Table 18) was dominated by  $SiO_2$  (45.71 – 87.6 %), Al<sub>2</sub>O<sub>3</sub> (5.38 - 18.21 %), Fe<sub>2</sub>O<sub>3</sub> (1.03 - 16.62 %), CaO (0.08 - 8.83 %), K<sub>2</sub>O (0.14 -4.49 %). Pearson's correlation showed that (Table 20) pH was negatively correlated to SiO<sub>2</sub> but positively correlated to Al<sub>2</sub>O<sub>3</sub>, CaO, Fe<sub>2</sub>O<sub>3</sub>, MgO, and SO<sub>3</sub>. Such result is likely to indicate that acidic soils are mainly dominant with quartz. The good correlation between Fe<sub>2</sub>O<sub>3</sub> with MgO and MnO indicates the predominance of clay minerals over oxides (Kabata-Pendias and Mukherjee, 2007). Silicon extracted by acetic acid (AASi) was positively correlated with  $Al_2O_3$ ,  $Fe_2O_3$ , MnO and TiO<sub>2</sub> indicating that this extractant assessed the fraction of Si adsorbed on the surface of oxides/oxyhydroxides and clays. These results validate the approach for assessing the bioavailable Si: CCSi for immediate dissolved Si; AASi for Si adsorbed on iron or aluminiumoxides. Silicon combined with free iron oxide dissolves easily when the redox potential of the soil was reduced (Schwertmann, 1991). Therefore, sesquioxides, such as Al and Fe oxides, and hydroxides play an important role in controlling the Si concentrations in the soil solution (Jones and Handreck, 1963; McKeague and Cline, 1962). Ammonium- and Na acetates (buffered at low pH with acetic acid) as well as acetic acid itself have been extensively used as extractants for soil Si (Sauer et al., 2006). The acid extraction would result in dissolution of amorphous Al and Fe oxides and hydroxides with release of adsorbed Si (Sauer et al., 2006; Hohn et al., 2008) and leads to dissolution of amorphous aluminosilicates and any highly soluble crystalline aluminosilicate materials, while the presence of the acetate anion might also favor desorption of adsorbed silicate. Monosilicic acid can be withdrawn from soil solution through its sorption onto aluminum and iron oxides. Iron oxides are ubiquitous in sediments, weathered rocks and soils, where they partly control the concentration of aqueous silicic acid (Delstanche et al., 2009).

Aluminium hydroxides, iron oxides and carbonates play a major role in the interaction between the solid and dissolved Si pools in the soil (Struyf et al., 2009). Silicon is chemically adsorbed at the surfaces of these secondary minerals. When Fe oxides are present, Si dynamics have been hypothesized to be influenced by redox processes. Reaeration of soils after periods of water-logging was observed to enhance DSi release from silicate minerals. A saturated solution of amorphous silica has 56 - 65 mg Si  $L^{-1}$  as monosilicic acid. Opaline silica behaves as amorphous silica, but in soil the phytoliths adsorb Fe and Al and form Fe and Al complexes which reduce their solubility to 10 - 15 mg  $L^{-1}$  (Jones and Handreck, 1963; Wilding *et al.*, 1979 and Bartoli, 1985). The Si concentration in a soil is controlled by the dissolution of the siliceous materials and by the sorption reactions between soluble silica and reactive soil materials, particularly the iron and aluminium oxides and hydroxides. Mineralogical properties, including the particle size distribution and mineral composition such as the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio clay fraction content and the amounts of CaO and MgO in silt-sized particles was positively correlated with the amount of available Si in the soil, but these correlations were not found for sand-sized particles. The SiO<sub>2</sub>, FeO and SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio clay fraction contents contributed approximately 50 per cent to the amount of available Si in the soils (Makabe et al., 2009). It is critically important to understand Si supplying power or capacity in soils in order to assess whether the amount of plant available Si in soils is sufficient for optimized crop production.

### 4.2. Assessment of silicon budget in wetland rice ecosystem.

Field experiment was carried out at C-Block ZARS V. C. Farm, Mandya during *summer* (Plate 11) and *kharif* (Plate 12) 2015 to understand the effect of plant activity and soil properties on biogeochemical cycle of silicon. The task was to monitor the input, output and the internal transfer of silicon in paddy field in order to estimate the mass balance, budgeting of Si, status of silicon and bioavailable silicon.

# 4.2.1 Effect of diatomite (DE) as Si source on growth parameters of rice crop grown during *summer* 2015

Data pertinent to effect of DE on growth parameters of rice grown under submergence are presented in Table 21.

## 4.2.1.1 Plant height and number of tillers hill<sup>-1</sup>

Results presented in the Table 21 revealed that there was numerical increase in the plant height with the application of DE @ 300 kg ha<sup>-1</sup> at 30 DAT ( $53.40 \pm 3.37$  cm), 60 DAT ( $106.00 \pm 8.98$  cm), 90 DAT ( $132.55 \pm 7.82$  cm) and at harvest ( $133.45 \pm 7.87$  cm) but statistically on par with treatment of no applied DE plots.

There was numerical increase the number of tillers per hill of rice crop with the application of DE @ 300 kg ha<sup>-1</sup> but statistically, on par with the control (Table 21). The increase in number of tillers per hill was noticed at 30 DAT (11.65  $\pm$  2.67), 60 DAT (11.65  $\pm$  2.11), 90 DAT (11.95  $\pm$  1.33) and at harvest (12.10 $\pm$  1.33).

There was increase in the plant height and number of tillers per plant with application of DE @ 300 kg ha<sup>-1</sup>. In general, there was increase in the plant growth with the application of DE compared to non-applied plot. This can be attributed to sufficient supply of nutrients from the fertilizer and beneficial effect of silicon released from the DE and thereby improvements in the nutrient use efficiency by crop. The increase in plant height can be accounted for the improvement in growth parameters by silicon which has been reported by several others like Nayar *et al.* (1982); Ma *et al.* (1989); Agarie *et al.* (1992) and Liang *et al.* (1994) in rice. Yoshida *et al.* (1969) reported that Si application increases plant height because leaves and stem become more erect, thus reducing self-shading and increasing photosynthesis rate, especially under conditions of high population densities and high doses of nitrogen.

| Treatments           | Plant height (cm)    |                       |                         |                      |  |  |  |  |  |  |
|----------------------|----------------------|-----------------------|-------------------------|----------------------|--|--|--|--|--|--|
| Treatments           | <b>30 DAT</b>        | 60 DAT                | 90 DAT                  | At harvest           |  |  |  |  |  |  |
| $Si_0 + RP$          | $51.00 \pm 3.71(a)$  | $102.60 \pm 7.65$ (a) | $125.30 \pm 4.36$ (a)   | 126.05±7.27(a)       |  |  |  |  |  |  |
| Si <sub>1</sub> + RP | $53.40 \pm 3.37$ (a) | $106.00 \pm 8.98$ (a) | $133.55 \pm 7.82(a)$    | $133.45 \pm 7.87(a)$ |  |  |  |  |  |  |
| S. Em±               | 1.76                 | 4.16                  | 3.05                    | 3.04                 |  |  |  |  |  |  |
| LSD (p≤0.05)         | NS                   | NS                    | NS                      | NS                   |  |  |  |  |  |  |
|                      |                      | Number of till        | lers hill <sup>-1</sup> |                      |  |  |  |  |  |  |
| $Si_0 + RP$          | $10.55 \pm 0.94$ (a) | $10.55 \pm 2.08$ (a)  | $10.55 \pm 2.15$ (a)    | $10.90 \pm 2.15(a)$  |  |  |  |  |  |  |
| Si <sub>1</sub> + RP | $11.65 \pm 2.67$ (a) | $11.65 \pm 2.11$ (a)  | 11.95±1.33(a)           | $12.10 \pm 1.33(a)$  |  |  |  |  |  |  |
| S. Em±               | 0.91                 | 1.05                  | 0.87                    | 0.87                 |  |  |  |  |  |  |
| LSD (p≤0.05)         | NS                   | NS                    | NS                      | NS                   |  |  |  |  |  |  |

Table 21: Effect of diatomite as Si source on plant height and number of tillers of rice crop during *summer* 2015

Mean value having same alphabets do not differ significantly at p≤0.05. DAT – Days after transplanting

2016



Plate 11: Influence of diatomite on rice crop at different growth stages during summer 2015

Increase in number of tillers plant<sup>-1</sup> of rice may be due to the application of DE in the present investigation and thereby, increased Si content in plants which induced silicification of cells of rice leaves and increased the number of tillers. Similar results were also noticed by Liang *et al.* (1994) who reported that supplementation of calcium silicate @ 2 t ha<sup>-1</sup> increased number of tillers in rice over control. Pereira *et al.* (2004) reported that application of Si @ 125 kg ha<sup>-1</sup> as wollastonite, enhanced the number of productive tillers, total number of tillers m<sup>-2</sup> and number of branches of rice plant. These results corroborate those of Savant *et al.* (1997) who reported that Si promoted the maximum plant height, number of tillers, number of panicles, number of spikelets/panicles, grain filling, grain yield and quality of rice.

## 4.2.2. Effect of diatomite as Si source on yield attributes of rice crop grown during *summer* 2015

Data pertinent to yield attributes of the crop are given in Table 22. Application of DE as Si source @ 300 kg ha<sup>-1</sup> recorded a numerical increase in the yield parameters such as number of panicle hill<sup>-1</sup> (9.85 ± 0.71), panicle length (21.23 ± 0.99cm), grain weight panicle<sup>-1</sup> (3.34 ± 0.26g), grain weight hill<sup>-1</sup> (32.42 ± 3.18 g), test weight (16.98 ± 0.67 g) and straw yield (11.67 ± 0.75 t ha<sup>-1</sup>) over control. However, there was a significant increase in grain yield (6.98 ± 0.3 t ha<sup>-1</sup>) with the application of DE compared to no DE application treatment (6.53 ± 0.2 t ha<sup>-1</sup>).

A significant increase in the grain yield and numerical increase in the other yield attributes compared to treatment with no DE may be attributed to beneficial effects of Si released from the DE material and also higher use efficiency of nutrients (Fig.17). It was observed that the application of DE increased the test weight of rice grains which may be attributed to greater deposition of Si on paleae and lemmas. The results are also in accordance with the findings of Balastra et al. (1989); Ma et al. (1989); Deren et al. (1994); Carvalho (2000) and Munir et al. (2003). These results also corroborate with the findings of Munir et al. (2003) in Brazil, Singh and Singh (2005) and Singh et al. (2006) in India who have shown that Si affects floral fertility and as such an increase in the number of filled spikelets and consequently number of grains and grain weights. According to Agarie et al. (1992) maintenance of photosynthetic activity due to Si fertilization could be one of the reasons for the increased dry matter production. Increase in rice yields under flooded condition was noticed with Si fertilization in Sri Lanka (Takajima et al., 1970), Florida (Datnoff et al., 1997) and India (Singh et al., 2006). Chagas et al. (2005) showed that increased application of calcium silicate increased the grain and biomass weight in clay soils.

Increase in the crop growth and yield attributes by the application of Si was also in agreement with many workers which were reflected in the present investigation. Snyder *et al.* (1986) showed that application of calcium silicate increased the rice yields in Histosols mainly due to the supply of available Si. According to Marschner (1995) and Takahashi (1996), Si accumulated in the rice plant reduces the transpiration rate, thus decreasing water intake necessity by the crop and improving the dry matter production.

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|                      | Number of panicles | Panicle length       | Grain weight              | Grain weight           | Test weight          | Straw yield           | Grain yield           |
|----------------------|--------------------|----------------------|---------------------------|------------------------|----------------------|-----------------------|-----------------------|
| Treatments           | hill <sup>-1</sup> | ( <b>cm</b> )        | panicle <sup>-1</sup> (g) | hill <sup>-1</sup> (g) | <b>(g)</b>           | (t ha <sup>-1</sup> ) | (t ha <sup>-1</sup> ) |
| Si <sub>0</sub> + RP | 9.15 ± 0.77 (a)    | $20.27 \pm 0.73$ (a) | $3.00 \pm 0.17$ (a)       | 27.35 ± 2.55 (a)       | $16.38 \pm 0.37$ (a) | $10.65 \pm 1.22$ (a)  | $6.53 \pm 0.2$ (b)    |
| Si <sub>1</sub> + RP | 9.85 ± 0.71 (a)    | $21.23 \pm 0.99(a)$  | $3.34 \pm 0.26$ (a)       | 32.42 ± 3.18 (a)       | 16.98 ± 0.67 (a)     | 11.67 ± 0.75 (a)      | $6.98 \pm 0.3$ (a)    |
| S. Em±               | 0.38               | 0.43                 | 0.11                      | 2.43                   | 0.26                 | 0.49                  | 0.17                  |
| LSD (p≤0.05)         | NS                 | NS                   | NS                        | NS                     | NS                   | NS                    | 0.44                  |

 Table 22: Effect of diatomite as Si source on yield attributes of rice crop during summer 2015

Prakash et al. (2010) reported that rice hull ash and rice straw could be used to improve the plant-available silicon status of soils for enhanced growth and yield of rice. The greater dry matter production with Si application may be due to a greater photosynthesizing area resulting in enhancing photosynthetic activity in comparison to calcium oxide treatments and control (Rani et al., 1997). Application of 2-4 t ha<sup>-1</sup> of rice hull ash as Si source increased the rice yields to an extent of 15 to 20 per cent during 2000-2002 (Prakash et al., 2007). Application of calcium silicate and silica gel as Si sources also increased the rice yield (Narayanaswamy, 2007). Savant et al. (1994) noticed that the percentage of perfect grain in brown rice and in milled rice hull where Si was applied increased by 7.5 and 3.5 per cent, respectively, as compared to the application of NPK (without Si). Similar results were also reported by Jafari et al. (2013) who noticed that Si application increased number of filled spikelet, grain and straw yield and decreased blank spikelet and harvest index of rice. Field trials conducted in Japan (Ma and Takahashi, 2002) using Si fertilization on rice growth and yield showed a slight increase in the panicle number but up to a 17 per cent yield increase. Wang et al. (2014) reported that the yield increase of rice may be caused partly due to an increase in soil organic carbon, total nitrogen, available P, Fe and Mn with the application of silicon fertilization.

In the present investigation, there was no severe incidence of plant diseases or pests during the cropping season. One of the most important roles of Si is to stimulate the plant's defence abilities against abiotic and biotic stresses. Si deposited on the tissue surface has been proposed to be responsible for the protective effect of silicon against biotic stress. Deposition of silicon on culm and vascular bundle and thereby increases the thickness, so preventing the lodging. The role of Si in conferring plant resistance to both biotic and abiotic stresses has been proved by many researchers and there is a cumulative body of evidence linking the presence of Si with resistance of plants against fungal pathogens. The effect of Si on reducing diseases unquestionably contributes to increased yields (Datnoff *et al.*, 1992) and Ma *et al.* (1989). No evidence of disease or pest also influenced the higher straw and grain yield of rice in the present investigation.

# 4.2.3 Effect of diatomite as Si source on content of Si, other nutrients and their uptake by rice crop (straw and grain) grown during *summer* 2015

## 4.2.3.1 Effect of diatomite on content of Si, other nutrients and their uptake by rice straw

Data with regard to the nutrient content and its uptake as affected by application of DE as Si source by rice straw are presented in Table 23 and 24.

Diatomite application @ 300 kg ha<sup>-1</sup> recorded numerical increase in the nutrient content and uptake by the rice straw but was statistically on par with no DE application treatment except in the uptake of nitrogen. There was increase in nutrient content with DE application over control *viz.*, Si =  $5.29 \pm 2.02$  per cent; N =  $1.98 \pm 0.14$  per cent; P =  $0.04 \pm 0.02$  per cent; K =  $1.83 \pm 0.32$  per cent; Ca =  $0.37 \pm 0.18$  per cent; Mg =  $0.44 \pm 0.18$  and micronutrients *viz.*, Fe =  $159.75 \pm 9.18$  mg kg<sup>-1</sup>; Mn =  $289.92 \pm 62.01$  mg kg<sup>-1</sup>; Cu

| Traatmonte           | Si                    | Ν                     | Р                  | K                        | Ca                  | Mg                   |  |  |  |  |  |
|----------------------|-----------------------|-----------------------|--------------------|--------------------------|---------------------|----------------------|--|--|--|--|--|
| Treatments           | Content (%)           |                       |                    |                          |                     |                      |  |  |  |  |  |
| Si <sub>0</sub> + RP | $4.96 \pm 1.94(a)$    | $1.78 \pm 0.24(a)$    | $0.03 \pm 0.01(a)$ | $1.84 \pm 0.19(a)$       | $0.42 \pm 0.056(a)$ | $0.36 \pm 0.16(a)$   |  |  |  |  |  |
| Si <sub>1</sub> + RP | $5.29 \pm 2.02(a)$    | $1.98 \pm 0.14(a)$    | $0.04 \pm 0.02(a)$ | $1.83 \pm 0.32(a)$       | $0.37 \pm 0.063(a)$ | $0.44 \pm 0.18(a)$   |  |  |  |  |  |
| S. Em±               | 0.99                  | 0.09                  | 0.01               | 0.13                     | 0.03                | 0.09                 |  |  |  |  |  |
| LSD (p<0.05)         | NS                    | NS                    | NS                 | NS                       | NS                  | NS                   |  |  |  |  |  |
|                      |                       |                       | Uptake             | e (kg ha <sup>-1</sup> ) |                     |                      |  |  |  |  |  |
| Si <sub>0</sub> + RP | $400.76 \pm 78.79(a)$ | 188.82 ± 17.39(b)     | $2.92 \pm 1.74(a)$ | $196.43 \pm 36.55(a)$    | $43.97 \pm 5.90(a)$ | 40.14± 22.18 (a)     |  |  |  |  |  |
| Si <sub>1</sub> + RP | $443.76 \pm 76.76(a)$ | $230.05 \pm 13.39(a)$ | $4.61 \pm 2.17(a)$ | $212.05 \pm 31.20(a)$    | $43.83 \pm 8.91(a)$ | $51.61 \pm 22.70(a)$ |  |  |  |  |  |
| S. Em±               | 38.89                 | 7.62                  | 0.98               | 16.94                    | 3.70                | 11.21                |  |  |  |  |  |
| LSD (p≤0.05)         | NS                    | 26.62                 | NS                 | NS                       | NS                  | NS                   |  |  |  |  |  |

Table 23: Effect of diatomite as Si source on Si content, other nutrients and their uptake by rice straw during *summer* 2015

| Treatments           | Fe                             | Mn                         | Cu                  | Zn                  |  |  |  |  |  |
|----------------------|--------------------------------|----------------------------|---------------------|---------------------|--|--|--|--|--|
| 1 reatments          | Content (mg kg <sup>-1</sup> ) |                            |                     |                     |  |  |  |  |  |
| Si <sub>0</sub> + RP | $170.54 \pm 6.42$ (a)          | 316.50 ± 100.04 (a)        | 18.58± 2.55 (a)     | 50.92 ± 17.59 (a)   |  |  |  |  |  |
| Si <sub>1</sub> + RP | $159.75 \pm 9.18(a)$           | $289.92 \pm 62.01(a)$      | $18.83 \pm 2.16(a)$ | 49.63 ± 8.29 (a)    |  |  |  |  |  |
| S. Em±               | 4.26                           | 40.51                      | 1.18                | 6.47                |  |  |  |  |  |
| LSD (p<0.05)         | NS                             | NS                         | NS                  | NS                  |  |  |  |  |  |
|                      |                                | Uptake (g ha <sup>-1</sup> | <sup>1</sup> )      |                     |  |  |  |  |  |
| Si <sub>0</sub> + RP | 1817.26 ± 193.08(a)            | $46.48 \pm 6.31(a)$        | 5.83 ± 1.10 (a)     | $0.93 \pm 0.24$ (a) |  |  |  |  |  |
| Si <sub>1</sub> + RP | $1862.94 \pm 135.60(a)$        | $53.91 \pm 16.69(a)$       | $5.55 \pm 1.86(a)$  | $0.94 \pm 0.23$ (a) |  |  |  |  |  |
| S. Em±               | 82.17                          | 5.75                       | 0.74                | 0.12                |  |  |  |  |  |
| LSD (p≤0.05)         | NS                             | NS                         | NS                  | NS                  |  |  |  |  |  |

Table 24: Effect of diatomite as Si source on content of micronutrient and their uptake by rice straw during summer 2015

 $1.18 \pm 2.16 \text{ mg kg}^{-1}$  and Zn = 49.63 ± 8.29 mg kg<sup>-1</sup>. Similarly, nutrient uptake by rice straw was also increased with application of DE over control *viz.*, Si = 443.76 ± 76.76 kg ha<sup>-1</sup>; N = 230.05 ± 13.39 kg ha<sup>-1</sup>; P = 4.61 ± 2.17 kg ha<sup>-1</sup>; K = 212.05 ± 31.20 kg ha<sup>-1</sup>; Ca = 43.83 ± 8.91 kg ha<sup>-1</sup>; Mg = 51.61 ± 22.70 kg ha<sup>-1</sup> and uptake of micronutrients *viz.*, Fe = 1862.94 ± 135.60 g ha<sup>-1</sup>; Mn = 53.91 ± 16.69 g ha<sup>-1</sup>; Cu = 5.55 ± 1.86 g ha<sup>-1</sup>; Zn = 0.94 ± 0.23 g ha<sup>-1</sup>.

# 4.2.3.2 Effect of diatomite on content of Si, other nutrients and their uptake by rice grain

Data pertinent to the nutrient content and their uptake as affected by application of DE as Si source in rice grain are presented in Table 25 and 26 respectively.

Diatomite application @ 300 kg ha<sup>-1</sup> recorded numerical increase in the nutrient content and their uptake by the rice grain but was statistically on par with no DE application treatment. Application of DE recorded increase in concentration of Si (1.13  $\pm$  0.01 %); N (1.02  $\pm$  0.14 %); P (0.19  $\pm$  0.01 %); K (0.25  $\pm$  0.02 %); Ca (0.31  $\pm$  0.08 %); Mg (0.35  $\pm$  0.08 %) and micronutrients *viz.*, Fe (41.96  $\pm$  7.70 mg kg<sup>-1</sup>); Mn (66.92  $\pm$  62.01 mg kg<sup>-1</sup>); Cu (21.08  $\pm$  2.08 mg kg<sup>-1</sup>) and Zn (32.25  $\pm$  8.29 mg kg<sup>-1</sup>). Similarly, nutrient uptake by rice grain was also increased with application of DE over control *viz.*, Si = 76.34  $\pm$  9.91 kg ha<sup>-1</sup>; N = 69.18  $\pm$  12.37 kg ha<sup>-1</sup>; P = 13.02  $\pm$  1.04 kg ha<sup>-1</sup>; K = 16.59  $\pm$  0.56 kg ha<sup>-1</sup>; Ca = 76.34  $\pm$  9.91 kg ha<sup>-1</sup>; Mg = 23.93  $\pm$  7.04 kg ha<sup>-1</sup> and micronutrients *viz.*, Fe = 284.09  $\pm$  71.00 g ha<sup>-1</sup>; Mn = 2.76  $\pm$  0.52 g ha<sup>-1</sup>; Cu = 1.42  $\pm$  0.28 kg ha<sup>-1</sup>; Zn = 0.52  $\pm$  0.43 kg ha<sup>-1</sup>.

Application DE @ 300 kg ha<sup>-1</sup> increased the nutrient contents and uptake by straw and grain compared to control (Fig. 18 &19). This may be due to beneficial effect of Si released from DE and other nutrient concentration in soil as well. Silicon increases nutrient balance, and reduces the metal toxicity in rice plant (Epstein, 1999). Application of calcium silicate showed higher concentration of Si in rice plants compared to control. Singh *et al.* (2006) found that 180 kg ha<sup>-1</sup> of Si increased nitrogen and phosphate levels in the grain and straw of rice. Bioavailability of Si in silicate is influenced by its dissolution and sorption reaction in soil. Mona (2010) reported that total nitrogen (TN) and total soluble nitrogen (TSN) and the concentrations of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) increased with application of diatomite than non-treated faba bean plants.

Rice is a Si accumulator plant and it requires Si to maintain healthy growth and high productivity. Deren *et al.* (1994) noticed increased Si concentration in plant tissue with increasing rate of Si fertilization. Similar results were reported by Winslow (1992) and Winslow *et al.* (1997) in South America. The presence of Si in nutrient solutions has also been reported to affect the absorption and translocation of several macro- and micronutrients (Epstein, 1999). The application of calcium silicate showed greater concentration of Si in rice plants compared to control. Rice is a typical Si-accumulating plant and Si can make up for 10 per cent of the shoot dry weight, which is several fold

| Treatments           | Si                   | Ν                    | Р                   | K                      | Ca                   | Mg                  |  |  |  |  |  |
|----------------------|----------------------|----------------------|---------------------|------------------------|----------------------|---------------------|--|--|--|--|--|
| Treatments           | Content (%)          |                      |                     |                        |                      |                     |  |  |  |  |  |
| Si <sub>0</sub> + RP | $1.11 \pm 0.02(a)$   | $0.87 \pm 0.17(a)$   | $0.18 \pm 0.02(a)$  | $0.24 \pm 0.02(a)$     | $0.30 \pm 0.08(a)$   | $0.26 \pm 0.13$ (a) |  |  |  |  |  |
| Si <sub>1</sub> + RP | 1.13 ± 0.01 (a)      | $1.02 \pm 0.14(a)$   | $0.19 \pm 0.01(a)$  | $0.25 \pm 0.02$ (a)    | $0.31 \pm 0.08(a)$   | $0.35 \pm 0.08(a)$  |  |  |  |  |  |
| S. Em±               | 0.12                 | 0.08                 | 0.01                | 0.01                   | 0.04                 | 0.05                |  |  |  |  |  |
| LSD (p<0.05)         | NS                   | NS                   | NS                  | NS                     | NS                   | NS                  |  |  |  |  |  |
|                      |                      |                      | Uptake (            | (kg ha <sup>-1</sup> ) |                      |                     |  |  |  |  |  |
| Si <sub>0</sub> + RP | $74.72 \pm 22.37(a)$ | $57.87 \pm 8.96(a)$  | $12.47 \pm 1.01(a)$ | $16.53 \pm 0.93(a)$    | $20.52 \pm 21.38(a)$ | $17.39 \pm 8.50(a)$ |  |  |  |  |  |
| Si <sub>1</sub> + RP | $76.34 \pm 9.91(a)$  | $69.18 \pm 12.37(a)$ | $13.02 \pm 1.04(a)$ | $16.59 \pm 0.56(a)$    | $76.34 \pm 9.91(a)$  | $23.93 \pm 7.04(a)$ |  |  |  |  |  |
| S. Em±               | 8.07                 | 5.33                 | 0.51                | 0.37                   | 2.75                 | 3.89                |  |  |  |  |  |
| LSD (p≤0.05)         | NS                   | NS                   | NS                  | NS                     | NS                   | NS                  |  |  |  |  |  |

 Table 25: Effect of diatomite as Si source on Si content, other nutrients and their uptake by rice grain during summer 2015

| Trootmonts           | Fe                             | Mn                         | Cu                  | Zn                 |  |  |  |  |  |
|----------------------|--------------------------------|----------------------------|---------------------|--------------------|--|--|--|--|--|
| Treatments           | Content (mg kg <sup>-1</sup> ) |                            |                     |                    |  |  |  |  |  |
| Si <sub>0</sub> + RP | $40.79 \pm 14.02(a)$           | 62.95±100.04 (a)           | 21.42± 2.25 (a)     | 30.50 ± 17.59 (a)  |  |  |  |  |  |
| Si <sub>1</sub> + RP | $41.96 \pm 7.70(a)$            | $66.92 \pm 62.01(a)$       | $21.08 \pm 2.08(a)$ | 32.25 ± 8.29 (a)   |  |  |  |  |  |
| S. Em±               | 7.18                           | 4.80                       | 1.08                | 7.02               |  |  |  |  |  |
| LSD (p<0.05)         | NS                             | NS                         | NS                  | NS                 |  |  |  |  |  |
|                      |                                | Uptake (g ha <sup>-1</sup> | <sup>1</sup> )      |                    |  |  |  |  |  |
| Si <sub>0</sub> + RP | $272.06 \pm 56.38(a)$          | $2.49 \pm 0.20(a)$         | $1.35 \pm 0.31(a)$  | $0.64 \pm 0.22(a)$ |  |  |  |  |  |
| Si <sub>1</sub> + RP | $284.09 \pm 71.00(a)$          | $2.76 \pm 0.52(a)$         | $1.42 \pm 0.28(a)$  | $0.52 \pm 0.43(a)$ |  |  |  |  |  |
| S. Em±               | 31.84                          | 0.18                       | 0.15                | 0.16               |  |  |  |  |  |
| LSD (p≤0.05)         | NS                             | NS                         | NS                  | NS                 |  |  |  |  |  |

 Table 26: Effect of diatomite as Si source on content of micronutrient and their uptake by rice grain during summer 2015



Fig. 17: Influence of diatomite on straw and grain yield of rice crop grown during *summer* 2015



Fig. 18: Influence of diatomite on silicon content of rice straw and grain during *summer* 2015



Fig. 19: Influence of diatomite on silicon uptake by rice straw and grain during *summer* 2015

higher than those of essential macronutrients such as N, P and K (Ma and Takahashi, 2002). These results are in agreement with the findings of Singh and Singh (2005) and Singh *et al.* (2006) in India and Ma *et al.* (1989) in Japan, Munier *et al.* (2003) in Brazil and Idris *et al.* (1975) in Bangladesh. Korndorfer and Gascho (1999) reported that both soil and plant parameters were significantly influenced by the Si sources.

## 4.2.4 Effect of diatomite as Si source on Si and other nutrient status of soil during *summer* 2015

Results of the present investigation mentioned in Table 27 to 28 revealed that the nutrient status of the soil after completion of experiment varied significantly between the treatments.

There was a significant difference in soil pH between absolute control and rest of the treatments. The treatment under the cropping situation recorded higher soil pH (7.95  $\pm$  0.21) along with the DE application @ 300 kg ha<sup>-1</sup>. Although, there was increase in the soil EC compared to initial values, but no significant difference in EC among the treatments. In general, there was increase in the pH among the treatments under submergence (Table 27). This may be due to cultivation of rice under flooded condition. Increase in acidic soil solution pH as a result of submergence is well known (Ponnamperuma, 1972) and attributed to the consumption of protons during reduction processes. In soil redox reactions, ferric iron (from amorphous ferric hydroxides) serves as an electron-acceptor and organic matter (CH<sub>2</sub>O) as the electron-donor. This reaction results in the neutralization of acidity and increase in pH (Sahrawat, 2005). Increase in the EC of soil due to increase in the solubility of the salts present in the soil and also salts contributed by diatomaceous earth. Ponnamperuma (1972) reported that increase in conductance during the first few weeks of flooding is due to the release of Fe and Mn from the insoluble Fe(III) and Mn(IV) oxide hydrates, the accumulation of NH<sub>4</sub><sup>+</sup>, HCO<sub>3</sub><sup>-</sup>, and RCOO<sup>-</sup>, and (in calcareous soils) the dissolution of CaCO<sub>3</sub>, by CO<sub>2</sub> and organic acids. Application of silicate material positively affects the soil reaction and electrical conductivity in acidic soil as noticed by Ribeiro et al. (1986). Silicates and slag pulverized to <1mm were reported to be efficient in correcting the soil acidity and has great potential use in the agriculture as an environmental safe liming material (Correa et al., 2007; Joulazadeh and Joulazadeh, 2010).

The content of acetic acid extractable Si (AASi) in the soil (96.19  $\pm$  9.87 mg kg<sup>-1</sup>) increased significantly with application of DE @ 300 kg ha<sup>-1</sup> where no rice was grown, whereas Si content decreased in the presence of crop even though the DE was applied because of Si uptake by crop and was on par with control with and without rice crop (Fig. 20). 0.01M calcium chloride extractable Si (CCSi) content was significantly higher in control where no crop was grown with (35.82  $\pm$  4.71 mg kg<sup>-1</sup>) or without (46.24  $\pm$  9.03 mg kg<sup>-1</sup>) added Si. However, in the presence of rice crop soil Si content decreased and was on par with the other treatments.

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|        | Treatments                        | рН              | EC                   | CCSi                 | AASi                  | Ν                  | <b>P</b> <sub>2</sub> <b>O</b> <sub>5</sub> | K <sub>2</sub> O    |
|--------|-----------------------------------|-----------------|----------------------|----------------------|-----------------------|--------------------|---|---------------------|
|        | I reatments                       | (1:2.5 water)   | (dSm <sup>-1</sup> ) | (                    | mg kg <sup>-1</sup> ) |                    |   |                     |
|        | $Si_0 + RP_0$                     | 7.62 ± 0.18 (b) | $0.24 \pm 0.02$ (a)  | $46.24 \pm 9.03$ (a) | 71.91 ± 6.87 (b)      | 398.32 ± 6.41 (a)  | 303.77 ± 27.35 (a)                          | 276.86 ± 75.36 (a)  |
| San    | Si <sub>0</sub> + RP              | 7.90 ± 0.19 (a) | $0.21 \pm 0.04$ (a)  | 19.64 ± 3.40 (c)     | 58.55 ± 15.58 (b)     | 371.37 ± 18.25 (b) | 253.18 ± 21.35 (b)                          | 162.46 ± 41.22 (b)  |
| dhya,  | Si <sub>1</sub> + RP <sub>0</sub> | 7.93 ± 0.13 (a) | $0.19 \pm 0.06$ (a)  | $35.82 \pm 4.71(b)$  | 96.19 ± 9.87 (a)      | 401.55 ± 6.43 (a)  | 296.75 ± 22.55 (a)                          | 217.22 ± 34.10 (ab) |
| K., Ph | Si <sub>1</sub> + RP              | 7.95 ± 0.21 (a) | $0.21 \pm 0.04$ (a)  | 17.83 ± 4.87 (c)     | 57.41 ± 16.66 (b)     | 377.66 ± 16.10(b)  | 277.90 ± 28.70 (ab)                         | 170.69 ± 51.00 (b)  |
| Ð      | S. Em±                            | 0.09            | 0.02                 | 2.75                 | 6.12                  | 5.90               | 12.49                                       | 25.21               |
|        | LSD (p≤0.05)                      | 0.27            | NS                   | 9.08                 | 19.86                 | 20.59              | 37.48                                       | 81.32               |

Table 27: Effect of diatomite as Si source on pH, EC, plant available Silicon ((CaCl<sub>2</sub> Si (CCSi) and acetic acid Si (AASi)) and available N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O of soil during *summer* 2015

| Tuesta                            | Ca                  | Mg   | Na                  | Fe                     | Mn               | Cu                  | Zn              |  |  |
|-----------------------------------|---------------------|--|---------------------|------------------------|------------------|---------------------|-----------------|--|--|
| 1 reatments                       |                     | (cmol (p <sup>+</sup> ) kg <sup>-1</sup> ) |                     | (mg kg <sup>-1</sup> ) |                  |                     |                 |  |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 5.95 ± 0.81 (a)     | $2.93 \pm 0.73(a)$                         | $0.43 \pm 0.04$ (a) | 89.05 ± 3.94 (a)       | 12.68 ± 6.44 (b) | $3.60 \pm 0.11$ (a) | 6.91 ± 1.12 (a) |  |  |
| Si <sub>0</sub> + RP              | $5.24 \pm 0.56$ (a) | $2.90 \pm 0.60(a)$                         | $0.47 \pm 0.08$ (a) | 78.17 ± 5.98 (ab)      | 14.82 ± 7.50 (a) | $3.62 \pm 0.52$ (a) | 4.12 ± 0.36 (b) |  |  |
| Si <sub>1</sub> + RP <sub>0</sub> | $5.64 \pm 0.49$ (a) | $2.88 \pm 0.31(a)$                         | $0.41 \pm 0.08$ (a) | 70.98 ± 13.62 (b)      | 11.57 ± 5.79 (b) | 3.51 ± 0.11 (a)     | 4.35 ± 0.70 (b) |  |  |
| Si <sub>1</sub> + RP              | 5.28 ± 0.74 (a)     | $2.88 \pm 0.69(a)$                         | 0.51 ± 0.11 (a)     | 80.38 ± 1.60 (ab)      | 11.89 ± 5.96 (b) | $3.69 \pm 0.30$ (a) | 4.10 ± 1.12 (b) |  |  |
| S. Em±                            | 0.32                | 0.29                                       | 0.04                | 3.14                   | 3.21             | 0.13                | 0.41            |  |  |
| LSD (p≤0.05)                      | NS                  | NS   | NS                  | 11.92                  | 1.31             | NS                  | 1.36            |  |  |

 Table 28: Effect of diatomite as Si source on status of exchangeable cations and DTPA extractable micronutrients during summer 2015

Available N content in soil was significantly higher in the treatment where no crop was grown (398.32 ± 6.41; 401.55 ± 6.43 kg ha<sup>-1</sup>) and was on par with or without DE application whereas in the presence of rice crop available N (371.18.25; 377 ± 16.10 kg ha<sup>-1</sup>) was significantly decreased with or without DE because of crop N uptake. Available P<sub>2</sub>O<sub>5</sub> also followed similar trend as that of available N. In the presence of rice, available P<sub>2</sub>O<sub>5</sub> content (253.18 ± 21.35; 277.90 ± 28.70 kg ha<sup>-1</sup>) decreased significantly compared to without crop and there was on par effect with each other. There was a significant difference in available K<sub>2</sub>O content in soil among the treatments. Significantly higher available K<sub>2</sub>O was recorded in control (276.86 ± 75.36 kg ha<sup>-1</sup>) whereas significantly lower K was recorded in control with rice crop (162.46 ± 41.22 kg ha<sup>-1</sup>).

The decrease in the available Si, N and P content in soil may be due to efficient utilisation of nutrients by crop. The convergence of soil pH to neutrality following submergence of soil benefits wetland rice crop through better availability of nutrients such as ammonium, P, K and exchangeable cations which are mobilized in soil solution (Sahrawat, 2005). Matichenkov and Bocharnikova (2010) also noticed that the application of Si amendments reduced the leaching of phosphate, nitrate and potassium (NPK). Ma and Takahashi (1990) reported that the added silicon enhanced the absorption of P and hence lower P content in the presence of crop. The ability of silicon to displace the fixed P in the soil and thereby rice plants was able to use acid soluble P under submerged conditions by acidifying the rhizosphere (Mohanthy *et al.*, 1977). Elawad and Green (1979) reported that Si has the potential to raise the optimum rate of nitrogen. Si also improves the availability and utilisation of P by rice plants (Savant *et al.*, 1997).

Exchangeable cations such as Ca, Mg, Na and micronutrient such as Cu was affected by the application of silicon and values were higher compared to initial content in soil. The increase in exchangeable Ca and Mg in the soil samples at the end of experiment may be due to synergistic interaction of silicon with calcium and magnesium and also contribution of cations by the diatomaceous earth. The dissolution of calcium silicate increased the soil pH and Ca content (Kato and Owa, 1998) of Japanese soils. Similar results were also noticed by Hossain *et al.* (2004) in some soils of Japan. Under flooding Ca and Mg attributed to displacement of exchangeable Ca and Mg by iron produced by reduction of iron compounds can also be a reason for increase in the exchangeable cations in the present investigation. The diffusive flux of calcium increased with increasing solution Ca concentration and moisture content (Mohanthy *et al.*, 1977). Kato and Owa (1998) reported that the application of slag silicates at early plant stage increased the pH and Ca<sup>2+</sup> concentration in the soil.

There was significant difference in the DTPA extractable Fe, Mn and Zn contents among the treatments. Fe and Zn content (89.05  $\pm$  3.94; 6.91  $\pm$  1.12 mg kg<sup>-1</sup>, respectively) was found to be significantly higher in control where no crop was grown whereas lower concentration was noticed in the presence of rice crop which can be



Fig. 20: Influence of diatomite on plant available silicon status of soil during *summer* 2015

attributed to crop uptake. Increase in Zn content in soil at the end of the experiment as compared to initial might be due to release of Zn from the applied ZnSO<sub>4</sub>.

# 4.2.5 Dissolved Si (DSi) and other nutrients in soil solution during different intervals of crop growth at 5cm and 40cm depth of soil during *summer* 2015

The dissolved nutrient content of soil solution collected at 5cm and 40cm depth of soil at different intervals during the period of field experiment at V C Farm, Mandya is presented in Table 29 to 35 and Fig. 21 to 27.

#### 4.2.5.1 Dissolved silicon

Dissolved silicon (DSi) content at 5cm depth of soil solution significantly varied between the treatments at different intervals of experiment (Table 29 & Fig. 21). DSi was found to be higher during initial period of crop growth and decreased significantly at 7 DAT again increased at 60 DAT in the treatments without crop plants and thereafter decreased at 90 DAT. At 0 DAT, there was no greater difference among the treatments but DSi was significantly higher without crop compared to with crop may be due to crop uptake of Si. This result depicts about the maximum utilization period of Si by the crop.

Analysis of soil solution collected from the rhizons installed at a depth of 40cm revealed that there was no significant variation in DSi levels among the treatments at different intervals of experimental period and found to be on par with each other (Table 29 & Fig. 21). This can be attributed to the fact that shallow water table induced the dilution of soil solution.

In the present investigation, DSi content was increased during some period and decreased at different stages of the experiment which can be attributed to adsorption/desorption process. The concentration of silica in the solutions of submerged soils increases slightly after flooding and then decreases gradually, and after several months of submergence the concentration may be lower than at the start. The increase in concentration after flooding may be due to the release of hydrous oxides of Fe (III) sorbing silica and action of  $CO_2$  on aluminosilicates (Bricker and Godfrey, 1967). The subsequent decrease may be due to recombination with aluminosilicates following the decrease in partial pressure of  $CO_2$  (Ponnamperuma, 1972). The trend in increase or decrease of DSi may be attributed to adsorption/desorption process. When Si source is applied to soil, Si dissolves in the soil solution and part of the dissolved Si is adsorbed onto the soil solid phase and then desorbed and redissolved into soil solution (Shuhei *et al.*, 2013).

| Table 29: Dissolved silicon ( $\mu$ mol L <sup>-1</sup> ) in soil solu | ition during different intervals of experimental period at 5 and 40 cm depths of |
|--|--|
| soil during summer 2015  |  |

| Treatments                        | 0 DAT                  | 7 DAT                   | 15 DAT                 | <b>30 DAT</b>         | 60 DAT                | 90 DAT                 |
|-----------------------------------|------------------------|-------------------------|------------------------|-----------------------|-----------------------|------------------------|
| Treatments                        |                        |                         | 5cm                    | ı depth               |                       |                        |
| Si <sub>0</sub> + RP <sub>0</sub> | 702.50± 124.19(b)      | 372.75± 80.07(ab)       | 526.00± 40.98(ab)      | 329.25± 81.93(ab)     | 619.75± 77.18(a)      | 439.00± 36.07(ab)      |
| Si <sub>0</sub> + RP              | 893.75± 31.22(a)       | $361.00 \pm 47.91(a)$   | 505.50± 111.9(a)       | 333.75± 51.37(a)      | $150.00 \pm 54.63(b)$ | 376.50± 136.74(ab)     |
| Si <sub>1</sub> + RP <sub>0</sub> | $650.00 \pm 99.52(b)$  | $373.75 \pm 42.44$ (ab) | 428.75±73.39(ab)       | 350.00± 39.64(ab)     | 495.75± 71.36(a)      | $490.50 \pm 61.24(a)$  |
| Si <sub>1</sub> + RP              | 640.25±127.25(b)       | 382.25± 46.74(ab)       | 435.50± 78.27(ab)      | 331.00±118.57(ab)     | 216.16±216.57(b)      | 208.55±78.61(b)        |
| S.Em±                             | 47.77                  | 27.14                   | 38.07                  | 36.44                 | 52.47                 | 39.08                  |
| LSD (p≤0.05)                      | 159.00                 | 87.00                   | 124.00                 | 122.00                | 190.00                | 267.00                 |
|                                   |                        |                         | 40                     | cm depth              |                       |                        |
| Si <sub>0</sub> + RP <sub>0</sub> | 269.50± 54.21(a)       | 276.50± 63.16(a)        | $264.00 \pm 48.24(a)$  | 269.00± 55.35(a)      | 285.75± 51.16(a)      | 281.25±79.44(a)        |
| Si <sub>0</sub> + RP              | $315.50 \pm 190.39(a)$ | 306.50±191.13(a)        | $308.75 \pm 190.65(a)$ | 251.25±136.10(a)      | 328.25± 189.43(a)     | $335.25 \pm 263.38(a)$ |
| Si <sub>1</sub> + RP <sub>0</sub> | 210.25± 17.69(a)       | $198.25 \pm 17.54(a)$   | $200.50 \pm 19.47(a)$  | $190.50 \pm 22.81(a)$ | $215.25 \pm 22.60(a)$ | $254.50 \pm 74.57(a)$  |
| Si <sub>1</sub> + RP              | 256.75± 63.97(a)       | $256.50 \pm 64.22(a)$   | 254.50± 64.36(a)       | 260.25± 68.72(a)      | 282.00± 68.72(a)      | 246.50±47.99(a)        |
| S.Em±                             | 40.78                  | 42.01                   | 40.34                  | 35.37                 | 39.95                 | 58.17                  |
| LSD (p≤0.05)                      | NS                     | NS                      | NS                     | NS                    | NS                    | NS                     |

### 4.2.5.2 Dissolved phosphate

The dissolved PO<sub>4</sub> significantly differed between the treatments (Table 30 and Fig. 22) at 5cm depth of the soil. At 0 DAT, solution PO<sub>4</sub> was significantly higher in the control with crop ( $310.50 \pm 81.67 \mu mol L^{-1}$ ), whereas other treatments were not affected. Dissolved PO<sub>4</sub> content was decreased at 7 DAT and stabilized further during the experimental period. However, slight increase in the phosphate was noticed at 15 DAT and 60 DAT.

At 40 cm depth of soil, dissolved PO<sub>4</sub> was significantly affected among the treatments and different intervals of experiment (Table 30 & Fig. 22). In general, significantly higher PO<sub>4</sub> content was recorded in control treatment compared to other treatments at all sampling intervals. Among the different intervals of sampling, higher PO<sub>4</sub> recorded during 60 DAT followed by 15 DAT and 90 DAT.

A significant increase in dissolved PO<sub>4</sub> content during the crop growth at different intervals may be due to increased solubility of phosphorus by microbially mediated mineralization of soil organic P to inorganic P from the native soil. Horta and Torrent (2007) reported that the ratio of fast desorbable P or total desorbable P to sorbed P increased with increasing degree of P saturation in the soil. When a soil is submerged, the oxygen supply is cut off and reduction sets in. A striking consequence of reduction is the increase in the concentration of water-soluble and available P (Ponnamperuma, 1972).

The increase or decrease in the phosphate at different intervals may be due to adsorption or desorption process or immobilization process which occurs within the soil. This is also in accordance with other researchers. The phosphorus mineralization or immobilization of organic materials or manures depends on the organic P content of the material as reported by Mafongoya *et al.* (2000). The phosphate ions released by these reactions and from the decomposition of organic matter may be resorbed by clay and hydrous oxides of Al in the anaerobic zone (Gasser and Bloomfield, 1955; Bromfield, 1960) or they may diffuse to oxidized zones and be reprecipitated (Hynes and Greib, 1970).

| Treatmonte                        | 0 DAT                 | 7 DAT                | 15 DAT              | <b>30 DAT</b>        | 60 DAT                | 90 DAT               |  |  |  |  |  |
|-----------------------------------|-----------------------|----------------------|---------------------|----------------------|-----------------------|----------------------|--|--|--|--|--|
| 1 reatments                       | 5cm depth             |                      |                     |                      |                       |                      |  |  |  |  |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 107.75± 106.36(b)     | 5.00± 5.77(b)        | $30.25 \pm 5.85(a)$ | $11.75 \pm 5.56(a)$  | $40.25 \pm 8.42(a)$   | 11.00± 13.11(b)      |  |  |  |  |  |
| Si <sub>0</sub> + RP              | $310.50 \pm 80.67(a)$ | $3.00 \pm 6.00(b)$   | $32.25 \pm 4.65(a)$ | 10.25± 4.92(ab)      | 25.75±18.23(ab)       | $23.50 \pm 5.20(a)$  |  |  |  |  |  |
| Si <sub>1</sub> + RP <sub>0</sub> | $78.75 \pm 60.54(b)$  | 0                    | 23.75±17.02(a)      | 4.50±1.29(b)         | 30.00±7.59(ab)        | $22.50 \pm 4.80(ab)$ |  |  |  |  |  |
| Si <sub>1</sub> + RP              | $52.50 \pm 30.51(b)$  | $14.25 \pm 2.63(a)$  | 41.50±13.77(a)      | 8.25±4.35(ab)        | 30.00±21.97(ab)       | $20.50 \pm 4.43(ab)$ |  |  |  |  |  |
| S.Em±                             | 34.76                 | 1.80                 | 5.16                | 2.02                 | 7.03                  | 3.44                 |  |  |  |  |  |
| LSD (p≤0.05)                      | 115.33                | 6.73                 | 17.82               | 6.70                 | 23.66                 | 11.98                |  |  |  |  |  |
|                                   |                       |                      | 40cm                | depth                |                       |                      |  |  |  |  |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 26.25±7.89(a)         | 24.75± 1.71(a)       | $34.25 \pm 4.03(a)$ | 3.75±1.89(a)         | 59.00± 40.91(a)       | $23.25 \pm 4.99(a)$  |  |  |  |  |  |
| Si <sub>0</sub> + RP              | 20.25±2.36(ab)        | 12.75± 8.54(b)       | 33.50±7.33(ab)      | 5.35±2.22(ab)        | $44.75 \pm 6.40$ (ab) | 26.50± 12.07(ab)     |  |  |  |  |  |
| Si <sub>1</sub> + RP <sub>0</sub> | 18.75±3.10(b)         | 12.75± 3.95(b)       | 31.25± 3.30(ab)     | $3.50 \pm 2.65 (ab)$ | 34.75± 3.30(ab)       | 21.00±7.53(ab)       |  |  |  |  |  |
| Si <sub>1</sub> + RP              | $18.25 \pm 3.59(b)$   | $19.25 \pm 6.24(ab)$ | 34.75± 3.86(ab)     | 2.50± 2.38(ab)       | $43.00 \pm 2.94(ab)$  | 32.25±11.84(ab)      |  |  |  |  |  |
| S.Em±                             | 2.12                  | 2.55                 | 2.32                | 1.14                 | 6.69                  | 4.55                 |  |  |  |  |  |
| LSD (p≤0.05)                      | 7.32                  | 8.79                 | 7.54                | 3.54                 | 21.08                 | 14.77                |  |  |  |  |  |

Table 30: Dissolved phosphate (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at 5 and 40cm depths of soil during *summer* 2015



Fig. 21: Dissolved silicon (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at a) 5cm and b) 40cm depth of soil during *summer* 2015



Fig. 22: Dissolved phosphate (µmol L<sup>-1</sup>) in soil solution during different intervals of crop growth at a) 5cm and b) 40cm depth of soil during *summer* 2015

### 4.2.5.3 Dissolved potassium

There was a gradual decrease in the dissolved K content during the experiment at 5cm depth of soil (Table 31 and Fig. 23). At 0 DAT, K content was higher and decreased significantly till 60 DAT and thereafter stabilized. During 30, 60 and 90 DAT there was significant difference between the treatments and lower dissolved K content was recorded in treatment with crop plants.

At 40cm depth of the soil, there was no variation in dissolved K content between the treatments as well in different intervals of crop growth period and values were found to be on par each other (Table 31 and Fig. 23) which can be attributed to higher water table and there by dilution of K content in soil solution.

Although potassium was not involved in oxidation-reduction reactions, the release of large amounts of  $Fe^{2+}$ ,  $Mn^{2+}$  and  $NH_4^+$  in soils with low O<sub>2</sub> resulted might have involved in displacement of K<sup>+</sup> ions from the exchange complexes to the soil solution as revealed by Reddy and Patrick (1983).

### 4.2.5.4 Dissolved calcium

Dissolved Ca in soil solution at 5 cm depth significantly affected due to the treatments during 0 DAT ( $3604.00 \pm 1444.21 \mu mol L^{-1}$ ), 7 DAT ( $2835.25 \pm 553.78 \mu mol L^{-1}$ ) and 30 DAT ( $1347.25 \pm 121.81 \mu mol L^{-1}$ ) days after transplanting (Table 32 and Fig. 24). Higher dissolved Ca concentration recorded in control treatment in the presence of crop. There was a gradual decrease in the dissolved Ca content from 0 – 30 DAT and thereafter increased at later stages of the experimental period.

At 40 cm depth of the soil, dissolved Ca content in soil solution was significantly affected only during 15 DAT between the treatments (Table 32 and Fig. 24). Among different intervals of soil solution samplings, dissolved Ca content was stabilized during 0 - 15 DAT and decreased at 30 DAT and thereafter slight increase was noticed at 60 DAT but decreased at 90 DAT.

The diffusive flux of Ca increased with increasing solution Ca concentration and moisture content as reported by Mohanthy *et al.* (1977). Similar results were also noticed by Kato and Owa (1998) who reported that the application of slag silicates as a Si source at early plant stage increased the pH and  $Ca^{2+}$  concentration in the soil.

| Treatments                        | 0 DAT              | 7 DAT             | 15 DAT            | <b>30 DAT</b>          | 60 DAT                 | 90 DAT                 |  |
|-----------------------------------|--------------------|-------------------|-------------------|------------------------|------------------------|------------------------|--|
|                                   | 5cm depth          |                   |                   |                        |                        |                        |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 896.75±199.96(a)   | 872.75± 94.35(a)  | 637.25±122.90(a)  | 377.00± 91.37(a)       | 287.75±106.30(a)       | $302.50 \pm 21.56(a)$  |  |
| Si <sub>0</sub> + RP              | 1323.50± 552.88(a) | 930.00± 240.16(a) | 668.75± 86.50(a)  | 424.25± 54.87(a)       | 68.75±27.43(b)         | 216.00± 60.06(bc)      |  |
| $Si_1 + RP_0$                     | 922.50±123.92(a)   | 916.00± 163.13(a) | 707.00±118.32(a)  | 499.25± 82.77(a)       | 293.25±21.87(a)        | 241.50± 45.42(bc)      |  |
| Si <sub>1</sub> + RP              | 854.25±170.00(a)   | 813.50± 58.82(a)  | 710.50± 63.84(a)  | 435.75±100.99(ab)      | 68.25±21.38(b)         | 157.50± 47.63(c)       |  |
| S.Em±                             | 210.84             | 69.56             | 48.95             | 41.25                  | 22.12                  | 21.83                  |  |
| LSD (p≤0.05)                      | NS                 | NS                | NS                | 129.84                 | 87.79                  | 66.55                  |  |
|                                   | 40cm depth         |                   |                   |                        |                        |                        |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 164.50±99.93(a)    | 188.75±122.21(a)  | 181.25± 128.08(a) | 217.25±138.37(a)       | 184.75± 174.20(a)      | 262.00±137.52(a)       |  |
| Si <sub>0</sub> + RP              | 96.00±113.52(a)    | 164.00± 198.10(a) | 134.50± 149.33(a) | 133.50±153.53(a)       | $192.25 \pm 182.86(a)$ | $165.00 \pm 147.33(a)$ |  |
| $Si_1 + RP_0$                     | 57.75±153.44(a)    | 86.00± 56.41(a)   | 80.75± 58.20(a)   | 87.75± 57.26(a)        | $137.50 \pm 86.03(a)$  | 173.75± 105.41(a)      |  |
| Si <sub>1</sub> + RP              | 110.50±157.33(a)   | 127.25± 177.79(a) | 118.00± 183.60(a) | $142.50 \pm 208.49(a)$ | 154.00± 230.29(a)      | $152.50 \pm 184.58(a)$ |  |
| S.Em±                             | 52.53              | 69.31             | 64.90             | 69.71                  | 84.17                  | 71.86                  |  |
| LSD (p≤0.05)                      | NS                 | NS                | NS                | NS                     | NS                     | NS                     |  |

Table 31: Dissolved potassium (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at 5 and 40cm depths of soil during *summer* 2015

| Treatments                        | 0 DAT                   | 7 DAT              | 15 DAT                  | 30 DAT                  | 60 DAT                   | 90 DAT                  |  |
|-----------------------------------|-------------------------|--------------------|-------------------------|-------------------------|--------------------------|-------------------------|--|
|                                   | 5 cm depth              |                    |                         |                         |                          |                         |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 2201.75±647.95(b)       | 2687.50±1243.27(b) | 1839.00±292.41(a)       | $1011.00 \pm 125.41(b)$ | 1774.00±238.66(a)        | 1833.75±313.66(a)       |  |
| Si <sub>0</sub> + RP              | 3604.00±1444.21(a)      | 2835.25± 553.78(a) | 2011.50±323.64(a)       | 1347.25±121.81(ab)      | 1645.25±139.82(a)        | 2261.75±180.59(a)       |  |
| Si <sub>1</sub> + RP <sub>0</sub> | 2341.50± 575.41(ab)     | 2443.25±731.01(a)  | 1704.25±244.88(a)       | $1020.25 \pm 154.67(b)$ | 1735.50±409.92(a)        | 1950.50± 310.39(a)      |  |
| Si <sub>1</sub> + RP              | 2285.25± 694.14(ab)     | 2092.25±369.91(a)  | $1794.00 \pm 621.36(a)$ | 1425.00±393.87(a)       | 1714.25±249.90(a)        | 2097.00± 312.83(a)      |  |
| S.Em±                             | 419.96                  | 362.25             | 185.29                  | 99.47                   | 129.79                   | 139.69                  |  |
| LSD (p≤0.05)                      | 1402.00                 | 1224.00            | NS                      | 352.69                  | NS                       | NS                      |  |
|                                   | 40 cm depth             |                    |                         |                         |                          |                         |  |
| Si <sub>0</sub> + RP <sub>0</sub> | $1729.25 \pm 118.45(a)$ | 1685.50± 517.96(a) | 2088.00±180.47(a)       | $1966.25 \pm 520.34(a)$ | $1972.00 \pm 1142.36(a)$ | 1515.00±282.51(a)       |  |
| Si <sub>0</sub> + RP              | $1835.00 \pm 419.62(a)$ | 2301.50±179.88(a)  | 2260.75±159.15(b)       | $1662.25 \pm 462.60(a)$ | $2445.25 \pm 280.62(a)$  | $1959.50 \pm 782.48(a)$ |  |
| Si <sub>1</sub> + RP <sub>0</sub> | 1756.00±409.92(a)       | 2266.75±147.89(a)  | 2178.00± 322.27(a)      | $1400.25 \pm 624.21(a)$ | 2012.50± 302.29(a)       | $1608.50 \pm 492.93(a)$ |  |
| Si <sub>1</sub> + RP              | $1819.00 \pm 506.08(a)$ | 1826.75±752.11(a)  | 2255.75±255.17(a)       | 1966.00±108.09(a)       | $2017.00 \pm 146.56(a)$  | 2240.25±1076.94(a)      |  |
| S.Em±                             | 181.76                  | 199.73             | 114.63                  | 214.41                  | 233.98                   | 329.36                  |  |
| LSD (p≤0.05)                      | NS                      | NS                 | 366.91                  | NS                      | NS                       | NS                      |  |

Table 32: Dissolved calcium (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at 5 and 40cm depths of soil during *summer* 2015

### 4.2.5.5 Dissolved magnesium

At 5 cm depth, significantly higher dissolved Mg was recorded with the application of DE in the presence of crop during 30 (1062.00  $\pm$  401.77 µmol L<sup>-1</sup>) and 60 DAT (1463.75  $\pm$  180.64 µmol L<sup>-1</sup>) (Table 33 and Fig. 25). Among the different intervals of soil solution sampling, dissolved Mg gradually decreased from 0 DAT to 30 DAT however, again increased at 60 and 90 DAT.

Irrespective of application of Si and presence or absence crop plants, there was no significant variation in the dissolved Mg content at 40cm depth at all intervals of sampling (Table 33 and Fig. 25).

In the present investigation, decreased trend of Ca and Mg content may be due to precipitation of Ca and Mg as MgCO<sub>3</sub> and CaCO<sub>3</sub> or Mg (OH)<sub>2</sub> and Ca (OH)<sub>2</sub> as reported by Miyazawa *et al.* (2001). At 40cm depth there was no significant difference among the treatment might be due to dilution of the Mg content in soil solution.

## 4.2.5.6 Dissolved sodium

There was a significant variation among the treatments with regard to dissolved Na content at 0 DAT in the soil solution collected at a depth of 5cm (Table 34 and Fig. 26). However, there was no definite trend in the dissolved Na content among different treatments collected at different intervals of samplings.

Whereas at 40 cm depth of soil, dissolved Na concentration was not affected between the treatments except at 60 DAT (Table 34 and Fig. 26). There was increase in sodium concentration during the experimental period and found higher at 60 and 90 DAT and stabilized may be due dilution of percolating water.

### 4.2.5.6 Dissolved chloride

There was no significant difference among the treatments and different intervals of soil solution samplings for dissolved Cl at 5cm depth of soil (Table 35 and Fig. 27). However, there was no definite trend in the dissolved chloride during the experimental period.

Whereas at 40 cm depth of soil, dissolved Cl concentration was not affected due to the treatments (Table 35 and Fig 27). There was increase in chloride concentration during the experimental period and found higher at 60 and 90 DAT and stabilized may be due dilution of percolating water.



Fig. 23: Dissolved potassium (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at a) 5cm and b) 40cm depth of soil during *summer* 2015



Fig. 24: Dissolved calcium (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at a) 5cm and b) 40cm depth of soil during *summer* 2015

| Treatments                        | 0 DAT              | 7 DAT              | 15 DAT                  | 30 DAT             | 60 DAT                   | 90 DAT                  |  |  |
|-----------------------------------|--------------------|--------------------|-------------------------|--------------------|--------------------------|-------------------------|--|--|
|                                   | 5 cm depth         |                    |                         |                    |                          |                         |  |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 1363.00±374.82(a)  | 1690.00± 870.27(a) | $1045.00 \pm 145.41(a)$ | 613.75±118.65(b)   | 1178.50±179.21(b)        | $1227.00 \pm 113.59(a)$ |  |  |
| Si <sub>0</sub> + RP              | 1885.75± 665.26(a) | 1407.50± 340.62(a) | 1003.50±75.52(a)        | 741.25±69.93(ab)   | $1267.00 \pm 149.24(ab)$ | 1429.50±115.27(a)       |  |  |
| Si <sub>1</sub> + RP <sub>0</sub> | 1479.00± 338.79(a) | 1523.25± 413.03(a) | 992.00±99.85(a)         | 625.50±98.53(b)    | 1167.25±185.24(b)        | 1248.25±93.29(a)        |  |  |
| Si <sub>1</sub> + RP              | 1446.50± 399.95(a) | 1351.75± 291.01(a) | $1110.50 \pm 425.34(a)$ | 1062.00± 401.77(a) | $1463.50 \pm 180.02(a)$  | $1463.75 \pm 250.64(a)$ |  |  |
| S.Em±                             | 222.35             | 239.37             | 93.26                   | 86.11              | 86.71                    | 71.60                   |  |  |
| LSD (p≤0.05)                      | NS                 | NS                 | NS                      | 265.86             | 268.08                   | NS                      |  |  |
|                                   | 40 cm depth        |                    |                         |                    |                          |                         |  |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 988.75± 55.18(a)   | 1267.50± 148.12(a) | 1131.25±114.39(a)       | 1214.00±263.32(a)  | 1212.00± 678.70(a)       | 1308.75±229.33(a)       |  |  |
| Si <sub>0</sub> + RP              | 1021.75± 224.44(a) | 1333.50±137.91(a)  | 1200.75± 54.52(a)       | 1062.00± 396.93(a) | $1593.50 \pm 353.24(a)$  | $1357.25 \pm 515.65(a)$ |  |  |
| Si <sub>1</sub> + RP <sub>0</sub> | 981.75±215.52(a)   | 1281.00±116.46(a)  | 1167.00±172.99(a)       | 1059.25± 425.87(a) | 1274.00± 339.86(a)       | 1187.00± 374.19(a)      |  |  |
| Si <sub>1</sub> + RP              | 1138.00± 227.20(a) | 1302.00±119.16(a)  | 1269.25±158.55(a)       | 1444.75± 237.99(a) | $1717.50 \pm 418.00(a)$  | 1733.25±717.63(a)       |  |  |
| S.Em±                             | 90.29              | 65.21              | 62.56                   | 165.51             | 223.72                   | 229.60                  |  |  |
| LSD (p≤0.05)                      | NS                 | NS                 | NS                      | NS                 | NS                       | NS                      |  |  |

Table 33: Dissolved magnesium (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at 5 and 40cm depths of soil during *summer* 2015

Table 34: Dissolved sodium (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at 5 and 40cm depths of soil during *summer* 2015

| Treatments                        | 0 DAT                | 7 DAT              | 15 DAT             | <b>30 DAT</b>           | 60 DAT                   | 90 DAT                  |  |
|-----------------------------------|----------------------|--------------------|--------------------|-------------------------|--------------------------|-------------------------|--|
| Traiments                         | 5cm depth            |                    |                    |                         |                          |                         |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 5127.25±720.04(b)    | 6360.00± 689.01(a) | 6457.00± 525.82(a) | 4469.75± 336.06(a)      | 7745.75±984.02(a)        | 6415.75±1258.68(a)      |  |
| Si <sub>0</sub> + RP              | 60.38.00± 310.50(ab) | 6161.00±1558.77(a) | 6330.75±273.78(a)  | 4557.25±529.88(a)       | 7640.25±376.83(a)        | 6068.00± 312.55(a)      |  |
| $Si_1 + RP_0$                     | 6196.00± 1012.76(a)  | 6584.50±1945.98(a) | 6617.25±1690.03(a) | 4427.00±666.31(a)       | 8281.50±1201.64(a)       | 6860.25±994.11(a)       |  |
| Si <sub>1</sub> + RP              | 6063.75±355.33(ab)   | 5906.75±1085.21(a) | 5572.00±1028.63(a) | $4743.50 \pm 570.21(a)$ | 8043.00± 593.32(a)       | $6214.50 \pm 478.25(a)$ |  |
| S.Em±                             | 299.83               | 659.87             | 439.78             | 262.81                  | 394.48                   | 380.45                  |  |
| LSD (p≤0.05)                      | 1024.00              | NS                 | NS                 | NS                      | NS                       | NS                      |  |
|                                   | 40 cm depth          |                    |                    |                         |                          |                         |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 2117.75± 426.69(a)   | 2641.75± 506.65(a) | 2650.00±669.91(a)  | 2948.00±602.19(a)       | 2793.00±1227.04(b)       | 4496.00±978.06(a)       |  |
| Si <sub>0</sub> + RP              | 2391.00± 417.57(a)   | 3034.50± 891.48(a) | 3038.50± 677.98(a) | $3105.50 \pm 583.27(a)$ | $4378.00 \pm 921.48(a)$  | 4633.00±945.17(a)       |  |
| $Si_1 + RP_0$                     | 2148.00±259.98(a)    | 3517.25±650.19(a)  | 3110.50± 340.27(a) | 3131.00± 363.60(a)      | 4833.75±934.31(a)        | 4557.75±393.04(a)       |  |
| Si <sub>1</sub> + RP              | 2498.50± 311.70(a)   | 2852.00± 342.80(a) | 2744.75±288.39(a)  | 3071.75± 326.30(a)      | $3692.50 \pm 614.67(ab)$ | 4035.00± 561.10(a)      |  |
| S.Em±                             | 176.99               | 298.89             | 247.07             | 324.42                  | 462.19                   | 359.67                  |  |
| LSD (p≤0.05)                      | NS                   | NS                 | NS                 | NS                      | 1463.00                  | NS                      |  |

Mean value having same alphabets do not differ significantly at  $p \le 0.05$ .



Fig. 25: Dissolved magnesium (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at a) 5cm and b) 40cm depth of soil during *summer* 2015



Fig. 26: Dissolved sodium (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at a) 5cm and b) 40cm depth of soil during *summer* 2015
| Treatments                        | 0 DAT                   | 7 DAT              | 15 DAT             | <b>30 DAT</b>      | 60 DAT                  | 90 DAT              |
|-----------------------------------|-------------------------|--------------------|--------------------|--------------------|-------------------------|---------------------|
| 11 cathlents                      |                         |                    | 5 cm (             | depth              |                         |                     |
| Si <sub>0</sub> + RP <sub>0</sub> | 5586.25±1517.18(a)      | 4621.00± 680.70(a) | 5083.50±1138.80(a) | 30.56.50±284.31(a) | $4879.25 \pm 570.54(a)$ | 5303.00± 1763.48(a) |
| Si <sub>0</sub> + RP              | 6116.00±958.09(a)       | 4264.25±1351.57(a) | 4517.50±341.00(a)  | 3643.25±743.10(a)  | 5460.00± 701.89(a)      | 4376.50±790.67(a)   |
| Si <sub>1</sub> + RP <sub>0</sub> | 5907.00± 960.89(a)      | 5366.25±2116.50(a) | 4904.50±2233.22(a) | 3626.50±940.21(a)  | 5007.00±524.15(a)       | 5037.00±672.51(a)   |
| Si <sub>1</sub> + RP              | 5525.75±948.56(a)       | 3879.25±929.50(a)  | 3758.50±771.83(a)  | 3328.50± 982.43(a) | $5400.25 \pm 930.91(a)$ | 4924.75±797.05(a)   |
| S.Em±                             | 548.09                  | 634.78             | 560.61             | 368.76             | 340.94                  | 502.96              |
| LSD (p≤0.05)                      | NS                      | NS                 | NS                 | NS                 | NS                      | NS                  |
|                                   |                         |                    | 40 cm              | depth              |                         |                     |
| Si <sub>0</sub> + RP <sub>0</sub> | 1715.00± 374.91(a)      | 2354.00± 523.19(a) | 2721.75±697.74(a)  | 3278.00±756.46(a)  | 3907.75±631.11(a)       | 3194.50±762.98(a)   |
| Si <sub>0</sub> + RP              | $1723.00 \pm 266.75(a)$ | 2615.25±1053.30(a) | 2870.00±1173.27(a) | 2270.75±717.58(a)  | 4392.00±484.21(a)       | 3256.75±1116.28(a)  |
| Si <sub>1</sub> + RP <sub>0</sub> | 1482.25± 502.90(a)      | 2649.00± 808.90(a) | 2860.00± 659.97(a) | 2483.25±958.86(a)  | 3945.25±300.98(a)       | 3198.75±789.71(a)   |
| Si <sub>1</sub> + RP              | $1696.50 \pm 264.67(a)$ | 2097.75± 572.66(a) | 2913.00±759.87(a)  | 2775.75±136.06(a)  | $3574.25 \pm 955.99(a)$ | 3994.50± 2023.28(a) |
| S.Em±                             | 176.15                  | 369.76             | 398.86             | 321.12             | 296.54                  | 586.53              |
| LSD (p≤0.05)                      | NS                      | NS                 | NS                 | NS                 | NS                      | NS                  |

Table 35: Dissolved chloride (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at 5 and 40cm depths of soil during *summer* 2015

## 4.2.6 Effect of diatomite as Si source on straw and grain yield and Si content of rice crop grown during *kharif* season

Data pertinent to yield attributes, plant Si content and uptake as influenced by the application of diatomite for rice crop grown during *kharif* season are given in Table 36.

Application of DE as Si source @ 300 kg ha<sup>-1</sup> recorded significantly higher straw yield  $(10.30 \pm 0.71 \text{ t ha}^{-1})$  compared to control  $(7.96 \pm 0.77 \text{ t ha}^{-1})$  (Fig. 28). However, there was no significant difference in grain yield between treatments. There was significant increase in the straw Si content (5.77  $\pm$  0.30 %) and its uptake (594.57  $\pm$  53.94 kg ha<sup>-1</sup>) with the application of DE over the control. There was no significant difference for grain Si content and uptake between the treatments (Fig. 29 & 30). The greater dry matter production may be due enhanced photosynthetic activity and also due to increased dissolution of Si, Ca, Mg and Fe from the applied DE material and from native soil. Similar results of the present investigation were also in agreement with the findings of Agarie et al. (1992) who reported that maintenance of photosynthetic activity due to Si fertilization could be one of the reasons for increased dry matter production in rice crop. Similarly, Prakash et al. (2010) reported that rice-hull ash can be used to improve the plant-available Si status of soil for enhanced growth and yield of rice. Singh et al. (2006) reported that dry matter production increased significantly with each increment in N and Si fertility level of 120 kg ha<sup>-1</sup>, due to increased chlorophyll formation which ultimately improved photosynthesis of the crop grown in different rice soils of India. Application of 18.7 g Si m<sup>-2</sup> as sodium metasilicate to upland rice doubled the plant Si concentration and increased grain yield by 48 per cent in West Africa (Winslow, 1992).

The significant variation in content and uptake of Si in rice straw in the present investigation may be due to distribution of silicic acid in the shoots in relation to transpirational termini and deposition in the plant parts. Deren *et al.* (1994) noticed increased Si concentration in plant tissue with increasing rate of Si fertilization, but within each Si treatment and that of control, there was significant variation in Si concentration and its uptake among different cultivars. Similar work was attributed by Sahu (1990) who reported that significant increase in Si uptake was noticed due to application of rice hull as a source of Si.

# 4.2.7 Effect of diatomite as Si source on pH, EC, plant available Si (CCSi and AASi) of soil during *kharif* season

Data with regard to pH, EC and Si concentration of post-harvest soil during *kharif* season are given in Table 37.



Fig. 27: Dissolved chloride (µmol L<sup>-1</sup>) in soil solution during different intervals of experimental period at a) 5cm and b) 40cm depth of soil during *summer* 2015



Plate 12: Influence of diatomite on rice crop at different growth stages during *kharif* 2015

| Truc a farm a refer  | Straw yield           | Grain yield           | Straw Si            | Straw Si uptake        | Grain Si           | Grain Si uptake        |
|----------------------|-----------------------|-----------------------|---------------------|------------------------|--------------------|------------------------|
| Treatments           | (t ha <sup>-1</sup> ) | (t ha <sup>-1</sup> ) | (%)                 | (kg ha <sup>-1</sup> ) | (%)                | (kg ha <sup>-1</sup> ) |
| Si <sub>0</sub> + RP | 7.96 ± 0.77 (b)       | $6.00 \pm 0.26(a)$    | $4.72 \pm 0.71$ (b) | $377.36 \pm 80.81(b)$  | $0.55 \pm 0.09(a)$ | $33.29 \pm 6.34(a)$    |
| Si <sub>1</sub> + RP | 10.30 ± 0.71 (a)      | $6.33 \pm 0.71$ (a)   | $5.77 \pm 0.30(a)$  | 594.57± 53.94(a)       | $0.59 \pm 0.04(a)$ | $37.46 \pm 4.46(a)$    |
| S. Em±               | 0.28                  | 0.24                  | 0.25                | 33.68                  | 0.034              | 2.69                   |
| LSD (p≤0.05)         | 1.12                  | NS                    | 1.10                | 107.29                 | NS                 | NS                     |

Table 36: Effect of diatomite as Si source on yield, Si content and its uptake of rice crop during *kharif* 2015

Mean value having same alphabets do not differ significantly at  $p \le 0.05$ .

| Tuesta                            | pН                 | EC                           | CCSi             | AASi                  |
|-----------------------------------|--------------------|------------------------------|------------------|-----------------------|
| I reatments                       | (1:2.5 water)      | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg           | 5 <sup>-1</sup> )     |
| Si <sub>0</sub> + RP <sub>0</sub> | $7.59 \pm 0.29(a)$ | $0.12 \pm 0.01(c)$           | 36.61± 7.95(a)   | 104.16± 21.08(a)      |
| Si <sub>0</sub> + RP              | $7.74 \pm 0.34(a)$ | $0.18 \pm 0.03(a)$           | 22.51±2.84(b)    | 91.20±13.82(a)        |
| Si <sub>1</sub> + RP <sub>0</sub> | $7.84 \pm 0.16(a)$ | $0.14 \pm 0.03$ (bc)         | 32.83± 13.82(ab) | $107.56 \pm 13.05(a)$ |
| Si <sub>1</sub> + RP              | $7.70 \pm 0.30(a)$ | 0.17± 0.02(ab)               | 32.00±7.95(ab)   | 92.38± 18.98(a)       |
| S. Em±                            | 0.14               | 0.012                        | 4.06             | 8.36                  |
| LSD (p≤0.05)                      | NS                 | 0.036                        | 16.02            | NS                    |

Table 37: Effect of diatomite as Si source on pH, EC, acetic acid – Si (AASi) and CaCl<sub>2</sub> –Si (CCSi) in soil during *kharif* 2015



Fig. 28: Influence of diatomite on straw and grain yield of rice crop grown during *kharif* 2015



Fig. 29: Influence of diatomite on silicon content of rice straw and grain during *kharif* 2015



Fig. 30: Influence of diatomite on silicon uptake by rice straw and grain during *Kharif* 2015



Fig. 31: Influence of diatomite on plant available silicon status of soil during *kharif* 2015

Soil pH and AASi content did not significantly differ among the treatments but, AASi content was found to be lower in plots where crop was grown may be due to crop uptake. Significantly higher soil EC  $(0.18 \pm 0.03 \text{ dSm}^{-1})$  recorded in the control plot with crop compared to other treatments. Si extracted by CaCl<sub>2</sub> was significantly affected and found to be highest in control ( $36.61\pm 7.95 \text{ mg kg}^{-1}$ ) and decreased significantly in the presence of crop either with or without DE application which can be attributed to efficient utilization of Si by the crop plants (Fig. 31). Si content as extracted by acetic acid and calcium chloride was found to be higher during *kharif* season compared to summer season.

## 4.2.8 Water mass balance at soil plant scale

### 4.2.8.1 Behavior of the Si, Cl and Na in the solute samples collected at 5cm depth

Behavior of the dissolved Si, Cl and Na in the solute samples collected at 5 cm by using rhizons during experimental period *kharif* 2015 is presented in Table 38 and Fig. 32. Dissolved silicon content at 5cm depth of soil solution varied between the treatments at different intervals of experimental period. DSi was found to be higher during initial period of crop growth and decreased at later stages of crop growth. DSi content was found to be lower in the presence of crop compared to non-cropped soil.

A similar behavior was noticed between dissolved Cl and Na content in soil solution during the crop growth period. Dissolved Cl and Na were found to be higher during the initial growth and had no definite trend in the later stages of growth period. There was no difference for dissolved Cl and Na content among the treatments.

### 4.2.8.2 Behavior of the Si, Cl and Na in the solute samples collected at 40 cm depth

Soil pore water collected by rhizons installed at depth of 40cm indicated a strong dilution effect by the local groundwater and irrigation canal and thus preventing the exploitation of pore water composition at 40cm. The data collected for calculation of mass balance of Na vs Cl and Si vs Cl (Fig. 33) clearly indicate that the concentration of Na in the soil solution at 40 cm depth increased with Cl concentration. The concentration of DSi in borewell water ranged from 1123 to 1261  $\mu$ mol L<sup>-1</sup> during the field experiment which was considered as input flux. While silicon concentration in soil solution at 40 cm depth during the field experimental period ranged from 191 to 335  $\mu$ mol L<sup>-1</sup> which was considered as output flux which clearly indicates dilution of most of the ions including Si due to shallow/ higher water table. There was a difficulty in calculating the budgeting of Si because of almost constant / uniform values of output flux of Si at 40 cm depth irrespective of cropped or non cropped plots and applied or no applied silicon plots.

|                                   |                            |          |          | Date of s | amplings          |          |          |          |      |  |  |  |
|-----------------------------------|----------------------------|----------|----------|-----------|-------------------|----------|----------|----------|------|--|--|--|
| Treatments                        | 22-08-15                   | 04-09-15 | 08-09-15 | 28-09-15  | 14-10-15          | 29-10-15 | 17-11-15 | 30-11-15 | Mean |  |  |  |
|                                   | Si (µmol L <sup>-1</sup> ) |          |          |           |                   |          |          |          |      |  |  |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 809                        | 622      | 632      | 852       | 620               | 573      | 716      | 376      | 650  |  |  |  |
| Si <sub>1</sub> + RP <sub>0</sub> | 886                        | 866      | 648      | 903       | 608               | 512      | 643      | 600      | 708  |  |  |  |
| Si <sub>0</sub> + RP              | 675                        | 581      | 643      | 741       | 299               | 184      | 600      | 538      | 532  |  |  |  |
| Si <sub>1</sub> + RP              | 655                        | 632      | 638      | 710       | 298               | 432      | 555      | 437      | 545  |  |  |  |
| Cl (µmol L <sup>-1</sup> )        |                            |          |          |           |                   |          |          |          |      |  |  |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 4828                       | 5250     | 3701     | 3779      | 1326              | 2254     | 2900     | 3502     | 3443 |  |  |  |
| Si <sub>1</sub> + RP <sub>0</sub> | 4949                       | 5151     | 3966     | 3646      | 2171              | 1629     | 2827     | 4276     | 3577 |  |  |  |
| Si <sub>0</sub> + RP              | 5628                       | 5562     | 3444     | 3622      | 1727              | 2211     | 3015     | 4030     | 3655 |  |  |  |
| Si <sub>1</sub> + RP              | 5472                       | 5016     | 3328     | 3507      | 1883              | 2516     | 3270     | 5410     | 3800 |  |  |  |
|                                   |                            |          |          | Na (µmo   | L <sup>-1</sup> ) |          |          |          |      |  |  |  |
| Si <sub>0</sub> + RP <sub>0</sub> | 6393                       | 7651     | 6428     | 6726      | 3248              | 4418     | 4967     | 5160     | 5624 |  |  |  |
| Si <sub>1</sub> + RP <sub>0</sub> | 6583                       | 7986     | 6784     | 6739      | 4373              | 3802     | 5152     | 6682     | 6012 |  |  |  |
| Si <sub>0</sub> + RP              | 7879                       | 8283     | 6621     | 6690      | 3829              | 4456     | 4683     | 6061     | 6063 |  |  |  |
| Si <sub>1</sub> + RP              | 6831                       | 7489     | 6209     | 6317      | 3966              | 5120     | 5353     | 6937     | 6028 |  |  |  |

 Table 38: Dissolved Si, Cl and Na at 5cm depth of soil during different intervals of experimental period in *kharif* 2015



Fig. 32: Dissolved Si, Cl and Na at 5cm depth of soil during different intervals of experimental period during *kharif* 2015



Fig. 33: Pore water concentration for Na vs Cl and Si vs Cl at 40 cm depth of soil

As an alternative, soil core samples up to 17.50 cm depth recovered at 80 days after transplanting to calculate the mass balance. Core sampler was inserted to a depth of 17.50 cm by adopting standard procedure and soil core was sliced into 5 sub samples, from surface to 17.50cm, and soil pore water was extracted by centrifugation and/or hydraulic press with an advantage to know variation of soil pore water composition with depth. Pore water was analysed for dissolved Si, Na and Cl and calculated for ratio for Si/Cl and Si/Na (Table 39). Major limitations of core sampling is are 1) Onsite coring and centrifugation is a heavy task, 2) Only one sample could be taken per experiment, 3) Provides only a snapshot of the pore water composition and 4) Composition would vary with the time of sampling.

Although following limitations exists with core sampling, this method would provide more valuable information for budgeting under the present circumstances of dilution at lower depths due to higher water table.

Perusal of the data presented in Table 39 and Fig. 34 (for Si evolution) revealed that Si concentration in the depth profiles recorded different pattern for cropped and non cropped soils. Concentration of Si was found to be higher in non-cropped plot either with or without silicon in the first two (1 and 3.5cm) depths of the core whereas Si content was depleted within the first depth of the core in rice plots. As the depth increased upto 17.50 cm there was almost similar concentration of Si recorded in all the plots (cropped and no cropped) confirming the dilution of the sample at 17.50 cm deep itself as indicated by the results of soil solution collected by rhizons at 40 cm depth due to shallow water table. Similar trend was also observed for Si/Cl ratio (Fig. 35) but ratio of Si/Na gradually decreased as the depth increased (Fig. 36). Irrespective of cropped and non cropped plots, at 15 to 17.55 cm, 80 to 90 per cent of dissolved silica has been removed from the solution, indicating that the impact of the rice cultivation on the solution budget is just slightly higher than in the no cropped soil.

## 4.2.9 Mass balance of water

Fluxes of DSi were calculated according to the water mass balance in the rice field. Water inputs are 1) total amount of water added as irrigation during the experiment (from August to December - 2015) which accounts to 570 mm, 2) total rainfall received during the experimental period which accounts to 411 mm. Water outputs are mainly by 1) potential evapotranspiration (PET) during the experimental period which accounts to 459 mm, 2) infiltration/drainage accounting to an extent of 522 mm as calculated by deducting the PET from total input water to the plot (Table 40). The results of mass balance of water and Si budgeting (input and output) calculated based on the chloride and sodium mass balance approach are discussed below.

|            | Si  | Cl   | Na                                | Si/Cl | Si/Na |
|------------|-----|------|-----------------------------------|-------|-------|
| -          |     |      | µmol L <sup>-1</sup>              |       |       |
| Depth (cm) |     |      | $Si_0 + RP_0$                     |       |       |
| 1.00       | 430 | 1030 | 2083                              | 0.417 | 0.206 |
| 3.50       | 523 | 1048 | 4187                              | 0.499 | 0.125 |
| 7.50       | 434 | 1580 | 5505                              | 0.275 | 0.079 |
| 12.50      | 319 | 2660 | 6360                              | 0.124 | 0.051 |
| 17.50      | 137 | 2504 | 5182                              | 0.055 | 0.026 |
|            |     |      | Si <sub>0</sub> + RP              |       |       |
| 1.00       | 220 | 3763 | 3632                              | 0.058 | 0.061 |
| 3.50       | 177 | 2196 | 4170                              | 0.081 | 0.042 |
| 7.50       | 124 | 1937 | 5292                              | 0.064 | 0.023 |
| 12.50      | 115 | 2173 | 5822                              | 0.052 | 0.019 |
| 17.50      | 105 | 2566 | 9139                              | 0.041 | 0.011 |
|            |     |      | Si <sub>1</sub> + RP <sub>0</sub> |       |       |
| 1.00       | 380 | 589  | 1459                              | 0.645 | 0.260 |
| 3.50       | 508 | 506  | 2739                              | 1.004 | 0.185 |
| 7.50       | 489 | 541  | 4165                              | 0.904 | 0.117 |
| 12.50      | 280 | 610  | 3787                              | 0.457 | 0.072 |
| 17.50      | 179 | 748  | 3365                              | 0.239 | 0.053 |
|            |     |      | Si <sub>1</sub> + RP              |       |       |
| 1.00       | 349 | 3178 | 4161                              | 0.110 | 0.084 |
| 3.50       | 101 | 1276 | 3650                              | 0.079 | 0.028 |
| 7.50       | 90  | 1481 | 6077                              | 0.061 | 0.015 |
| 12.50      | 90  | 3237 | 9305                              | 0.028 | 0.010 |
| 17.50      | 202 | 5440 | 10966                             | 0.037 | 0.018 |

Table 39: Pore water concentration of core samples for Si, Cl and Na and their ratio



Fig. 34: Concentration of Si in pore water of core sample at different depths of soil



Fig. 35: Ratio of Si to Cl in pore water of core sample at different depths of soil



Fig. 36: Ratio of Si to Na in pore water of core sample at different depths of soil

### 4.2.9.1 Input of silicon

## 4.2.9.1.1 Above ground input

Above ground input of Si was computed by considering the irrigation water, rainfall and fertilizer added during the experimental period (Table 40). The flux of Si supplied through irrigation water was 18.37 g m<sup>-2</sup> which accounts to 99 per cent in non-DE applied plots and 67 per cent in DE applied plots. In the present investigation, the concentration of DSi in rain water and irrigation water was 3 µmol L<sup>-1</sup> and 1151 µmol L<sup>-1</sup>, respectively. The flux of Si contributed by rainfall received during experimental period was very negligible (0.03 g m<sup>-2</sup>). Si contributed through irrigation water was much higher compared to other studies. Despalnques et al. (2005) revealed that atmospheric and irrigation inputs represent 1 and roughly 10 per cent, respectively, of the annual need for rice. Husnain et al. (2010) and Darmavan et al. (2006) also noticed that (92 kg ha<sup>-1</sup>) was mainly derived from irrigation water. Input of Si by irrigation water and rainfall was also studied by Klotzbucher et al. (2015) and revealed that concentrations of DSi in rain water was below detection limit (26  $\mu$ g L<sup>-1</sup>) where as in irrigation waters, it ranged from 31 to 68 mg L<sup>-1</sup>. Diatomaceous earth applied as Si source @ 300 kg ha<sup>-1</sup> accounted to 9.00 g m<sup>-2</sup> of Si out of total aboveground Si input (27.40 g m<sup>-2</sup>) and was lower than the Si supplied through irrigation water. The input of Cl from KCl accounted only to an extent of 6 per cent (4.68 g m<sup>-2</sup>) of the total Cl input (79.07g m<sup>-2</sup>), while 93 per cent was contributed by irrigation water and only 1 per cent by rain. Hence, it was opined that the KCl fertilization did not significantly affected the chloride mass balance. Although sodium was mainly added as irrigation source to an extent of 99 per cent (less than 1 % by rain) of the inputs, the concentration and inputs were slightly higher than that of chlorides.

## 4.2.9.1.2 Solute input to the soil

Solute input of Si brought to the soil computed based on the Na and Cl mass balance approach revealed that, about 49 per cent (based on Fw Na input) and 19 per cent (based on Fw Cl input) of Si was lost in above ground surface in no cropped plots. Whereas in rice planted plots, the amount of Si lost was accounted to an extent of 61 to 73 per cent based on Fw Na input and 38 to 59 per cent based on Fw Cl input to the soil. In general, decrease of solute Si input was higher in the presence of crop irrespective of DE applied or non-applied plots. Based on the actual input to the soil, the decrease in solute Si input in rice plot could be due to plant uptake when compared to no cropped plots which warrants the advantage of Na and Cl mass balance approach for Si budgeting.

## 4.2.9.2 Output of silicon

In the present investigation, solute output from the soil was calculated based on PET, Na and Cl mass balance approach (Table 40).

## 4.2.9.2.1 Solute output from the soil

The above ground loss of water by PET (459 mm) accounts to more than  $\frac{1}{2}$  (53 %) of the total water budget (981mm). Silicon output from the plot through drainage was calculated by deducting the PET (459 mm) from total input of water (981mm), which accounted to an extent of 522 mm (Table 40). The flux of Si computed by deducting the PET from total input water and Si content in core sampler solution (17.50 cm) was found to be higher in DE applied plots (2.62 and 2.96 g m<sup>-2</sup>) compared to non-applied plots (2.00 and 1.53 g m<sup>-2</sup>) and higher value was noticed in the presence of crop. Despalnques *et al.* (2005) reported that drainage and infiltration outputs represented 17±14 and 12± 9 kg Si ha<sup>-1</sup> year<sup>-1</sup> respectively; and the balance of budget shows that at least 170 kg Si ha<sup>-1</sup> year<sup>-1</sup> are exported from the soil.

Si output calculated based on the Na mass balance was found to be higher in Si fertilized plots irrespective of no cropped (11.10 g m<sup>-2</sup>) or cropped (3.36 g m<sup>-2</sup>) plots. Irrespective of the treatments, Si output was found to be lower in the presence of crop compared to no cropped plots which can be due to crop Si uptake. In the present investigation, higher flux for water, Si, Cl and Na were noticed when calculated based on Cl mass balance, which could be attributed to higher rainfall received coupled with KCl application a day before sampling. This further revealed that adoption of Cl mass balance for solute output from soil could be improper as the Fw Si, Fw Cl and Fw Na output were very high. Hence, the solute output from the soil based on Fw deduced from PET and Fw Na was mainly considered and discussed.

## 4.2.9.2.2 Plant available Si stock in soil

Plant available Si stock ( $\Delta AASi$  and  $\Delta CCSi$ ) in soil was computed as the difference between Si content in the soil after the experiment and before the experiment for each treatment (Table 40). AASi and CCSi correspond to Si content of soil estimated as extracted by 0.5M acetic acid and 0.01M calcium chloride extractants respectively.  $\Delta AASi$  and  $\Delta CCSi$  contents were found to be negative in all the treatment plots indicating decrease in Si content after the completion of experiment compared to initial soil Si content. However, the extent of decrease in  $\triangle AASi$  content was higher in DE applied plots irrespective of non cropped (-19.32 g m<sup>-2</sup>) or cropped (-22.68 g m<sup>-2</sup>) compared to non-applied plots. Although, there was no definite trend in  $\Delta CCSi$  content of soil among the treatments, the Si content in plots without DE application noticed higher depletion in rice grown plot which was attributed to crop Si uptake. Si present in the soil was effectively utilized by the crop. Loss of soil Si was also noticed in no cropping system (non-cropped plots), which could be due to the utilization of Si by algae or diatoms existed in the soil. The output of Si estimated by considering the PET loss or by Fw Na output and crop Si uptake was higher than input of Si estimated by aboveground and solute to the soil. The major input of Si was by irrigation water applied during experimental period and remaining amount may be contributed by soil minerals and hence decrease in the plant available Si stock content in the present investigation. Similar results were also reported by Despalnques et al. (2005) and showed that input of Si in the rice field of Camargue, where in diatom BSi + DSi accounted only for 44 per cent of the rice needs and 56 per cent was provided by the soil constituents.

#### Table 40: Mass balance of water and Si, Cl and Na

|  |       | Si <sub>0</sub> + | RP <sub>0</sub>   |        |       | Si <sub>1</sub> + | RP <sub>0</sub>   |        |       | Si <sub>0</sub> + | RP                |        | Si <sub>1</sub> + RP |        |                   |        |
|--|-------|-------------------|-------------------|--------|-------|-------------------|-------------------|--------|-------|-------------------|-------------------|--------|----------------------|--------|-------------------|--------|
| Mass balance   | Water | Si                | Cl                | Na     | Water | Si                | Cl                | Na     | Water | Si                | Cl                | Na     | Water                | Si     | Cl                | Na     |
|  | mm    |                   | g m <sup>-2</sup> |        | Mm    |                   | g m <sup>-2</sup> |        | mm    |                   | g m <sup>-2</sup> |        | mm                   |        | g m <sup>-2</sup> |        |
| Above ground input                                     | _     |                   |                   |        |       |                   |                   |        |       |                   |                   |        |                      |        |                   |        |
| Fw by irrigation***                                    | 570   | 18.37             | 74.08             | 80.99  | 570   | 18.37             | 74.08             | 80.99  | 570   | 18.37             | 74.08             | 80.99  | 570                  | 18.37  | 74.08             | 80.99  |
| Fw by rain***  | 411   | 0.03              | 0.31              | 0.25   | 411   | 0.03              | 0.31              | 0.25   | 411   | 0.03              | 0.31              | 0.25   | 411                  | 0.03   | 0.31              | 0.25   |
| Fw by fertilizer                                       |       | 0                 | 3.87*             | 0      |       | 9.00**            | 3.87*             | 0      |       | 0                 | 3.87*             | 0      |                      | 9.00** | 3.87*             | 0      |
| Total  | 981   | 18.40             | 78.26             | 81.25  | 981   | 27.40             | 78.26             | 81.25  | 981   | 18.40             | 78.26             | 81.25  | 981                  | 27.40  | 78.26             | 81.25  |
| Solute input to the soil                               |       |                   |                   |        |       |                   |                   |        |       |                   |                   |        |                      |        |                   |        |
| Av. conc. in rhizon sampler solution at 5cm (g/L)      |       | 0.02              | 0.10              | 0.16   |       | 0.02              | 0.10              | 0.17   |       | 0.01              | 0.10              | 0.17   |                      | 0.02   | 0.11              | 0.17   |
| Fw Na input 🌲  | 514   | 9.36              | 49.58             | 81.25  | 481   | 9.54              | 48.19             | 81.25  | 477   | 7.11              | 48.83             | 81.25  | 480                  | 7.32   | 51.06             | 81.25  |
| Fw Cl input *  | 812   | 14.77             | 78.26             | 127.84 | 781   | 15.49             | 78.26             | 131.54 | 765   | 11.39             | 78.26             | 129.82 | 736                  | 11.22  | 78.26             | 124.15 |
| PET  | 459   |                   |                   |        | 459   |                   |                   |        | 459   |                   |                   |        | 459                  |        |                   |        |
| Solute output from the soil                            |       |                   |                   |        |       |                   |                   |        |       |                   |                   |        |                      |        |                   |        |
| Conc. in core sampler solution at 17.50 cm depth (g/L) | -     | 0.004             | 0.070             | 0.145  |       | 0.005             | 0.021             | 0.094  |       | 0.003             | 0.072             | 0.256  |                      | 0.006  | 0.152             | 0.307  |
| Fw deduced from PET                                    | 522   | 2.00              | 36.60             | 75.74  | 522   | 2.62              | 10.93             | 49.18  | 522   | 1.53              | 37.50             | 133.58 | 522                  | 2.96   | 79.52             | 160.27 |
| Fw Na output♦  | 207   | 5.47              | 99.90             | 81.25  | 209   | 11.10             | 46.37             | 81.25  | 190   | 2.18              | 53.23             | 81.25  | 182                  | 3.36   | 90.34             | 81.25  |
| Fw Cl output ♦   | 334   | 18.27             | 78.26             | 691    | 615   | 147.00            | 78.26             | 2768   | 1121  | 45.89             | 78.26             | 3994   | 430                  | 15.98  | 78.26             | 866    |
| Plant available Si stock in soil                       | _     |                   |                   |        |       |                   |                   |        |       |                   |                   |        |                      |        |                   |        |
| ±∆AASi   |       | -13.72            |                   |        |       | -19.32            |                   |        |       | -14.56            |                   |        |                      | -22.68 |                   |        |
| ±∆CCSi   |       | 0.56              |                   |        |       | -3.36             |                   |        |       | -4.48             |                   |        |                      | -1.68  |                   |        |
| Plant uptake   |       | 0                 |                   |        |       | 0                 |                   |        |       | 41.00             |                   |        |                      | 63.20  |                   |        |

\*Cl added through MOP fertilizer (50 kg ha<sup>-1</sup>) which contains 45 per cent Cl; \*\*Si added through DE (300 kg ha<sup>-1</sup>) which contains 30 per cent Si.

\*\*\*Fw of Si or Cl or Na by irrigation or rain (g m<sup>2</sup>) = Total irrigation water or rainfall (mm) X Si or Cl or Na conc. (µmol L<sup>-1</sup>) X At. weight of Si or Cl or Na

1000 X1000

Av. Conc. in rhizon solution sample at 5cm (g/L) = Si or Cl or Na conc. ( $\mu$ mol L<sup>-1</sup>) X At. weight of Si or Cl or Na

1000 X1000

♣ Fw Na or Cl input (mm) = <u>Fw of Na or Cl by irrigation  $(g m^2) + rain (g m^2)$ </u>

Av. Conc. in rhizon solution sample at 5cm (g/L)

Solute input for Si or Cl or Na (g m<sup>2</sup>) = Fw Na or Cl input (mm) X Av. Conc. of Si or Cl or Na(g/L) in rhizon sampler solution at 5cm

Fw deduced from PET (mm) = Total water input - PET

Solute output for Si or Cl or Na deduced from PET (g m<sup>2</sup>) = Fw deduced from PET (mm) X Conc. of Si or Cl or Na (g/L) in core sampler solution at 17.50cm

• Fw Na or Cl output (mm) = Fw Na or Cl input (mm) X Conc. of Cl or Na (g/L) in core sampler solution at 1cm depth

Conc. of Cl or Na (g/L) in core sampler solution at 17.50cm depth

Solute output for Si or Cl or Na  $(g m^2)$  = Fw Na or Cl ouput (mm) X Conc. of Si or Cl or Na in core sampler solution at 17.50cm depth

 $\pm \Delta$  AASi or CCSi represents the difference between the final and initial Si content of soil

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## 4.2.9.2.3 Plant uptake

Plant Si uptake was calculated as the sum of straw and grain uptake for each treatment. There was higher Si uptake by straw and grain with the application of DE  $(63.20 \text{ gm}^{-2})$  compared to non-applied plot (41.00 g m<sup>-2</sup>) which was considered as major output of Si. In the present investigation, crop Si uptake was considered as major Si output from the system, which could increase the depletion or even lead to a deficiency of Si. It was noticed by Husnain *et al.* (2010) that loss of silica through harvest was more than double that of the other major nutrients, including N, P and K and this deficit implies that the enormous amount of Si removed during rice harvest cannot be replenished by a natural Si source such as geological fertilization alone. Gerard *et al.* (2008) estimated that only 38 per cent of the Si cycle was attributed to chemical weathering, while 47 per cent was comprised of plant uptake and to a lesser extent (15 %) was by the access of biogenic Si dissolving from phytoliths present in the soil.

In the present investigation, mass balance calculations indicated that majority of the biogeochemical cycle of Si was controlled by Si-uptake, dissolution of Si, and contribution by irrigation. Biogeochemical cycle of Si was varied in cropped and noncropped situations. The difference between the volume of inputs and outputs constitute the nutrient balance. Negative balances of Si indicated that soils are being mined and thereby rice systems were deficient in Soil Si which was unsustainable over long term rice cultivation and thus emphasis the need of Si fertilization.

## **4.3** Bioavailability of Si from different sources to rice crop and budgeting of Si in acidic, neutral and alkaline soils

To assess the bioavailability and budgeting of Si from different sources of Si, a pot experiment was conducted in acidic, neutral and alkaline soils with and without rice crop. Calcium silicate (CaSiO<sub>3</sub>), diatomaceous earth or diatomite (DE) and rice husk biochar (RHB) were used as Si sources (Plate 13). Silicon budgeting was calculated as the difference between the inputs and outputs by monitoring the soil solution concentration with the help of rhizons. The solute samples were analysed for pH and dissolved silicon (DSi) at different intervals. Plant growth parameters at different growth stages and yield attributes were recorded at harvest. Plant samples were analysed for pH, EC, plant available Si, available P, K, exchangeable cations (Ca, Mg and Na), micronutrients (Fe, Mn, Cu and Zn) concentration.

## 4.3.1 Effect of different sources of Si on soil solution pH

Application of different sources of Si and their rates of application had a significant effect on soil solution pH in acidic, neutral and alkaline soils (Table 41, 42, 43 and Fig. 37).



Plate 13: Effect of different sources of Si on plant growth in acidic, neutral and alkaline soil at 30 days after transplanting.

Application of 250 and 500 kg Si ha<sup>-1</sup> differ significantly on soil solution pH among the different sources of Si over the control in the presence or absence of crop. The solution pH of acidic, neutral and alkaline soils ranged from 5.62 - 8.59, 6.62 - 9.13 and 7.64 - 9.37 respectively with different Si sources and rates of application during the experimental period with or without crop.

Irrespective of the sources of Si, the pH of soil solution stabilized from 7 DAT to 120 DAT in acidic, neutral and alkaline soil and lower pH was recorded at 0 DAT (Fig. 37). However, soil solution pH decreased at 60 DAT in neutral and alkaline soil irrespective of treatments but increased thereafter.

At 0 DAT, significant lower pH was recorded irrespective of presence or absence of crop in acidic soil (Table 41). DE applied @ 500 kg Si ha<sup>-1</sup>resulted in significantly higher pH (7.94  $\pm$  0.04) compared to other treatments in the presence of crop followed by RHB @ 500 kg Si ha<sup>-1</sup> (7.57 $\pm$  0). In general, higher pH was recorded in the presence of rice crop. There was a significant increase in soil solution pH at 7 DAT, and application of CaSiO<sub>3</sub> @ 250 and 500 kg Si ha<sup>-1</sup> (8.63  $\pm$  0.02, 8.72  $\pm$  0.11 respectively) significantly increased pH compared to other treatments in the presence of rice crop followed by RHB and DE. At 15 DAT, there was no difference in soil solution pH between the treatments. Application of CaSiO<sub>3</sub> followed by application of RHB and DE recorded higher pH compared to control may be due to difference in the solubility/ reactivity of material.

The results of effect of Si sources and levels of their application on pH of neutral soil with or without rice crop are presented in Table 42. At 0 DAT, the application of RHB @ 250 and 500 kg Si ha<sup>-1</sup> recorded significantly higher pH (8.97  $\pm$  0, 8.80  $\pm$  0.002 respectively) compared to other treatments. There was a significant difference in pH between the treatments with or without crop and it was higher in the presence of crop plants. From 7 DAT, application of CaSiO<sub>3</sub> followed by RHB and DE increased and maintained higher pH at all intervals of crop period compared to control. There was no definite pattern in the soil solution pH as the rate of Si increased. However, there was no significant difference in soil solution pH at 90 DAT irrespective of sources, their rates of application and presence of crop.

In alkaline soil (Table 43), there was a significant increase in the soil solution pH with application of Si sources during the different intervals of crop growth with or without crop. At 0 DAT, higher soil solution pH was recorded with the application of RHB @ 500 and DE @ 250 kg Si ha<sup>-1</sup> (8.85  $\pm$  0.007, 8.82 $\pm$  0 respectively). Wide variation in pH was found between the treatments at 15 DAT. Higher pH was noticed at 15 DAT with the application of DE @ 500 kg Si ha<sup>-1</sup> (9.37  $\pm$  0.70) but, application of RHB @ 500 kg Si ha<sup>-1</sup> (8.13  $\pm$  0.64) recorded very low soil solution pH. Similar to that of neutral soil, there was no significant difference in soil solution pH at 90 DAT irrespective of sources, their rates of application and presence or absence of crop. In general, application of RHB followed by DE recorded higher soil solution pH during the crop growth.

| Table 41. Effect of different sources  | of Si on soil solution : | nH at different intervals of e   | experimental period in a | acidic soil |
|--|--------------------------|----------------------------------|--------------------------|-------------|
| Table 41. Effect of united ent sources | of SI on son solution    | pri al unici chi inici vais ul c | aperimental periou in a  | acture som  |

| Treatments                                      | 0 DAT                | 7 DAT                        | 15 DAT               | <b>30 DAT</b>        | 60 DAT               | 90 DAT                 | 120 DAT              |
|---|----------------------|------------------------------|----------------------|----------------------|----------------------|------------------------|----------------------|
| Ck - Without plant                              | $7.32 \pm 0.003$ (d) | $7.95 \pm 0.0$ (bc)          | 8.15 ± 0.10 (a)      | 8.14 ± 0.10 (b)      | $8.15 \pm 0.40$ (ab) | $7.84 \pm 0.40$ (de)   | 8.03 ± 0.50 (ab)     |
| Ck – With plant                                 | $6.97 \pm 0.003$ (f) | $7.61 \pm 0.90 \text{ (cd)}$ | $7.81 \pm 0.50$ (b)  | $8.33 \pm 0.10$ (ab) | $8.38 \pm 0.02$ (a)  | $8.04 \pm 0.20$ (bcde) | 8.31 ± 0.40 (a)      |
| Without plant                                   |                      |                              |                      |                      |                      |                        |                      |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $5.62 \pm 0.01$ (k)  | $8.25 \pm 0.40$ (abc)        | 8.21 ± 0.10 (a)      | $8.56 \pm 0.10(a)$   | $8.53 \pm 0.04$ (a)  | $8.09 \pm 0.50$ (bcde) | $8.23\pm0.58(ab)$    |
| $CaSiO_3 @ 500 \text{ kg Si ha}^{-1}$           | $7.46 \pm 0.00(c)$   | $8.25 \pm 0.03$ (abc)        | 8.31 ± 0.30 (a)      | 8.43 ± 0.30 (ab)     | $8.08 \pm 0.60$ (ab) | $7.86 \pm 0.01$ (cde)  | $8.00\pm0.18(ab)$    |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $7.04 \pm 0.00(e)$   | $7.21 \pm 0.90$ (d)          | $8.06 \pm 0.01$ (ab) | $8.41 \pm 0.10$ (ab) | $7.94 \pm 0.50(ab)$  | $8.30 \pm 0.20$ (abcd) | $8.05 \pm 0.62$ (ab) |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $5.82 \pm 0.00(j)$   | 8.46 ± 0.10 (ab)             | $8.19 \pm 0.02$ (a)  | 8.18 ± 0.20 (b)      | $8.30 \pm 0.10$ (ab) | 8.39 ± 0.10 (abc)      | $8.59 \pm 0.07(a)$   |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $6.92 \pm 0.00(g)$   | 8.22 ± 0.10 (abc)            | $8.10 \pm 0.02$ (a)  | 8.35 ± 0.05 (ab)     | $8.32 \pm 0.01$ (ab) | 7.95 ± 0.10 (bcde)     | $8.58 \pm 0.04(a)$   |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $5.88 \pm 0.00$ (i)  | 8.65 ± 0.01 (ab)             | $8.25 \pm 0.10(a)$   | $8.39 \pm 0.01$ (ab) | 8.16 ± 0.20 (ab)     | 8.33 ± 0.20 (abcd)     | $8.12 \pm 0.06 (ab)$ |
| With plant                                      |                      |                              |                      |                      |                      |                        |                      |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $5.85 \pm 0.01(i)$   | $8.63 \pm 0.02(a)$           | $8.39 \pm 0.08(a)$   | $8.10 \pm 0.49(b)$   | $8.01 \pm 0.38(ab)$  | $8.61 \pm 0.06(a)$     | $8.37 \pm 0.27(a)$   |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $6.18 \pm 0.00(h)$   | $8.72 \pm 0.11(a)$           | $8.28 \pm 0.28(a)$   | $8.23 \pm 0.39$ (ab) | $8.37 \pm 0.53(a)$   | 8.28±0.46(abcd)        | $8.25 \pm 0.55$ (ab) |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $7.46 \pm 0.00(d)$   | 8.25± 0.17(ab)               | 818± 0.03(a)         | 8.36± 0.09(ab)       | 8.14± 0.20(ab)       | 8.14±0.19(abcde)       | $7.63 \pm 0.45$ (b)  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $7.94 \pm 0.04(a)$   | 8.21±0.11(abc)               | $8.15 \pm 0.03(a)$   | $8.38 \pm 0.03$ (ab) | 8.03±0.33(ab)        | 8.38±0.17(abc)         | $8.12 \pm 0.47(ab)$  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $6.91 \pm 0.00(g)$   | 8.45± 0.21(ab)               | $8.19 \pm 0.04(a)$   | $8.20 \pm 0.28(b)$   | $8.44 \pm 0.18(a)$   | $7.64 \pm 0.14(e)$     | $8.27 \pm 0.27$ (ab) |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $7.57 \pm 0.00$ (b)  | 8.31± 0.19(ab)               | $8.22 \pm 0.08(a)$   | $8.36 \pm 0.04(ab)$  | 7.76±0.53(b)         | 7.93±0.40(cde)         | 8.12±0.21(ab)        |
| S. Em±  | 0.005                | 0.16                         | 0.07                 | 0.09                 | 0.18                 | 0.14                   | 0.20                 |
| LSD (p≤0.05)                                    | 0.02                 | 0.51                         | 0.24                 | 0.34                 | 0.59                 | 0.49                   | 0.68                 |

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Mean value having same alphabets do not differ significantly at p≤0.05.

| Treatments                                      | 0 DAT                 | 7 DAT                | 15 DAT              | 30 DAT             | 60 DAT               | 90 DAT             | 120 DAT              |
|---|-----------------------|----------------------|---------------------|--------------------|----------------------|--------------------|----------------------|
| Ck - Without plant                              | 7.06± 0.009(j)        | $9.13 \pm 0.05(a)$   | 8.75±0.08(abc)      | 8.69± 0.12(abc)    | 8.41±0.31(abc)       | 8.14± 0.34(a)      | $7.98 \pm 0.64$ (de) |
| Ck – With plant                                 | $6.62 \pm 0.02(m)$    | $8.98 \pm 0.07$ (bc) | 8.65±0.06(abc)      | $8.24 \pm 0.40(d)$ | $8.46 \pm 0.37(ab)$  | $8.02 \pm 0.37(a)$ | 8.29± 0.62(abcde)    |
| Without plant                                   |                       |                      |                     |                    |                      |                    |                      |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $6.78 \pm 0.007(m)$   | $8.90 \pm 0.25$ (cd) | 8.51±0.09(bc)       | 8.69± 0.01(abc)    | 8.35± 0.37(abc)      | $8.31 \pm 0.06(a)$ | $7.83 \pm 0.01$ (de) |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $7.13 \pm 0.007(i)$   | 9.11±0.01(ab)        | 8.78±0.02(abc)      | 8.74± 0.13(abc)    | $7.84 \pm 0.03$ (bc) | $8.61 \pm 0.42(a)$ | 8.48±0.06(abcde)     |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $6.81 \pm 0.007(1)$   | 9.00± 0.03(abc)      | 8.72±0.04(abc)      | 8.74± 0.07(abc)    | 7.98± 0.27(abc)      | $7.96 \pm 0.03(a)$ | 8.45±0.45(abcde)     |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $6.94 \pm 0.007(k)$   | 8.95±0.11(bc)        | 8.49±0.18(bc)       | 8.75± 0.00(ab)     | 8.41±0.59(abc)       | 8.14±0.97(a)       | 8.64± 0.08(abc)      |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $7.32 \pm 0.007(h)$   | 8.99± 0.08(abc)      | 8.64± 0.04(abc)     | 8.73±0.007(abc)    | $7.76 \pm 0.01(c)$   | 8.27± 0.39(a)      | 8.26± 0.44(abcde)    |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 8.78±0.12(b)          | 8.93±0.12(bc)        | 8.68± 0.004(abc)    | 8.66± 0.33(ab)     | 8.28± 0.39(abc)      | $8.22 \pm 0.54(a)$ | 8.20± 0.23(bcde)     |
| With plant                                      |                       |                      |                     |                    |                      |                    |                      |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $8.33 \pm 0.005$ (de) | $9.13 \pm 0.04(a)$   | 8.82± 0.19(ab)      | $8.90 \pm 0.03(a)$ | 8.40± 0.42(abc)      | $8.41 \pm 0.50(a)$ | $8.73 \pm 0.18$ (ab) |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $8.63 \pm 0.005(c)$   | 8.88± 0.11(cd)       | $8.84 \pm 0.08(ab)$ | 8.77± 0.24(ab)     | 8.11±0.70(abc)       | $8.49 \pm 0.25(a)$ | 8.61±0.32(abcd)      |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $8.35 \pm 0.005(d)$   | 8.71±0.08(ef)        | $8.93 \pm 0.34(a)$  | 8.74± 0.04(ab)     | 8.04± 0.45(abc)      | 8.41±0.17(a)       | $8.85 \pm 0.07(ab)$  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $8.00 \pm 0.003(f)$   | $8.62 \pm 0.10$ (fg) | $8.94 \pm 0.44(a)$  | 8.55± 0.19(bcd)    | $8.65 \pm 0.30(a)$   | 8.38± 0.21(a)      | $8.87 \pm 0.05(a)$   |
| RHB @ 250 kg Si ha <sup>-1</sup> a              | $8.97 \pm 0.00(a)$    | $8.68 \pm 0.08(f)$   | 8.75±0.03(abc)      | 8.75± 0.01(ab)     | $8.55 \pm 0.05(ab)$  | $8.37 \pm 0.24(a)$ | $8.87 \pm 0.05(a)$   |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $8.80 \pm 0.002$ (b)  | 8.74± 0.05(def)      | 8.70±0.03(abc)      | 8.69± 0.01(abc)    | $7.80 \pm 0.42(c)$   | $8.49 \pm 0.14(a)$ | 8.83± 0.01(ab)       |
| S. Em±  | 0.01                  | 0.06                 | 0.07                | 0.06               | 0.21                 | 0.21               | 0.14                 |
| LSD (p≤0.05)                                    | 0.05                  | 0.16                 | 0.31                | 0.21               | 0.71                 | 0.64               | 0.44                 |

Table 42: Effect of different sources of Si on soil solution pH at different intervals of experimental period in neutral soil

| Table 43: Effect of different sources | of Si on soil solution pH at different in | tervals of experimental period in alkaline soi |
|---------------------------------------|---|--|
|                                       |   | 1 1  |

| Treatments                                      | 0 DAT                | 7 DAT                | 15 DAT                | <b>30 DAT</b>      | 60 DAT               | 90 DAT             | 120 DAT            |
|---|----------------------|----------------------|-----------------------|--------------------|----------------------|--------------------|--------------------|
| Ck - Without plant                              | $8.13 \pm 0.009(e)$  | 8.65±0.17(cde)       | 8.60± 0.06(bcd)       | 8.66± 0.05(abcd)   | 8.57±0.12(ab)        | 8.68± 0.17(a)      | 8.88±0.02(abcd)    |
| Ck – With plant                                 | 8.11±0.013(j)        | $8.61 \pm 0.02(def)$ | 8.68± 0.04(bcd)       | 8.69± 0.02(abc)    | $8.63 \pm 0.12$ (ab) | $8.75 \pm 0.15(a)$ | 8.99± 0.02(abc)    |
| Without plant                                   |                      |                      |                       |                    |                      |                    |                    |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 8.34±0.007(j)        | 8.52±0.02(ef)        | 8.51±0.01(bcd)        | 8.54± 0.01(ef)     | $8.61 \pm 0.00 (ab)$ | $8.70 \pm 0.24(a)$ | 8.83±0.01(cd)      |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 8.73±0.014(c)        | $8.43 \pm 0.07(f)$   | $8.40 \pm 0.008(bcd)$ | 8.48± 0.01(f)      | $8.48 \pm 0.03$ (ab) | $8.79 \pm 0.04(a)$ | $8.80 \pm 0.00(d)$ |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $8.82 \pm 0.000$ (b) | 8.57±0.02(def)       | 8.59± 0.06(bcd)       | 8.54±0.15(ef)      | $8.64 \pm 0.14$ (ab) | $8.49 \pm 0.09(a)$ | 8.87±0.03(abcd)    |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 8.53±0.007(f)        | 8.67±0.11(bcdef)     | 8.57±0.12(bcd)        | 8.63±0.00(bcde)    | $8.58 \pm 0.05 (ab)$ | $8.70 \pm 0.26(a)$ | 8.91±0.02(abcd)    |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 8.61±0.007(d)        | 8.51±0.29(ef)        | 8.19±0.66(cd)         | 8.57±0.05(def)     | $8.57 \pm 0.24(ab)$  | $8.79 \pm 0.19(a)$ | 8.94± 0.00(abcd)   |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 8.85±0.007(a)        | 8.59±0.42(def)       | 8.65±0.02(bcd)        | 8.71±0.12(abc)     | 8.34± 0.00(b)        | $8.67 \pm 0.22(a)$ | 8.59±0.42(e)       |
| With plant                                      |                      |                      |                       |                    |                      |                    |                    |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 7.64±0.005(m)        | 8.81±0.06(abcd)      | 8.59±0.10(bcd)        | 8.61±0.04(cde)     | $8.47 \pm 0.11$ (ab) | $8.46 \pm 0.04(a)$ | 8.91±0.03(abcd)    |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $7.83 \pm 0.005(k)$  | 8.71±0.08(abcde)     | 8.54± 0.02(bcd)       | 8.54± 0.07(ef)     | $8.52 \pm 0.05 (ab)$ | $8.67 \pm 0.08(a)$ | 8.86± 0.04(bcd)    |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $8.56 \pm 0.005(e)$  | 8.83±0.01(abc)       | 9.03±0.55(ab)         | $8.76 \pm 0.08(a)$ | $8.65 \pm 0.24(a)$   | $8.40 \pm 0.65(a)$ | $9.00 \pm 0.02(a)$ |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 7.75±0.005(1)        | 8.84± 0.09(abc)      | 9.37±0.70(a)          | $8.75 \pm 0.02(a)$ | 8.47±0.17(ab)        | $8.47 \pm 0.05(a)$ | 8.98± 0.02(abc)    |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $8.74 \pm 0.005(c)$  | 8.81±0.05(abcd)      | 8.77±0.53(abc)        | 8.71±0.01(abc)     | 8.41±0.18(ab)        | $8.56 \pm 0.40(a)$ | 9.00± 0.03(ab)     |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $8.62 \pm 0.005(d)$  | 8.92±0.15(a)         | $8.13 \pm 0.64(d)$    | 8.75±0.01(ab)      | 8.41±0.06(ab)        | $8.76 \pm 0.23(a)$ | 8.99± 0.02(abc)    |
| S. Em±  | 0.005                | 0.08                 | 0.16                  | 0.03               | 0.07                 | 0.13               | 0.04               |
| LSD (p≤0.05)                                    | 0.02                 | 0.24                 | 0.54                  | 0.12               | 0.25                 | 0.47               | 0.16               |



Fig. 37: Effect of Si sources on soil solution pH at different intervals with and without crop in a) acidic, b) neutral and c) alkaline soil (T<sub>1</sub>: Si<sub>0</sub>+ RP<sub>0</sub>, T<sub>2</sub>: Si<sub>0</sub>+ RP, T<sub>3</sub>: RP<sub>0</sub>+ CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup>, T<sub>4</sub>: RP<sub>0</sub>+ CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup>, T<sub>5</sub>: RP<sub>0</sub>+ DE @ 250 kg Si ha<sup>-1</sup>, T<sub>6</sub>: RP<sub>0</sub>+ DE @ 500 kg Si ha<sup>-1</sup>, T<sub>7</sub>: RP<sub>0</sub>+ RHB @ 250 kg Si ha<sup>-1</sup>, T<sub>8</sub>: RP<sub>0</sub>+ RHB @ 500 kg Si ha<sup>-1</sup>, T<sub>9</sub>: RP + CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup>, T<sub>10</sub>: RP + CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup>, T<sub>11</sub>: RP + DE @ 250 kg Si ha<sup>-1</sup>, T<sub>12</sub>: RP + DE @ 500 kg Si ha<sup>-1</sup>, T<sub>13</sub>: RP + RHB @ 250 kg Si ha<sup>-1</sup>, T<sub>14</sub>: RP + RHB @ 500 kg Si ha<sup>-1</sup>).

Perusal of data presented in Table 41, 42 and 43 revealed that application of Si sources increased the soil solution pH. The effectiveness of different sources varied among the soils. In acidic and neutral soil, application of calcium silicate followed by rice husk biochar and diatomite recorded higher pH whereas in alkaline soil application of rice husk biochar followed by diatomite recorded higher soil solution pH. Among the sources of Si, calcium silicate recorded higher soil solution pH from other two sources especially in acidic and neutral soil. The reactivity/solubility of the Si sources varied based on the soil reaction. Haynes, (2014) reported that wollastonite has more solubility in acidic soil whereas DE has limited solubility in acidic conditions and its solubility increases more at pH > 9. Khan *et al.* (2007) reported an increase in soil pH at different periods of incubation with the application of slag under saturated moisture regime. Initial increase in the soil pH in acidic and neutral soil can be due to the neutralization of soil acidity by the release of basic cations. Later it might have attained a state of equilibrium. Kato and Owa (1998) also reported an increase in pH when alkalinity of the applied slag was high. Basic slag as a source of lime was very effective to increase and sustain the productivity of acid red and lateritic soils of West Bengal (Bhat et al., 2007). Application of DE also increased the soil solution pH in all three soils which may be due to CaO content (2.70 %) of DE material used in the study and its dissolution lead to increase in the pH. Alcarde (1992) reported that the reactions involving silicate materials that occur in the soil can increase pH by neutralizing exchangeable Al and other toxic elements. Ribeiro et al. (1986) showed that application of silicate material helps in correcting soil acidity in clay textured soils. Under submergence, soil pH attains neutrality due to several soil chemical reactions. Increase in soil solution pH as a result of submergence into water is well known (Ponnamperuma, 1972) and attributed to the consumption of protons during reduction processes.

The observed changes in pH with biochar can be ascribed to the release of alkaline compounds, which neutralized the soil acidity and thus increased the soil pH. During pyrolysis, cations (primarily K, Ca, Si and Mg) present in the feedstock formed respective metal oxides and once applied to soil, these oxides can react with H<sup>+</sup> and monomeric Al species and thus alleviate soil pH. As biochar contain significant quantity of Ca, it can replace the monomeric Al species from soil exchange complex especially in acidic and neutral soil and also in alkaline soil. Accompanying this reaction, there could be increase in soil solution pH caused by the depletion of the readily hydrolysable monomeric Al and the formation of the more neutral [Al(OH)<sub>3</sub>] species (Novak *et al.*, 2009). The findings of present study are in line with several authors (Chan *et al.*, 2007; Laird *et al.*, 2010b; Yamato *et al.*, 2006) who recorded increase in soil pH by applying different kinds of biochar to soil. Application of wood bark biochar at 37 t ha<sup>-1</sup> increased the pH by 1.0 to 1.5 units (Yamato *et al.*, 2006).

## 4.3.2 Effect of different sources of Si on dissolved Si (DSi)

Application of different sources of Si and their rates of application had a significant effect on dissolved Si (DSi) in acidic, neutral and alkaline soils (Table 44, 45, 46 and Fig. 38).

The amount of DSi with the application of different sources and levels of Si ranged from  $47 - 447 \mu mol L^{-1}$ ,  $139 - 751 \mu mol L^{-1}$  and  $161 - 374 \mu mol L^{-1}$  in acidic, neutral and alkaline soil respectively. Irrespective of the Si sources, there was no definite trend in the content of DSi as the rate of Si increased at different intervals of crop growth.

In general, there was a gradual decrease in DSi from 0 DAT to 30 DAT and thereafter stabilized till the end of the crop growth period in acidic soil. In neutral soil, DSi content decreased from 0 DAT to 30 DAT and significantly increased at 60 DAT but decreased further till 120 DAT. Whereas, DSi increased as the duration increased from 0 to 60 DAT but at the end of crop growth decreased in alkaline soil (Fig. 38).

Irrespective of Si sources, application of different sources of Si had a significant effect on the DSi in acidic soil (Table 44). There was significantly higher DSi content in the control maintained with  $(447\pm 13 \ \mu\text{mol}\ \text{L}^{-1})$  or without plant  $(420\pm 95 \ \mu\text{mol}\ \text{L}^{-1})$  followed by DE @ 250 kg Si ha<sup>-1</sup> (415 ± 35  $\mu\text{mol}\ \text{L}^{-1})$  in the presence of crop, whereas application of CaSiO<sub>3</sub>@ 250 and 500 kg Si ha<sup>-1</sup> recorded significantly lower DSi with or without plant at 0DAT. At 15 and 30 DAT, significantly higher DSi was recorded with application of RHB @ 500 kg Si ha<sup>-1</sup> (222 ± 43, 154 ± 38  $\mu\text{mol}\ \text{L}^{-1}$  respectively) maintained without plant. However, during later intervals (60, 90 and 120 DAT) of the solution sampling, significantly higher DSi was recorded with the application of CaSiO<sub>3</sub> (140 ± 11, 153 ± 77 and 119 ± 104  $\mu\text{mol}\ \text{L}^{-1}$  respectively) followed by RHB (139 ± 3, 148 ± 21 and 107 ± 172  $\mu\text{mol}\ \text{L}^{-1}$  respectively) and least with DE.

In neutral soil (Table 45), there was a significant difference in DSi with the application of different sources of Si. Significantly higher DSi was found with the application of CaSiO<sub>3</sub> either with or without crop at 0 and 7 DAT. At 15 and 30 DAT, significantly higher DSi recorded with the application of RHB @ 250 kg Si ha<sup>-1</sup> (587  $\pm$  57 and 393  $\pm$  31 µmol L<sup>-1</sup> respectively) and was on par with RHB @ 500 kg Si ha<sup>-1</sup> (562  $\pm$  3 and 388  $\pm$  20 µmol L<sup>-1</sup> respectively) maintained without crop. At 60 DAT significantly higher DSi was recorded with the application of RHB @ 500 kg Si ha<sup>-1</sup> (518  $\pm$  148 µmol L<sup>-1</sup>) in the presence of crop plants. However, application of CaSiO<sub>3</sub> recorded significantly higher DSi at the end of the crop growth period.

Changes in the DSi with the application of different Si sources during different intervals of crop growth are reported in alkaline soil (Table 46). There was a significant increase in the DSi content with the application of RHB @ 500 kg Si ha<sup>-1</sup> at all intervals of samplings *viz.*, 0 DAT (308 ± 19 µmol L<sup>-1</sup> without plant), 7 DAT (353 ± 20, 338 ± 8 µmol L<sup>-1</sup> with and without plant respectively), 15 DAT (341 ± 54 µmol L<sup>-1</sup> with plant), 30 DAT (314 ± 49 µmol L<sup>-1</sup> with plant), 60 DAT (443 ± 78 µmol L<sup>-1</sup> with plant), 90 DAT (411 ± 73 µmol L<sup>-1</sup> with plant) and 120 DAT (351 ± 46 µmol L<sup>-1</sup> with plant). In general, application of RHB recorded higher DSi followed by DE and least with the CaSiO<sub>3</sub>.

| Treatments                                      | 0 DAT            | 7 DAT             | 15 DAT        | 30 DAT             | 60 DAT          | 90 DAT            | 120 DAT         |
|---|------------------|-------------------|---------------|--------------------|-----------------|-------------------|-----------------|
| Ck - Without plant                              | $420 \pm 95$ (a) | 344 ± 77 (ab)     | 185 ± 45 (ab) | 81 ±13 (d)         | 112 ± 8 (ab)    | 59 ± 5 (defg)     | 63 ± 95 (ef)    |
| Ck – With plant                                 | 447 ±13 (a)      | 385 ±126 (a)      | 187 ±15 (ab)  | 94 ±13 (cd)        | 73 ±14 (b)      | $57 \pm 4(eg)$    | 59 ±131(ef)     |
| Without plant                                   |                  |                   |               |                    |                 |                   |                 |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $220 \pm 3 (c)$  | $200 \pm 26$ (e)  | 162 ± 29 (ab) | $108 \pm 29$ (bcd) | 85 ± 5 (ab)     | $153 \pm 76(a)$   | 93±2(abcd)      |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $208 \pm 12(c)$  | $216 \pm 10$ (de) | 172 ± 17 (ab) | 134 ± 32 (ab)      | 115 ± 0 (ab)    | 127± 5(abc)       | 103± 12(abc)    |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 413 ± 28 (ab)    | $330 \pm 60$ (ab) | 172 ± 45 (ab) | $80 \pm 7 (d)$     | 105 ± 7 (ab)    | $65 \pm 6(cdefg)$ | 72± 28(de)      |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 372 ± 4 (ab)     | 337 ± 46 (ab)     | 187 ± 12 (ab) | 92 ± 5 (cd)        | 65 ± 12 (b)     | 74±11(cdefg)      | 69± 4(def)      |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 370 ± 30 (ab)    | 311 ± 58 (abcd)   | 176 ± 32 (ab) | 87 ± 3 (cd)        | $80 \pm 1$ (ab) | 79±4(bcdefg)      | 83±29(bcde)     |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 359 ± 172 (ab)   | 328 ± 73 (ab)     | 222 ± 43 (a)  | 154 ± 38 (a)       | 125 ± 10 (ab)   | 108± 15(abcde)    | 107± 172(ab)    |
| With plant                                      |                  |                   |               |                    |                 |                   |                 |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $234 \pm 32(c)$  | 229± 17(de)       | 165± 7(ab)    | 105±2(bcd)         | 97± 14 (ab)     | 100±13(bcdef)     | 91± 32(bcd)     |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 311±104(bc)      | 236± 40(cde)      | 177± 23(ab)   | 134± 33(ab)        | $140 \pm 11(a)$ | 121±21(abcd)      | 119± 104(a)     |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $415 \pm 34(a)$  | 321± 49(abc)      | 173± 38 (ab)  | 80± 9(d)           | 65±10 (b)       | 56± 17(eg)        | $47 \pm 35(f)$  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $407 \pm 24(ab)$ | 368± 27(ab)       | 178± 11(ab)   | 82± 14(d)          | 73±5 (b)        | 84± 32(bcdefg)    | $72 \pm 24(de)$ |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 370± 82(ab)      | 293± 68(bcde)     | 147± 34 (b)   | 96± 13(cd)         | 127±2 (ab)      | 95±39(bcdefg)     | 75± 82(de)      |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 368± 9(ab)       | 324± 19(ab)       | 186± 24 (ab)  | $120 \pm 22(bc)$   | 139±3 (a)       | 148± 21(ab)       | 79± 9(cde)      |
| S. Em±  | 28.47            | 26.79             | 16.95         | 10.61              | 16.82           | 12.36             | 5.64            |
| LSD (p≤0.05)                                    | 109.81           | 90.03             | 54.52         | 31.72              | 59.90           | 42.11             | 25.42           |

Table 44: Effect of different sources of Si on dissolved silicon (µmol L<sup>-1</sup>) at different intervals of experimental period in acidic soil

| Treatments                                      | 0 DAT           | 7 DAT           | 15 DAT          | 30 DAT         | 60 DAT           | 90 DAT           | 120 DAT         |
|---|-----------------|-----------------|-----------------|----------------|------------------|------------------|-----------------|
| Ck - Without plant                              | $489 \pm 51(h)$ | $523 \pm 74(d)$ | $259 \pm 52(f)$ | 220± 65(defg)  | 318±46(bcd)      | $460 \pm 124(a)$ | 269± 31(cde)    |
| Ck – With plant                                 | 534±27.8(h)     | 533± 53(cd)     | 365±95(bcdef)   | 191± 52(fg)    | 324± 96(bcd)     | 287± 41(cdefg)   | 195± 52(fgh)    |
| Without plant                                   |                 |                 |                 |                |                  |                  |                 |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 693± 6(ab)      | 655± 66(ab)     | 509± 2(ab)      | 316± 33(abc)   | 366± 40(bcd)     | 349± 38(bcde)    | $356 \pm 49(a)$ |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 705± 6(ab)      | 633± 42(abc)    | 375± 55(bcdef)  | 334± 31(ab)    | 391±13(abcd)     | 330± 19(bcdef)   | 345± 3(ab)      |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 556± 3(efg)     | 652± 70(ab)     | 507± 17(abc)    | 267± 59(bcdef) | 242± 18(d)       | 279± 47(cdefg)   | 229± 7(defg)    |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 552± 48(efg)    | 585±0(bcd)      | 485± 50(abcd)   | 253±63(cdefg)  | 285± 10(cd)      | 271±36(cdefg)    | 274± 33(bcde)   |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 621±16(cd)      | 646± 24(ab)     | $587 \pm 57(a)$ | 393±31(a)      | 423± 0.9(abc)    | 374± 23(abc)     | $365 \pm 38(a)$ |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 649± 68(bc)     | 622±0(abc)      | $562 \pm 3(a)$  | 388± 19(a)     | 426± 21(abc)     | $432 \pm 47(ab)$ | 305±25(abc)     |
| With plant                                      |                 |                 |                 |                |                  |                  |                 |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 629± 14(cd)     | 617±76(abc)     | 355± 89(cdef)   | 232± 19(defg)  | 287±27(cd)       | 252±29(defg)     | 195± 14(fgh)    |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 751±23(a)       | 711±72(a)       | 442± 77(abcde)  | 286± 5(bcde)   | 357±74(bcd)      | 315± 18(cdefg)   | 258± 52(cde)    |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 578±23(defg)    | $522 \pm 51(d)$ | 321±102(ef)     | 181± 16(g)     | 286± 65(cd)      | 223± 18(efg)     | 173±13(gh)      |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 610± 27(cde)    | 572±27(bcd)     | 384± 129(bcdef) | 226± 55(defg)  | 286± 53(cd)      | 213±68(fg)       | 139± 9(h)       |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 559± 46(efg)    | 493± 75(d)      | 296±135(f)      | 286± 48(cdefg) | 436± 159(ab)     | 241±48(defg)     | 180± 53(gh)     |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 587±25(def)     | $495 \pm 75(d)$ | 337± 81(def)    | 293±26(bcd)    | $518 \pm 148(a)$ | 257±46(defg)     | 217±23(efg)     |
| S. Em±  | 17.02           | 30.60           | 40.09           | 23.31          | 32.25            | 26.03            | 17.79           |
| LSD (p≤0.05)                                    | 58.1            | 102.43          | 144.49          | 76.22          | 136.75           | 105.68           | 65.46           |

Table 45: Effect of different sources of Si on dissolved silicon (µmol L<sup>-1</sup>) at different intervals of experimental period in neutral soil

| Treatments                                      | 0 DAT          | 7 DAT             | 15 DAT           | <b>30 DAT</b>   | 60 DAT            | 90 DAT           | 120 DAT         |
|---|----------------|-------------------|------------------|-----------------|-------------------|------------------|-----------------|
| Ck - Without plant                              | $266 \pm 6(b)$ | 256± 16(bc)       | 263±14(cdef)     | 232±7(c)        | $277 \pm 24(cde)$ | 251±29(def)      | 217±17(fg)      |
| Ck – With plant                                 | 247± 15(bc)    | 242± 12(cd)       | 221± 8(ef)       | $231 \pm 9(c)$  | 270± 19.9(cde)    | $256 \pm 6(def)$ | 261±26(cde)     |
| Without plant                                   |                |                   |                  |                 |                   |                  |                 |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 203± 18(def)   | $204 \pm 0.4(ef)$ | 176± 3(gh)       | 247±94(bc)      | 214± 38(de)       | $201 \pm 53(f)$  | $200 \pm 57(g)$ |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 252± 81(bc)    | 181±13(f)         | 174± 31(gh)      | $161 \pm 31(e)$ | 193± 38(e)        | 224±38(ef)       | 218± 37(efg)    |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 258± 15(bc)    | $280 \pm 28(b)$   | 249± 7(cde)      | $235 \pm 3(c)$  | 251±43(cde)       | 278±3(bcde)      | 238± 0.4(defg)  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 243±11(bcd)    | $281 \pm 45(b)$   | 255± 26(cde)     | 213± 5(cd)      | 220± 17(de)       | 262± 33(cdef)    | 229±13(defg)    |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 280± 7(ab)     | $283 \pm 14(b)$   | 253±22(cde)      | $238 \pm 15(c)$ | 313± 30(bcd)      | $322 \pm 5(bc)$  | 259± 36(cdef)   |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 308± 19(a)     | $338 \pm 8(a)$    | 313±38(ab)       | 299± 31(ab)     | 349±13(abc)       | $416 \pm 40(a)$  | 319± 4(ab)      |
| With plant                                      |                |                   |                  |                 |                   |                  |                 |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 156± 11(g)     | $220\pm5(de)$     | 202± 23(fgh)     | 187± 18(de)     | $230 \pm 54$ (de) | 281± 6(bcde)     | 238±9(defg)     |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 163±23(fg)     | 185± 16(f)        | 168±17(h)        | 162± 19(e)      | $198 \pm 20(e)$   | 254± 14(def)     | 234± 19(defg)   |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 184± 7(efg)    | 263±2(bc)         | 216± 8(efg)      | 211±9(cd)       | 374± 171(ab)      | 282± 9(bcde)     | 254± 12(def)    |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 209±11(de)     | 260± 36(bc)       | 236± 20(cdef)    | 230± 18(cd)     | 279± 20(bcde)     | 293±12(bcd)      | 246± 19(defg)   |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 219± 19(cde)   | 279±19(b)         | $271 \pm 25(bc)$ | 253±11(bc)      | 343±16(bc)        | 329±11(b)        | 299±12(bc)      |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 243± 33(bcd)   | $353 \pm 20(a)$   | $341 \pm 54(a)$  | $314 \pm 49(a)$ | $443 \pm 78(a)$   | 411±73(a)        | $351 \pm 46(a)$ |
| S. Em±  | 12.68          | 10.59             | 13.31            | 14.81           | 24.54             | 15.34            | 13.88           |
| LSD (p≤0.05)                                    | 39.64          | 35.93             | 42.05            | 47.17           | 101.70            | 56.65            | 43.39           |

Table 46: Effect of different sources of Si on dissolved silicon (µmol L<sup>-1</sup>) at different intervals of experimental period in alkaline soil

Perusal of the data revealed that there was increase in the DSi with the applied Si sources. Application of CaSiO<sub>3</sub> followed by RHB increased the DSi in acidic and neutral soil whereas RHB and DE in alkaline soil. In acidic and neutral soil gradual decrease in DSi was observed from 0 - 30 DAT and thereafter stabilized. However, in alkaline soil the DSi content increased constantly from 0 to 60 DAT and stabilized thereafter. The variation among the different Si sources for DSi in different soils can be due to reactivity or solubility of the material in types of soil. However, DSi was found to be low in the presence of crop, which may be due to crop uptake.

When added to the soil, silica reacts rapidly with amorphous surfaces of clay. The differences in Si content with time between soils are an indication of the type of solid phases in the soil that are acting as Si sinks/sources, available to replenish the soluble Si in the soil solution. The concentration of Si in the soil solution is controlled by the exchange/dissolution reactions in the soil, which can have no relationship to the total Si in the soil. Sorption/desorption reactions by sesquioxides and silicate clays can result in faster equilibrium between the solid and liquid phases of Si in the soil than dissolution/precipitation reactions as silicates and carbonates (Mckeague and Cline, 1962; Jones and Handreck, 1963; Beckwith and Reeve, 1964). Increased pH could also enhance the specific adsorption of silicic acid by the soil, hence a relatively large percentage of water soluble Si derived from both soil and the Si sources could be adsorbed by the solid phases. This also can limit the increase in the soil solution Si concentration.

Calcium silicate application increased the DSi content significantly in acidic and neutral soil in the presence or absence of crop, which can be attributed to high solubility rate of material in acidic to neutral soil (Haynes *et al.*, 2013). Slag silicate fertilizer (SSF) application to gleysols increased the Si supply in soil solutions regardless of the soil, but the effect of SSF varied with soil type. Soil factors associated with Si dissolution from SSF, Si adsorption capacity, and soil Si availability was negatively correlated with the effects of SSF on Si supply in soil solutions (Shuhei *et al.*, 2013).

In alkaline soil, the initial pH and Ca content in soil was high enough to cause a suppressed dissolution of Si from calcium silicate. The solubility of Si from silicate slags is low in soil solutions with high pH levels and Ca concentrations (Kato and Owa, 1996; Shuhei *et al.*, 2013). Aoki *et al.* (1986) reported that the Ca dissolution from the blast furnace slag was accelerated when Ca ions in a solvent was taken away in the form of Ca-EDTA. Hence it can be presumed that a decrease in the Ca concentration can promote dissolution of slags and calcium s ilicates in soil and the *vice – versa*. However, application of RHB increased the DSi in alkaline soil, which can be attributed to higher dissolution rate of biochar at higher pH. Xin *et al.* (2014) noticed higher pH, which leads to higher dissolution rate of Si from biochars. Dissolution of SiO<sub>2</sub>can be attributed to nucleophillic attack of water molecules that cause the breaking of siloxane bonds, >Si-O-Si<, at the particle surface. Increase in pH leads to the deprotonation of surface silanol groups; thereby facilitate further breaking of bridging siloxane bonds. Such increased dissolution of phytoliths was also reported by Fraysse *et al.* (2006), (2009); Nguyen *et al.* (2014); Tavakkoli *et al.* (2011); Houben *et al.* (2014).



Fig. 38: Effect of Si sources on DSi at different intervals with and without crop in a) acidic, b) neutral and c) alkaline soil (T<sub>1</sub>: Si<sub>0</sub>+ RP<sub>0</sub>, T<sub>2</sub>: Si<sub>0</sub>+ RP, T<sub>3</sub>: RP<sub>0</sub>+ CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup>, T<sub>4</sub>: RP<sub>0</sub>+ CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup>, T<sub>5</sub>: RP<sub>0</sub>+ DE @ 250 kg Si ha<sup>-1</sup>, T<sub>6</sub>: RP<sub>0</sub>+ DE @ 500 kg Si ha<sup>-1</sup>, T<sub>7</sub>: RP<sub>0</sub>+ RHB @ 250 kg Si ha<sup>-1</sup>, T<sub>8</sub>: RP<sub>0</sub>+ RHB @ 500 kg Si ha<sup>-1</sup>, T<sub>9</sub>: RP + CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup>, T<sub>10</sub>: RP + CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup>, T<sub>11</sub>: RP + DE @ 250 kg Si ha<sup>-1</sup>, T<sub>12</sub>: RP + DE @ 500 kg Si ha<sup>-1</sup>, T<sub>13</sub>: RP + RHB @ 250 kg Si ha<sup>-1</sup>, T<sub>14</sub>: RP + RHB @ 500 kg Si ha<sup>-1</sup>, T<sub>14</sub>: RP + RHB @ 500 kg Si ha<sup>-1</sup>, T<sub>14</sub>: RP + RHB @ 500 kg Si ha<sup>-1</sup>).

Dissolution of silicon takes place at higher pH. Similar observations were also noticed by Nayar et al. (1977); Savant et al. (1997); Gontijo (2000); Korndorfer et al. (2001) and Meyer and Keeping, (2001). Korndorfer et al. (2005) reported that slightly higher soil pH promotes the transformation of polysilicic (insoluble) acid into monosilicic acid (soluble) and played a dominant role in silicon availability. The effect of soil pH on the soluble Si was studied by Oliveira et al. (2005) in sandy soils cultivated with dry land rice and indicated that with increase in soil pH from 4.5 to 6.0, there was increase in available Si. Similar results were also noticed by McKeague and Cline (2001) in soils of Florida, USA and indicated that degree of ionization in the soil solution increased as pH increased, i.e., at alkaline pH levels there was greater formation of silicate ions (H<sub>3</sub>SiO<sub>4</sub>). At the normal pH range (5.5 to 6.5), H<sub>4</sub>SiO<sub>4</sub> was the main Si form present in soil solution. In soils of extreme alkalinity where pH reaches 9.5 or more, the solubility of silica will be greater. The solubility of silica is independent of pH (Lindsay, 1979), but in soil, dissolution decreases with increasing pH up to 8-9 due to changes in adsorption and then rapidly increases due to the formation of silicate ions (Beckwith and Reeve, 1964). Temperature, redox conditions, other anions and organic matter content also influence dissolution. Navar et al. (1982) reported that dissolution of silica takes place at a higher pH and plant available silicon was higher at neutral pH than at acidic pH.

According to Drees *et al.* (1989) the dissolution kinetics of soil Si was influenced not only by nature of Si polymorphs but also by a myriad of soil factors such as organic matter, redox potential, metallic ions, phyllo-silicates, sesqui-oxides, surface area, surface coatings, and overall soil solution dynamics. Organic compounds such as alginic acid, ATP, and amino acids may enhance the dissolution of soil Si. The particle size and surface area of applied silicon minerals also influence the dissolution rate of silicon in soils (Huang and Vogler, 1972 and Lidstrom, 1968).

#### 4.3.3 Effect of different sources of Si on growth parameters of rice crop

Data pertinent to effect of different sources of Si on growth parameters of rice grown under submergence in acidic, neutral and alkaline soils are presented in Table 47, 48 and 49, respectively.

## 4.3.3.1 Effect of Si sources on plant height

The effect of different sources of Si on plant height at different growth stages in acidic, neutral and alkaline soils is presented in Tables 47, 48 and 49, respectively.

In acidic soil, application of different sources of Si significantly increased the plant height at different growth stages of crop (Table 47). There was significant increase in the plant height with the application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> at 30 (57.50  $\pm$  0.50 cm), 60 (98.33  $\pm$  2.52 cm), 90 (100.66  $\pm$  3.79 cm), 120 (101.56  $\pm$  3.61 cm) days after transplanting (DAT). This was followed by significant increase with the application of DE @ 250 kg Si ha<sup>-1</sup> at 30 (54.50  $\pm$  0.50 cm), 60 (93.65  $\pm$  0.65 cm), 90 (95.33  $\pm$  2.57

cm), 120 (95.73  $\pm$  2.40 cm). There was no definite trend in increase of plant height with application of higher rate of Si independent of sources.

Plant height recorded at 30, 60, 90 and 120 DAT differed significantly by the application of different sources of Si compared to control in neutral soil (Table 48). Application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> and DE @ 250 kg Si ha<sup>-1</sup> recorded significantly higher plant height ( $52.00 \pm 2.29$ ,  $58.75 \pm 1.25$  cm respectively) at 30 DAT. However, at 60, 90 and 120 DAT application of RHB @ 500 kg Si ha<sup>-1</sup>significantly increased the plant height to an extent of 97.00  $\pm$  7.21, 105.83  $\pm$  5.75, 106.33  $\pm$  6.03 cm, respectively and remaining treatments were on par with each other but significantly higher compared to control.

In case of alkaline soil, there was a very poor growth of the plant but with the application of Si sources plant height was significantly increased compared to control (Table 49). At 30 DAT, application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> recorded significantly higher plant height to an extent of  $31.50 \pm 0.50$  cm followed by CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (25.25 ± 2.75 cm) and RHB @ 250 kg Si ha<sup>-1</sup> (25.50 ± 1.50 cm). However, at 60, 90 and 120 DAT, application of RHB @ 250 kg Si ha<sup>-1</sup> significantly increased the plant height (41.33 ± 10.69, 43.50 ± 1.80, 43.50 ± 1.80 cm respectively) and was on par with RHB @ 500 kg Si ha<sup>-1</sup> (39.33 ± 2.52, 39.53 ± 6.47, 39.93 ± 6.15 cm, respectively).

## 4.3.3.2 Effect of Si sources on number of tillers pot<sup>-1</sup>

The number of tillers pot<sup>-1</sup> differed significantly with the application of different sources of Si in acidic and neutral soils (Table 47 and 48) whereas in alkaline soil, no tillers were noticed due to poor growth of the crop (data not presented).

In acidic soil, there was a significant increase in the number of tillers by the application of different Si sources compared to control with an exception to CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> at all growth stages (Table 47). Application of DE @ 250 kg Si ha<sup>-1</sup> significantly increased the tillers at 60 (2.00  $\pm$  0), 90 (2.00  $\pm$  0) and 120 (3.33  $\pm$  0.58) days after transplanting. Independent of sources and levels, application of Si significantly increased the number of tillers pot<sup>-1</sup> over control at all growth stages.

Application of Si sources significantly increased the number of tillers at 60 and 90 DAT in neutral soil (Table 48) compared to control but was on par at 120DAT. Application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> and DE @ 250 kg Si ha<sup>-1</sup>recorded significantly higher number of tillers at 60 ( $3.00 \pm 1.00$  and  $3.00 \pm 0$  respectively) and 90 DAT ( $3.00 \pm 1.0$  and  $3.00 \pm 0$  respectively), whereas other treatments are on par with each other but significantly higher compared to control.

| Treatments                                      | Plant height (cm)     |                     |                     |                      | No. of tillers pot <sup>-1</sup> |                     |                    |
|---|-----------------------|---------------------|---------------------|----------------------|----------------------------------|---------------------|--------------------|
| (With plant)                                    | 30 DAT                | 60 DAT              | 90 DAT              | 120 DAT              | 60 DAT                           | 90 DAT              | 120 DAT            |
| Ck  | $51.55 \pm 1.20$ (de) | 81.00± 1.08(ef)     | 85.00± 3.16(de)     | 85.57±2.71(cd)       | 1.25± 0.50(b)                    | $1.25 \pm 0.50(b)$  | 2.25± 0.50(ab)     |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $57.50 \pm 0.50(a)$   | 98.33± 2.52(a)      | 100.66± 3.79(a)     | $101.56 \pm 3.61(a)$ | 1.66± 0.58(ab)                   | 1.66± 0.58(ab)      | 2.66± 1.15(ab)     |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 52.75± 2.75(cd)       | 90.50± 3.80(bc)     | 91.83± 3.79(bc)     | 91.86± 2.06(bc)      | $1.00 \pm 0.00$ (b)              | $1.00 \pm 0.00$ (b) | $1.66 \pm 0.58(b)$ |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $54.50 \pm 0.50$ (bc) | 93.65± 0.65(ab)     | 95.33± 2.57(ab)     | 95.73± 2.40(ab)      | 2.00± 0.00(a)                    | $2.00 \pm 0.00(a)$  | $3.33 \pm 0.58(a)$ |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $50.00 \pm 1.50(e)$   | 85.06± 4.41(de)     | 88.40± 5.72(bcd)    | 89.53± 5.47(bc)      | 1.66± 0.58(ab)                   | 1.66± 0.58(ab)      | 2.33± 1.53(ab)     |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $45.00 \pm 2.00(f)$   | $80.00 \pm 1.00(f)$ | $80.93 \pm 4.65(e)$ | $82.55 \pm 4.08(d)$  | 1.66± 0.58(ab)                   | 1.66± 0.58(ab)      | 2.00± 1.00(ab)     |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $50.25 \pm 0.75$ (de) | 84.20± 3.12(def)    | 86.30± 5.20(cde)    | 87.63± 5.92(ab)      | 1.66± 0.58(ab)                   | 1.66± 0.58(ab)      | 2.00± 0.00(ab)     |
| S. Em±  | 0.75                  | 1.36                | 2.35                | 2.14                 | 0.23                             | 0.23                | 0.44               |
| LSD (p≤0.05)                                    | 2.46                  | 4.69                | 7.02                | 6.69                 | 0.76                             | 0.76                | 1.49               |

Table 47: Effect of different sources of Si on growth parameters at different intervals of crop growth in acidic soil

| Treatments                                      | Plant height (cm) |                       |                      |                      | No. of tillers pot <sup>-1</sup> |                    |                     |
|---|-------------------|-----------------------|----------------------|----------------------|----------------------------------|--------------------|---------------------|
| (With plant)                                    | 30 DAT            | 60 DAT                | 90 DAT               | 120 DAT              | 60 DAT                           | 90 DAT             | 120 DAT             |
| Ck  | 48.62±4.50(de)    | 85.50±7.55(d)         | 93.15±12.82(b)       | 93.40±12.84(b)       | 1.75±0.50(b)                     | $1.75 \pm 0.50(b)$ | $3.00 \pm 0.82(a)$  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 52.00± 2.29(cd)   | 90.00±1.00(bcd)       | 94.16± 1.89(ab)      | 93.66± 2.75(b)       | 2.66± 0.58(ab)                   | 2.66± 0.58(ab)     | 4.33± 1.15(a)       |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 58.75±1.25(ab)    | 89.25±1.75(cd)        | 100.85±9.85(ab)      | 101.50± 10.50(ab)    | $3.00 \pm 1.00(a)$               | $3.00 \pm 1.00(a)$ | $4.335 \pm 0.58(a)$ |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 58.00±2.50(ab)    | 92.66± 2.08(bc)       | 100.90±1.70(ab)      | 101.35± 1.65(ab)     | $3.00 \pm 0.00(a)$               | $3.00 \pm 0.00(a)$ | $4.66 \pm 2.08(a)$  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 54.00±1.50(bc)    | $93.00 \pm 2.00$ (bc) | 96.80± 2.20(ab)      | 97.75± 2.25(ab)      | 2.33±0.58(ab)                    | 2.33± 0.58(ab)     | 5.33± 3.21(a)       |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 44.66± 4.91(e)    | 92.00±1.00(bcd)       | 99.23±1.57(ab)       | 99.33± 82.67(ab)     | 2.33±0.58(ab)                    | 2.33± 0.58(ab)     | $3.33 \pm 0.58(a)$  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 55.56±2.11(abc)   | 97.00±7.21(a)         | $105.83 \pm 5.75(a)$ | $106.33 \pm 6.03(a)$ | 2.33±0.58(ab)                    | 2.33± 0.58(ab)     | $3.00 \pm 0.00(a)$  |
| S. Em±  | 1.52              | 2.44                  | 2.81                 | 2.95                 | 0.31                             | 0.31               | 0.69                |
| LSD (p≤0.05)                                    | 5.61              | 7.28                  | 11.66                | 11.93                | 1.01                             | 1.01               | NS                  |

Table 48: Effect of different sources of Si on growth parameters at different intervals of crop growth in neutral soil
| Treatments                                      | Plant height (cm)   |                     |                       |                       | Straw dry weight not <sup>-1</sup> (g) |  |
|---|---------------------|---------------------|-----------------------|-----------------------|--|--|
| (With plant)                                    | 30 DAT              | 60 DAT              | 90 DAT                | 120 DAT               | Shun ary neight por (g)                |  |
| Ck  | 22.00±0.82(cd)      | $22.33 \pm 2.62(c)$ | $23.77 \pm 2.91(d)$   | 24.77±2.25(d)         | 0.507±0.08(c)                          |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $31.50 \pm 0.50(a)$ | 30.33±1.53(b)       | $30.83 \pm 2.84$ (bc) | 32.16± 3.33(c)        | $0.562 \pm 0.03$ (bc)                  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 25.25±2.75(bc)      | 33.33± 4.51(ab)     | 33.60± 1.10(b)        | $34.85 \pm 0.15$ (bc) | $0.53 \pm 0.16$ (bc)                   |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 26.50± 3.97(b)      | 22.33±2.52(c)       | 27.73±3.19(bcd)       | $25.76 \pm 2.25(d)$   | $0.61 \pm 0.11$ (bc)                   |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $20.75 \pm 1.25(d)$ | 34.93± 5.48(ab)     | $25.20 \pm 4.75$ (cd) | 35.60± 3.14(bc)       | $0.51 \pm 0.10$ (bc)                   |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 25.50±1.50(bc)      | 41.33±10.69(a)      | $43.50 \pm 1.80(a)$   | $43.50 \pm 1.80(a)$   | $0.67 \pm 0.10$ (ab)                   |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $26.50 \pm 4.50(b)$ | 39.33±2.52(a)       | $39.53 \pm 6.47(a)$   | 39.93± 6.15(ab)       | $0.54 \pm 0.02$ (bc)                   |  |
| S. Em±  | 1.25                | 2.43                | 1.87                  | 1.55                  | 0.05                                   |  |
| LSD (p≤0.05)                                    | 4.08                | 8.05                | 5.78                  | 5.05                  | 0.16                                   |  |

 Table 49: Effect of different sources of Si on growth parameters at different intervals of crop growth and straw yield at harvest in alkaline soil

DAT – Days after transplanting

Data presented in Table 47, 48 and 49 revealed that there was a significant increase in the plant height and number of tillers with the application of different sources of Si in acidic, neutral and alkaline soil. The effectiveness of the different sources varied based on its reactivity in respective soils. Comparatively, plant growth was reduced in alkaline soil may be due to soil with high pH and soluble salt content like sodium. Also alkaline soil was recorded with high amount initial Ca content and low amount of micronutrients in the soil and there by plants might have suffered from deficiency. It is reported that, low availability of Fe, Mn, Zn, Cu and B are associated with Ca rich soils (Talibudeen, 1981; Lindsay and Schwab, 1982; Marschner, 1995). Decreased availability of these nutrients resulted from both pH effect and interaction with soil carbonates. Calcareous nature of the soil was reported to impede root penetration and growth (Mueller and Cline, 1959). Within the calcareous soil, rooting depth was shallow in waterlogged condition than in well drained soils. Total root mass was found to be greater but root biomass was lower in calcareous soils hence affects the crop growth.

There was significant increase in the growth parameters with the application of Si sources over control in all three soils. The improvement in growth parameters by application of Si was also reported in rice by Nayar *et al.* (1982); Anderson (1991); Raid *et al.* (1992) and Korndorfer and Gaschov (1999). Increased number of tillers due to application of Si was also noticed by Liang *et al.* (1994). However significant increase in number of tillers was noticed due to the supplement of calcium silicate at 2 tha<sup>-1</sup>over control in the present investigation. Gong *et al.* (2003) observed increased plant height, leaf area and dry matter of wheat even in drought conditions with the foliar application of silicon. Application of different Si sources increased plant height in accordance with the findings of Ma *et al.* (1989) in Japan, Munir *et al.* (2003) in Brazil, Singh *et al.* (2005) and Singh *et al.* (2006) in India.

#### 4.3.4 Effect of different sources of Si on yield parameters of rice crop

The data pertinent to yield parameters of rice recorded after harvest of crop in pot culture experiment are given in Table 49, 50 and 51.

Table 50 represents the effect of the Si sources on the yield parameters of rice crop such as panicle number pot<sup>-1</sup>, panicle length pot<sup>-1</sup>, straw dry weight pot<sup>-1</sup> and grain weight pot<sup>-1</sup> in acidic soil (Fig. 39 and 40). The yield parameters increased with increased rate of Si application. There was a significant increase in the panicle number pot<sup>-1</sup> (2.33  $\pm$  0.58), panicle length pot<sup>-1</sup> (16.17  $\pm$  0.29 cm), straw dry weight pot<sup>-1</sup> (8.45  $\pm$  1.37 g) and grain weight pot<sup>-1</sup> (2.12  $\pm$  0.34 g) with application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup>. Panicle number pot<sup>-1</sup>recorded on par with each other by the application of Si with exception of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> but significantly higher compared to control. Panicle length pot<sup>-1</sup> recorded significantly higher by the application of CaSiO<sub>3</sub> @ 250 and 500 kg Si ha<sup>-1</sup> followed by RHB and DE.

Table 51 depicts the effect of different Si sources on the yield parameters of rice crop such as panicle number pot<sup>-1</sup>, panicle length pot<sup>-1</sup>, straw dry weight pot<sup>-1</sup> and grain weight pot<sup>-1</sup> in neutral soil (Fig. 39 and Fig. 40). Panicle number pot<sup>-1</sup> recorded highest

with application of CaSiO<sub>3</sub> @ 250 (1.67 ± 1.15) and 500 (2.33 ± 1.53) kg Si ha<sup>-1</sup> followed by DE @ 250 (2.33 ± 0.58) and 500 (2.33 ± 0.58) kg Si ha<sup>-1</sup> but it was on par with the control (1.25 ± 0.58) whereas significantly higher compared to RHB treatment. There was significantly higher panicle length pot<sup>-1</sup> with application of DE @ 250 kg Si ha<sup>-1</sup> (17.44 ± 1.71 cm) and RHB @ 500 kg Si ha<sup>-1</sup> (15.03 ± 0.06 cm). Straw dry weight pot<sup>-1</sup> recorded significantly higher with the application of DE @ 500 kg Si ha<sup>-1</sup> (9.36 ± 0.63 g) followed by DE @ 250 kg Si ha<sup>-1</sup> (8.48 ± 1.58 g). However, application of RHB and CaSiO<sub>3</sub> recorded significantly higher compared to control. Grain weight pot<sup>-1</sup> recorded significantly higher with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (4.42 ± 0.14 g) followed by DE @ 250 kg Si ha<sup>-1</sup> (3.96 ± 0.07g). In general, there was a significant increase in the yield parameters by the application of Si sources compared to control.

There was a stunted and reduced growth of crop noticed in alkaline soil and therefore only straw yield is reported in Table 49 and Fig. 39. However, there was significantly higher straw dry weight pot<sup>-1</sup> with application of RHB @ 250 kg Si ha<sup>-1</sup> (0.67  $\pm$  0.10 g), while remaining treatments noticed on par straw yield but significantly higher compared to control.

There was a significant increase in the yield parameters such as panicle number pot<sup>-1</sup>, panicle length pot<sup>-1</sup>; straw dry weight pot<sup>-1</sup> and grain weight pot<sup>-1</sup> in acidic and neutral soil, whereas straw dry weight pot<sup>-1</sup> in alkaline soil with the application of Si sources over control. The efficiency of different Si sources in improving the yield parameters of rice varied with soils based on the reactivity of material. Ma and Takahashi (2002) noticed a slight increase in the panicle number and number of tillers of rice (Liang et al., 1994) with Si fertilization. Kim et al. (2012) reported that spikelets per panicle, spikelet filling and grain weight were regulated by the application of Si (liquid Si @ 36 %) but number of panicles per square meter was considerably increased by Si application compared to control in rice plants. Singh et al. (2005) also noticed, application of Si in rice increased the grain yield by increasing spikelets number per panicle, mature grain percentage and 1000 grain weight. Application of calcium silicate as Si source significantly increased the grain and straw yield in acidic, neutral and alkaline soils Karnataka (Narayanaswamy and Prakash, 2009). Pati et al. (2016) showed that application of diatomite as silicon source significantly increased grain and straw yield as well as yield attributing parameters such as plant height (cm), number of tillers m<sup>-2</sup>, number of panicle m<sup>-2</sup>, and 1000 grain weight (g) of rice. Similarly, in the present investigation, increased yield parameters were noticed in field experiment with application of DE @ 300 kg ha<sup>-1</sup>.

Rice husk biochar significantly increased the growth and yield parameters of rice in all three soils. The growth and yield was found to be much higher especially in alkaline soil with application of RHB and attributed to higher dissolution rate of biochar under high pH soil (Xin *et al.*, 2014). Application of crop residues such as rice straw and rice hull has a beneficial effect on the build-up of organic matter and increased the N – supplying capacity of the wetland soils as there is a strong relationship between organic

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| Treatments                                      | Panicle number      | Panicle length pot <sup>-1</sup> | Straw dry weight      | Grain weight pot <sup>-1</sup> |
|---|---------------------|----------------------------------|-----------------------|--------------------------------|
| (With plant)                                    | pot <sup>-1</sup>   | ( <b>cm</b> )                    | pot <sup>-1</sup> (g) | ( <b>g</b> )                   |
| Ck  | 1.25±0.50(b)        | 13.13±0.85(d)                    | 4.85± 0.73(cd)        | 0.99±0.05(c)                   |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $1.67 \pm 0.58(ab)$ | 15.83± 0.76(ab)                  | 8.21±1.08(a)          | $1.85 \pm 0.40(a)$             |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $2.33 \pm 0.58(a)$  | $16.17 \pm 0.29(a)$              | $8.45 \pm 1.37(a)$    | $2.12 \pm 0.34(a)$             |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 1.67±0.58(ab)       | 13.33±0.58(cd)                   | 6.18±0.60(b)          | $1.12 \pm 0.03$ (bc)           |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 2.00± 1.00(ab)      | $13.50 \pm 1.32$ (cd)            | $5.89 \pm 0.51$ (bc)  | $1.01 \pm 0.01(c)$             |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 1.33±0.58(ab)       | $14.50 \pm 0.87$ (bc)            | $4.47 \pm 0.22(d)$    | $1.14 \pm 0.09$ (bc)           |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $1.67 \pm 0.58(ab)$ | 15.03± 0.06(ab)                  | 4.76± 0.32(cd)        | $1.39 \pm 0.04(b)$             |
| S. Em±  | 0.36                | 0.38                             | 0.39                  | 0.08                           |
| LSD (p≤0.05)                                    | 1.11                | 1.36                             | 1.24                  | 0.31                           |

Table 50: Effect of different sources of Si on yield parameters of rice crop in acidic soil

| Treatments                                      |                                 | Panicle length pot <sup>-1</sup> | Straw dry weight      | Grain weight pot <sup>-1</sup> |  |
|---|---------------------------------|----------------------------------|-----------------------|--------------------------------|--|
| (With plant)                                    | Panicle number pot <sup>1</sup> | (cm)                             | pot <sup>-1</sup> (g) | <b>(g)</b>                     |  |
| Ck  | $1.25 \pm 0.58(a)$              | 14.23± 2.83(c)                   | 5.25±0.89(e)          | 2.74±0.46(e)                   |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $1.67 \pm 1.15(a)$              | $14.33 \pm 0.76$ (bc)            | $7.60 \pm 0.52$ (bc)  | $3.09 \pm 0.10$ (de)           |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 2.33±1.53(a)                    | $14.79 \pm 1.32(bc)$             | $7.83 \pm 1.01$ (bc)  | $4.42 \pm 0.14(a)$             |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 2.33±0.58(a)                    | 17.44±1.71(ab)                   | 8.48±1.58(ab)         | $3.96 \pm 0.07$ (b)            |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $2.33 \pm 0.58(a)$              | 15.33±1.53(bc)                   | $9.36 \pm 0.63(a)$    | 3.38±0.16(cd)                  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 1.33± 0.58(ab)                  | $14.50 \pm 0.87$ (bc)            | $4.47 \pm 0.22(d)$    | $1.14 \pm 0.09$ (bc)           |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 1.67± 0.58(ab)                  | $15.03 \pm 0.06(ab)$             | $4.76 \pm 0.32$ (cd)  | $1.39 \pm 0.04$ (b)            |  |
| S. Em±  | 0.45                            | 0.87                             | 0.44                  | 0.11                           |  |
| LSD (p≤0.05)                                    | 1.49                            | 3.14                             | 1.24                  | 0.31                           |  |

Table 51: Effect of different sources of Si on yield parameters of rice crop in neutral soil

matter content and potentially mineralizable N as reported by Sahrawat (1983). Prakash *et al.* (2002) and Akshatha (2015) reported that application of 2 - 8 t ha<sup>-1</sup> of rice hull ash recorded maximum straw and grain yield of rice. Xin *et al.* (2014) studied transformation and dissolution of Si from Si rich biochar. They reported that the release of Si from biochar produced at low temperature (200 - 400°C) increased the dissolution of Si linearly with time. Similar observation was also made by Nguyen *et al.* (2014).

Application of Si material enhanced the growth and straw yield in alkaline soils. These soils noticed higher pH and electrical conductivity. However, the presence of soluble salts mainly reduced the growth and development of rice plants in the present investigation. Usually under salt stressed condition, plant growth will be reduced and nutrient ratio will be altered by the higher accumulation of salts. Salt stress causes both osmotic and ionic stress in the plant which affect the physiological activities of the plant and thereby plant growth and yield. Silicon is one of the elements which helps in reducing the salt stress in plants and enhances the growth of the plant (Liang et al., 2003a; Ashraf et al., 2010). Most of the beneficial effects of Si are attributed to its deposition in cell walls of the roots, leaves and stems (Ma et al., 2006). Deposition of Si in roots reduces apoplastic bypass flow and provides binding sites for salts resulting in reduced uptake and translocation of salts from roots to shoots. According to Bradbury and Ahmad (1990) and Ahmad et al. (1992), silica deposition in the leaves limits transpiration and hence salt accumulation in wheat. Romero-Aranda et al. (2006) have suggested that silicate crystals deposited in the epidermal cells form a barrier that reduces water loss through cuticle, which in turn, contributes to salt dilution, mitigating salt toxicity effects in tomato. Silicon benefits on salt tolerance of barley and cucumber and has been related to antioxidant enzyme activity (Liang et al., 2003b and Zhu et al., 2004). Addition of different levels of Si under salt stress interacted with Na<sup>+</sup>, reduced its uptake and transport to shoots with a resultant improvement in cane yield and juice quality of both genotypes. The ameliorative effect of added Si in alleviating deleterious effects of NaCl could be related to Si being irreversibly precipitated as amorphous silica (SiO<sub>2</sub>. nH<sub>2</sub>O) in cell walls and lumens and thus reduced the translocation of salts to shoots (Bradbury and Ahmad, 1990; Epstein, 1999; Gong et al., 2006 and Gunes et al., 2007).

# 4.3.5 Effect of different sources of Si on nutrient content and uptake by rice straw in different soils

Data pertaining to nutrient content and uptake by rice straw in acidic, neutral and alkaline soils are presented in Table 52 to 57.

There was a significant difference in the nutrient content and uptake by rice straw in acidic soil (Table 52 and 53) with application of different sources of Si over control.

Application of Si sources significantly increased straw Si content over control in acidic soil (Fig. 41). Application of RHB @ 250 kg Si ha<sup>-1</sup> (7.18  $\pm$  0.21 %) followed by DE @ 500 kg Si ha<sup>-1</sup> (6.46  $\pm$  0.65 %) recorded significantly higher Si compared to other treatments. Phosphorus content of rice straw was significantly higher with the application



Fig. 39: Effect of different sources of silicon on straw dry weight of rice crop grown in acidic, neutral and alkaline soils



Fig. 40: Effect of different sources of silicon on grain weight of rice crop grown in acidic and neutral soils

| Treatments                                      | Si                 | Р                    | K                              | Ca                    | Mg                 |  |
|---|--------------------|----------------------|--------------------------------|-----------------------|--------------------|--|
| (With plant)                                    | Content (%)        |                      |                                |                       |                    |  |
| Ck  | $4.59 \pm 0.06(d)$ | 0.19± 0.04(b)        | 2.41±0.44(ab)                  | $0.85 \pm 0.03$ (ab)  | 0.30± 0.19(a)      |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $4.56 \pm 0.19(d)$ | $0.28 \pm 0.06(a)$   | 1.88± 0.34(ab)                 | $1.00 \pm 0.42(a)$    | $0.32 \pm 0.14(a)$ |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $6.30 \pm 0.57(c)$ | $0.24 \pm 0.06 (ab)$ | $1.62 \pm 0.05(b)$             | $0.75 \pm 0.03$ (ab)  | $0.25 \pm 0.03(a)$ |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $6.29 \pm 0.78(c)$ | $0.25 \pm 0.04$ (ab) | $2.05 \pm 0.39$ (ab)           | $0.72 \pm 0.03$ (b)   | $0.28 \pm 0.03(a)$ |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 6.46± 0.65(ab)     | $0.29 \pm 0.03(a)$   | 1.93± 0.17(ab)                 | $0.68 \pm 0.04(b)$    | $0.32 \pm 0.04(a)$ |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 7.18± 0.21(a)      | $0.23 \pm 0.07 (ab)$ | $2.00 \pm 0.42$ (ab)           | $0.63 \pm 0.01$ (b)   | $0.37 \pm 0.01(a)$ |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $5.88 \pm 0.18(c)$ | 0.24± 0.09(ab)       | $2.61 \pm 0.29(a)$             | 0.83± 0.09(ab)        | $0.34 \pm 0.04(a)$ |  |
| S. Em±  | 0.22               | 0.03                 | 0.17                           | 0.05                  | 0.04               |  |
| LSD (p≤0.05)                                    | 0.71               | 0.10                 | 0.59                           | 0.28                  | NS                 |  |
|   |                    |                      | Uptake (mg pot <sup>-1</sup> ) |                       |                    |  |
| Ck  | 223.00± 33.00(e)   | 8.96± 1.32(d)        | 119.08± 36.92(ab)              | 41.06± 5.96(bc)       | 14.70±10.84(b)     |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 375.96± 59.90(bc)  | $22.88 \pm 2.61(a)$  | $156.17 \pm 47.47(a)$          | $84.54 \pm 45.82(a)$  | 27.20±15.10(a)     |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 527.49± 39.15(a)   | 20.07± 4.46(ab)      | $137.21 \pm 24.45(a)$          | 63.29±11.77(ab)       | 21.25± 3.19(ab)    |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 388.64± 56.03(b)   | 15.09± 1.96(bc)      | 125.38± 13.26(ab)              | $44.81 \pm 6.34$ (bc) | 17.03± 0.86(ab)    |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 379.49± 19.98(bc)  | $16.95 \pm 0.55(b)$  | $113.27 \pm 4.64(ab)$          | $40.16 \pm 1.98$ (bc) | 18.82± 3.78(ab)    |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 321.13±21.46(cd)   | $10.36 \pm 2.55(cd)$ | 88.67± 14.25(b)                | $28.38 \pm 1.68(c)$   | 16.32± 0.68(ab)    |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 280.20± 16.27(de)  | 11.58± 5.11(cd)      | 125.06± 22.38(ab)              | $39.51 \pm 5.64$ (bc) | 16.09± 1.67(ab)    |  |
| S. Em±  | 19.91              | 1.52                 | 13.07                          | 6.47                  | 2.86               |  |
| LSD (p≤0.05)                                    | 61.01              | 5.17                 | 48.39                          | 20.94                 | 11.22              |  |

Table 52: Effect of different sources of Si on nutrient content and uptake by rice straw in acidic soil

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 Table 53: Effect of different sources of Si on micronutrient content and uptake by rice straw in acidic soil

| Treatments                                      | Fe                             | Mn                 | Cu                       | Zn                   |  |  |  |
|---|--------------------------------|--------------------|--------------------------|----------------------|--|--|--|
| (With plant)                                    | Content (mg kg <sup>-1</sup> ) |                    |                          |                      |  |  |  |
| Ck  | 331.00± 33.82(a)               | 380.42± 142.49(ab) | 27.92± 3.78(a)           | 63.00± 6.55(b)       |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $290.00 \pm 12.20(a)$          | 283.11± 63.90(ab)  | 23.67± 1.45(ab)          | 66.33±7.62(ab)       |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 311.50± 0.83(a)                | 222.17±19.50(b)    | 21.67±2.67(b)            | 69.17±2.50(ab)       |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $288.78 \pm 45.62(a)$          | 278.89± 24.93(ab)  | 20.78± 3.15(b)           | 69.67±2.40(ab)       |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 297.22± 38.50(a)               | 295.33± 103.23(ab) | 23.56± 2.69(ab)          | 65.44± 5.06(ab)      |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $322.33 \pm 35.34(a)$          | 298.56± 135.16(ab) | $29.22 \pm 6.81(a)$      | 78.33±15.76(a)       |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $329.00 \pm 24.01(a)$          | 420.33± 87.99(a)   | 25.11±2.01(ab)           | 70.44± 4.95(ab)      |  |  |  |
| S. Em±  | 15.32                          | 46.03              | 1.82                     | 3.63                 |  |  |  |
| LSD (p≤0.05)                                    | NS                             | 140.77             | 6.30                     | 11.22                |  |  |  |
|   |                                | Uptake (mg po      | <b>t</b> <sup>-1</sup> ) |                      |  |  |  |
| Ck  | $1.62 \pm 0.37(c)$             | $1.89 \pm 0.93(a)$ | $0.14 \pm 0.03$ (bc)     | $0.30 \pm 0.02(d)$   |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $2.38 \pm 0.24$ (ab)           | $2.32 \pm 0.57(a)$ | $0.20 \pm 0.04(a)$       | 0.55±0.13(ab)        |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $2.63 \pm 0.42(a)$             | $1.87 \pm 0.26(a)$ | $0.18 \pm 0.04(ab)$      | $0.59 \pm 0.11(a)$   |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $1.80 \pm 0.46$ (bc)           | $1.73 \pm 0.32(a)$ | $0.13 \pm 0.03(c)$       | $0.43 \pm 0.04$ (bc) |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $1.76 \pm 0.38(c)$             | $1.75 \pm 0.64(a)$ | $0.14 \pm 0.03$ (bc)     | $0.39 \pm 0.05$ (cd) |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $1.45 \pm 0.23(c)$             | $1.34 \pm 0.62(a)$ | $0.13 \pm 0.03$ (bc)     | $0.35 \pm 0.07$ (cd) |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $1.57 \pm 0.21(c)$             | $1.99 \pm 0.35(a)$ | $0.12 \pm 0.002(c)$      | $0.33 \pm 0.01$ (cd) |  |  |  |
| S. Em±  | 0.19                           | 0.29               | 0.02                     | 0.03                 |  |  |  |
| LSD (p≤0.05)                                    | 0.59                           | NS                 | 0.06                     | 0.12                 |  |  |  |

of DE @ 500 kg Si ha<sup>-1</sup> (0.29 ± 0.03 %) followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (0.28 ± 0.06 %) compared to other treatments. There was significant increase in K content with the application of RHB @ 500 kg Si ha<sup>-1</sup> (2.61 ± 0.29 %) whereas other treatments were found to be on par with control. There was also significant increase in the Ca content in straw with the application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (1.00 ± 0.42 %), however there was no significant effect on Mg and Fe content. Manganese content was significantly increased with the application of RHB @ 500 kg Si ha<sup>-1</sup> (420.33 ± 87.99 mg kg<sup>-1</sup>) in the rice straw. Conspicuously, there was significant reduction in the Cu content with the application of Si sources compared to control, with an exception to application of RHB @ 250 kg Si ha<sup>-1</sup>. Straw Zn content (78.33 ± 15.76 mg kg<sup>-1</sup>) was significantly higher with application of RHB @ 250 kg Si ha<sup>-1</sup>.

Calcium silicate application @ 500 kg Si ha<sup>-1</sup>significantly increased the straw Si uptake (527.49 ± 39.15 mg pot<sup>-1</sup>) compared to other treatments (Fig. 43). Phosphorus uptake significantly increased with application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (22.88 ± 2.61 mg pot<sup>-1</sup>) followed by CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (20.07 ± 4.46 mg pot<sup>-1</sup>). Significantly higher K uptake was noticed with the application of CaSiO<sub>3</sub>@ 250 (156.17 ± 47.47 mg pot<sup>-1</sup>) and 500 (137.21 ± 24.45 mg pot<sup>-1</sup>) kg Si ha<sup>-1</sup>. Straw Ca (84.54 ± 45.82 mg pot<sup>-1</sup>) and Mg (27.20 ± 15.10 mg pot<sup>-1</sup>) uptake significantly increased with application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup>. Also application of calcium silicate significantly increased the uptake of Fe (2.63 ± 0.42 mg pot<sup>-1</sup>), Cu (0.20 ± 0.04 mg pot<sup>-1</sup>) and Zn (0.59 ± 0.11 mg pot<sup>-1</sup>). However, there was no significant effect of applied Si on Mn uptake by rice straw in acidic soil.

Data with regard to straw nutrient content and its uptake as affected by Si sources in neutral soil are presented in Table 54 and 55.

Application of Si sources significantly increased the straw Si content over control in neutral soil (Fig. 41). Application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup>recorded significantly higher Si content (7.98  $\pm$  0.94 %) compared to other treatments. Phosphorus content of rice straw was significantly higher with the application of DE @ 250 kg Si ha<sup>-1</sup> (0.18  $\pm$ 0.03 %) followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (0.14  $\pm$  0.02 %) compared to other treatments. There was no significant effect of Si sources on straw K content among the treatments. Significant increase in Ca content (1.12  $\pm$  0.05 %) in straw was recorded with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup>. There was no significant effect on Mg content of rice straw with the application of Si sources. Significantly higher Fe content (746.33  $\pm$  316.29 mg kg<sup>-1</sup>) was recorded with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup>. Manganese content (1529.78  $\pm$  315.73 mg kg<sup>-1</sup>) was significantly increased with the application of DE @ 250 kg Si ha<sup>-1</sup> in the rice straw. There was no significant effect of Si sources on straw Cu content between the treatments. Straw Zn content was found to be significantly high with application of DE @ 250 kg Si ha<sup>-1</sup>.

Calcium silicate application @ 250 kg Si ha<sup>-1</sup>significantly increased the straw Si uptake (609.64  $\pm$  112.21 mg pot<sup>-1</sup>) compared to other treatments followed by CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (584.17  $\pm$  80.82 mg pot<sup>-1</sup>) (Fig. 43). Uptake of phosphorus significantly

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|   | CaSiO  |
|---|--------|
|   | DE @   |
|   | DE @   |
|   | RHB @  |
|   | RHB @  |
|   | S. Em: |
|   | LSD (j |
| 7 |        |
|   |        |

| Table 54: Effect of different sources of Si on nutrient content and uptake by rice straw in neutral soil |  |
|--|--|
|--|--|

| Treatments                                      | Si                    | Р                    | K                              | Ca                   | Mg                   |
|---|-----------------------|----------------------|--------------------------------|----------------------|----------------------|
| (With plant)                                    |                       |                      | Content (%)                    |                      |                      |
| Ck  | $4.92 \pm 0.26(b)$    | 0.16± 0.05(ab)       | $1.37 \pm 0.17(a)$             | $0.68 \pm 0.07(c)$   | 0.38± 0.17(a)        |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $7.98 \pm 0.94(a)$    | 0.14± 0.02(abc)      | 1.47±0.16(a)                   | $0.84 \pm 0.09$ (bc) | 0.16± 0.09(abc)      |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 7.45±7.45(ab)         | $0.11 \pm 0.01$ (bc) | 1.77±0.19(a)                   | $1.12 \pm 0.05(a)$   | $0.19 \pm 0.08$ (bc) |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $5.39 \pm 0.70(b)$    | $0.18 \pm 0.03(a)$   | $1.69 \pm 0.34(a)$             | $1.03 \pm 0.18(ab)$  | 0.18±0.03(abc)       |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $5.05 \pm 0.80(b)$    | 0.11± 0.05(abc)      | $1.40 \pm 0.21(a)$             | 0.99± 0.11(ab)       | 0.38± 0.22(ab)       |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $5.03 \pm 0.31(b)$    | $0.08 \pm 0.06(c)$   | $1.94 \pm 0.21(a)$             | $0.85 \pm 0.20$ (b)  | 0.26± 0.13(abc)      |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $5.13 \pm 0.45(b)$    | $0.09 \pm 0.03(c)$   | $135 \pm 0.80(a)$              | $0.94 \pm 0.16(ab)$  | $0.14 \pm 0.02(c)$   |
| S. Em±  | 0.29                  | 0.02                 | 0.17                           | 0.07                 | 0.06                 |
| LSD (p≤0.05)                                    | 0.90                  | 0.08                 | NS                             | 0.23                 | 0.22                 |
|   |                       |                      | Uptake (mg pot <sup>-1</sup> ) |                      |                      |
| Ck  | 257.34± 33.31(e)      | 8.23± 1.43(bc)       | 71.03± 5.27(b)                 | 35.97± 8.80(d)       | 18.92± 5.54(b)       |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 609.64±112.21(a)      | 10.81± 1.80(b)       | 112.30±19.33(ab)               | $63.80 \pm 5.00(bc)$ | 12.22± 7.17(b)       |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 584.17± 80.82(ab)     | $8.60 \pm 1.44$ (bc) | 138.89±28.81(a)                | 87.71± 9.99(ab)      | 14.69± 5.91(b)       |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 461.19±119.59(cd)     | $14.84 \pm 1.95(a)$  | $146.58 \pm 55.52(a)$          | 87.93± 25.14(ab)     | $15.52 \pm 4.71(b)$  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 471.27±67.15(bc)      | $10.40 \pm 3.57(b)$  | 132.15±28.07(a)                | $92.80 \pm 15.75(a)$ | $36.02 \pm 22.20(a)$ |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $301.09 \pm 23.64(e)$ | $5.00 \pm 3.40(c)$   | 115.92±11.68(ab)               | 50.79±11.42(cd)      | 15.18±7.71(b)        |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 346.18± 24.98(de)     | $6.40 \pm 1.80(c)$   | 93.87± 60.26(ab)               | 64.15±16.72(bc)      | $9.56 \pm 0.48(b)$   |
| S. Em±  | 37.71                 | 1.25                 | 17.18                          | 7.56                 | 4.37                 |
| LSD (p≤0.05)                                    | 61.02                 | 4.01                 | 59.90                          | 24.88                | 16.90                |

| Treatments                                      | Fe                             | Mn                    | Cu                       | Zn                   |  |  |  |
|---|--------------------------------|-----------------------|--------------------------|----------------------|--|--|--|
| (With plant)                                    | Content (mg kg <sup>-1</sup> ) |                       |                          |                      |  |  |  |
| Ck  | 345.67±77.30(b)                | 1073.83± 524.60(ab)   | 28.33± 2.89(a)           | 93.50± 16.97(c)      |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 446.78±316.54(ab)              | 832.78±211.21(ab)     | 20.89± 1.39(a)           | 90.78±12.71(abc)     |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 746.33± 316.29(a)              | 524.44±237.35(b)      | 23.89±13.15(a)           | 66.11± 3.86(bc)      |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $312.22 \pm 46.90(b)$          | 1529.78± 315.73(a)    | 31.11±12.85(a)           | 98.11±11.17(a)       |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 407.00± 225.84(ab)             | 1246.11±632.19(ab)    | 30.67±17.75(a)           | 84.44± 27.28(ab)     |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 304.56± 25.29(b)               | 1083.33±612.68(ab)    | $19.11 \pm 6.01(a)$      | $75.00 \pm 22.52(c)$ |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 363.89±162.36(b)               | 1513.67± 407.28(a)    | $23.22 \pm 2.78(a)$      | 85.33±13.30(abc)     |  |  |  |
| S. Em±  | 95.69                          | 236.78                | 4.65                     | 8.70                 |  |  |  |
| LSD (p≤0.05)                                    | 341.88                         | 792.31                | NS                       | 29.544               |  |  |  |
|   |                                | Uptake (mg po         | <b>t</b> <sup>-1</sup> ) |                      |  |  |  |
| Ck  | 1.80± 0.43(b)                  | 5.99± 3.70(bc)        | 0.15± 0.03(a)            | 0.50± 0.16(ab)       |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $3.51 \pm 2.72(ab)$            | $6.30 \pm 1.46$ (bc)  | $0.16 \pm 0.02(a)$       | $0.69 \pm 0.14$ (ab) |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $5.65 \pm 1.97(a)$             | $4.24 \pm 2.44(c)$    | $0.19 \pm 0.13(a)$       | $0.52 \pm 0.09$ (b)  |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $2.63 \pm 0.48$ (b)            | 13.23±4.53(a)         | $0.27 \pm 0.16(a)$       | $0.84 \pm 0.22(a)$   |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $3.89 \pm 2.404(ab)$           | 11.40± 5.15(ab)       | $0.28 \pm 0.16(a)$       | 0.78± 0.20(ab)       |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $1.82 \pm 0.10$ (b)            | $6.47 \pm 3.66(bc)$   | $0.11 \pm 0.04(a)$       | $0.45 \pm 0.14$ (ab) |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $2.45 \pm 1.05$ (b)            | $10.11 \pm 2.25(abc)$ | $0.16 \pm 0.02(a)$       | 0.57±0.08(ab)        |  |  |  |
| S. Em±  | 0.75                           | 1.87                  | 0.05                     | 0.08                 |  |  |  |
| LSD (p≤0.05)                                    | 2.75                           | 6.17                  | NS                       | 0.27                 |  |  |  |

Table 55: Effect of different sources of Si on micronutrient content and uptake by rice straw in neutral soil

increased with application of DE @ 250 kg Si ha<sup>-1</sup> (14.84  $\pm$  1.95 mg pot<sup>-1</sup>) followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (10.81  $\pm$  1.80 mg pot<sup>-1</sup>). Significantly higher K uptake was noticed with the application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (138.89  $\pm$  28.81 mg pot<sup>-1</sup>) and DE @ 250 kg Si ha<sup>-1</sup> (146.58  $\pm$  55.52 mg pot<sup>-1</sup>), 500 kg Si ha<sup>-1</sup> (132.15 $\pm$  28.07 mg pot<sup>-1</sup>). Straw Ca (92.80 $\pm$  15.75 mg pot<sup>-1</sup>) and Mg (36.02 $\pm$  22.20 mg pot<sup>-1</sup>) uptake significantly increased with application of DE @ 500 kg Si ha<sup>-1</sup>. Application of calcium silicate @ 500 kg Si ha<sup>-1</sup> significantly increased the uptake of Fe (5.65 $\pm$  1.97 mg pot<sup>-1</sup>). There was no significant effect of Si sources on straw Cu uptake between the treatments. Uptake of Mn (13.23 $\pm$  4.53 mg pot<sup>-1</sup>) and Zn (0.84 $\pm$  0.22 mg pot<sup>-1</sup>) significantly increased with the application of DE @ 250 kg Si ha<sup>-1</sup>.

There was significant difference in the nutrient content and its uptake by rice straw in alkaline soil (Table 56 and 57) with application of different sources of Si over control.

Results revealed that Si content (5.89  $\pm$  0.57 %) of rice straw significantly increased with the application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup>compared to other treatments (Fig. 41). Content of P was found to be significantly higher in straw with the application of RHB @ 250 kg Si ha<sup>-1</sup> (0.035 $\pm$  0.013 %) followed by RHB @ 500 kg Si ha<sup>-1</sup> (0.029 $\pm$ 0.0003 %). There was significantly higher K (0.43  $\pm$  0.05 %) with the application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> and was found to be on par with the control (0.39  $\pm$  0.01 %). Calcium content (0.83  $\pm$  0.02 %) of rice straw increased significantly with the application of RHB @ 500 kg Si ha<sup>-1</sup>. There was a significant decrease in the content of Mg, Mn and Cu in rice straw with application of Si sources. There was significant increase in the Fe content by the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (158.89  $\pm$  104.97 mg kg<sup>-1</sup>), whereas Zn content increased with the application of DE @ 500 kg Si ha<sup>-1</sup> (51.00  $\pm$  16.33 mg kg<sup>-1</sup>).

The uptake of Si by straw was significantly increased with the application of RHB @ 500 kg Si ha<sup>-1</sup> (35.32 ± 4.60 mg pot<sup>-1</sup>) followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (33.28 ± 5.20 mg pot<sup>-1</sup>) (Fig. 43). Uptake of P by rice straw was significantly increased with the application of RHB @ 500 kg Si ha<sup>-1</sup> (1.598 ± 0.081 mg pot<sup>-1</sup>) followed by RHB @ 250 kg Si ha<sup>-1</sup> (0.24 ± 0.119 mg pot<sup>-1</sup>) compared to other treatments. Uptake of potassium by rice straw was significantly increased with the application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (2.42 ± 0.43 mg pot<sup>-1</sup>), whereas Ca uptake increased significantly with the application of RHB @ 250 kg Si ha<sup>-1</sup> (5.00 ± 0.73 mg pot<sup>-1</sup>). Although higher uptake was observed with the application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (2.35 ± 0.07 mg pot<sup>-1</sup>) compared to other treatments there was no significant increase in the Mg uptake by rice straw. Uptake of micronutrients such as Fe, Mn and Zn by rice straw was not affected by the applied Si sources but there was a significant increase in the uptake of Cu with the application of RHB @ 250 kg Si ha<sup>-1</sup> (0.01 ± 0.002 mg pot<sup>-1</sup>).

| Treatments                                      | Si                    | Р                       | K                            | Ca                   | Mg                   |  |
|---|-----------------------|-------------------------|------------------------------|----------------------|----------------------|--|
| (With plant)                                    | Content (%)           |                         |                              |                      |                      |  |
| Ck  | $4.31 \pm 0.14(c)$    | 0.019± 0.003(cd)        | $0.39 \pm 0.01(a)$           | $0.54 \pm 0.02(e)$   | $0.46 \pm 0.02(a)$   |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $5.89 \pm 0.57(a)$    | $0.011 \pm 0.002(d)$    | $0.43 \pm 0.05(a)$           | $0.58 \pm 0.04$ (de) | $0.42 \pm 0.04$ (ab) |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 5.55±0.73(ab)         | $0.020 \pm 0.020$ (bcd) | $0.37 \pm 0.05$ (ab)         | $0.65 \pm 0.09$ (cd) | $0.35 \pm 0.09$ (bc) |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $3.72 \pm 0.16(d)$    | $0.027 \pm 0.003$ (bcd) | $0.37 \pm 0.05 (ab)$         | $0.61 \pm 0.03$ (cd) | $0.39 \pm 0.03$ (bc) |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $3.64 \pm 0.21(d)$    | $0.031 \pm 0.01$ (bc)   | $0.31 \pm 0.06(b)$           | $0.67 \pm 0.04$ (bc) | $0.33 \pm 0.04$ (cd) |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 5.21±0.17(b)          | $0.035 \pm 0.013(a)$    | $0.30 \pm 0.04(c)$           | $0.74 \pm 0.01(b)$   | $0.26 \pm 0.01(d)$   |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $4.94 \pm 0.07$ (b)   | $0.029 \pm 0.0003$ (b)  | $0.29 \pm 0.03(c)$           | $0.83 \pm 0.02(a)$   | $0.16 \pm 0.02(e)$   |  |
| S. Em±  | 0.17                  | 0.004                   | 0.02                         | 0.02                 | 0.02                 |  |
| LSD (p≤0.05)                                    | 0.61                  | 0.02                    | 0.08                         | 0.08                 | 0.08                 |  |
|   |                       | Up                      | take (mg pot <sup>-1</sup> ) |                      |                      |  |
| Ck  | 21.89± 3.36(de)       | $0.09 \pm 0.019(c)$     | 1.98± 0.30(ab)               | $2.75 \pm 0.44(d)$   | $2.32 \pm 0.35(a)$   |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 33.28± 5.20(abc)      | $0.06 \pm 0.013(c)$     | $2.42 \pm 0.43(a)$           | $3.28 \pm 0.40$ (cd) | $2.35 \pm 0.07(a)$   |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 29.22± 7.86(bcd)      | $0.09 \pm 0.076(c)$     | 2.01±0.77(ab)                | $3.36 \pm 0.51$ (cd) | $1.94 \pm 1.07(a)$   |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $22.74 \pm 4.68$ (de) | $0.17 \pm 0.039$ (bc)   | 2.29± 0.59(ab)               | $3.74 \pm 0.77$ (bc) | $2.36 \pm 0.40(a)$   |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $18.85 \pm 3.87(e)$   | $0.16 \pm 0.030$ (bc)   | $1.62 \pm 0.44(b)$           | $3.47 \pm 0.68$ (cd) | $1.71 \pm 0.42$ (ab) |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 35.32± 4.60(ab)       | 0.24± 0.119(b)          | 2.01±0.29(ab)                | $5.00 \pm 0.73(a)$   | $1.78 \pm 0.25(a)$   |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 27.03±0.95(cd)        | $1.59 \pm 0.081(a)$     | $1.56 \pm 0.13(b)$           | 4.52±0.10(ab)        | $0.88 \pm 0.06(b)$   |  |
| S. Em±  | 2.48                  | 0.03                    | 0.24                         | 0.30                 | 0.21                 |  |
| LSD (p≤0.05)                                    | 7.99                  | 0.11                    | 0.79                         | 0.97                 | 0.84                 |  |

 Table 56: Effect of different sources of Si on nutrient content and uptake by rice straw in alkaline soil

| Treatments                                      | Fe                             | Mn                   | Cu                    | Zn                   |  |  |  |
|---|--------------------------------|----------------------|-----------------------|----------------------|--|--|--|
| (With plant)                                    | Content (mg kg <sup>-1</sup> ) |                      |                       |                      |  |  |  |
| Ck  | 98.11±17.09(ab)                | 140.78±25.93(a)      | $15.33 \pm 0.94(a)$   | 35.56± 3.85(b)       |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 111.89±40.23(ab)               | 126.44± 15.28(ab)    | $14.89 \pm 0.69(a)$   | 33.89±7.38(b)        |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 158.89±104.97(a)               | 98.89± 27.32(b)      | 14.11±0.51(ab)        | 33.22± 3.75(b)       |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 88.50± 15.50(ab)               | 112.67±28.67(ab)     | 14.33±0.33(ab)        | 39.67±1.33(ab)       |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 87.33± 0.67(ab)                | 108.50± 37.83(ab)    | $14.50 \pm 0.17 (ab)$ | 51.00± 16.33(a)      |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 94.00± 7.33(ab)                | 100.67±14.33(b)      | 14.83±0.50(a)         | 39.33±2.33(ab)       |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 84.18± 1.51(b)                 | 91.50± 6.50(b)       | $13.35 \pm 1.60$ (b)  | 43.12±0.55(ab)       |  |  |  |
| S.E m±  | 15.26                          | 12.57                | 0.38                  | 2.89                 |  |  |  |
| LSD (p≤0.05)                                    | 73.49                          | 42.58                | 1.43                  | 12.14                |  |  |  |
|   |                                | Uptake (mg           | pot <sup>-1</sup> )   |                      |  |  |  |
| Ck  | $0.050 \pm 0.010(a)$           | $0.071 \pm 0.015(a)$ | 0.008± 0.001(ab)      | 0.018± 0.003(a)      |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $0.064 \pm 0.027(a)$           | $0.071 \pm 0.007(a)$ | $0.008 \pm 0.001(ab)$ | $0.019 \pm 0.005(a)$ |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $0.077 \pm 0.035(a)$           | 0.051±0.012(a)       | $0.007 \pm 0.002(b)$  | $0.017 \pm 0.005(a)$ |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $0.055 \pm 0.016(a)$           | $0.068 \pm 0.015(a)$ | $0.009 \pm 0.002(ab)$ | $0.024 \pm 0.004(a)$ |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $0.045 \pm 0.009(a)$           | $0.056 \pm 0.023(a)$ | $0.008 \pm 0.001$ (b) | $0.026 \pm 0.011(a)$ |  |  |  |
|   |                                |                      |                       |                      |  |  |  |

0.068±0.010(a)

 $0.050 \pm 0.002(a)$ 

0.007

NS

0.010±0.002(a)

 $0.007 \pm 0.001$ (b)

0.0008

0.002

 $0.027 \pm 0.003(a)$ 

 $0.024 \pm 0.001$ (a)

0.003

NS

Table 57: Effect of different sources of Si on micronutrient content and uptake by rice straw in alkaline soil

Mean value having same alphabets do not differ significantly at  $p \le 0.05$ .

 $0.064 \pm 0.008(a)$ 

 $0.046 \pm 0.003(a)$ 

0.009

NS

RHB @ 250 kg Si ha<sup>-1</sup>

RHB @ 500 kg Si ha<sup>-1</sup>

S. Em±

LSD (p≤0.05)

## 4.3.6 Effect of different sources of Si on nutrient content and uptake by rice grain in acidic and neutral soil

Data pertaining to nutrient content and uptake by rice grain in acidic and neutral soil are presented in Table 58 to 61.

There was a significant difference in the nutrient content and uptake by rice grain in acidic soil (Table 58 and 59) with application of different sources of Si over control.

Application of Si sources significantly increased the grain Si content over control in acidic soil (Fig. 42). Application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (0.92  $\pm$  0.03 %) followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (0.84  $\pm$  0.01 %) recorded significantly higher Si compared to other treatments. Phosphorus content of rice grain was found to be significantly higher with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (0.43  $\pm$  0.01 %) followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (0.41  $\pm$  0.001 %) compared to other treatments. There was a significant increase in K content with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (0.60  $\pm$  0.02 %) followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (0.58  $\pm$  0.01 %) compared to other treatments. Significantly higher Ca content in grain recorded in control  $(0.67 \pm 0.01 \%)$  followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (0.58  $\pm$  0.005 %). Magnesium content increased with application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (0.53  $\pm$  0.02 %). The content of Fe (96.54  $\pm$  0.01 mg kg<sup>-1</sup>) was significantly increased with the application of DE @ 500 kg Si ha<sup>-1</sup> whereas Mn content (166.50  $\pm$  0.50 mg kg<sup>-1</sup>) increased significantly with the application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> in rice grain. Significant increase in the Cu content was noticed with the application of RHB @ 250 (18.46  $\pm$  1.10 mg kg<sup>-1</sup>) and 500 (18.77  $\pm$  0.66 mg kg<sup>-1</sup>) kg Si ha<sup>-1</sup>. Zn content rice grain was significantly higher with application of DE @  $500 (16.55 \pm 0.31 \text{ mg kg}^{-1})$  and  $250 (15.67 \pm 0.67 \text{ mg kg}^{-1}) \text{ kg Si ha}^{-1}$ .

Perusal of the data revealed that application of calcium silicate significantly increased the nutrient uptake in rice grain. Application of calcium silicate @ 500 kg Si ha<sup>-1</sup> (19.67  $\pm$  3.72 mg pot<sup>-1</sup>) significantly increased the grain Si uptake (Fig. 44) compared to other treatments followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (15.58  $\pm$  3.31 mg pot<sup>-1</sup>). Uptake of P by rice grain was significantly higher with application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (9.09  $\pm$  1.58 mg pot<sup>-1</sup>) followed by CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (7.63  $\pm$  1.65 mg pot<sup>-1</sup>). Significantly higher grain K and Ca uptake was noticed with the application of CaSiO<sub>3</sub> @ 250 (10.69  $\pm$  2.11, 10.74  $\pm$  2.30 mg pot<sup>-1</sup> respectively) and 500 (12.35  $\pm$  1.65, 11.46  $\pm$  1.36 mg pot<sup>-1</sup> respectively) kg Si ha<sup>-1</sup>. Uptake of Mg by rice grain was significantly higher with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (11.23  $\pm$  1.34 mg pot<sup>-1</sup>) than other treatments. Micronutrients such as Fe, Mn, Cu and Zn uptake by rice grain was also found to be significantly higher with the application of both the rates of calcium silicate.

Data with regard to grain nutrient content and uptake as affected by Si sources in neutral soil are presented in Table 60 and 61.

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| Treatments                                      | Si                   | Р                    | K                              | Ca                   | Mg                    |  |  |
|---|----------------------|----------------------|--------------------------------|----------------------|-----------------------|--|--|
| (With plant)                                    |                      | Content (%)          |                                |                      |                       |  |  |
| Ck  | $0.50 \pm 0.01(e)$   | $0.34 \pm 0.01(c)$   | $0.54 \pm 0.0005(bc)$          | $0.67 \pm 0.01(a)$   | $0.33 \pm 0.005(c)$   |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $0.84 \pm 0.01$ (b)  | 0.41±0.001 (a)       | 0.58± 0.01 (a)                 | 0.58± 0.0005 (b)     | 0.41± 0.008 (b)       |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $0.92 \pm 0.03(a)$   | $0.43 \pm 0.01(a)$   | $0.60 \pm 0.02(a)$             | $0.54 \pm 0.022(c)$  | $0.53 \pm 0.02(a)$    |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $0.79 \pm 0.06 (bc)$ | $0.37 \pm 0.05$ (bc) | $0.55 \pm 0.002$ (bc)          | $0.49 \pm 0.029(d)$  | $0.41 \pm 0.13(b)$    |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $0.75 \pm 0.05(c)$   | $0.41 \pm 0.01(ab)$  | $0.55 \pm 0.002$ (b)           | $0.48 \pm 0.008(d)$  | $0.54 \pm 0.004(a)$   |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $0.59 \pm 0.02(d)$   | $0.35 \pm 0.01(c)$   | $0.54 \pm 0.006(c)$            | $0.42 \pm 0.005(e)$  | $0.40 \pm 0.002$ (bc) |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $0.62 \pm 0.03(d)$   | $0.40 \pm 0.02 (ab)$ | $0.53 \pm 0.001(c)$            | $0.43 \pm 0.001(e)$  | $0.42 \pm 0.01$ (b)   |  |  |
| S. Em±  | 0.017                | 0.008                | 0.004                          | 0.005                | 0.013                 |  |  |
| LSD (p≤0.05)                                    | 0.062                | 0.038                | 0.016                          | 0.025                | 0.078                 |  |  |
|   |                      |                      | Uptake (mg pot <sup>-1</sup> ) |                      |                       |  |  |
| Ck  | 4.95±0.12(d)         | $3.35 \pm 0.12(c)$   | $5.36 \pm 0.26(c)$             | 6.63±0.23(b)         | $3.23 \pm 0.20(d)$    |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 15.58± 3.31(b)       | 7.63± 1.65 (a)       | 10.69± 2.11 (a)                | 10.74± 2.30 (a)      | 7.61± 1.77 (b)        |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $19.68 \pm 3.72(a)$  | 9.09± 1.58(a)        | $12.35 \pm 1.65(a)$            | $11.46 \pm 1.36(a)$  | $11.23 \pm 1.34(a)$   |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $8.96 \pm 0.68(c)$   | $4.16 \pm 0.73$ (bc) | $6.11 \pm 0.19$ (bc)           | $5.48 \pm 0.49(c)$   | 4.59±1.32(cd)         |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $7.53 \pm 0.48$ (cd) | $4.07 \pm 0.10$ (bc) | $5.57 \pm 0.06(c)$             | $4.79 \pm 0.05$ (bc) | $5.40 \pm 0.08(c)$    |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $6.67 \pm 0.50$ (cd) | $4.03 \pm 0.37$ (bc) | $6.12 \pm 0.54$ (bc)           | $4.76 \pm 0.32(c)$   | $4.57 \pm 0.38$ (cd)  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $8.64 \pm 0.28(c)$   | $5.49 \pm 0.10$ (b)  | $7.39 \pm 0.19(b)$             | $5.92 \pm 0.14$ (bc) | $5.87 \pm 0.01(c)$    |  |  |
| S. Em±  | 0.75                 | 0.38                 | 0.41                           | 0.40                 | 0.42                  |  |  |
| LSD (p≤0.05)                                    | 2.95                 | 1.55                 | 1.76                           | 1.75                 | 1.67                  |  |  |

Table 58: Effect of different sources of Si on nutrient content and uptake by rice grain in acidic soil

| Treatments                                      | Fe                             | Mn                   | Cu                         | Zn                     |  |  |
|---|--------------------------------|----------------------|----------------------------|------------------------|--|--|
| (With plant)                                    |                                | Conte                | ent (mg kg <sup>-1</sup> ) |                        |  |  |
| Ck  | 86.69± 1.99(bc)                | $78.34 \pm 0.55(e)$  | $13.61 \pm 0.77(d)$        | $15.15 \pm 0.47(b)$    |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 81.71± 1.65 (c)                | 166.50± 0.50 (a)     | 17.49±0.84 (b)             | 14.96± 0.71 (b)        |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $81.66 \pm 0.66(c)$            | 151.99± 0.33(b)      | $17.43 \pm 0.10(b)$        | $13.45 \pm 0.78(b)$    |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 90.83±9.83(ab)                 | $146.28 \pm 1.05(c)$ | $15.67 \pm 0.67(c)$        | $15.67 \pm 0.67(a)$    |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $96.54 \pm 0.01(a)$            | $147.88 \pm 0.35(c)$ | $16.07 \pm 0.20(c)$        | $16.55 \pm 0.31(a)$    |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 92.45± 1.16(ab)                | $123.08 \pm 2.55(d)$ | $18.46 \pm 1.10(a)$        | $14.74 \pm 0.49(b)$    |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $96.15 \pm 0.29(a)$            | $123.54 \pm 0.99(d)$ | $18.77 \pm 0.66(a)$        | $15.41 \pm 0.82(b)$    |  |  |
| S. Em±  | 1.26                           | 0.51                 | 0.35                       | 035                    |  |  |
| LSD (p≤0.05)                                    | 6.58                           | 1.96                 | 1.23                       | 1.08                   |  |  |
|   | Uptake (mg pot <sup>-1</sup> ) |                      |                            |                        |  |  |
| Ck  | $0.09 \pm 0.002(c)$            | $0.08 \pm 0.003(c)$  | $0.013 \pm 0.001(d)$       | $0.015 \pm 0.001(c)$   |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 0.15±0.03 (ab)                 | 0.31± 0.065 (a)      | $0.032 \pm 0.007$ (a)      | $0.028 \pm 0.007$ (a)  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $0.17 \pm 0.03(a)$             | $0.32 \pm 0.051(a)$  | $0.037 \pm 0.006(a)$       | $0.028 \pm 0.003(a)$   |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $0.10 \pm 0.01(c)$             | $0.16 \pm 0.004(b)$  | $0.018 \pm 0.001$ (cd)     | $0.018 \pm 0.001$ (bc) |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $0.10 \pm 0.001(c)$            | $0.15 \pm 0.001(b)$  | $0.016 \pm 0.0003$ (cd)    | $0.017 \pm 0.004$ (bc) |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $0.11 \pm 0.01(c)$             | $0.14 \pm 0.008(b)$  | $0.021 \pm 0.002$ (bc)     | $0.017 \pm 0.002$ (bc) |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $0.13 \pm 0.04$ (b)            | $0.17 \pm 0.003(b)$  | $0.026 \pm 0.002$ (b)      | $0.021 \pm 0.001$ (b)  |  |  |
| S. Em±  | 0.007                          | 0.011                | 0.002                      | 0.001                  |  |  |
| LSD (p≤0.05)                                    | 0.025                          | 0.055                | 0.006                      | 0.005                  |  |  |

Table 59: Effect of different sources of Si on micronutrient content and uptake by rice grain in acidic soil

Application of Si sources significantly increased rice grain Si content over control in neutral soil (Fig. 42). Application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> (0.74  $\pm$  0.01 %) and 500 kg Si ha<sup>-1</sup> (0.75  $\pm$  0.02 %) recorded significantly higher Si compared to other treatments. Phosphorus content of rice grain was found to be significantly higher with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (0.47  $\pm$  0.005 %) and found to be on par with application of RHB @ 500 kg Si ha<sup>-1</sup> (0.47  $\pm$  0.04 %) and other treatments. There was no significant difference in the rice grain K content with the applied Si but found to be higher with the application of RHB @ 500 kg Si ha<sup>-1</sup> (0.55  $\pm$  0.02 %) and on par with the control (0.54  $\pm$ 0.08 %). Application of Si sources had no significant effect on the grain Ca content among the treatments. Significantly higher Mg content was noticed with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> (0.48  $\pm$  0.004 %) and was on par with the application of DE @ 500 kg Si ha<sup>-1</sup> (0.47  $\pm$  0.01 %) and control (0.42  $\pm$  0.12 %). Application of CaSiO<sub>3</sub> @ 250 (77.18  $\pm$  0.51 mg kg<sup>-1</sup>) and 500 kg Si ha<sup>-1</sup> (77.43  $\pm$  1.09 mg kg<sup>-1</sup>) significantly reduced the Fe content in rice grain, whereas other treatments were on par with each other. Mn content was found to be significantly higher with the application of RHB @ 500 kg Si ha<sup>-1</sup> (90.78  $\pm$  7.71 mg kg<sup>-1</sup>), whereas Cu content was not affected by the applied Si sources and was on par with each other. Zn content of rice grain was found to be significantly low with application of RHB @ 500 kg Si ha<sup>-1</sup> (10.67  $\pm$  1.20 mg kg<sup>-1</sup>) and it was on par with control  $(11.11 \pm 2.27 \text{ mg kg}^{-1})$  whereas, rest of the treatments recorded significantly higher Zn content.

Uptake of Si and P by rice grain was significantly increased with the application of calcium silicate @ 500 kg Si ha<sup>-1</sup> (33.25  $\pm$  0.16 and 20.80  $\pm$  0.88 mg pot<sup>-1</sup> respectively) followed by RHB and DE (Fig. 44). Significantly higher K uptake by rice grain was noticed with the application of DE @ 250 (19.88 $\pm$  0.55 mg pot<sup>-1</sup>) and RHB @ 500 (19.91 $\pm$  2.24 mg pot<sup>-1</sup>) kg Si ha<sup>-1</sup>. Higher grain uptake of Ca (26.07  $\pm$  3.75 mg pot<sup>-1</sup>) and Mg (21.27  $\pm$  0.86 mg pot<sup>-1</sup>) recorded with the calcium silicate treatment at 500 kg Si ha<sup>-1</sup>. Micronutrients such as Fe (0.34  $\pm$  0.02 mg pot<sup>-1</sup>), Mn (0.32  $\pm$  0.01 mg pot<sup>-1</sup>), Cu (0.07  $\pm$  0.004 mg pot<sup>-1</sup>) and Zn (0.08  $\pm$  0.003 mg pot<sup>-1</sup>) uptake by rice grain also increased significantly with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup>while uptake of Fe (0.31  $\pm$  0.01 mg pot<sup>-1</sup>) and Mn (0.32  $\pm$  0.0 mg pot<sup>-1</sup>) were on par with application of DE @ 500 and 250 kg Si ha<sup>-1</sup>.

Perusal of the data presented in Tables 58 to 61 revealed that higher nutrient content and uptake was noticed in neutral soil followed by acidic and alkaline soil. In acidic and neutral soil, application of calcium silicate influenced the nutrient concentration compared to other sources whereas rice husk biochar performed better in alkaline soil. The difference in effectiveness can be due to variation in reactivity of respective sources based on soil type. Although different Si sources were applied @ 250 and 500 kg Si ha<sup>-1</sup>, there was a significant difference in the nutrient content and uptake by rice among the Si sources. The performance of these materials as Si source for rice varied among the test soils.

| Treatments                                      | Si                   | Р                     | K                              | Ca                  | Mg                    |
|---|----------------------|-----------------------|--------------------------------|---------------------|-----------------------|
| (With plant)                                    | Content (%)          |                       |                                |                     |                       |
| Ck  | $0.41 \pm 0(d)$      | 0.46± 0.01(ab)        | $0.54 \pm 0.08(a)$             | $0.59 \pm 0.12(a)$  | $0.42 \pm 0.12(a)$    |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $0.74 \pm 0.01(a)$   | $0.46 \pm 0.005(ab)$  | $0.44 \pm 0.01(b)$             | $0.63 \pm 0.001(a)$ | $0.38 \pm 0.005(b)$   |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $0.75 \pm 0.02(a)$   | $0.47 \pm 0.005(a)$   | $0.43 \pm 0.01(b)$             | $0.59 \pm 0.07(a)$  | $0.48 \pm 0.004(a)$   |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $0.57 \pm 0.06(c)$   | $0.42 \pm 0.002(c)$   | $0.50 \pm 0.005 (ab)$          | $0.64 \pm 0.005(a)$ | $0.37 \pm 0.01$ (b)   |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $0.58 \pm 0.02(c)$   | 0.46± 0.01(ab)        | $0.48 \pm 0.01$ (ab)           | $0.59 \pm 0.07(a)$  | $0.47 \pm 0.01(a)$    |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $0.59 \pm 0.03$ (bc) | $0.44 \pm 0.01$ (bc)  | $0.53 \pm 0.09(a)$             | $0.72 \pm 0.08(a)$  | $0.28 \pm 0.08$ (c)   |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $0.61 \pm 0.02$ (bc) | $0.47 \pm 0.04(a)$    | $0.55 \pm 0.02(a)$             | $0.63 \pm 0.15(a)$  | $0.37 \pm 0.15(b)$    |
| S. Em±  | 0.013                | 0.006                 | 0.02                           | 0.04                | 0.03                  |
| LSD (p≤0.05)                                    | 0.05                 | 0.028                 | 0.08                           | NS                  | 0.15                  |
|   |                      |                       | Uptake (mg pot <sup>-1</sup> ) | )                   |                       |
| Ck  | $11.22 \pm 1.84(e)$  | 12.53±1.81(d)         | 15.12±4.49(bc)                 | $16.40 \pm 4.78(b)$ | 11.30± 3.48(cd)       |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $23.01 \pm 0.79(b)$  | $14.15 \pm 0.47$ (cd) | $13.73 \pm 0.54(c)$            | 19.39±0.60(ab)      | $11.70 \pm 0.40$ (cd) |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $33.25 \pm 0.16(a)$  | 20.80±0.88(a)         | 18.83± 0.87(ab)                | $26.07 \pm 3.75(a)$ | 21.27±0.86(a)         |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $22.49 \pm 1.80(b)$  | $16.61 \pm 0.40(b)$   | $19.88 \pm 0.55(a)$            | $25.46 \pm 0.66(a)$ | $14.63 \pm 0.51$ (bc) |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $19.52 \pm 0.86(c)$  | $15.42 \pm 0.68$ (bc) | 16.19±0.71(abc)                | 19.90±1.95(ab)      | $15.92 \pm 0.89$ (b)  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $16.61 \pm 0.83(d)$  | $12.27 \pm 0.71(d)$   | $14.64 \pm 1.89(c)$            | 20.11±2.81(ab)      | $7.69 \pm 1.85(d)$    |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $21.98 \pm 1.92(b)$  | $16.86 \pm 1.31(b)$   | $19.91 \pm 2.24(a)$            | 23.22± 8.19(a)      | 12.76± 4.39(bc)       |
| S. Em±  | 0.66                 | 0.50                  | 0.88                           | 1.82                | 0.98                  |
| LSD (p≤0.05)                                    | 2.17                 | 1.88                  | 3.05                           | 6.19                | 4.16                  |

Table 60: Effect of different sources of Si on nutrient content and uptake by rice grain in neutral soil

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 Table 61: Effect of different sources of Si on micronutrient content and uptake by rice grain in neutral soil

| Treatments                                      | Fe                             | Mn                   | Cu                          | Zn                     |  |  |
|---|--------------------------------|----------------------|-----------------------------|------------------------|--|--|
| (With plant)                                    | Content (mg kg <sup>-1</sup> ) |                      |                             |                        |  |  |
| Ck  | 86.56± 2.88(a)                 | $49.33 \pm 6.06(c)$  | 17.11±1.37(a)               | 11.11±2.27(b)          |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $77.18 \pm 0.51(b)$            | $70.78 \pm 0.45(b)$  | $17.49 \pm 0.16(a)$         | $18.10 \pm 0.57(a)$    |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $77.43 \pm 1.09(b)$            | $71.62 \pm 0.95$ (b) | $17.60 \pm 0.27(a)$         | $17.99 \pm 0.01(a)$    |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $84.97 \pm 0.30(a)$            | 80.93± 1.60(ab)      | $16.93 \pm 0.60(a)$         | $17.93 \pm 0.60(a)$    |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $90.93 \pm 0.60(a)$            | $70.47 \pm 4.80(b)$  | $16.45 \pm 0.45(a)$         | $16.10 \pm 0.43(a)$    |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $86.22 \pm 6.26(a)$            | 75.78± 1.67(ab)      | $16.22 \pm 1.39(a)$         | $18.22 \pm 7.32(a)$    |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $89.44 \pm 6.71(a)$            | $90.78 \pm 7.71(a)$  | $17.89 \pm 1.54(a)$         | 10.67±1.20(b)          |  |  |
| S. Em±  | 1.48                           | 3.88                 | 0.46                        | 1.00                   |  |  |
| LSD (p≤0.05)                                    | 6.31                           | 12.35                | NS                          | 4.07                   |  |  |
|   |                                | Upta                 | ake (mg pot <sup>-1</sup> ) |                        |  |  |
| Ck  | $0.24 \pm 0.03(c)$             | $0.13 \pm 0.03(c)$   | 0.047±0.010(d)              | 0.030±0.009(e)         |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $0.24 \pm 0.01(c)$             | $0.22 \pm 0.01$ (b)  | 0.054±0.002(cd)             | $0.056 \pm 0.002$ (bc) |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $0.34 \pm 0.02(a)$             | $0.32 \pm 0.01(a)$   | $0.078 \pm 0.004(a)$        | $0.080 \pm 0.003(a)$   |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $0.34 \pm 0.01$ (ab)           | $0.32 \pm 0.01(a)$   | $0.067 \pm 0.004(ab)$       | $0.071 \pm 0.004(ab)$  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $0.31 \pm 0.01(a)$             | $0.24 \pm 0.01(b)$   | $0.056 \pm 0.002$ (bcd)     | $0.054 \pm 0.002(c)$   |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $0.24 \pm 0.02(c)$             | $0.21 \pm 0.07(b)$   | $0.045 \pm 0.005(d)$        | $0.051 \pm 0.022$ (cd) |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $0.32 \pm 0.02$ (ab)           | $0.33 \pm 0.04(a)$   | 0.065±0.013(bc)             | 0.038±0.001(de)        |  |  |
| S. Em±  | 0.009                          | 0.015                | 0.003                       | 0.003                  |  |  |
| LSD (p≤0.05)                                    | 0.033                          | 0.055                | 0.012                       | 0.017                  |  |  |

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Fig. 41: Effect of different sources of silicon on straw Si content of rice crop grown in acidic, neutral and alkaline soils



Fig. 42: Effect of different sources of silicon on grain Si content of rice crop grown in acidic and neutral soils



Fig. 43: Effect of different sources of silicon on straw Si uptake of rice crop grown in acidic, neutral and alkaline soils



Fig. 44: Effect of different sources of silicon on grain Si uptake of rice crop grown in acidic and neutral soils

Application of calcium silicate recorded higher concentration of Si in rice plants compared to control particularly in acidic and neutral soil. This result corroborates with the findings of Tavakkoli et al. (2011) who reported that Si uptake in rice was highest in acidic to neutral soil. The uptake of Si by plant significantly increased by around 60 per cent at the higher level of Si application as wollastonite @ 800 kg ha<sup>-1</sup> than 200 kg ha<sup>-1</sup>. Similar work was attributed by Sahu (1990) who reported that significant increase in Si uptake by rice plant due to the application of rice hull as a source of Si. Deren et al. (1994) noticed increased Si concentration in plant tissue with increasing rate of Si fertilization. Similar results were also reported by Winslow (1992) and Winslow et al. (1997) in South America. The presence of Si in nutrient solutions has also been reported to affect the absorption and translocation of several macro- and micro-nutrients (Epstein, 1999). The application of calcium silicate recorded higher concentration of Si in rice plants compared to control. Rice is a typical Si-accumulating plant and Si can make up to 10 per cent of the shoot dry weight, which is several fold higher than those of essential macronutrients such as N, P and K (Ma and Takahashi, 2002). These results are in agreement with the findings of Singh and Singh (2005) and Singh et al. (2006) in India and Ma et al. (1989) in Japan, Munir et al. (2003) in Brazil and Idris et al. (1975) in Bangladesh. Korndorfer and Gascho (1999) reported that both soil and plant parameters were significantly affected by the Si sources.

Significant increase in the content of P in rice straw and grain with the application of Si materials may be attributed to increased availability of P from native soil and dissolution of fixed Pinto soil available pool as facilitated by the applied Si materials and thereby better uptake of P content in straw and grain. Kumar (2008) reported highest available P with the application of calcium silicate @2t ha<sup>-1</sup> along with 100 kg N ha<sup>-1</sup> (RDF) in aerobic rice. The results also revealed decrease in P adsorption by the application of calcium silicate as Si source due to corresponding increase in soil pH. Savant et al. (1997) noticed positive interaction between Si as CaSiO<sub>3</sub> and other nutrients in rice for higher content of Si and P and its uptake in rice straw as well as grain yield. Zhang et al. (1996) noticed increase in uptake of NPK by rice with the application of silicate material. Ma and Takahashi (1990) noticed significant increase in shoot dry weight with increased application of P when Si was applied suggesting Si application raised the optimum P level in rice. Mona (2010) reported that the concentrations of P, K, Ca and Mg increased with DE application than non-treated Faba bean plants. These findings are also in agreement with Islam and Saha (1969), Talashilkar and Chavan (1956) and Inanaga et al. (2002).

In general, the content and uptake of K in rice straw and grain was significantly higher in acidic and neutral soil as compared to alkaline soil may be due to beneficial effect of dissolution of Si from applied Si material, which might have facilitated the release of K content in soil and thereby better uptake of K in straw and grain. It has been reported that most of the absorbed K accumulates in shoot and a little proportion is transferred to rice grains (Fageria *et al.*, 2011). From the absorbed K, 76 to 86 per cent found in shoot and 11 to 21 per cent in grains, depending on the cultivar (Fageria *et al.*, 1991). Soratto *et al.* (2012) also found that the foliar application of Si as calcium silicate increased K concentration in the wheat flag leaves. Application of 9.6 Mg ha<sup>-1</sup> of calcium

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silicate increased the K and Ca concentrations in the wheat flag leaves by 29 and 38 per cent, respectively as compared to control (Soratto *et al.*, 2012). Rocha *et al.* (2011) reported that the residual effect of silicate tends to enhance the K concentration in sorghum leaves.

Content of Ca in rice straw and grain was higher with the application of calcium silicate material in the soils as compared to control but higher content of Ca was recorded in alkaline soil compared to acidic and neutral soil. This may be due to the presence of high exchangeable Ca content in alkaline soil than acidic and neutral soil besides alkaline nature of applied material and thereby recorded higher Ca content in straw as well as grain compared to control. Ashique (2014) reported that application of wollastonite significantly increased Ca content in rice straw and thereby higher uptake. Similarly, Sharma *et al.* (1991) noticed higher Ca content and uptake of soybean plant with the application of 40 kg  $P_2O_5$  ha<sup>-1</sup> as superphosphate with the application of potassium or calcium silicate in alluvial soils.

Higher content of Mg in rice straw and grain in alkaline soil as compared to acidic and neutral soil may be due to the presence of high exchangeable Mg content in alkaline soil and alkalinity nature of applied Si materials. According to Korndorfer and Gascho (1999), addition of silicate as source of Ca and Mg were also good source of Si and beneficial for growth and development of plant from physiological and metabolic point of view.

In general, there was a significant increase in content of all micronutrients in rice straw in both acidic and alkaline soil with the application of different Si materials. Hai-Hong *et al.* (2012) noticed a significant increase in Zn concentration in shoots with the application of 0.5 mM Si to rice seedling but reduced the Zn content with the higher concentration of Si. There was a significant increase in Fe and Mn content in rice straw and grain with the application of different Si source. According to Okuda and Takahashi (1962), Si may provide better nutritional balance in the rice plant due to its ability to reduce the absorption and balance of Mn. Raij and Camargo (1973) reported that calcium silicate provided better balance in the absorption of Mn by grain while maintaining the appropriate concentration range (25 to 150 mg kg<sup>-1</sup>).

#### 4.3.7 Effect of Si sources on nutrient status of soil after the experiment

The pot experiment was conducted using different Si sources in the presence or absence of crop up to 120 days in acidic, neutral and alkaline soil. The nutrient status of soil as influenced by the Si sources was recorded after completion of the experiment and data are presented in Table 62 to 70.

Nutritional status of the acidic soil after the experiment varied significantly among the treatments (Table 62, 63 and 64) with or without plant. In general, there was a decrease in the nutrient content in the presence of crop. Most of the nutrients were significantly increased by the application of calcium silicate followed by DE and RHB applied at higher rate of Si.

| Trantmonts                                      | nU                   | <b>E.</b> C.                 | CCSi                   | AASi                  | P <sub>2</sub> O <sub>5</sub> | K <sub>2</sub> O     |
|---|----------------------|------------------------------|------------------------|-----------------------|-------------------------------|----------------------|
| Treatments                                      | pm                   | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) |                       | (kg ha <sup>-1</sup> )        |                      |
| Ck - Without plant                              | $5.89 \pm 0.11(d)$   | $0.19 \pm 0.01$ (cdef)       | 31.85± 2.93(cd)        | 76.71± 5.49(def)      | $15.83 \pm 4.87(b)$           | 317.52± 127.28(a)    |
| Ck – With plant                                 | $6.15 \pm 0.09$ (cd) | 0.17±0.03(ef)                | 28.32± 3.83(cdef)      | $62.84 \pm 2.58(f)$   | 11.99± 4.64(b)                | $203.28 \pm 8.46(c)$ |
| Without plant                                   |                      |                              |                        |                       |                               |                      |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $6.51 \pm 0.05$ (bc) | $0.20 \pm 0.07$ (bcdef)      | 28.16± 0.86(cdef)      | $105.25 \pm 5.48(b)$  | $12.43 \pm 0.54(b)$           | 260.06± 4.75(abc)    |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $7.01 \pm 0.08(a)$   | $0.27 \pm 0.01(a)$           | 26.72± 0.28(defg)      | $104.00 \pm 5.13(a)$  | 17.44± 1.81(b)                | 267.45± 1.90(abc)    |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $6.02 \pm 0.20(d)$   | $0.231 \pm 0.01$ (abcd)      | 33.64± 1.29(bc)        | 78.18± 5.39(def)      | $14.49 \pm 0.54(b)$           | 265.44± 10.45(abc)   |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $5.95 \pm 0.07(d)$   | 0.19± 0.01(cdef)             | 33.841± 1.77(bc)       | 84.62±13.44(cdef)     | $17.44 \pm 5.44(b)$           | 265.44± 4.75(abc)    |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $6.00 \pm 0.01(d)$   | 0.22± 0.01(abcde)            | 38.17± 1.49(ab)        | 79.62± 2.83(cdef)     | 18.98± 5.44(ab)               | 278.88± 2.85(abc)    |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $5.92 \pm 0.01(d)$   | $0.18 \pm 0.00(def)$         | 40.79± 0.21(a)         | 95.06±27.31(bcd)      | 16.28± 6.71(b)                | 288.96± 3.80(ab)     |
| With plant                                      |                      |                              |                        |                       |                               |                      |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 6.82±0.19(ab)        | 0.17±0.01(ef)                | 21.81± 4.89(g)         | 98.37±16.48(bc)       | 16.41± 4.00(b)                | 216.83±15.75(bc)     |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 7.12±0.19(a)         | $0.26 \pm 0.01(a)$           | 25.16± 2.46(fg)        | $150.00 \pm 20.14(a)$ | 16.15±2.10(b)                 | 242.81±14.37(bc)     |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $6.25 \pm 0.04$ (cd) | $0.15 \pm 0.01(f)$           | 26.32± 2.74(efg)       | $62.45 \pm 2.70(f)$   | 17.18± 3.33(b)                | 205.63±22.97(bc)     |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $6.14 \pm 0.13$ (cd) | 0.20± 0.03(bcdef)            | 28.01± 2.67(cdef)      | 72.41±11.81(ef)       | 27.70±13.01(a)                | 218.62±17.02(bc)     |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $5.89 \pm 0.70(d)$   | $0.24 \pm 0.02$ (abc)        | 31.67± 5.39(cde)       | 78.66± 4.27(cdef)     | 17.86± 82.67(ab)              | 242.81±13.52(bc)     |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $6.14 \pm 0.05$ (cd) | 0.19±0.02(cdef)              | 30.70± 2.26(cde)       | 71.45± 13.57(ef)      | 21.20± 8.97(ab)               | 227.58± 17.54(bc)    |
| S. Em±  | 0.08                 | 0.007                        | 1.38                   | 6.14                  | 2.79                          | 10.46                |
| LSD (p≤0.05)                                    | 0.39                 | 0.03                         | 5.73                   | 19.28                 | 9.288                         | 78.79                |

### Table 62: Effect of different sources of Si on nutrient status of the acidic soil

| Table 63: Effect of differen | t sources of Si on | exchangeable cati | ion status of acidic soil |
|------------------------------|--------------------|-------------------|---------------------------|
|                              |                    |                   |                           |

| Treatments                                      | Ca   | Mg                   | Na                    |  |  |  |  |
|---|--|----------------------|-----------------------|--|--|--|--|
| Treatments                                      | (cmol (p <sup>+</sup> ) kg <sup>-1</sup> ) |                      |                       |  |  |  |  |
| Ck - Without plant                              | $3.35 \pm 0.92$ (bc)                       | 1.54± 0.77(b)        | 0.31±0.04(c)          |  |  |  |  |
| Ck – With plant                                 | $2.89 \pm 0.06(c)$                         | $3.29 \pm 1.38(a)$   | $0.33 \pm 0.06$ (bc)  |  |  |  |  |
| Without plant                                   |  |                      |                       |  |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 3.59± 0.07(ab)                             | $3.04 \pm 0.34(a)$   | $0.43 \pm 0.01(a)$    |  |  |  |  |
| CaSiO3 @ 500 kg Si ha <sup>-1</sup>             | $4.02 \pm 0.20(a)$                         | $2.12 \pm 1.10$ (ab) | $0.37 \pm 0.04$ (abc) |  |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $3.13 \pm 0.27$ (bc)                       | $2.09 \pm 0.41$ (ab) | $0.35 \pm 0.03$ (abc) |  |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $2.83 \pm 0.02(c)$                         | $2.46 \pm 0.14$ (ab) | $0.30 \pm 0.02$ (c)   |  |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $2.78 \pm 0.04(c)$                         | $2.26 \pm 0.02$ (ab) | $0.36 \pm 0.05 (abc)$ |  |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $2.83 \pm 0.06(c)$                         | $2.93 \pm 0.43(a)$   | $0.31 \pm 0.04(c)$    |  |  |  |  |
| With plant                                      |  |                      |                       |  |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $3.38 \pm 0.05$ (bc)                       | $3.25 \pm 0.91(a)$   | $0.32 \pm 0.04$ (bc)  |  |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $4.14 \pm 0.25(a)$                         | $2.88 \pm 1.36(a)$   | $0.32 \pm 0.04$ (c)   |  |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $2.87 \pm 0.08(c)$                         | $2.74 \pm 0.40$ (ab) | 0.35±0.03(bc)         |  |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $2.87 \pm 0.21(c)$                         | $3.26 \pm 0.94(a)$   | $0.36 \pm 0.06 (abc)$ |  |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $2.99 \pm 0.06$ (bc)                       | $3.28 \pm 0.37(a)$   | $0.37 \pm 0.02$ (abc) |  |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $3.11 \pm 0.06$ (bc)                       | $3.55 \pm 0.36(a)$   | $0.37 \pm 0.03$ (abc) |  |  |  |  |
| S.Em±   | 0.10                                       | 0.38                 | 0.02                  |  |  |  |  |
| LSD (p≤0.05)                                    | 0.59                                       | 1.44                 | 0.07                  |  |  |  |  |

| Treatmonte                                      | Fe                      | Mn                     | Cu                    | Zn                   |
|---|-------------------------|------------------------|-----------------------|----------------------|
| I reatments                                     |                         | (mg kg <sup>-1</sup> ) |                       |                      |
| Ck - Without plant                              | 59.10± 5.81(abc)        | 48.63± 6.76(ab)        | $2.28 \pm 0.22$ (bcd) | 1.23±0.12(ab)        |
| Ck – With plant                                 | $48.76 \pm 6.54$ (cd)   | 45.154±9.71(abc)       | $2.15 \pm 0.06$ (de)  | $1.22 \pm 0.09 (ab)$ |
| Without plant                                   |                         |                        |                       |                      |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 45.87± 3.10(cd)         | $28.07 \pm 0.38$ (cd)  | $2.03 \pm 0.01(e)$    | $1.21 \pm 0.11(b)$   |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $43.29 \pm 8.64(d)$     | $19.06 \pm 2.27(d)$    | $2.05 \pm 0.10(e)$    | $1.24 \pm 0.01$ (ab) |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 57.59±1.56(abcd)        | 51.38±9.51(ab)         | $2.44 \pm 0.21$ (abc) | $1.34 \pm 0.11$ (ab) |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 61.26± 1.34(abc)        | 49.12±4.36(ab)         | $2.49 \pm 0.07 (abc)$ | $1.32 \pm 0.10$ (ab) |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $62.06 \pm 2.16$ (abc)  | 43.44±1.41(abc)        | $2.51 \pm 0.05$ (ab)  | $1.44 \pm 0.13$ (ab) |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 72.96±12.19(a)          | 54.06±0.98(ab)         | $2.70 \pm 0.00(a)$    | $1.43 \pm 0.06(ab)$  |
| With plant                                      |                         |                        |                       |                      |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 50.80±10.86(bcd)        | 39.57±15.90(abc)       | $2.23 \pm 0.09$ (cde) | $1.32 \pm 0.16$ (ab) |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $50.76 \pm 3.43$ (bcd)  | $36.75 \pm 16.56(bcd)$ | $2.35 \pm 0.09$ (bcd) | $1.21 \pm 0.05(b)$   |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $47.65 \pm 6.30$ (cd)   | $54.50 \pm 16.22(a)$   | $2.39 \pm 0.05$ (bc)  | $1.43 \pm 0.26(ab)$  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $52.16 \pm 15.84$ (bcd) | 45.08± 8.22(abc)       | $2.38 \pm 0.32$ (bc)  | $1.53 \pm 0.29(a)$   |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $63.02 \pm 3.29$ (ab)   | 47.53±13.77(ab)        | $2.45 \pm 0.15$ (abc) | $1.36 \pm 0.10$ (ab) |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 50.88± 12.20(bcd)       | $38.62 \pm 4.70(abc)$  | $2.35 \pm 0.09$ (bcd) | $1.52 \pm 0.40$ (ab) |
| S. Em±  | 4.05                    | 4.65                   | 0.06                  | 0.09                 |
| LSD (p≤0.05)                                    | 14.07                   | 15.68                  | 0.25                  | 0.31                 |

Table 64: Effect of different sources of Si on micronutrient status of acidic soil

There was a significant increase in soil pH and EC with application of calcium silicate @ 500 kg Si ha<sup>-1</sup> maintained without plant (7.01  $\pm$  0.08, 0.27  $\pm$  0.01 dSm<sup>-1</sup> respectively) or with plant (7.12  $\pm$  0.19, 0.26  $\pm$  0.01 dSm<sup>-1</sup> respectively) compared to other treatments. In general, Si extracted by acetic acid (AASi) and calcium chloride (CCSi) significantly decreased in the presence of crop. CCSi content was significantly higher with the application of RHB @ 500 kg Si ha<sup>-1</sup> maintained without plant (40.79 ± 0.21 mg kg<sup>-1</sup>) followed by DE applied at both rates. AASi content was significantly higher with application of calcium silicate and was on par between without plant (104.00  $\pm$  5.13 mg kg<sup>-1</sup>) and with plant (150.00 $\pm$  20.14 mg kg<sup>-1</sup>). The concentration of available  $P_2O_5$  was higher with application of DE @ 500 kg Si ha<sup>-1</sup> maintained with plant (27.70 ± 13.01 kg ha<sup>-1</sup>) compared to other treatments. Available  $K_2O$  was found to be significantly high in control where crop was not grown  $(317.52 \pm 127.28 \text{ kg ha}^{-1})$  whereas applied Si had no significant effect on the status of the available K<sub>2</sub>O in the soil. Calcium silicate applied treatments recorded significantly higher Ca (4.14  $\pm$  0.25 cmol (p+) kg<sup>-1</sup>), Mg  $(2.88 \pm 1.36 \text{ cmol } (p+) \text{ kg}^{-1})$  and Na  $(0.43 \pm 0.01 \text{ cmol } (p+) \text{ kg}^{-1})$  content in soil either with or without crop. There was a significant increase in the DTPA extractable micronutrients such as Fe with application of RHB @ 500 kg Si ha<sup>-1</sup> maintained without plant (72.96  $\pm$  12.19 mg kg<sup>-1</sup>); Mn with application of DE @ 250 kg Si ha<sup>-1</sup> maintained with plant (54.50  $\pm$  16.22 mg kg<sup>-1</sup>); Cu with application of RHB @ 500 kg Si ha<sup>-1</sup> maintained without plant  $(2.70 \pm 0 \text{ mg kg}^{-1})$  and Zn with application of DE @ 500 kg Si ha<sup>-1</sup> maintained with plant  $(1.53 \pm 0.29 \text{ mg kg}^{-1})$  compared to other treatments.

Perusal of data presented in Tables 65, 66 and 67 revealed that nutritional status of the soil varied greatly with the application of different Si sources in neutral soil. There was significant increase in the soil pH (7.81  $\pm$  0.15) and EC (0.27  $\pm$  0.04 dSm<sup>-1</sup>) with the application of calcium silicate @ 500 kg Si ha<sup>-1</sup> maintained with crop. The content of CCSi in soil increased significantly with the application of DE @ 500 kg Si ha<sup>-1</sup> (51.88  $\pm$ 3.03 mg kg^-1), RHB @ 250 (53.00  $\pm$  0.60 mg kg^-1) and 500 kg Si ha^-1 (51.57  $\pm$  2.43 mg kg<sup>-1</sup>) maintained without plant and RHB @ 500 kg Si ha<sup>-1</sup> (51.27  $\pm$  10.64 mg kg<sup>-1</sup>) maintained with plant but was on par with each other. Acetic acid extractable Si content increased significantly with the application of calcium silicate applied @ 500 kg Si ha<sup>-1</sup> maintained with  $(139.25 \pm 4.84 \text{ mg kg}^{-1})$  and without crop  $(133.00 \pm 0.35 \text{ mg kg}^{-1})$  and was on par with each other. The available P<sub>2</sub>O<sub>5</sub>content recorded significantly higher on application of RHB @ 500 kg Si ha<sup>-1</sup> maintained with plant (379.07  $\pm$  1.45 kg ha<sup>-1</sup>) compared to other treatments. Available K<sub>2</sub>O was significantly higher in control (542.30  $\pm$  13.77 kg ha<sup>-1</sup>) where crop was not grown whereas applied Si did not affect the status of available K<sub>2</sub>O in the soil rather decreased with or without crop. Calcium silicate applied treatments recorded significantly higher Ca with  $(5.28 \pm 0.48 \text{ cmol } (p+) \text{ kg}^{-1})$  or without crop (5.18  $\pm$  0.43 cmol (p+) kg<sup>-1</sup>). The content of Mg and Na was found significantly higher with the application of DE @ 500 kg Si ha<sup>-1</sup> (3.31  $\pm$  0.22, 0.46  $\pm$  0.04 cmol (p+) kg<sup>-1</sup> respectively). Soil Fe and Mn content were found to be significantly higher in control (163.80  $\pm$  5.18, 10.61  $\pm$  1.28 mg kg<sup>-1</sup> respectively) compared to other treatments.

| Treatments                                      | ъЦ                  | <b>E. C.</b>                 | CCSi                  | AASi                   | P <sub>2</sub> O <sub>5</sub> | K <sub>2</sub> O         |
|---|---------------------|------------------------------|-----------------------|------------------------|-------------------------------|--------------------------|
|   | рп                  | ( <b>dSm</b> <sup>-1</sup> ) | (mg k                 | g <sup>-1</sup> )      | (kg                           | ha <sup>-1</sup> )       |
| Ck - Without plant                              | $6.68 \pm 0.07(d)$  | $0.24 \pm 0.04$ (ab)         | 49 90+ 0 78(ab)       | 81 46+ 2 27(ef)        | 334.06+15.57(cde)             | 542 30 + 13 77(a)        |
| Ck – With plant                                 | $6.98 \pm 0.12$ (c) | $0.21 \pm 0.02$ (bcd)        | $42.33 \pm 4.66$ (cd) | $80.34 \pm 5.02(f)$    | $334.83 \pm 8.60$ (cde)       | $483.50 \pm 38.77$ (cde) |
| Without plant                                   |                     |                              |                       |                        |                               |                          |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $7.34 \pm 0.01$ (b) | $0.22 \pm 0.04$ (bcd)        | 45.84± 1.86(abcd)     | 112.00± 0.88(b)        | 342.40±11.61(bcde)            | 530.20± 12.35(ab)        |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 7.73±0.13(a)        | 0.23± 0.01(ab)               | 43.52± 3.41(abcd)     | $133.00 \pm 0.35(a)$   | 359.58± 3.63(abcd)            | 528.19± 1.90(ab)         |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $6.75 \pm 0.17(d)$  | $0.17 \pm 0.00(d)$           | 49.81±1.96(abc)       | $87.25 \pm 4.60$ (cde) | 347.01± 17.41(abcde)          | 528.19±11.40(ab)         |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $6.68 \pm 0.10(d)$  | $0.17 \pm 0.02$ (cd)         | $51.88 \pm 3.03(a)$   | 88.06± 0.62(cde)       | 356.89± 35.73(abcde)          | 518.78±11.40(abc)        |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $6.70 \pm 0.14(d)$  | $0.22 \pm 0.02$ (bc)         | $53.00 \pm 0.60(a)$   | 88.75± 5.66(cd)        | 348.17±24.12(abcde)           | 533.56± 1.90(ab)         |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $6.66 \pm 0.02(d)$  | $0.25 \pm 0.05 (ab)$         | $51.57 \pm 2.43(a)$   | 84.43± 1.15(def)       | $379.07 \pm 1.45(a)$          | 525.50± 0.00(ab)         |
| With plant                                      |                     |                              |                       |                        |                               |                          |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $7.49 \pm 0.05$ (b) | $0.24 \pm 0.02$ (ab)         | 37.74±2.38(d)         | 108.70± 3.13(b)        | 343.34±15.69(bcde)            | 496.38± 35.72(bcde)      |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $7.81 \pm 0.15(a)$  | $0.27 \pm 0.04(a)$           | $37.98 \pm 1.56(d)$   | $139.25 \pm 4.84(a)$   | 342.40± 30.13(bcde)           | 469.95±21.73(de)         |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $7.07 \pm 0.07(c)$  | $0.22 \pm 0.02$ (b)          | 43.03±7.69(bcd)       | 87.16± 2.67(cde)       | 342.48± 8.89(bcde)            | 479.36± 17.54(cde)       |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $7.08 \pm 0.03(c)$  | $0.20 \pm 0.02$ (bcd)        | $41.27 \pm 4.62$ (cd) | 91.45± 8.45(cd)        | 354.28±31.53(abcde)           | 470.40± 21.12(de)        |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $6.98 \pm 0.05(c)$  | $0.23 \pm 0.02$ (ab)         | $41.93 \pm 2.64$ (cd) | 91.54± 2.77(cd)        | 364.80± 14.46(abc)            | 499.52±11.27(bcd)        |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $7.03 \pm 0.07(c)$  | $0.21 \pm 0.01$ (bcd)        | 51.27±10.64(a)        | $92.20 \pm 2.31(c)$    | 324.36± 15.31(de)             | 474.88± 21.52(de)        |
| S. Em±  | 0.05                | 0.01                         | 2.08                  | 1.93                   | 10.39                         | 9.16                     |
| LSD (p≤0.05)                                    | 0.16                | 0.05                         | 8.21                  | 6.96                   | 32.38                         | 30.12                    |

#### Table 65: Effect of different sources of Si on nutrient status of neutral soil

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|--|---------------------|---------------------|----------|--------------|---------------|-----------------|
|--|---------------------|---------------------|----------|--------------|---------------|-----------------|

| Tucotmonto                                      | Ca                    | Mg   | Na                     |  |  |  |  |  |
|---|-----------------------|--|------------------------|--|--|--|--|--|
| 1 reatments                                     |                       | (cmol (p <sup>+</sup> ) kg <sup>-1</sup> ) |                        |  |  |  |  |  |
| Ck - Without plant                              | $4.39 \pm 0.08$ (cd)  | 2.68± 0.27(bc)                             | $0.38 \pm 0.05$ (cde)  |  |  |  |  |  |
| Ck – With plant                                 | $4.40 \pm 0.18$ (cd)  | $2.59 \pm 0.52$ (bc)                       | $0.42 \pm 0.01$ (abc)  |  |  |  |  |  |
| Without plant                                   |                       |  |                        |  |  |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 4.97± 0.02(ab)        | $2.89 \pm 0.42$ (abc)                      | $0.33 \pm 0.08$ (def)  |  |  |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $5.18 \pm 0.43(a)$    | $3.14 \pm 0.62 (ab)$                       | $0.33 \pm 0.00$ (def)  |  |  |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $4.33 \pm 0.01$ (cd)  | $2.89 \pm 0.25$ (abc)                      | $0.32 \pm 0.02$ (ef)   |  |  |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $4.24 \pm 0.06$ (cd)  | $2.55 \pm 0.02$ (bc)                       | $0.29 \pm 0.01(f)$     |  |  |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $4.18 \pm 0.13$ (cd)  | $2.62 \pm 0.23$ (bc)                       | $0.33 \pm 0.01$ (def)  |  |  |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $4.52 \pm 0.00$ (bcd) | $1.77 \pm 0.00(d)$                         | $0.32 \pm 0.00(ef)$    |  |  |  |  |  |
| With plant                                      |                       |  |                        |  |  |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 4.87± 0.38(ab)        | $2.43 \pm 0.23(c)$                         | $0.39 \pm 0.02$ (bcd)  |  |  |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $5.28 \pm 0.48(a)$    | $2.95 \pm 0.31$ (abc)                      | $0.39 \pm 0.01$ (bcd)  |  |  |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $4.58 \pm 0.09$ (bcd) | $2.80 \pm 0.27$ (abc)                      | $0.43 \pm 0.06 (ab)$   |  |  |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $4.39 \pm 0.08$ (cd)  | $3.31 \pm 0.22(a)$                         | $0.46 \pm 0.04(a)$     |  |  |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $4.38 \pm 0.05$ (cd)  | $3.04 \pm 0.31(ab)$                        | $0.38 \pm 0.01$ (bcde) |  |  |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $4.64 \pm 0.17$ (bc)  | $2.70 \pm 0.53$ (bc)                       | $0.41 \pm 0.04$ (abc)  |  |  |  |  |  |
| S. Em±  | 0.09                  | 0.18                                       | 0.02                   |  |  |  |  |  |
| LSD (p≤0.05)                                    | 0.32                  | 0.60                                       | 0.06                   |  |  |  |  |  |

| Treatmonte                                      | Fe                      | Mn                     | Cu                   | Zn                    |  |  |  |
|---|-------------------------|------------------------|----------------------|-----------------------|--|--|--|
| Treatments                                      | (mg kg <sup>-1</sup> )  |                        |                      |                       |  |  |  |
| Ck - Without plant                              | $163.80 \pm 5.18(a)$    | 10.61± 1.28(a)         | 2.68± 0.23(ab)       | 4.39 ±0.23(a)         |  |  |  |
| Ck – With plant                                 | $137.05 \pm 7.34(fg)$   | $7.66 \pm 0.18(defg)$  | 2.59± 0.11(ab)       | $4.33 \pm 0.43(a)$    |  |  |  |
| Without plant                                   |                         |                        |                      |                       |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 124.85± 7.42(hi)        | $7.43 \pm 0.23$ (defg) | $2.55 \pm 0.06(ab)$  | $3.74 \pm 0.01$ (bc)  |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 118.00± 3.11(ij)        | $7.10 \pm 0.40(efg)$   | 2.77±0.10(ab)        | $3.62 \pm 0.27(c)$    |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $157.40 \pm 3.11(abc)$  | 9.27±1.02(abc)         | 2.61±0.18(ab)        | $4.08 \pm 0.01$ (abc) |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $156.05 \pm 0.35(abc)$  | 8.91±1.04(abc)         | 2.70± 0.03(ab)       | $3.96 \pm 0.04$ (abc) |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 159.90± 0.57(ab)        | $10.12 \pm 1.47(ab)$   | 2.80± 0.11(ab)       | $4.32 \pm 0.23$ (ab)  |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 158.15±11.38(abc)       | $8.49 \pm 0.42$ (bcde) | 2.67± 0.06(ab)       | $4.32 \pm 0.05 (ab)$  |  |  |  |
| With plant                                      |                         |                        |                      |                       |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 115.36± 2.22(ij)        | $6.86 \pm 0.46 (fg)$   | 2.57±0.09(ab)        | $4.17 \pm 0.10$ (abc) |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $107.96 \pm 2.82(j)$    | $6.55 \pm 0.21(g)$     | $2.75 \pm 0.06(ab)$  | $3.82 \pm 0.05$ (bc)  |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $138.83 \pm 5.61(fg)$   | $8.23 \pm 0.89$ (cde)  | $2.82 \pm 0.23(a)$   | $4.44 \pm 0.56(a)$    |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $140.36 \pm 5.49(ef)$   | $7.72 \pm 0.46 (defg)$ | $2.84 \pm 0.17(a)$   | $4.48 \pm 0.34(a)$    |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $148.23 \pm 3.59$ (cde) | $8.35 \pm 0.81$ (cde)  | $2.77 \pm 0.04 (ab)$ | $4.36 \pm 0.24(a)$    |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $140.93 \pm 7.64(def)$  | $8.24 \pm 0.42$ (cde)  | $2.72 \pm 0.34$ (ab) | $4.06 \pm 0.47$ (abc) |  |  |  |
| S. Em±  | 2.89                    | 0.42                   | 0.08                 | 0.13                  |  |  |  |
| LSD (p≤0.05)                                    | 9.79                    | 1.41                   | 0.29                 | 0.58                  |  |  |  |

 Table 67: Effect of different sources of Si on micronutrient status of neutral soil

Soil Cu content increased significantly with application of DE @ 250 ( $2.82 \pm 0.23$  mg kg<sup>-1</sup>) and 500 ( $2.84 \pm 0.17$  mg kg<sup>-1</sup>) kg Si ha<sup>-1</sup> maintained with crop and both rates of application was on par with each other. Zn content of soil was significantly higher with application of DE @ 500 kg Si ha<sup>-1</sup> ( $4.48 \pm 0.34$  mg kg<sup>-1</sup>) but was on par with control and DE and RHB @ 250 kg Si ha<sup>-1</sup>.

Nutrient status of alkaline soil after the experiment varied significantly among the treatments (Table 68, 69 and 70) with or without plant. There was a significant increase in soil pH with application of calcium silicate @  $250 (9.19 \pm 0.01)$  and  $500 (9.18 \pm 0.10)$ kg Si ha<sup>-1</sup> compared to other treatments but was on par with control (8.99  $\pm$  0.08). Soil EC was significantly high with the application of RHB @ 250 kg Si ha<sup>-1</sup> (0.37  $\pm$  0.08). Irrespective of the sources of Si, the plant available Si content was significantly higher in alkaline soil in the presence of rice plant compared to without crop. CCSi content was significantly higher with the application of RHB @ 500 kg Si ha<sup>-1</sup> maintained with plant  $(52.46 \pm 6.26 \text{ mg kg}^{-1})$  in alkaline soil. AASi content was significantly higher with application of calcium silicate @ 250 kg Si ha<sup>-1</sup> (146.47  $\pm$  18.90 mg kg<sup>-1</sup>). The available P<sub>2</sub>O<sub>5</sub> recorded significantly higher concentration with application of RHB @ 250 kg Si ha<sup>-1</sup> maintained without plant (52.57 $\pm$  2.18 kg ha<sup>-1</sup>) compared to other treatments. Available K<sub>2</sub>O was significantly higher with application of calcium silicate @ 250 kg Si  $ha^{-1}(351.68 \pm 6.35 \text{ kg } ha^{-1})$  and DE @ 250 kg Si  $ha^{-1}(353.02 \pm 16.91 \text{ kg } ha^{-1})$  where crop was grown. However, there was no significant effect of the treatments on calcium content. Soil Mg content was significantly increased with the application of RHB @ 250 kg Si ha<sup>-1</sup> (19.23  $\pm$  6.35cmol (p+) kg<sup>-1</sup>) maintained with crop. Sodium content decreased significantly with the application of Si and recorded high in control. There was significant increase in the DTPA extractable micronutrients such as Fe with application of DE @ 500 kg Si ha<sup>-1</sup> maintained with plant ( $8.05 \pm 0.63 \text{ mg kg}^{-1}$ ); Mn with application of CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> maintained with plant (8.76  $\pm$  1.19 mg kg<sup>-1</sup>); Cu with application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> maintained with plant  $(1.77 \pm 0.20 \text{ mg kg}^{-1})$  and Zn with application of RHB @ 250 kg Si ha<sup>-1</sup> maintained with plant  $(0.88 \pm 0.06 \text{ mg kg}^{-1})$ compared to other treatments. In general, there was significantly higher nutrient concentration recorded with the treatments maintained with crop which may be attributed to activity of plant at initial stage and thereby release of nutrients but unutilized by the crop because of poor growth in alkaline soil.

There was significant difference in nutrient status of the soil with the application of different Si sources over control in all three soils. Application of calcium silicate increased the soil pH in all three soils. In acidic and neutral soil, application of calcium silicate significantly increased the nutrient status of the soils whereas in alkaline soil application of RHB significantly affected chemical properties. The nutrient status of soil decreased in the presence crop due to utilization by crop plants in acidic and neutral soil, but increased content in alkaline soil due to poor growth of plants.

In the present investigation, there was a significant increase in the soil pH with the application of calcium silicate. The increase in the pH of the soil by the application of

| Table 68: Effect of different sources of Si on nutrient status of alkaline soil |                  |                              |                        |                       |                               |                        |  |
|---|------------------|------------------------------|------------------------|-----------------------|-------------------------------|------------------------|--|
| Treatments  | nН               | E. C.                        | CCSi                   | AASi                  | P <sub>2</sub> O <sub>5</sub> | K <sub>2</sub> O       |  |
| Treatments  | pm               | ( <b>dSm</b> <sup>-1</sup> ) | (mg kg <sup>-1</sup> ) |                       | (kg ha <sup>-1</sup> )        |                        |  |
| Ck - Without plant  | 8.99± 0.08(a)    | $0.27 \pm 0.01$ (cde)        | $42.89 \pm 2.10(d)$    | 116.46± 18.41(d)      | 41.10± 5.03(bcd)              | 333.31±9.38(bcd)       |  |
| Ck – With plant   | 9.04±0.07(abcd)  | $0.30 \pm 0.01$ (bcde)       | 44.90± 1.20(bcd)       | 115.28± 7.90(d)       | $35.65 \pm 5.28(d)$           | 321.21± 1.10(d)        |  |
| Without plant   |                  |                              |                        |                       |                               |                        |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup>                                 | 9.19±0.01(a)     | 0.28± 0.01(cde)              | 44.38± 0.91(bcd)       | 143.12± 1.94(ab)      | 42.44± 6.35(abcd)             | 327.93±7.60(bcd)       |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup>                                 | 9.18±.0.10(a)    | $0.27 \pm 0.00$ (de)         | 45.55± 2.28(bcd)       | 131.37± 0.53(abcd)    | 37.70±0.73(cd)                | 322.64±23.76(bcd)      |  |
| DE @ 250 kg Si ha <sup>-1</sup>   | 9.19±0.01(a)     | $0.27 \pm 0.01$ (de)         | $41.20 \pm 0.37(d)$    | 122.50± 5.30(bcd)     | 44.11± 6.53(abcd)             | 338.01±14.26(abcd)     |  |
| DE @ 500 kg Si ha <sup>-1</sup>   | 9.15±0.01(ab)    | $0.27 \pm 0.01$ (de)         | 43.34±2.11(cd)         | 119.75± 9.37(cd)      | 41.42± 1.99(abcd)             | 327.93±11.40(bcd)      |  |
| RHB @ 250 kg Si ha <sup>-1</sup>  | 9.11±0.02(abc)   | 0.30± 0.01(bcde)             | 45.27±0.21(bcd)        | 130.18±11.05(abcd)    | 52.57±2.18(ab)                | 323.90± 1.90(cd)       |  |
| RHB @ 500 kg Si ha <sup>-1</sup>  | 9.11±0.01(abc)   | 0.29± 0.00(bcde)             | $48.49 \pm 4.47(ab)$   | 127.87± 6.01(abcd)    | 40.39± 4.53(bcd)              | 339.36± 4.75(abc)      |  |
| With plant  |                  |                              |                        |                       |                               |                        |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup>                                 | 9.06± 0.12(abcd) | 0.30± 0.02(bcde)             | $44.04 \pm 0.43$ (bcd) | $146.47 \pm 18.90(a)$ | 47.79±12.75(abc)              | $351.68 \pm 6.35(a)$   |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup>                                 | 9.09±0.09(abc)   | 0.33±0.03(abcd)              | 44.75±2.28(bcd)        | 143.12± 6.93(ab)      | 43.58± 2.45(abcd)             | 336.44± 5.43(abcd)     |  |
| DE @ 250 kg Si ha <sup>-1</sup>   | 8.99± 0.17(cde)  | $0.34 \pm 0.06(ab)$          | 43.17±1.36(cd)         | 133.75±11.51(abc)     | 44.71±7.04(abcd)              | $353.02 \pm 16.91(a)$  |  |
| DE @ 500 kg Si ha <sup>-1</sup>   | 8.91±0.06(e)     | 0.33±0.04(abc)               | $42.59 \pm 1.75(d)$    | $133.54 \pm 6.66(d)$  | 48.98± 8.26(abc)              | 366.44± 8.64(abcd)     |  |
| RHB @ 250 kg Si ha <sup>-1</sup>  | 8.94± 0.13(de)   | $0.37 \pm 0.08(a)$           | 47.79±1.95(bc)         | 117.70± 6.99(cd)      | 39.92± 3.44(bcd)              | 341.37±7.48(abc)       |  |
| RHB @ 500 kg Si ha <sup>-1</sup>  | 8.99± 0.03(bcde) | $0.35 \pm 0.04$ (ab)         | $52.46 \pm 6.26(a)$    | 121.16± 5.01(cd)      | 41.20± 4.27(bcd)              | $345.40 \pm 10.67(ab)$ |  |
| S. Em±  | 0.04             | 0.01                         | 4.98                   | 1.22                  | 3.02                          | 5.88                   |  |
| LSD (p≤0.05)  | 0.15             | 0.06                         | 4.45                   | 18.16                 | 10.76                         | 17.86                  |  |

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| Table 07. Effect of united the sources of St on exchangeable cation status of alkaline so | Table | 69: Effect | of differen | t sources ( | of Si on | exchangeable | cation | status of | f alkaline : | soil |
|---|-------|------------|-------------|-------------|----------|--------------|--------|-----------|--------------|------|
|---|-------|------------|-------------|-------------|----------|--------------|--------|-----------|--------------|------|

| Treatmonte                                      | Ca   | Mg                    | Na                     |  |  |  |  |
|---|--|-----------------------|------------------------|--|--|--|--|
| Treatments                                      | (cmol (p <sup>+</sup> ) kg <sup>-1</sup> ) |                       |                        |  |  |  |  |
| Ck - Without plant                              | 23.52± 0.76(a)                             | 14.70±0.39(b)         | 3.89±0.16(abcd)        |  |  |  |  |
| Ck – With plant                                 | $24.07 \pm 0.92(a)$                        | $14.17 \pm 2.74(b)$   | 4.12±0.33(a)           |  |  |  |  |
| Without plant                                   |  |                       |                        |  |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 24.60± 0.15(a)                             | $14.10 \pm 1.61(b)$   | $3.72 \pm 0.03$ (bcde) |  |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $24.09 \pm 1.43(a)$                        | 14.84± 1.38(ab)       | 3.87±0.20(abcde)       |  |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $23.76 \pm 0.48(a)$                        | $13.45 \pm 2.22(b)$   | $3.75 \pm 0.10$ (bcde) |  |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $24.31 \pm 1.46(a)$                        | 13.66± 3.87(b)        | $3.81 \pm 0.05$ (bcde) |  |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $24.55 \pm 0.64(a)$                        | $14.20 \pm 1.74(b)$   | $4.01 \pm 0.02$ (abc)  |  |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $24.04 \pm 0.38(a)$                        | $13.53 \pm 1.12(b)$   | 3.68± 0.00(cde)        |  |  |  |  |
| With plant                                      |  |                       |                        |  |  |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 24.70± 0.77(a)                             | $15.95 \pm 1.43$ (ab) | $3.93 \pm 0.09$ (abcd) |  |  |  |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | $24.12 \pm 0.51(a)$                        | 14.79± 1.16(ab)       | 4.01±0.08(ab)          |  |  |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | $24.49 \pm 0.67(a)$                        | $16.40 \pm 0.66$ (ab) | $3.98 \pm 0.07$ (abc)  |  |  |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $22.65 \pm 2.26(a)$                        | $15.36 \pm 1.92$ (ab) | 3.98±0.18(abc)         |  |  |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $21.99 \pm 6.45(a)$                        | $19.23 \pm 6.35(a)$   | $3.66 \pm 0.05$ (de)   |  |  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $25.07 \pm 1.22(a)$                        | $15.55 \pm 2.51(ab)$  | 3.78±0.17(bcde)        |  |  |  |  |
| S. Em±  | 0.78                                       | 1.29                  | 0.06                   |  |  |  |  |
| LSD (p≤0.05)                                    | 3.62                                       | 4.52                  | 0.21                   |  |  |  |  |

| Treatmonts                                      | Fe                      | Mn                     | Cu                     | Zn                    |
|---|-------------------------|------------------------|------------------------|-----------------------|
| Treatments                                      |                         |                        |                        |                       |
| Ck - Without plant                              | $8.05 \pm 0.45$ (ab)    | 7.71±0.33(abcd)        | 1.69± 0.06(ab)         | $0.43 \pm 0.15(e)$    |
| Ck – With plant                                 | $7.29 \pm 0.32$ (bcde)  | $7.45 \pm 0.16$ (bcde) | $1.54 \pm 0.04$ (cde)  | $0.57 \pm 0.08$ (de)  |
| Without plant                                   |                         |                        |                        |                       |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $7.27 \pm 0.35$ (bcde)  | 8.20± 0.74(abc)        | $1.82 \pm 0.09(a)$     | $0.61 \pm 0.04$ (cd)  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 7.35±0.30(abcde)        | 7.71±0.32(abcde)       | 1.75±0.03(ab)          | $0.55 \pm 0.04$ (de)  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 7.91±0.21(abc)          | $7.50 \pm 0.45$ (bcde) | 1.70± 0.04(ab)         | $0.75 \pm 0.12$ (abc) |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 7.91±0.11(abc)          | $7.50 \pm 0.28$ (bcde) | 1.69± 0.01(abc)        | $0.55 \pm 0.01$ (de)  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $6.96 \pm 0.35$ (cdef)  | $7.39 \pm 0.31$ (bcde) | $1.54 \pm 0.08$ (cde)  | $0.56 \pm 0.11$ (de)  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 7.34±0.49(abcde)        | $6.63 \pm 1.08$ (cdef) | $1.58 \pm 0.01$ (bcde) | $0.82 \pm 0.03$ (ab)  |
| With plant                                      |                         |                        |                        |                       |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | $7.36 \pm 0.73$ (abcde) | 8.76± 1.19(a)          | 1.74± 0.13(ab)         | $0.60 \pm 0.08$ (cd)  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 7.71±0.36(abcd)         | 7.18±0.78(bcdef)       | $1.77 \pm 0.20(a)$     | $0.66 \pm 0.02$ (bcd) |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 7.51±0.58(abcde)        | $6.55 \pm 0.16(def)$   | $1.61 \pm 0.12$ (bc)   | $0.65 \pm 0.14$ (bcd) |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $8.05 \pm 0.63(a)$      | $7.43 \pm 1.14$ (bcde) | $1.62 \pm 0.10$ (bc)   | $0.67 \pm 0.08$ (bcd) |
| RHB @ 250 kg Si ha <sup>-1</sup>                | $6.89 \pm 0.30(def)$    | $6.14 \pm 0.16(ef)$    | $1.46 \pm 0.02$ (de)   | $0.88 \pm 0.06(a)$    |
| RHB @ 500 kg Si ha <sup>-1</sup>                | $6.32 \pm 0.06(ef)$     | $5.86 \pm 0.11(f)$     | $1.42 \pm 0.04(e)$     | $0.76 \pm 0.14$ (abc) |
| S.Em±   | 0.23                    | 0.32                   | 0.04                   | 0.05                  |
| LSD (p≤0.05)                                    | 0.74                    | 1.11                   | 0.16                   | 0.17                  |

Table 70: Effect of different sources of Si on micronutrient status of alkaline soil
calcium silicate is in agreement with findings of other workers who reported that silicates and slag pulverized to <1mm reported to be efficient in correcting the soil acidity and had great potential use in the agriculture as an environmental safe liming material (Correa *et al.*, 2007; Joulazadeh and Joulazadeh, 2010). Application of slags increased pH and calcium content in the soil solution (Kato *et al.*, 1996; Kato and Owa, 1996). Increase in soil pH and thereby correcting soil acidity with the application of calcium silicate was reported by Bauera *et al.* (2011). Alcarde (1992) reported that the reactions involving silicate materials that occur in the soil could increase pH, neutralizing exchangeable Al and other toxic elements.

Application of calcium silicate and RHB significantly increased the plant available Si in soil. In alkaline soil the CCSi content was significantly high with RHB application. Increase in extractable Si with the application of silicates was also reported by Wang *et al.* (2014), Agarie *et al.* (1992) and Camargo *et al.* (2010). Haefele *et al.* (2011) reported that biochar from rice residues can be beneficial in rice based systems but its effects on soil fertility depends on site specific conditions. Steyferth *et al.* (2013) and Savant *et al.* (1997) suggested that recycling of crop residues like rice husk to soils to provide a low cost, affordable means of Si fertilization and facilitates increase in plant available Si which is comparatively rapid. Other nutrients such as P, K, Ca, Mg and micronutrients were also significantly affected by the application of different Si sources such as calcium silicate, DE and RHB. Bhat *et al.* (2010) reported higher amounts of available Ca, Si and Zn in residual soil with application of slags.

In the present investigation, nutrient status increased with application of biochar in all three soils. Increase in Mehlich-3 extractable macro (P, K, S, Ca and Mg) and micronutrients (Cu, Zn, Mn and Fe) as a result of biochar application was noticed by Hass *et al.* (2012). However increased application rate decreased the Mehlich-3 extractable Mn and Fe possibly due to liming effect of biochar. Zheng *et al.* (2013) studied the effect of solution pH on release of N, P and K from biochar. Silber *et al.* (2010) studied the pH dependent release of nutrient and its agronomic implication from corn straw biochar. Laird *et al.* (2010a) in a 500-day incubation study observed significant increase in Mehlich-3 extractable P, K, Ca, and Mn with the amount of biochar added. The biochar treatments had no significant effect on Mehlich-3 extractable Mg, Cu and Zn. Increase in Mehlich-3 extractable K, Ca and Mn with increasing levels of biochar were most likely due to the presence of these nutrients in the biochar itself.

Increased nutritional status of the soil with the application of biochar corroborates other findings of De Luca *et al.* (2009); Novak *et al.* (2009); Gaskin *et al.* (2010); Van Zwieten *et al.* (2010). Van Zwieten *et al.* (2010) observed an increase in soil exchangeable K content with application of wood waste chip biochar at 10 Mg ha<sup>-1</sup>. Similarly, Gaskin *et al.* (2010) observed a linear increase in soil-extractable K content after adding peanut hull biochar into Tifton sand in first year of study. However, in the second year, the K effect diminished, suggesting that biochar served only as a temporary source of K or that the soil failed to retain K. Novak *et al.* (2009) conducted an incubation study to know the impact of biochar application on fertility of Norfolk loamy sand soil. After 67 days and two leaching events biochar additions increased the soil

organic carbon, Ca, K, Mn and P and decreased exchangeable acidity, S and Zn. Biochar additions did not significantly increase soil cation exchange capacity. Leachates contained higher concentration of K and Na concentrations, but decreasing levels of Ca, P, Mn and Zn. These effects reflect the addition of elements and higher sorption capacity of biochar for selective nutrients (especially Ca, P, Zn and Mn). Biochar can alter P availability directly through its anion exchange capacity or by influencing activity/ availability of the cations that interact with P. An increase in pH can increase alkaline metal (Mg<sup>2+</sup>, Ca<sup>2+</sup> and K<sup>+</sup>) oxides which reduces soluble forms of aluminum suggested to be most significant biochar factor affecting P solubility (De Luca *et al.*, 2009).

#### 4.3.8 Budgeting of input and output of Si in acidic, neutral and alkaline soil

The data presented in Table 71 to 73 represents the budgeting of Si input and output in three soils of pot experiment. In the present investigation, Si budgeting was estimated by considering the input and output of Si by irrigation water, added Si fertilizers, crop uptake and plant available Si stock ( $\Delta$ CCSi and  $\Delta$ AASi) in soil. Plant available Si (PAS) stock in soil was computed as the difference between final soil Si content and initial soil Si content as estimated by calcium chloride (CCSi) and acetic acid (AASi).

Si budget estimated for acidic soil (Table 71) revealed that irrigation water contributed to an extent of 28 and 16 per cent (238 mg pot<sup>-1</sup>) of the total Si input of 863 and 1488 mg pot<sup>-1</sup>, respectively, while remaining 72 and 84 per cent supplied through Si sources applied at 250 (625 mg pot<sup>-1</sup>) and 500 (1250 mg pot<sup>-1</sup>) kg Si ha<sup>-1</sup> respectively. As there was no chance of leaching/ runoff losses of Si, the most important output of Si considered in the present investigation was crop Si uptake and ranged from 228 to 547 mg pot<sup>-1</sup> and found to be lower in control while higher content was noticed with application calcium silicate @ 500 kg Si ha<sup>-1</sup>. In general, higher Si uptake was noticed with application of calcium silicate followed by DE and RHB. The difference between total input and output was found to be lower in the presence of crop. PAS stock in soil ( $\Delta$ CCSi and  $\Delta$ AASi) was found to be lower in the presence of crop than without crop and ranged from -44 to 38 mg pot<sup>-1</sup> of  $\Delta$ CCSi and 99 to 535 mg pot<sup>-1</sup> of  $\Delta$ AASi. The extent of decrease in PAS stock in soil (-27 to -44 mg pot<sup>-1</sup>) was higher in calcium silicate treatment compared to RHB and DE. Even though higher Si uptake was recorded with application of calcium silicate @ 500 kg Si ha<sup>-1</sup>, PAS stock in soil as extracted by acetic acid was also higher in the same treatment in the presence of crop.

The results presented in the Table 72, represent the Si budget for neutral soil. Likewise, in acidic soil, irrigation water contributed to an extent of 28 and 16 per cent (238 mg pot<sup>-1</sup>) of the total Si input 863 and 1488 mg pot<sup>-1</sup> respectively, while remaining 72 and 84 per cent was supplied through Si sources applied at 250 (625 mg pot<sup>-1</sup>) and 500 (1250 mg pot<sup>-1</sup>) kg Si ha<sup>-1</sup> respectively. Crop Si uptake ranged from 269 to 617 mg pot<sup>-1</sup> and lower in control while higher value was noticed with application calcium silicate @ 500 kg Si ha<sup>-1</sup>. In general, higher Si uptake was noticed with application of calcium

|                                  |         | <               | <                  |        | Si @25 | <>Si @500 kg ha <sup>-1</sup> > |        |                   |                    |        |        |        |        |        |
|----------------------------------|---------|-----------------|--------------------|--------|--------|---------------------------------|--------|-------------------|--------------------|--------|--------|--------|--------|--------|
| ACIDIC SOIL                      | Control |                 | CaSiO <sub>3</sub> |        | DE     |                                 | RHB    |                   | CaSiO <sub>3</sub> |        | DE     |        | RHB    |        |
|                                  | (-) RP♦ | (+) RP <b>*</b> | (-) RP             | (+) RP | (-) RP | (+) RP                          | (-) RP | (+) RP            | (-) RP             | (+) RP | (-) RP | (+) RP | (-) RP | (+) RP |
| A)Input                          | •       |                 | 1                  |        |        |                                 | — mg   | pot <sup>-1</sup> |                    |        |        |        |        |        |
| Irrigation water*                | 238     | 238             | 238                | 238    | 238    | 238                             | 238    | 238               | 238                | 238    | 238    | 238    | 238    | 238    |
| Si Fertilizer**                  | 0       | 0               | 625                | 625    | 625    | 625                             | 625    | 625               | 1250               | 1250   | 1250   | 1250   | 1250   | 1250   |
| Total input                      | 238     | 238             | 863                | 863    | 863    | 863                             | 863    | 863               | 1488               | 1488   | 1488   | 1488   | 1488   | 1488   |
| B)Output (uptake)                |         |                 |                    |        |        |                                 |        |                   |                    |        |        |        |        |        |
| Straw Si uptake                  | 0       | 223             | 0                  | 376    | 0      | 389                             | 0      | 321               | 0                  | 527    | 0      | 379    | 0      | 280    |
| Grain Si uptake                  | 0       | 5               | 0                  | 16     | 0      | 9                               | 0      | 7                 | 0                  | 20     | 0      | 8      | 0      | 9      |
| Total uptake                     | 0       | 228             | 0                  | 392    | 0      | 398                             | 0      | 328               | 0                  | 547    | 0      | 387    | 0      | 289    |
| Input - output                   | 228     | 10              | 863                | 471    | 863    | 165                             | 863    | 535               | 1/00               | 040    | 1/00   | 1100   | 1/00   | 1100   |
| ( <b>A - B</b> )                 | 230     | 10              | 003                | 4/1    | 003    | 405                             | 003    | 555               | 1400               | 940    | 1400   | 1100   | 1400   | 1199   |
| Plant available Si stock in soil |         |                 | •                  |        |        |                                 |        |                   |                    |        |        |        |        |        |
| ±∆CCSi                           | 6       | -11             | -12                | -44    | 15     | -21                             | 38     | 5                 | -19                | -27    | 16     | -13    | 51     | 1      |
| ±∆AASi                           | 168     | 99              | 331                | 276    | 175    | 97                              | 183    | 178               | 485                | 535    | 208    | 147    | 260    | 142    |

# Table 71: Silicon budgeting as input and output in acidic soil

♦ Without rice crop

♣ With rice crop

\*Total amount of water used as irrigation (8 L pot<sup>-1</sup>) with a Si concentration of 29.69 mg kg<sup>-1</sup>. \*\*Si fertilizers used @ 250 and 500 kg Si ha<sup>-1</sup>

CCSi – 0.01M Calcium chloride extractable Si; AASi - 0.5M Acetic acid extractable Si

2016  $\pm \Delta$  Difference between Si content in soil estimated after and before the experiment silicate followed by DE and RHB. The difference between total input and output was found to be lower in the presence of crop. PAS stock in soil was lower in the presence of crop which ranged from -21 to 55 mg pot<sup>-1</sup> of  $\Delta$ CCSi and 33 to 327 mg pot<sup>-1</sup> of  $\Delta$ AASi. The extent of decrease in PAS stock in soil (-21 to -20 mg pot<sup>-1</sup>) was higher in calcium silicate treatment compared to RHB and DE. Even though higher Si uptake was recorded with application of calcium silicate (@ 500 kg Si ha<sup>-1</sup>, PAS stock in soil as extracted by acetic acid was also higher in the same treatment in the presence of crop.

Budgeting of Si in alkaline soil (Table 73) revealed that irrigation water was contributed only 19 and 10 per cent (143 mg pot<sup>-1</sup>) of the total Si input 768 mg pot<sup>-1</sup> and 1393 mg pot<sup>-1</sup> respectively, which was lower compared to acidic and neutral soil due to lesser amount of added water (4.8 L pot<sup>-1</sup>) as irrigation due to higher water holding capacity of alkaline soil compared to other two studied soils. While, 81 and 90 per cent of the Si was supplied through Si sources applied at 250 (625 mg pot<sup>-1</sup>) and 500 (1250 mg pot<sup>-1</sup>) kg Si ha<sup>-1</sup> respectively. There was poor growth of crop in alkaline soil and thereby only straw Si uptake was considered as Si output. Straw Si uptake was found to be higher with application of RHB and calcium silicate at both rates of applied Si and ranged from 19 to 35 mg pot<sup>-1</sup>. The difference in input and output was found to be lower in the presence of crop which can be due to crop Si uptake. PAS stock in soil estimated as  $\Delta$ CCSi was found to be negative in most of treatments with an exception to RHB treatments and ranged from -25 to 31 mg pot<sup>-1</sup>. Likewise, in acidic and neutral soil, PAS stock in soil extracted by acetic acid was found to be higher or on par with the application of calcium silicate even in the presence of crop in alkaline soil.

The results of present investigation revealed that there was negative Si budget in control and extent was higher in the presence of crop in all three studied soils. About 16 to 28 per cent of Si in acidic and neutral soil and 10 to 19 per cent Si in alkaline soil was accounted by irrigation water. Similar observations were also made by Klotzbucher et al. (2015) who reported that irrigation water can also contributes dissolved Si to the soil which can be a part of readily available or adsorbed Si in soil. Studies on inputs of Si also suggested that irrigation provides 27 to 44 per cent of Si uptake by plants in irrigated lowland rice production (Ma et al. 2001; Desplanques et al. 2006). Crop Si uptake was found to be higher in neutral soil followed by acidic and alkaline soil. Effectiveness of the different sources of Si varied based on the type of soil, calcium silicate followed by RHB in acidic and neutral soil and RHB in alkaline soil performed better which can be due to variation in the reactivity of material based on the type of soil. Haynes (2014) also reported that usefulness of the Si sources depends on the reactivity rather than total Si content. Application of calcium silicate increased the PAS stock in soil as extracted by acetic acid in all soil which may be due to extraction of part of the Si adsorbed into the soil which might be useful for the succeeding crop. Empirical relationships between concentrations of acetate-extractable Si in soils (an estimate for amounts of Si adsorbed onto mineral surfaces) and the plant-Si-uptake suggested that adsorbed Si is a major Si source for plants (Barbosa- Filho et al., 2001; Narayanaswamy and Prakash, 2010). These results are in agreement with Shuhei et al. (2013) who revealed that when Si source was

|                                  | <>Si @250 kg ha <sup>-1</sup> > |                 |                    |        |        |        |        |                   | <>Si @500 kg ha <sup>-1</sup> > |        |        |        |        |        |  |
|----------------------------------|---------------------------------|-----------------|--------------------|--------|--------|--------|--------|-------------------|---------------------------------|--------|--------|--------|--------|--------|--|
| NEUTRAL SOIL                     | Control                         |                 | CaSiO <sub>3</sub> |        | DE     |        | RHB    |                   | CaSiO <sub>3</sub>              |        | DE     |        | RHB    |        |  |
|                                  | (-) RP♦                         | (+) RP <b>*</b> | (-) RP             | (+) RP | (-) RP | (+) RP | (-) RP | (+) RP            | (-) RP                          | (+) RP | (-) RP | (+) RP | (-) RP | (+) RP |  |
| A)Input                          | •                               |                 |                    |        |        |        | — mg   | pot <sup>-1</sup> | -                               |        |        |        |        |        |  |
| Irrigation water*                | 238                             | 238             | 238                | 238    | 238    | 238    | 238    | 238               | 238                             | 238    | 238    | 238    | 238    | 238    |  |
| Si Fertilizer**                  | 0                               | 0               | 625                | 625    | 625    | 625    | 625    | 625               | 1250                            | 1250   | 1250   | 1250   | 1250   | 1250   |  |
| Total                            | 238                             | 238             | 863                | 863    | 863    | 863    | 863    | 863               | 1488                            | 1488   | 1488   | 1488   | 1488   | 1488   |  |
| B)Output (uptake)                |                                 |                 |                    |        |        |        |        |                   |                                 |        |        |        |        |        |  |
| Straw Si uptake                  | 0                               | 257             | 0                  | 610    | 0      | 461    | 0      | 301               | 0                               | 584    | 0      | 471    | 0      | 346    |  |
| Grain Si uptake                  | 0                               | 11              | 0                  | 23     | 0      | 22     | 0      | 17                | 0                               | 33     | 0      | 20     | 0      | 22     |  |
| Total uptake                     | 0                               | 269             | 0                  | 633    | 0      | 484    | 0      | 318               | 0                               | 617    | 0      | 491    | 0      | 368    |  |
| Input – output<br>(A-B)          | 238                             | -31             | 863                | 230    | 863    | 379    | 863    | 545               | 1488                            | 870    | 1488   | 997    | 1488   | 1119   |  |
| Plant available Si stock in soil |                                 |                 |                    |        |        |        |        |                   |                                 |        |        |        |        |        |  |
| ±∆CCSi                           | 40                              | 2               | 19                 | -21    | 39     | 8      | 55     | 0                 | 8                               | -20    | 50     | -4     | 48     | 46     |  |
| ±∆AASi                           | 38                              | 33              | 191                | 174    | 67     | 67     | 75     | 89                | 296                             | 327    | 71     | 88     | 53     | 92     |  |

# Table 72: Silicon budgeting as input and output in neutral soil

♦ Without rice crop

♣ With rice crop

\*Total amount of water used as irrigation (8 L pot<sup>-1</sup>) with Si concentration of 29.69 mg kg<sup>-1</sup>.

\*\*Si fertilizers used @ 250 and 500 kg Si ha-1.

CCSi – 0.01M Calcium chloride extractable Si; AASi - 0.5M Acetic acid extractable Si

 $\pm \Delta$  Difference between Si content in soil estimated after and before the experiment

|                                  |         |         | <si @250="" ha<sup="" kg="">-1&gt;</si> |        |        |        |        |                     |                    | <>Si @500 kg ha <sup>-1</sup> > |        |        |        |        |  |  |
|----------------------------------|---------|---------|---|--------|--------|--------|--------|---------------------|--------------------|---------------------------------|--------|--------|--------|--------|--|--|
| ALKALINE SOIL                    | Control |         | CaSiO                                   | 3      | DE     |        | RHB    |                     | CaSiO <sub>3</sub> | 3                               | DE     |        | RHB    |        |  |  |
|                                  | (-) RP♦ | (+) RP♣ | (-) RP                                  | (+) RP | (-) RP | (+) RP | (-) RP | (+) RP              | (-) RP             | (+) RP                          | (-) RP | (+) RP | (-) RP | (+) RP |  |  |
| A)Input                          | •       |         |   |        |        |        | — mgj  | pot <sup>-1</sup> — |                    |                                 |        |        |        |        |  |  |
| Irrigation water*                | 143     | 143     | 143                                     | 143    | 143    | 143    | 143    | 143                 | 143                | 143                             | 143    | 143    | 143    | 143    |  |  |
| Si Fertilizer**                  | 0       | 0       | 625                                     | 625    | 625    | 625    | 625    | 625                 | 1250               | 1250                            | 1250   | 1250   | 1250   | 1250   |  |  |
| Total                            | 143     | 143     | 768                                     | 768    | 768    | 768    | 768    | 768                 | 1393               | 1393                            | 1393   | 1393   | 1393   | 1393   |  |  |
| B)Output (uptake)                |         |         |   |        |        |        |        |                     |                    |                                 |        |        |        |        |  |  |
| Straw Si uptake                  | 0       | 22      | 0                                       | 33     | 0      | 23     | 0      | 35                  | 0                  | 29                              | 0      | 19     | 0      | 27     |  |  |
| Total uptake                     | 0       | 22      | 0                                       | 33     | 0      | 23     | 0      | 35                  | 0                  | 29                              | 0      | 19     | 0      | 27     |  |  |
| Input – output                   |         |         |   |        |        |        |        |                     |                    |                                 |        |        |        |        |  |  |
| ( <b>A</b> - <b>B</b> )          | 143     | 121     | 768                                     | 735    | 768    | 745    | 768    | 733                 | 1393               | 1364                            | 1393   | 1374   | 1393   | 1366   |  |  |
| Plant available Si stock in soil | 1       |         |   |        |        |        |        |                     |                    |                                 |        |        |        |        |  |  |
| ±∆ CCSi                          | □16     | -9      | -9                                      | -11    | -25    | -15    | -5     | 7                   | -3                 | -7                              | -14    | -18    | 12     | 31     |  |  |
| ±∆AASi                           | 35      | 29      | 168                                     | 185    | 65     | 121    | 104    | 41                  | 110                | 145                             | 51     | 20     | 92     | 58     |  |  |

### Table 73: Silicon budgeting as input and output in alkaline soil

♦ Without rice crop

♣ With rice crop

\*Total amount of water used as irrigation (4.8 L pot<sup>-1</sup>) with Si concentration of 29.69 mg kg<sup>-1</sup>.

\*\*Si fertilizers used @ 250 and 500 kg Si ha-1

CCSi – 0.01M Calcium chloride extractable Si; AASi - 0.5M Acetic acid extractable Si

 $\pm \Delta$  Difference between Si content in soil estimated after and before the experiment

applied to soil, Si dissolves in the soil solution and part of the dissolved Si was adsorbed onto the soil solid phase and then desorbed and redissolved into soil solution. In the present investigation, there was negative Si budget in control treatments for the acidic and neutral soil and values were lower in the presence of crop in all three soils which emphasis the need of Si fertilization. The nutrient budget quantifies the amount of nutrients imported to and exported from a system. The budget is considered in balance if inputs and outputs are equal. Several such studies were reported for nutrient budgeting mainly for N (Hedlund *et al.*, 2003; Hossain *et al.*, 2012), P (Mercy *et al.*, 2006; Sukristiyonubowo *et al.*, 2010), K (Nguyen *et al.*, 2006) in the field scale.

Although the nutrient balances for major nutrients and budgeting was available under rice crop, an attempt was made for Si budgeting by use of different sources in different soils emphasis on its supplementation for higher yields besides managing acidic and alkaline stress conditions.

#### **Future line of work:**

- 1. Status of the Si in soils in relation to geology and climate need to be assessed at watershed levels to delineate the deficient soils and reactive soils to applied Si.
- 2. Need to asses biogeochemical cycle of nutrients together with Si under rice ecosystem for long term period in different types of soil.
- 3. Isotopic studies to partition different Si pools in soil-plant system.

# **V SUMMARY**

The present investigation was undertaken to understand the "Biogeochemistry of silicon in different rice ecosystems of Karnataka". In this investigation, soil samples were collected from rice ecosystems which comprise of different agro climatic zones of Karnataka. The field experiment was conducted at V. C. Farm, Mandya to assess the budgeting of silicon in wetland rice system. A pot culture experiment was conducted by using acidic, neutral and alkaline soil collected from different locations at Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bengaluru, Karnataka. The findings of this investigation are summarized below.

# 5.1 Silicon status and other physico-chemical properties of the soil samples collected from different agro climatic zones of Karnataka.

- ✓ Analysis of soil samples representing nine agro climatic zones of Karnataka revealed that 40 per cent are in acidic, 46 per cent are in alkaline and only 14 per cent are in neutral pH level. Almost 98 per cent of the soil samples are in normal range of soil EC and only 2 per cent of them are slightly saline in nature. Among nine agro climatic zones of Karnataka, the highest soil pH and EC recorded in NEDZ soil samples and the lowest in HZ and CZ.
- ✓ Cation exchange capacity of 200 soil samples ranged from 8.20 122.83 cmol (p+) kg <sup>-1</sup> and lower CEC was recorded in HZ and higher CEC found in SDZ soil sample.
- $\checkmark$  Textural class of the total soil samples greatly varied from sandy to clay nature.
- ✓ 30 to 50 per cent of soils were low to medium in plant available Si content as extracted by both calcium chloride and acetic acid. Relatively, higher Si content was noticed in soil samples of northern part of Karnataka than hilly and coastal zone samples.
- ✓ Most of the soil samples collected from different agro climatic zones of Karnataka showed significantly positive correlation for soil pH, Si content, silt and CEC and negatively correlated with sand content. There was good correlation between Si content with clay and CEC.
- ✓ Results of the XRD analysis indicated that quartz, Na and K feldspars, amphibole, and phyllosilicates (chlorite, muscovite) are the major primary minerals identified in most of the soil samples. The composition of clay minerals includes smectite, kaolinite and illite and vermiculite in various proportions.
- ✓ Total elemental composition was dominated by SiO<sub>2</sub> (45.71 87.6 %), Al<sub>2</sub>O<sub>3</sub> (5.38 18.21 %), Fe<sub>2</sub>O<sub>3</sub> (1.03 16.62 %), CaO (0.08 8.83 %), K<sub>2</sub>O (0.14 4.49

%). Pearson's correlation showed that pH was negatively correlated to  $SiO_2$  but positively correlated to  $Al_2O_3$ , CaO, Fe<sub>2</sub>O<sub>3</sub>, MgO, and SO<sub>3</sub>.

- ✓ A good correlation between Fe<sub>2</sub>O<sub>3</sub> with MgO and MnO indicates the predominance of clay minerals over oxides. Silicon extracted by acetic acid (AASi) was positively correlated with Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO and TiO<sub>2</sub> indicating that this extractant assessed the fraction of Si adsorbed on the surface of oxides/oxyhydroxides and clays.
- ✓ Results also validate the approach for assessing the bioavailable Si: CCSi for immediate dissolved Si; AASi for Si adsorbed on iron or aluminum oxides. Therefore, sesquioxides, such as Al and Fe oxides, and hydroxides play an important role in controlling the Si concentrations in the soil solution.

## 5.2 To assess the silicon budget in wetland rice ecosystem

### 5.2.1 Filed experiment during *summer* season 2015

- ✓ There was increase in the plant height and number of tillers per plant with application of DE @ 300 kg ha<sup>-1</sup>.
- ✓ Application of DE significantly increased the grain yield and numerical increase in the other yield attributes over control.
- ✓ Application of DE @ 300 kg ha<sup>-1</sup> increased the nutrient content of rice and uptake by straw and grain compared to control.
- ✓ Treatment under the cropping situation recorded higher soil pH (7.95 ± 0.21) along with the DE application @ 300 kg ha<sup>-1</sup>. Although, there was increase in the soil EC compared to initial values, there was no significant difference in EC among the treatment.
- ✓ 0.01M calcium chloride extractable Si (CCSi) content was significantly higher in control where no crop was grown with (35.82 ± 4.71 mg kg<sup>-1</sup>) or without (46.24 ± 9.03 mg kg<sup>-1</sup>) added Si. However, in the presence of rice crop, soil Si content decreased and was on par with the other treatments.
- ✓ The content of acetic acid extractable Si (AASi) in the soil (96.19 ± 9.87 mg kg<sup>-1</sup>) was increased significantly with application of DE @ 300 kg ha<sup>-1</sup> where no rice was grown, whereas Si content decreased in the presence of crop even though the DE was applied.
- ✓ Available N, P and K content decreased in the presence of crop.

- ✓ Exchangeable cations such as Ca, Mg, Na and micronutrient such as Cu affected by the application of DE but values were higher compared to initial content in soil. There was significant difference in the DTPA extractable Fe, Mn and Zn content among the treatments.
- ✓ Dissolved silicon (DSi) content at 5cm depth of soil solution significantly varied between the treatments at different intervals of experiment. Analysis of soil solution collected from the rhizons installed at a depth of 40 cm revealed that there was no significant variation in DSi levels among the treatments at different intervals of experimental period and found to be on par with each other.
- ✓ The dissolved PO<sub>4</sub> was differed significantly between the treatments at 5 and 40 cm depth of the soil.
- ✓ There was a gradual decrease in the dissolved K content during the experimental period at 5 cm depth of soil. At 40 cm depth, the dissolved K content did not vary between the treatments as well as different intervals of experimental period and values were on par with each other.
- ✓ Dissolved Ca in soil solution at 5 and 40 cm depth significantly affected between the treatments during experimental period.
- ✓ At 5cm depth, significantly higher dissolved Mg content was recorded with the application of DE in the presence of crop during 30 and 60 DAT. Irrespective of application of DE and presence or absence of crop plants; there was no significant variation in the dissolved Mg content at 40 cm depth at all intervals of samplings.
- ✓ There was a significant variation among the treatments with regard to dissolved Na content at 0 DAT in the soil solution collected at a depth of 5 cm. At 40 cm depth of soil, dissolved Na content was not varied the treatments except at 60 DAT.
- ✓ There was no significant difference among the treatments and different intervals of soil solution samplings for dissolved chloride at 5 and 40 cm depth of soil.

#### 5.2.2 Field experiment during *kharif* season 2015

- ✓ Application of DE as Si source @ 300 kg ha<sup>-1</sup> recorded significantly higher straw yield (10.30 ± 0.71 t ha<sup>-1</sup>) compared to control. However, there was no significant difference in grain yield between treatments.
- ✓ Significant increase in the straw Si content (5.77 ± 0.30 %) and its uptake (594.57 ± 53.94 kg ha<sup>-1</sup>) was noticed with the application of DE over control but there was no significant difference in grain Si content and uptake between the treatments.

- ✓ Soil pH and AASi content were not differed significantly among the treatments but, AASi content was found to be lower in plots where crop was grown. Significantly higher soil EC (0.18 ± 0.03dSm<sup>-1</sup>) recorded in the control plot with crop compared to other treatments. Si extracted by CaCl₂ was affected significantly and found to be highest in control (36.61± 7.95 mg kg<sup>-1</sup>) and decreased significantly in the presence of crop either with or without DE application.
- ✓ DSi was higher during initial period of crop growth and decreased at later stages. DSi content was found to be lower in the presence of crop compared to non-cropped soil collected at 5cm by using rhizons.
- ✓ DSi in soil solution at 40cm depth ranged from  $191 335 \mu$  molL<sup>-1</sup> as considered as output flux which was lower than the borewell samples ( $1123 1261 \mu$  molL<sup>-1</sup>) indicated dilution of most of the DSi.
- ✓ As an alternative, soil core samples up to 17.50 cm depth recovered at 80 days after transplanting to calculate the mass balance. Si concentration in the depth profiles recorded different pattern for cropped and no cropped soils. As the depth increased upto 17.50 cm there was similar concentration of Si recorded in all the plots (cropped and non cropped) confirming the dilution of the sample at 17.50cm deep itself as indicated by the results of soil solution collected by rhizons at 40cm depth.
- ✓ Mass balance calculations indicated that majority of the biogeochemical cycle of Si was controlled by Si-uptake, dissolution of Si, and contribution by irrigation. Biogeochemical cycle of Si was varied in cropped and non cropped situations.

# 5.3 Bioavailability of different sources of Si for rice crop and Si budgeting in acidic, neutral and alkaline soils

- ✓ Application of different sources of Si and their rates of application had a significant effect on soil solution pH in acidic, neutral and alkaline soils. Irrespective of the sources of Si, there was a stabilized pH of soil solution from 7 DAT to 120 DAT in acidic, neutral and alkaline soil and lowest pH was noticed at 0 DAT. Soil solution pH was decreased at 60 DAT in neutral and alkaline soil irrespective of treatments but increased further.
- ✓ DSi decreased gradually from 0 DAT to 30 DAT and thereafter stabilized till the end of the experiment in acidic soil. In neutral soil, the DSi content decreased from 0 DAT to 30 DAT and significantly increased at 60 DAT but decreased further till 120 DAT. Whereas, DSi increased as the duration increased from 0 to 60 DAT but at the end of experimental period decreased in alkaline soil.
- ✓ There was a significant increase in the plant height with the application of CaSiO<sub>3</sub> @ 250 and 500 kg Si ha<sup>-1</sup> in acidic and neutral soil. In case of alkaline soil, there was a

very poor growth of the plant but with the application of Si sources plant height was significantly increased.

- ✓ A significant increase in the number of tillers was noticed in acidic and neutral soil with application of different Si sources compared to control.
- ✓ There was a significant increase in the yield parameters such as panicle number pot<sup>-1</sup>, panicle length pot<sup>-1</sup>, straw dry weight pot<sup>-1</sup> and grain weight pot<sup>-1</sup> in acidic and neutral soil, whereas straw dry weight pot<sup>-1</sup> in alkaline soil with the application of Si sources over control.
- ✓ Higher nutrient content and uptake was noticed in neutral soil followed by acidic and alkaline soil. Although the application rate of different Si sources was 250 and 500 kg Si ha<sup>-1</sup>, there was a significant difference in the nutrient content and uptake by rice among the Si sources.
- ✓ Significant difference in nutrient status of the soil was noticed with the application of different Si sources over control in all three studied soils. In acidic and neutral soil, application of calcium silicate significantly increased the nutrient status of the soil whereas rice husk biochar in alkaline soil. The nutrient status of soil decreased in the presence crop in acidic and neutral soil while increased in alkaline soil.
- ✓ Si budgeting calculations revealed a negative Si budget in control and the extent was higher in the presence of crop in all three studied soils. About 16 to 28 per cent of Si in acidic and neutral soil and 10 to 19 per cent Si in alkaline soil was accounted by irrigation water.
- ✓ Crop Si uptake was found to be higher in neutral soil followed by acidic and alkaline soil. Effectiveness of the different sources of Si was varied based on the type of soil and the performance was higher with calcium silicate followed by RHB in acidic and neutral soil and with RHB in alkaline soil.
- ✓ Application of calcium silicate increased the PAS stock in soil as extracted by acetic acid in all studied soils.

#### **Conclusion:**

Soil Si availability vary with soil types, depending mainly on the type of parent material, weathering, intensity of rainfall and land use. Desilication was most pronounced in humid tropical environments and occurs to a lesser extent in temperate regions and thus hilly and coastal zones have a characteristically low Si status. Plant available Si had good correlation with pH, which depicts that solubility depends on the surface properties of the soil. A significant correlation between clays and Si indicated that clay minerals or clays can act as major source of the Si to the soil besides influencing CEC of the soil. Aluminium hydroxides, iron oxides and carbonates play a major role in the interaction between the solid and dissolved Si pools of the soil. Si mass balance and budgeting calculations indicated that majority of the biogeochemical cycle of Si was controlled by crop Si uptake, dissolution of Si, and contribution by irrigation. Negative balances of Si in the present investigation depicts that soils being mined to a greater extent and thereby rice systems were deficient in soil Si which was unsustainable for intensive rice cultivation over long term and thus emphasizes the need of Si fertilization. The bioavailability of different sources of Si was varied based on the type of soil indicating variability in reactivity of the Si sources rather than total Si content.

#### **VI REFERENCES**

- AFLIZAR, H., HARMAILIS, WAKATSUKI, T. AND MASUNAGA, T., 2009, Distribution of available Si in soils in relation with land uses types and soil erosion status in Sumani watershed, West Sumatra Indonesia. *The 9th international conference of the East and Southeast Asia Federation of Soil Science Societies.*
- AGARIE, S., DGATA, W., KUBOTAH AND KAUFONANN, P. S., 1992, Physiological role of silicon in photosynthesis and dry matter production in rice plant. *J. Crop Sci.*, **61**:200-208.
- AKSHATHA, M. K., 2015, Characterization of biochar, nutrient release and its effect on growth and yield of aerobic rice. *M.Sc. (Agri.) Thesis, Univ. Agric. Sci., Bengaluru, Karnataka, India.*
- ALCARDE, J. C., 1992, Corretivos da acidez dos solos, características interpretacoes tecnicas. *Sao Paulo, ANDA. (Boletim Tecnico)*. pp:6-9.
- ALEXANDRE, A., MEUNIER, J. D., COLIN, F. D. AND KOUD, J. M., 1997, Plant impact on the biogeochemical cycle of silicon and related weathering processes. *Geochim. Cosmochim. Acta*, **61**:677-682.
- ANDERSON, D. L., 1991, Soil and leaf nutrient interactions following application of calcium silicate slag to sugarcane. *Fert. Res.*, **30**(1):9-18.
- ANNA, D. S., DANIELA, B., JORN, H., LUDGER, Z. M. AND KARL, S., 2010, Development of a method for sequential extraction of Si-pools from soils. World Congress of Soil Science, Soil Solution for a Changing World, 1-6 August 2010, Brisbane. pp :31-34.
- ANONYMOUS, 2015, Agricultural statistics at a glance -2015, Directorate of economic and statistics, Department of Agriculture and Cooperation. **204**:17 -23.
- AOKI, S., FUJISAWA, H. AND ARAI, Y., 1986, Ion exchange reaction of granulated blast furnace slag in acid solution. *Gypsum Lime*, **204**:17-23.
- ASHIQUE, 2014, Effect of different sources of silicon on zinc and phosphorus interaction, growth and yield of aerobic rice. M.Sc. (Agri.) Thesis, Univ. Agric. Sci., Bengaluru, Karnataka, India.
- ASHRAF, M., RAHMATULLA, H., AFZAL, M., AHMED, R., MUJEEB, F., SARWAR, A. AND ALI, L., 2010, Alleviation of detrimental effects of NaCl by silicon nutrition in salt-sensitive and salt-tolerant genotypes of sugarcane (Saccharum officinarum L.). *Plant Soil*, **326**:381-391.

- BADRINATH, M. S., CHIDANANDAPPA, H. M., ALI, H. M. AND CHAMEGOWDA, T.C., 1995, Impact of lime on rice yield and available potassium in coastal acid soils of Karnataka. *Agropedology*, 5:43-46.
- BALASTRA, M. L. F., PEREZ, C. M., JULIANO, B. O. AND VILLAREAL, P., 1989, Effects of silica level on some properties of *Oryza sativa* straw and hull. *Canadian J. Bot.*, 67:2356-2363.
- BARBOSA-FILHO, M. P., SNYDER, G. H., ELLIOTT, C. L. AND DATNOFF, L. E., 2001, Evaluation of soil test procedures for determining plant available silicon. *Commun. Soil Sci. Plant Anal.*, **32**:1779-1792.
- BARKER, W. W., WELCH, S. A., CHU, S. AND BANFIELD, J. F., 1998, Experimental observations of the effects of bacteria on aluminosilicate weathering. *Am. Mineral.*, **83**:1551-1563.
- BARTOLI, F., 1985, Crystallochemistry and surface properties of biogenic opal. J. Soil Sci., **36**:335-350.
- BARTOLI, F. AND WILDING, L. P., 1980, Dissolution of biogenic opal as a function of its physical and chemical properties. *Soil Sci. Soc. Am. J.*, **44**:873-878.
- BARUAH, T. C. AND BARTHAKUR, H. P., 1997, A text book of soil analysis, pp: 142-190.
- BAUERA, P., ELBAUM, R. AND WEISS, I. M., 2011, Calcium and silicon mineralization in land plants: Transport, structure and function. *Plant Sci.*, **180**: 746-756.
- BECKWITH, R.S. AND REEVE, R., 1964, Studies of soluble silica in soils. I. The sorption of silicic acid by soils and minerals. *Aust. Soil Res.*, **2**:33-45.
- BELANGER, R. B., NICOLE, B. AND MENZIES, J. G., 2003, Cytological evidence of an active role of silicon in wheat resistance to powdery mildew. *Phytopathology*, 93:402-412.
- BENNETT, P. C., ROGERS, J. R., CHOI, W. J. AND HIEBERT, F. K., 2001, Silicates, silicate weathering and microbial ecology. *Geomicrobiology J.*, **18**(1):3-19.
- BENNET, P. C., SIEGEL, D. I., HILL, B. M. AND GLASER, P. H., 1991, Fate of silicate minerals in a peat bog. *Geology*, **19**:328-331.
- BERTHELSEN, S., NOBLE, A., KINGSTON, G., HURNEY, A., RUDD, A. AND GARSIDE, A., 2003, Improving yield and ccs in sugarcane through the

application of silicon based amendments. Final report on SRDC Project CL W009.

- BHAT, J. A., BISWAPATI, M. AND HAZRA, G. C., 2007, Basic Slag as a Liming Material to Ameliorate Soil Acidity in Alfisols of Sub-tropical India. American-Eurasian. J. Agric. Environ. Sci., 2(4):321-327.
- BHAT, J. A., KUNDU, M. C., HAZRA, G. C., SANTRA, G. H. AND MANDAL, B., 2010, Rehabilitating acid soils for increasing crop productivity through low-cost liming material. *Sci. Total Environ.*, **408**:4346-4353.
- BOKHTIAR, S. M., HAIRONG, H. AND LI, Y. R., 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(10):1363-1381.
- BRADBURY, M. AND AHMAD, R., 1990, The effect of silicon on the growth of Prosopis juliflora growing in saline soil. *Plant Soil*, **125**:71-74.
- BRAY, R. H. AND KURTZ, L. T., 1945, Determination of total organic and available forms of phosphorus in soils. *Soil Sci.*, **59**:39-45.
- BRICKER, O. P. AND GODFREY, A. E., 1967, Mineral-water interaction during chemical weathering of silicates. *Advan. Chem. Ser.*, **73**:128-182.
- BRIMHALL, G. H., CHADWICK, O. A., LEWIS, C. J., COMPSTON, W., WILLIAM, I. S., DANTI, K. J., DIETRICH, W. E., POWER, M. E., HENDRICKS, D. AND BRATT, J., 1991, Deformatial mass transport and invasive processes in soil evolution. *Science*, 255:695-702.
- BRINKMAN, R., 1979, Ferrolysis, a soil forming process in hydromorphic conditions. Center for Agricultural Publishing and Documentation, Wageningen.
- BROMFIELD, S. M., 1960, Some factors affecting the solubility of phosphate during the microbial decomposition of plant material. *Aust. J. Agr. Res.*, **11**:304-316.
- CAI, A. Y., XUE, Z. Z., PENG, J. G., LU, H. D. AND LIN, Y. J., 1997, Studies of available silicon content in the soils of Fujian province and the prerequisite for its variation. J. Fijia. Acad. Agric. Sci., 12(14):47-51.
- CALPE, C., 2001, Medium-term projections for the world rice economy: major issues at stake International Rice Commission Newsletter, FAO. **50**:1-4.
- CAMARGO, M. S. D., ALCIDES, R. G. J., PATRICIA, W. AND KORNDORFER, G. H., 2010, Silicate fertilization in sugarcane: Effects on soluble silicon soil, uptake

and occurrence of stalk borer (*Diatraea sacharalis*). 19<sup>th</sup> World Congress of Soil Science,  $1 - 6^{th}$  August, 259-262.

- CAMARGO, M. S. D., AMORIM, L. AND ALCIDES, R. G. J., 2013, Silicon fertilisation decreases brown rust incidence in sugarcane. *Crop Prot.*, **53**:72-79.
- CAMARGO, M. S. D., PEREIRA, H. S., KORNDORFER, G. H., QUEIROZ, A. A. AND REIS, C. B., 2007, Soil reaction and absorption of silicon by rice. *Scientia Agricola*, **64**:176-180.
- CARROL, D., 1974, Rock Weathering. Plenum Press, New York.
- CARVALHO, J. C., 2000, Analise de crescimento e producao de graos da cultura doarrozrrigado por aspersao em funca da aplicacao de escorias de siderurgia como fonte de silico. *Botucatu: UNSEP/FCA*, **119.**
- CHADWICK, O. A., HENDRICKS, D. M. AND NETTLETON, W. D., 1987, Silica in duric soils: I. A depositional model. *Soil Sci. Soc. Am. J.*, **51**:975-982
- CHAGAS, R., DEC, S., KORNDORFER, G. H., MURAOKA, T., PEREIRA AND LEANDRO, W. M., 2005, Silicon sources and biomass production on rice crop. *2nd conference on Silicon in Agriculture*, Tsuruoka, Yamagata, Japan: 146.
- CHAN, K. Y., VAN ZWIETEN, L., MESZAROS, I., DOWNIE, A. AND JOSEPH, S., 2007, Agronomic values of green waste biochar as a soil amendment. *Aust. J. Soil Res.*, **45**:629-634.
- CHEN, J., CALDWELL, R. D., ROBINSON, C. A. AND STEINKAMP, R., 2000, Differential responses of container-grown ornamental foliage plants to silicon application. *Hort. Sci.*, **35**(3):458.
- CHENG. B. T., 1982, Some significant functions of silicon to higher plants. J. Plant Nutr., 5:1345-1353.
- CHEONG, Y., ROSS, L. AND CAVALOT, P. C., 1968, Silicon status of Mauritius Soils. In: 1967 report of the Mauritius sugarcane industry research Institute, Mauritius. Sugarcane Industry Research Institute, Mauritius, pp.78-81.
- CLYMANS, W., GOVERS, G., VAN WESEMAEL, B., MEIRE, P. AND STRUYF, E., 2011, Amorphous silica analysis in terrestrial runoff samples. *Geoderma*, **167**(16): 228-235.
- CONLEY, D. J., 1997, An interlaboratory comparison for the measurement of biogenic silica in sediments. *Mar. Chem.*, **63**:39-48.

- CONLEY, D. J., SOMMER, M., MEUNIER, J. D., KACZOREK, D. AND SACCONE, L., 2005, Silicon in the terrestrial biogeosphere. *In*: ITTEKOT, V., HUMBORG, C. AND GARNIER, J. (*eds*), Land–Ocean Nutrient Fluxes: Silica Cycle. SCOPE.
- CORNELIS, J. T., TITEUX H., RANGER, J. AND DELVAUX, B., 2011, Identification and distribution of the readily soluble silicon pool in a temperate forest soil below three distinct tree species. *Plant Soil*, **342**:369-378.
- CORREA, J. C., BULL, L. T., CRUSCIOL, C. A. C., MARCELINO, R. AND MAUAD, M., 2007, Liming and ion mobility in an Oxisol under surface application of flue dust, aqueous lime, sewage sludge and limestone. *Pesq. Agropec. Bras.*, 42:1307-1317.
- DANILOVA, A., SAUER, D., BREUER, J., HERRMANN, L., ZAREI, M. AND STAHR, K., 2010, Development of a method for sequential extraction of Si-pools from soils. *In 19th World Congress of Soil Science, Soil Solutions for a Changing World*, 1 – 6 August, Brisbane, Australia. pp .31-34.
- DATNOFF L. E., SNYDER, G. H. AND DEREN, C.W., 1992, Influence of silicon fertilizer grades on blast and brown spot development and on rice yields. *Plant Dis.*, **76**:1011-1013.
- DATNOFF, L. E., DEREN, C.W. AND SNYDER G. H., 1997, Silicon fertilization for disease management of rice in Florida. *Crop Prot.*, **16**:525-531.
- DE LUCA, T. H., MACKENZIE, M. D. AND GUNDALE, M. J., 2009, Biochar effects on soil nutrient transformations. In: Lehmann J, Joseph S (Eds) Biochar for environmental management science and technology. Earth scan, London, pp. 72-87.
- DELSTANCHE, S., OPFERGELT, S. AND CARDINAL, D., 2009, Silicon isotopic fractionation during adsorption of aqueous monosilicic acid onto iron oxide. *Geochim. Cosmochim Acta*, **73**:923-934.
- DEREN, C. W., DATNOFF, L. E., SNYDER, G. H. AND MARTIN, F. G., 1994, Silicon concentration, disease response and yield components of rice genotypes grown on flooded organic histosols. *Crop Sci.*, 34:733-737.
- 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.
- DESPLANQUES, V., CARY, L., MOURET, J. C., TROLARD, F., BOURRIÉ, G., GRAUBY, O. AND MEUNIER, J. D., 2006, Silicon transfers in a rice field in Camargue (France). J. Geochem Explor., **88**:190-193.

- DETTINGER, M. D., 1989, Reconnaisance estimates of natural recharge to desert basins in Nevada, U.S.A., by using chloride-Balance Calculations. J. Hydrol., 106:55-78.
- DHANANJAYA, B. C. AND ANANTHANARAYANA, R., 2009, Soil acidity and exchange chemistry in soils of southern Karnataka Introduction. *Agropedology*, **19** (2):99-105.
- DIETZEL, M., 2000, Dissolution of silicates and the stability of polysilicic acid. *Geochim. Cosmochim. Acta*, **64**:3275-3281.
- DIETZEL, M., 2002, Interaction of polysilicic and monosilicic acid with mineral surfaces, in Stober, I., Bucher, K. (eds.): Water-rock interaction. Kluwer, Dordrecht, The Netherlands, pp. 207-235.
- DING, T. D., WAN, C., WANG AND ZHANG, F., 2003, Silicon isotope compositions of dissolved silicon and suspended matter in the Yangtze River, China. *Geochim. Cosmochim. Acta*, **68**(2):205-216.
- DORWEILER, J. AND DOEBLEY, J., 1997, Developmental analysis of *teosinte* glume architecture: A key locus in the evolution of maize (poaceae). *American J. Bot.*, **84**:1313.
- DOVE, P. M. AND NIX, C. J., 1997, The influence of the alkaline earth cations, magnesium, calcium, and barium on the dissolution kinetics of quartz. *Geochim. Cosmochim. Acta*, **61**(16):3329-3340.
- DOVE, P. M., 1995, Kinetic and thermodynamic controls on silica reactivity in weathering environments, in White, A. F., Brantley, S. L. (eds.): Chemical weathering rates of silicate minerals. Rev. in Mineralogy 31, Mineralogical Society of America, Washington D. C., pp. 235-290.
- DREES, L. R., WILDING, L. P., SMECK, N. E. AND SANKAYI, A. L., 1989, Silica in soils: quartz and disordered silica polymorphs. *Minerals in Soil Environments*, pp. 913-974.
- DREVER, J. I. AND ZOBRIST, J., 1992, Chemical weathering of silicate rocks as a function of elevation in the southern Swiss Alps. *Geochim. Cosmochim. Acta*, **56**:3209-3216.
- ELAWAD, S. H. AND GREEN, V. E., 1979, Silicon and the rice plant environment: a review of recent research. *II Riso.*, **28**:235-253.
- ELGAWHARY, S. M. AND LINDSAY, S. M., 1972, Solubility of silica in soils. Soil Sci. Soc. Am. Proc., 36:42-439.

- EPSTEIN, E., 1994, The anomaly of silicon in plant biology. *Proc. Natl. Acad. Sci.*, **91**: 11-17.
- EPSTEIN, E., 1999, Silicon. Annual review of plant physiology. *Plant Mol. Biol.*, **50**: 641-644.
- FAGERIA, N. K., BALIGER, V. C. AND JONES, C. A., 1991, Growth and mineral nutrition of field crops. (Books in Soils, Plants, and the Environment Series), Marcel Dekker, New York.
- 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. *Commun. Soil Sci. Plant Anal.*, 42:1913-1933.
- FAO, 2006, World agriculture: towards 2030/2050 Interim report. Rome.
- FARMER, V. C., DELBOS, E. AND MILLER, J. D., 2005, The role of phytolith formation and dissolution in controlling concentrations of silica in soil solutions and streams. *Geoderma*, **127**:71-79.
- FASSIL, K., 2009, Silicon status and its relationship with major physico-chemical properties of vertisols of northern highlands of Ethiopia. *Momona Ethiopian J. Sci.*, **1**(1):74-81.
- FAWE, A. M., ABOU-ZAID, J. G., MENZIES AND BELANGER, R. R., 1998, Silicon mediated accumulation of flavenoid phytoalexins in cucumber. *Phytopathology*, 88:396-401.
- FLINN, J. C. AND DEDATTA, S. K., 1984, Trends in irrigated rice yields under intensive cropping at Philippine research stations. *Field Crops Res.*, **9**:1-15.
- FOX, R., SILVA, L. J., YOUNGE, A. O. R., PLUCKNETT, D. L. AND SHERMAN, G. D., 1967, Soil and plant silicon and silicate response by sugarcane. *Soil Sci. Soc. Am. Proc.*, **31**:775-779.
- FOY, C. D., 1992, Soil chemical factors limiting plant root growth, Limitations to plant root growth, eds. Hatfield J.L, and Stewart B.A. *Adv. Soil Sci.*, **19**:97-149.
- FRANK, U., 1993, Chemisch-mineralogische Reaktion von Waldböden auf anthropogene Säurebelastungen und ihre Auswirkungen auf den Kationen-Antagonismus im System Boden- Pflanze. Ph.D. Thesis, FB Biologie, University of Oldenburg, Germany.

- FRAYSSE, F., POKROVSKY, O. S., SCHOTT, J. AND MEUNIER, J. D., 2006, Surface properties, solubility and dissolution kinetics of bamboo phytoliths. *Geochim. Cosmochim. Acta*, **70**:1939-1951.
- 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.
- GALLEZ, A., HERBILLON, A. J. AND JUO, A. S. R., 1977, Characteristics of silica sorption and solubility as parameters to evaluate the surfaces properties of tropical soils: I. The index of silica reactivity. *Soil Sci. Soc. Am. J.*, **41**:1146-1150.
- GARRELS, R. M., 1967, Genesis of some ground waters from igneous rocks. In: Abelson P (ed) Research in geochemistry. Wiley, NewYork, pp. 405-420.
- 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 B.V. Amsterdam, The Netherlands.
- GASKIN, J. W., SPEIR, A., MORRIS, L. M., OGDEN, L., HARRIS, K., LEE, D. AND DAS, K. C., 2010, Potential for pyrolysis char to affect soil moisture and nutrient status of a loamy sand soil. In: *Proceedings of the 2007 Georgia Water Resources Conference*, held March 27-29, 2007, at the University of Georgia.
- GASSER, J. K. R. AND BLOOMFIELD, C., 1955, The mobilization of phosphate in waterlogged soils. *J. Soil Sci.*, **6**:221-232.
- GERARD, F. A., MAYER, K. U., HODSON, M. J. AND RANGER, J., 2008, Modelling the biogeochemical cycle of silicon in soils: Application to a temperate forest ecosystem. *Geochim. Cosmochi. Acta*, **72**:741-758.
- GERARD, F., FRANCOIS, M. AND RANGER, J., 2002, Processes controlling silica concentration in leaching and capillary soil solutions of an acidic brown forest soil (Rhone, France). *Geoderma*, **107**:197-226.
- GERARD, F., RANGER, J., MENETRIER, C. AND BONNAUD, P., 2003, Silicate weathering mechanisms determined using soil solutions held at high matric potential. *Chem. Geol.*, **202:**443-460.
- GERMANIQUE, J. C., 1994, Major, trace and rare-earth elements in fourteen gsj reference samples. Determination by x-ray fluorescence spectrometry and inductively coupled plasma optical emission spectrometry. *Geostandards Geoanalytical Res.*, **18**:91-100.

GLASAUER, S. M., 1995, Silicate associated with Fe(Hydr)oxides. *Ph.D. Thesis, Munich University of Technology.* 

GNANAMANIKAM, S. S., 2009, Biological Control of Rice Diseases. pp:1-108.

- GOCKE, M., LIANG, W., SOMMER, M. AND KUZYAKOV, Y., 2013, Silicon uptake by wheat: Effects of Si pools and pH. *J. Plant Nutr. Soil Sci.*, **176**:551-560.
- GOLDICH, S.S., 1938, A study in rock-weathering. J. Geol., 46: 17-58.
- GONG, A. H. J., CHEN, A. K. M., CHEN, A. G. C., WANG, A, S. M. AND CHENG-LIE ZHANG., 2003, Effects of silicon on growth of wheat under drought. J. Plant Nutr., 26(5):1055-1063.
- GONG, H. J., RANDALL, D. P. AND FLOWERS, T.J., 2006, Silicon deposition in root reduces sodium uptake in rice (Oryza sativa L.) seedlings by reducing bypass flow. *Plant Cell Environ.*, **29**:1970-1979.
- GONTIJO, I., 2000, Characteristics fisicas e quimicas dos solos determination da disponibilidade do silicio para as plantas. *Monografia- Instituto de Ciencias Agrarias da universidade federal de Uberlanda*, **35**:347-356.
- GUNES, A., INAL, A., BAGCI, E. G. AND PILBEAM, D. J., 2007, Silicon mediated changes of some physiological and enzymatic parameters symptomatic for oxidative stress in spinach and tomato grown in sodic-B toxic soil. *Plant Soil*, **290**:103-114.
- GUNTZER, F., KELLER, C. AND MEUNIER, J. D., 2012, Benefits of plant silicon for crops: a review. *Agron. Sust. Develop.*, **32**:201-213.
- GUSTAFSSON, J. P., BERGGREN, D., SIMONSSON, M., ZYSSET, M. AND MULDER, J., 2001, Aluminium solubility mechanisms in moderately acid Bs horizons of podzolized soils. *Eur. J. Soil Sci.*, **52**:655-665.
- HAEFELE, S. M., KONBOON, Y., WONGBOON, W., AMARANTE, S., MAARIFAT, A. A., PFEIFFER, E. M. AND KNOBLAUCH, C., 2011, Effects and fate of biochar from rice residues in rice-based systems. *Field Crop Res.*, **121**:430-440.
- HAI-HONG, G., SHU-SHUN, Z., SHI-ZHONG, W., YE-TAO, T., XIAO-HANG. F., XIN-DE CAI, AND RONG-LIANG QIU, 2012, Mitigation effect of silicon rich amendments on heavy metal accumulation in rice planted on multi-metal contaminated acidic soil. *Chemosphere*, 83:1234-1240.

- HASS, A., JAVIER, M. G., ISABEL M. L., HARRY, W. G., JONATHAN J. H. AND DOUGLAS G. B., 2012, Chicken manure biochar as liming and nutrient source for acid appalachian Soil. *J. Environ. Qual.*, **41**(4):1096-1106.
- HAYASAKA, T., FUJII, H. AND NAMAI, T., 2005, Silicon content in rice seedlings to protect rice blast fungus at the nursery stage. *J. Gen. Plant Pathol.*, **71**:169-173.
- HAYNES, R. J., 2014, A contemporary overview of silicon availability in agricultural soils. *J. Plant Nutr. Soil Sci.*, **177**:831-844.
- HAYNES, R. J., BELYAEVA, O. N. AND KINGSTON, G., 2013, Evaluation of industrial wastes as sources of fertilizer silicon using chemical extractions and plant uptake. *J. Plant Nutr. Soil Sci.*, **176**:238-248.
- HAYSOM, M. B. C. AND CHAPMAN, L. S., 1975, Some aspects of the calcium silicate trials at Mackay. *Sugar Cane Technol.*, **42**:117-122.
- HE, D. Y., 1993, Form, content and availability of silicon in main farmland of Hunan province and research on furnace slag fertilizer. *Res. Agric. Modern.*, **14**:7-43.
- HE, L. Y. AND LI. X. L., 1995, Content and distribution of available silicon in paddy soils of Hubei province. J. Huazhong Agric. Univ., 14:8-363.
- HEDLUND, A., WITTER, E. AND BUI, X, A., 2003, Assessment of N, P and K management by nutrient balances and flows on peri-urban smallholder farms in southern Vietnam. *Europ. J. Agron.*, **20**:71-87.
- HENRIET, C. N., JAEGER, D. M., DOREL, E. S. AND OPFERGELT, B. D., 2008, The reserve of weatherable primary silicates impacts the accumulation of biogenic silicon in volcanic ash soils. *Biogeochemistry*, **90**:209-223.
- HERBILLON, A. J., GALLEZ, A. AND JUO, A. S. R., 1977, Characteristics of silica sorption and solubility as parameters to evaluate the surfaces properties of tropical soils: II. The index of silica saturation. *Soil Sci. Soc. Am. J.*, **41**:1151-1154.
- HODA, A. A., MAHER, G. N., HODA A. M. AND MAGDA, A. H., 2016, Assessment of Silicon Status in Calcareous Soils of Banger Elsokkar Region, Egypt, *Alexandria Sci. Exch. J.*, **37**:45-52.
- HODSON, M. AND SANGSTER, A., 1988, Silica deposition in the inflorescence bracts of wheat (*Triticum aestivum*) I: scanning electron microscopy and light microscopy. *Canadian J. Bot.*, **66**:829-838.
- HODSON, M. J. AND EVANS, E. D., 1995, Aluminium/silicon interactions in higher plants. J. Exp. Bot., 46(2):161-171.

- HOHN, A., SOMMER, M., KACZOREK, D., SCHELITZ, G. AND BREURE, J., 2008, Silicon fractions in histosols and gleysols of a temperate grassland site. J. Plant Nutr. Soil Sci., 171:409-418.
- HORTA, M. D. AND TORRENT, J., 2007, Phosphorus desorption kinetics in relation to phosphorus forms and sorption properties of Portuguese acid soils. *Soil Sci.*, 172: 631-638.
- HOSSAIN, M. F., ELAHID, S. F., WHITEC, S. K., ALAME, Q. K., ROTHERF, J. A. AND GAUNT, J. L., 2012, Nitrogen budgets for Boro rice (*Oryza sativa* L.) fields in Bangladesh. *Filed Crops Res.*, **131**:97-109.
- 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 Nutr.*, **24**:1-13.
- HOSSAIN, K. A., TAKATSUGU, H. AND SHUICHI, M., 2004, Effects of powdered rice chaff on growth and yield of rice under different soil pH conditions. *Comm. Soil Sci. Plant Anal.*, **35**(9-10):1469-1484.
- HOUBEN, D. D., PHILIPPE, S. AND JEAN, T. C., 2014, Biochar from Miscanthus: A potential silicon fertilizer. *Plant Soil*, **374**:871-882.
- HOUSE, W. A., LEACH, D. V. AND ARMITAGE, P. D., 2000, Study of dissolved silicon and nitrate dynamics: In a freshwater stream. *Wat. Res.* **35**(11):2749-2757.
- HUANG, W. H. AND VOGLER, D. L., 1972, Dissolution of opal in water and its water content. *Naturl. Physcl. Sci.*, **235**:157-158.
- HUSNAIN, H., TSUGIYUKI, M. AND WAKATSUKI, T., 2010, Field assessment of nutrient balance under intensive rice-farming systems, and its effects on the sustainability of rice production in Java Island, Indonesia. J. Agri. Food Envi. Sci., **4:**1-14.
- HUSNAIN, TOSHIYUKI, W., SETYORINI, D., HERMANSAH, SATO, K. AND TSUGIYUKI, M., 2008, Silica availability in soils and river water in two watersheds on Java Island, Indonesia. *Soil Sci. Plant Nutr.*, **54**:916-927.
- HYNES, H. B. N. AND GREIB, B. J., 1970, Movement of phosphate and other ions from and through lake muds. J. lilsh Res. Bd. Catn., 27:653-668.
- IDRIS, M. D., HOSSAIN, M. H. AND CHOUDHARY, F. A., 1975, The effect of silicon on lodging of rice in presence of added nitrogen. *Plant Soil*, **43**:691-695.

- ILLER, R. K., 1979, The chemistry of silica solubility, polymerization, colloid and surface properties, and biochemistry. Wiley & Sons, New York, pp. 866.
- IMAIZUMI, K. AND YOSHIDA, S., 1958, Edaphological studies on silicon supplying power of paddy soils. *Bull. Natl. Inst. Agric. Sci. (Jpn.)*, **8**:261-304.
- INANAGA, S., HIGUES, Y. AND NAOYA, C., 2002, Effect of silicon application on reproductive growth of rice plant. *Soil Sci. Pl. Nutr.*, **48**(3):341-347.
- INANAGA, S., OKASAKA, A. AND TANAKA, S., 1995, Does silicon exist in association with organic compounds in rice plant? *J. Soil Sci. Plant Nutr.*, **41**:111-117.
- ISLAM, A. AND SAHA, R., 1969, Effects of silicon on the chemical composition of rice plants. *Plant Soil*, **30**:446-458.
- JACKSON, M. L., 1973, Soil chemical analysis. Prentice Hall of India Pvt. Ltd. New Delhi.
- JACKSON, M. L., HSEUNG, Y., COREY, R. B., EVANS, E. J. AND VANDEN HEUVEL, R. C., 1952, Weathering sequence of clay-size minerals in soils and sediments. II. Chemical weathering of layer silicates. *Soil Sci. Soc. Am. Proc.*, 16: 3-6.
- JACKSON, M. L., TYLER, S. A., WILLIS, A. L., BOURBEAU, G. A. AND PENNINGTON, R. P., 1948, Weathering sequence of clay-size minerals in soils and sediments. I. Fundamental generalizations. J. Phys. Coll. Chem., 52:1237-1260.
- JAFARI, H., MADANI, H., DASTAN, S., MALIDARREH, A. G. AND MOHAMMADI, B., 2013, Effect of nitrogen and silicon fertilizer on rice growth in two irrigation regimes. *Intl. J. Agron. Plant Prod.*, **4**:3756-3761.
- JOANNA, M., SIMONE, H., WERNER, G. A., GUNTER, M., RUDIGER, F., ERNST, B. AND OTTO, W., 2007, Effect of silicon fertilizers on silicon accumulation in wheat. J. Plant Nutr. Soil Sci. 17:769-772.
- JONES, L. H. P. AND HANDRECK, K. A., 1963, Effect of iron and aluminium oxides on silica solution in soils. *Nature*, **198**:852-853.
- JOULAZADEH M. H. AND JOULAZADEH, F., 2010, Slag value added steel industry byproducts. *Arch. Metall. Mater.*, **35**(4):1138-1145.
- KABATA, A. P. AND MUKHERJEE, A. B., 2007, Trace Elements from Soil to Human. pp.1-562.

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- KAMENIDOU, S., CAVINS, T. J. AND MAREK, S., 2009, Evaluation of silicon as a nutritional supplement for greenhouse zinnia production. *Sci. Hort.*, **119**(3):297-301.
- KARATHANASIS, A. D., 1989, Solution chemistry of fragipans thermodynamic approach to understanding fragipan formation. *SSSA Spec. Publ.*, **24**:113-139.
- KATO, N., IMORI, H. AND OWA, N., 1996, The dissolution of calcium silicate slag fertilizers in flooded soil. *Jpn. J. Soil Sci. Plant Nutr.*, **67**:640-647 (in Japanese with English summary).
- KATO, N. AND OWA, N., 1996, Evaluation of Si availability in slag fertilizers by an extraction method using a cation exchange resin. *Soil Sci. plant Nutr.*, 43:351-357.
- KATO, N. AND OWA, N., 1998, Dissolution mechanism of silicate slag fertilizers in paddy soils. *Proc.* 14<sup>th</sup> International Congress of Soil Science., **4**:609-610.
- KHALID, R. A., SILVA, J. A. AND FOX, R. L., 1978, Residual effects of calcium silicate in tropical soils: II. Biological extraction of residual soil silicon. *Soil Sci. Soc. Am. J.*, 42:94-97.
- KHAN, M. H. R., BHUIYAN, M. M. A., KABIR, S. M., BLUME, H. P., OKI, Y. AND ADACHI, T., 2007, Consequences of basic slag on soil pH, calcium and magnesium status in acid sulfate soils under various water contents. J. Biol. Sci., 7(6):896-903.
- KHANDAKER, A, H., TAKATSUGU, H. AND SHUICHI, M., 2001, Effects of silicate materials on growth and grain yield of rice plants grown in clay loam and sandy loam soils. *J. Plant Nutr.*, **24**(1):1-13.
- KIM, Y. H., KHAN, A. L., SHINWARI, Z. K., KIM, D. H., WAQAS, M., MUHAMMAD, K. AND LEE, L., 2012, Silicon treatment to rice (*Oryza sativa*) plants during different growth periods and its effects on growth and grain yield. *Pak. J. Bot.*, 44(3):891-897.
- KINA, K., 1989, Fertility studies on soils of Okinawa in relation to sugarcane production.
  3. pH and soluble silica in dark red soils. *Sci. Bull. College of Agric. Univ. of Ryukyus, Okinawa*, **36**:25-31.
- KITTRICK, J. A., 1969, Soil minerals in the Al<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub>–H<sub>2</sub>O system and the theory of their formation. *Clays Clay Miner.*, **51**:1457-1466.
- KLOTZBUCHER, T., LEUTHER, F., MARXEN, A., VETTERLEIN, D., HORGAN, F. G. AND JAHN, R., 2015, Forms and fluxes of potential plant available silicon in

irrigated lowland rice production (Laguna, the Philippines). *Plant Soil*, **393**(1):177-191.

- KNIGHT, C. T. G. AND KINRADE, S. D., 2001, A primer on the aqueous chemistry of silicon. In: Datnoff LE, Snyder GH, Korndörfer GH (eds) Silicon in agriculture, Studies in plant science. Elsevier, Amsterdam, pp 8:57-84.
- KOMOR, S. C., 1994, Geochemistry and hydrology of a calcareous fen within the Savage Fen wetlands complex, Minnesota, USA. *Geochim. Cosmochim. Acta*, **58**: 3353-3367.
- KORNDORFER, G. H. AND GASCHO, L., 1999, Availability of Si from several sources determined by chemical and biological method. Agron Abstr., *Annual Meeting Am. Soc. Agron.*, Baltimore, 18-22 Oct, pp: 308.
- KORNDÖRFER, G. H., PEREIRA, H. S. AND NOLLA, A., 2005, Silicon analysis in soil, plant and fertilizers. Brazil, GPSi/ICIAG/UFU.
- KORNDORFER, G. H., SNYDER, G. H., ULLOA, M. AND DATNOFF, L. E., 2001, Calibration of soil and plant silicon for rice production. *J. Plant Nutr.*, **24**(7): 1071-1084.
- KORNDORFER, G. H., NOLLA, A. AND RAMOS, L. A., 2005, Available silicon in tropical soils and crop yield. *Proceedings of the Third Silicon in Agriculture Conference*; Uberlândia:Universidade Federal de Uberlândia. pp. 76-85.
- KRASKA, J. E. AND BREITENBECK, A. G., 2010, Survey of the silicon status of flooded Rice in Louisiana, *Agron. J.*, **102**:523-529.
- KRAUSKOPF, K. B., 1959, In HA Ireland (ed) Silica in sediments special publ 7 econ palenteologists mineralogists Oklahoma.
- KROGER, N., LORENZ, S., BRUNNER, E. AND SUMPER, M., 2002, Self-assembly of highly phosphorylated silaffins and their function in biosilica morphogenesis. *Science*, **298**:584-586.
- KROM, M., 1980, Spectrophotometric determination of ammonia; a study of modified Berthelot reaction using salicylate and dichloroisocyanurate", *The Analyst.*, **105**:305-316.
- KUMAR, B. H., 2008, Effect of silicon on nitrogen management in aerobic rice. *M.Sc.* (*Agri.*) *Thesis, Univ. Agric. Sci.*, Bengaluru, Karnataka, India.
- LAING, M. D., GATARAYIHA, M. C. AND ADANDONON, A., 2006, Silicon use for pest control in Agriculture. A review. *Proc. Afr. Sug. Technol. Ass.*, **80**:278.

- LAIRD, D. A., FLEMING, P., DAVIS, D. D., ROBERT, H., WANG, B. AND KARLEN, D. L., 2010a, Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, **158**:436-442.
- LAIRD, D. A., FLEMING, P., DAVIS, D. D., ROBERT, H., WANG, B. AND KARLEN, D. L., 2010b, Impact of biochar amendments on the quality of a typical midwestern agricultural soil. *Geoderma*, **158**:443-449.
- LANGLEY, T. S. J. AND BOCKHEIM, J. G., 1998, Mass balance of soil evolution on late Quaternary marine terraces in coastal Oregon. *Geoderma*, **84**:265-288.
- LEWIN, J. AND REIMANN, B. E. F., 1969, Silicon and Plant Growth. *Annu. Rev. Plant Physiol.*, **20**:289-304.
- LIAN, S., 1976, Silica fertilization of rice. The fertility of paddy soils and fertilizer applicatons for rice. Taipei: food fertilser technology center; pp. 197-220.
- LIANG, Y. C., CHEN, Q., LIU, Q., ZHANG, W. H. AND DING, R. X., 2003a, Exogenous silicon (Si) increases antioxidant enzyme activity and reduces lipid peroxidation in roots of salt-stressed barley (*Hordeum vulgare L.*). J. Plant Physiol., **160**:1157-1164.
- LIANG, Y., HUA, H., ZHU, Y. G., ZHANG, J., CHENG, C. AND ROMHELD, V., 2006, Importance of plant species and external silicon concentration to active silicon uptake and transport. *New Phytol.*, **172**:63-72.
- 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., NIKOLIC, M., BÉLANGER, R., GONG, H. AND SONG, A., 2015, *Silicon in Agriculture*. Dordrecht: Springer. pp: 1-235.
- LIANG, Y. C., SHEN Q. R. AND MA. T. S., 2003b, Effects of silicon on salinity tolerance of two barley cultivars. *J. Plant Nutr.*, **19**: 173-183.
- LIDSTROM, L., 1968, Surface and bond froming properties of quartz and silicate minerals and their application in mineral processing techniques. *Acta. Polytech. Scand. Chem. Metal. Ser.*, **75**:1-50.
- LINCA, A., HUSNAIN, ANTONIUS, K., SATO, K. AND TSUGIYUKI, M., 2016, Relationships between soil properties and rice growth with steel slag application in Indonesia. J. Agril. Sci., 8(5): 1-14.

- LINDSAY, W. L. AND SCHWAB, A. P., 1982, The chemistry of iron in soils and its availability to plants. *J. Plant. Nutr.*, **5**:821-840
- LINDSAY, W. L., 1979, Chemical equilibria in soil. John Wiley and Sons., New York.
- LINDSAY, W. L. AND NORVELL, W. A., 1978, Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci. Soc. Am. J.*, **42**:421-428.
- LUCAS, Y., LUIZAO, F. J., CHAUVEL, A., ROUILLER, J. AND NAHON, D., 1993, The relation between biological activity of the rainforest and mineralogical composition of soils. *Science*, **260**(5107):521-523.
- MA, J. F. AND TAKAHASHI, E., 1989, Release of silicon from rice straw under flooded conditions. *Soil Sci. Plant Nutr.*, **35**(4):663-667.
- MA, J. F., 2007, Plant Root Responses to Three abundant soil minerals: Silicon, aluminum and iron. *Critical Rev. Plant Sci.*, **24**(4):267-281.
- MA, J. F. AND TAKAHASHI, E., 1990, The effect of silicic acid on rice in a P deficient soil. *Plant Soil*, **126**:121-125.
- MA, J. F. AND TAKAHASHI, E., 2002, Soil, fertilizer, and plant silicon research in Japan. Elsevier, Amsterdam. 1<sup>st</sup> edition. pp. 1 -294.
- MA, J. F., MIYAKE, Y. AND TAKAHASHI, E., 2001, Silicon as a beneficial element for crop plants. Silicon in Agriculture. Ed. L. E. Datnoff, G. H. Snyder. and G. H Korndorfer, Elsevier Science, Amsterdam pp: 17-39.
- MA, J. F., NISHIMURA, K. AND TAKAHASHI, E., 1989, Effect of silicon on the growth of rice plant at different growth stages. *Soil Sci. Plant Nutr.*, **35**: 347-356.
- MA, J. F., TAMAI, K., ICHII, M. AND WU, K., 2002, A rice mutant defective in active Si uptake. *Plant Physiol.*, **130**:211-217.
- MA, J. F., TAMAL, K., YAMAJI, N., MITANI, N., KONISHI, S., KATUHARA, M., ISHIGURO, M. AND YANO, M., 2006, A Si transporter in rice. *Nature*, **440**: 688-691.
- MA, T. S., LI, F. J., LIANG, Y. C. AND CHEN, X. H., 1993, Silicon nutrient status and yield increase effect of silicon fertilizers. *Chin. J. Soil Sci.*, **24**:3-263.
- MA, Z., TOBIAS, I. B., KATHLEEN, M. B. AND JONATHAN, P. L., 2003, Regulation of Root Elongation under Phosphorus Stress Involves Changes in Ethylene Responsiveness. *Plant Physiol.*, **131**:1381-1390.

- MAFONGOYA, P., BARAK, P. AND REED, J. D., 2000, Carbon, nitrogen and phosphorus mineralization of tree leaves and manure. *Biol. Fertil. Soils*, **30**:298-305.
- MAKABE, S., KAKUDA, K., SASAKI, S., ANDO, T., FUJII, H. AND ANDO, H., 2009, Relationship between mineral composition or soil texture and available silicon in alluvial paddy soils on the Shounai Plain, Japan. *Soil Sci. Plant Nutr.*, 55:300-308.
- MARQUES, L. A., CATURLA, M. J., DE LA RUBIA, T. D. AND GILMER, G. H., 1996, Ion beam induced recrystallization of amorphous silicon: A molecular dynamics study. *J. Appl. Physics*, **80**(11):6160-6169.
- MARSCHENER, H., OBERLE, H., CAKMAK, I. AND ROMHELD, 1990, Growth enhancement by silicon in cucumber plants depends on imbalance in phosphorous and zinc supply. *Plant Soil*, **124**:211-219.
- MARSCHNER, H., 1995, Mineral nutrition of higher plants. 2<sup>nd</sup> edition. London: Academics Press, pp.1-889.
- MARTINA G., LIANG, W., SOMMER, M. AND KUZYAKOV, Y., 2013, Silicon uptake by wheat: Effects of Si pools and pH. *J. Plant Nutr. Soil Sci.*, **176**:551-560.
- MARXEN, A. T., KLOTZBUCHE, R. J., KAISER, K., NGUYEN, V. S., SCHMIDT, A., SCHADLER, M. AND VETTERLEIN, D., 2016, Interaction between silicon cycling and straw decomposition in a silicon deficient rice production system. *Plant Soil*, **398**:153-163.
- MASAHIKO, F. AND FEI, C., 2005, Effects of biogenic silica dissolution on silicon recycling and export production. *Geophysical Res. Letters*, **32**:1-4.
- MATICHENKOV, V. V., PINSKY, D. L. AND BOCHARNIKOVA, E. A., 1995, Influence of mechanical compaction of soils on the state and form of available silicon. *Euras. Soil Sci.*, **27**:58-67.
- MATICHENKOV, V. V. AND BOCHARNIKOVA, E. A, 2010, Technology for natural water protection against pollution from cultivated areas. *15<sup>th</sup> Annual Australian Agronomy Conference*, pp.15-18.
- MATICHENKOV, V. V., AMMOSAOVA, Y. M. AND BOCHARINKOVA, E. A., 2001, Influence of silicon fertilisation on soil and plants. *Agri. Chem.*, **12**:30-35.
- MAUAD, M., CRUSCIO, C. A. C., FILHO, H. G. AND CORREA, J. C., 2003, Nitrogen and silicon fertilization of upland rice. *Scientia Agricola*, **60**:1-4.

- McKEAGUE, J. A. AND CLINE, M. G., 1962, Silica in soil solutions-the form and concentration of dissolved silica in aqueous extracts of some soils. *Can. J. Soil Sci.*, **43**:70-81.
- McKEAGUE, J. A. AND CLINE, M. G., 2001, Silica in soil solution. II. The adsorption of mono silicic acid by soil and by other substances. *Can. J. Soil Sci.*, **43**:83.
- MECFEL, J., HINKE, S., GOEDEL, W. A., MARX, G., FEHLHABER, R., BAUCKER, E. AND WIENHAUS, O., 2007, Effect of silicon fertilizers on Si accumulation in wheat. *J. Plant Nutr. Soil Sci.*, **170**:769-772.
- MERCY, J. B., ELIZABETH, W. B., WILLIAM, H. M. AND CHARLES, A. H., 2006, Nitrogen and phosphorus budgets for a tropical watershed impacted by agricultural land use. *Biogeochemistry*, **79**:135-161.
- MERRITTS, D. J., CHADWICK, O. A., HENDRICKS, D. M., BRIMHALL, G. H. AND LEWIS, C. J., 1992, The mass balance of soil evolution on late quaternary marine terraces, northern California. *Geol. Soc. Am. Bull.*, **104**:1456-1470.
- MEUNIER, J. D., GUNTZER, F., KIRMAN, S. AND KELLER, C., 2008, Terrestrial plant-Si and environmental change. *Mineral. Mag.*, **72**(1):63-267.
- MEYER, J. H. AND KEEPING, M. G., 2001, The impact of silicon in alleviating biotic and abiotic stress in sugarcane in south Africa. *Proc. Int. Soc. Sugarcane Technol.*, **3**:42-46.
- MILES, N., MANSON A. D., RHODES, R., VAN, A. R. AND WELGEL, A., 2014, Extractable silicon in soils of the South African sugar industry and relationships with crop uptake. *Commun. Soil Sci. Plant Anal.*, **45**(22):2949-2958.
- MITANI, N., MA, J. F. AND IWASHITA, T., 2005, Identification of the Silicon Form in Xylem Sap of Rice (*Oryza sativa* L.). *Plant Cell Physiol.*, **46**:279-283.
- MOHANTHY, S. K., PATNAIK, S., RANGA REDDY, P. AND SRIDHAR, R., 1977, Effect of submergence on the chemical changes in different rice soils. *Acta. Agri. Acad. Sci.*, **26**:187-191.
- MONA, A. M., 2010, Sustainable effects of diatomite on the growth criteria and phytochemical contents of *Vicia faba* plants. *Agric. Biol. J. N. Am.*, **1**(5):1076-1089.
- MONGER, H. C. AND KELLY, E. F., 2002, Silica minerals, Chap. 20, in Dixon, J. B., Schulze, D. G.: Soil Mineralogy with environmental applications. Book Series SSSA No.7, Madison, WI, pp. 611-636.

- MORRIS, R. C. AND FLETCHER, A. B., 1987, Increased solubility of quartz following ferrous-ferric iron reactions. *Nature*, **330**:558-561.
- MOTOMURA, H., MITA, N. AND SUZUKI, M., 2002, Silica accumulation in longlived leaves of *Sasa veitchii* (carriere) *Rehder* (poaceae-bambusoideae). *Annals Bot.*, **90**:149-152.
- MUELLER, O.P. AND CLINE, M.G., 1959, Effects of mechanical soil barriers and soil wetness on rooting of irees and soil-mixing by blowdown in central New York. *Soil Sci.*, **88**:107-111.
- MUKTHAR, A., ATIF, K., ASIF, M., UMMARA, Q., IQBAL, Z. AND AKASH, G., 2013, Silicon priming, a potential source to impart abiotic stress tolerance in wheat. *Aust. J. Crop Sci.*, **7**(4):484-491.
- MUNIR, M., CARLOS, A. C. C., HEILO, G. F. AND JULIANO, C. C., 2003, Nitrogen and silicon fertilization of upland rice. *Sci. Agricola.*, **60**(4):1-10.
- NAIR, P. K. AND AIYER, R. S., 1968, Study of available silicon in rice soils of Kerala state (India). In: silicon uptake by different varieties of rice in relation to available silicon contributed by soil and irrigation water. *Agric. Res. J. Kerala*, **6**:88-99.
- NARAYANASWAMY, C., 2007, Calibration and categorization of plant available soil silicon in different rice ecosystems for evaluating drought and disease resistance rice genotypes. *Ph.D. Thesis Univ. Agric. Sci., Bangalore.*
- NAYAR, P. K., MISRA, A. K. AND PATNAIK, S., 1982, Silica in rice (*Oryza sativa* L.) and flooded rice soils. II. Uptake of silica in relation to growth of rice varieties of different durations grown on an Inceptisol. *Oryza*, **19**: 88-92.
- 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.
- NARAYANASWAMY, C. AND PRAKASH, N. B., 2009, Calibration and Categorization of Plant Available Silicon in Rice Soils of South India. *J. Plant Nutr.*, **32**(8):1237-1254.
- NGUYEN, M. H., BERT, H. J., OENE, O. B. AND DOBERMANN, A., 2006, Comparison of partial and complete soil K budgets under intensive rice cropping in the Mekong Delta, Vietnam. *Agric. Ecosyst. Envrn.*, **116**:121-131.
- NGUYEN, M. N., DULTZ, S. AND GUGGENBERGER, G., 2014, Effects of pretreatment and solution chemistry on solubility of rice-straw phytoliths. *J. Plant Nutr. Soil Sci.*, **177**:349-359.

- NOVAK, J. M., BUSSCHER, W. J., LAIRD, D. L., AHMEDNA, M., WATTS, D. W. AND NIANDOU, M. A. S., 2009, Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil Sci.*, **174**:105-112.
- OBIHARA, C. H. AND RUSSELL, E. W., 1972, Specific adsorption of silicate and phosphate by soils. *J. Soil Sci.*, **23**:105-117.
- OKUDA, A. AND TAKAHASHI, E., 1962, The role of silicon. In The Mineral Nutrition of the Rice Plant. Proc. Symposium of the International Rice Research Institute. Johns Hopkins Press. Baltimore, MD., pp.123-146.
- OLIVEIRA, L. A., KORNDORFER, G. H., CAMPOS, A. C. P., CHAGAS, R. S. AND JORGE, R. F., 2005, Silicon accumulation in rice under different rhizosphere pH conditions. *Second Silicon in Agriculture Conference*, **1**:31.
- OLIVEIRA, L. A., KORNDÖRFER, G. H. AND PEREIRA, A. C., 2007, Acumulação de silício em arroz em diferentes condições de pH da rizosfera. *Revista Brasileira de Ciência do Solo*, **31**:685-690.
- OLSEN, 1954, Determination of total organic and available forms of phosphorus in soils. *Soil Sci.*, **59**:39-45.
- OYA, K. AND KINA, K., 1989, Fertility studies on soils of Okinawa in relation to sugarcane production. 3. pH and soluble silica in dark red soils. *Sci. Bull.* College of Agric. Univ. of Ryukyus, Okinawa, **36**:25-31.
- OYA, K., KUROSHIO, K. AND HOKAMA, Y., 1989, Fertility studies on soils of Okinawa in relation to sugarcane production. 2. Soil pH and soluble silica. *Sci. Bull.College of Agric. Univ. of Ryukyus, Okinawa*, **36**:19-23.
- PAGE, A. L., MILLE, R. H. AND KEENEY, 1982, Methods of Soil Analysis. 2nd Edn., Ame. Soc. Agron, Madison, WI., USA.
- PAQUET, H. AND CLAUER, N., 1997, Soils and sediments. Springer Verlag, Berlin.
- PATI, S., BIPLAB, P., SHRIKANT, B., GORA, HAZRA, C. AND BISWAPATI, M., 2016, Effect of Silicon Fertilization on Growth, Yield, and Nutrient Uptake of Rice. *Commun. Soil Sci. Plant Anal.*, 47(3):284-290.
- PEREIRA, H. S., KORNDORFER, G. H., DOS REIS, C. B. AND CORREA, G. F., 2004, Silicon sources for rice crop. *Biosci. J. Uberlandia*, **20**:47-56.
- PETRA, T., MARIA, L. AND VIRPI, S., 2010, Distribution of silicon in soils and sediments of a small catchment area: similarities and differences. 19th World

Congress of Soil Science, Soil Solutions for a Changing World 1-6 August, Brisbane, Australia.

- PIPERNO, D. R., HOLST, I., WESSEL-BEAVER, L. AND ANDRES, T. C., 2002, Evidence for the control of phytolith formation in cucurbita fruits by the hard rind (hr) genetic locus: Archaeological and ecological implications. *Proceedings of the National Academy of Sciences of the United States of America*, **99**:10923-10928.
- POKROVSKI, G. S., SCHOTT, J., FARGES, F. AND HAZEMANN, J. L., 2003, Iron (III)-silica interactions in aqueous solution: Insights from X-ray absorption fine structure spectroscopy. *Geochim. Cosmochim. Acta*, 67: 3559-3573.
- PONNAMPERUMA F.N., 1972, The Chemistry of submerged soils. *Adv. Agron.*, **24**:29-96.
- PRAKASH, N. B., 2002, Status and utilization of silicon in Indian rice farming. *Japanese Soc. Soil Sci. Plant Nutr.*, **1**:266-273.
- PRAKASH, N. B., CHANDRASHEKAR, N., MAHENDRA, C., PATIL, S. U., THIPPESHAPPA, G. N. AND LAANE, H. M., 2011, Effect of foliar spray of soluble silicic acid on growth and yield parameters of wetland rice in hilly and coastal zone soils of Karnataka, south India. J. Plant Nutr., 34:1883-1893.
- PRAKASH, N. B., NAGARAJ, H., GURUSWAMY, K. T., VISHWANATHA, B. N., NARAYANASWAMY, C., GOWDA, N. A. J., VASUKI, N. AND SIDDARAMAPPA, R., 2007, Rice hull ash as a source of silicon and phosphatic fertilizers: effect on growth and yield of rice in coastal Karnataka, India. *IRRN*, 32(1):34-36.
- PRAKASH, N. B., NARAYANASWAMY, C. AND CHANDRASHEKAR, N., 2010, Status, Calibration, and categorization of plant available silicon in different rice soils of Karnataka. Technical Bulletin from Department of Soil Science and Agricultural Chemistry, University of Agricultural Sciences, Bangalore, India.
- PRASANTA, K. P. AND NEUE, U. N., 2009, 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.
- PULAKESHI, H. B. P., PATIL P. L. AND DASOG, G. S., 2014, Characterization and classification of soil resources derived from chlorite schist in northern transition zone of Karnataka. *Karnataka J. Agric. Sci.*, **27**(1):14-21.
- PULAKESHI, H. B. P., PATIL, P. L., DASOG, G. S., RADDER, B. M., BIDARI, B. I. AND MANSUR, C. P., 2012, Mapping of nutrients status by geographic

information system (GIS) in Mantagani village under northern transition zone of Karnataka. *Karnataka J. Agric. Sci.*, **25**(3):332-335.

- QUAN, W. J., ZOU, Q. AND DU, C. X., 1999, Available silicon content in soil and its distribution in Shandong province. *Shandong Agric. Sci.*, **5**:4-11.
- QIN, F. J., WANG, F., LU, H., CEN, T. X., WANG, B., HAN, H. X., ZHUANG, Y. Q. AND ZHANG, H., 2012, study on available silicon contents in cultivated land and its influencing factors in Ningbo City. *Acta. Agric. Zhejiangenesis.*, **24**:7-263.
- RAID, R. N., ANDERSON, D. L. AND ULLOA, M. F., 1992, Influence of cultivar and amendment of soil with calcium silicate slag on foliar disease development and yield of sugarcane. *Crop Protection*, **11**(1): 84-88.
- RAIJ, B. AND CAMARGO, O. A., 1973, Sílica solúvel em solos. *Bragantia*, **32**:223-236.
- RAJANNA, M. P., 2013, Recent Rice Varieties and Hybrids of Karnataka. Zonal Agricultural Research Station, Mandya, Bangalore, India: University of Agriculture Science.
- RANGASWAMY, R., 2010, A textbook of agricultural statistics. 2<sup>nd</sup> edition.
- RANI, A., NARAYANAN, A., SARASWATHIDEVI, V. AND SUBBARAMAMMAM, P., 1997, The effect of silicon application on growth and yield of rice plants. *Ann. Rev. Plant Physiol.*, **11**(2):123-128.
- RAVEN, J. A., 2003, Cycling silicon-the role of accumulation in plants. *New Phytol.*, **158**:419-430.
- REDDY, K. R. AND PATRICK, W. H., 1983, Effects of aeration on reactivity and mobility of soil constituents. *In Chemical Mobility and Reactivity in Soil System.*,11-33. ASA, SSSA, 677 South Segoe Road, Madison, WI 53711.
- REMUS-BOREL, W., JAMES, G. M., RICHARD, R. AND BELANGER, 2005, Silicon induces anti-fungal compounds in powdery mildew-infected wheat. *Physiol. Mol. Plant Pathol.*, **66**:108-115.
- RIBEIRO, A. C., FIRME, D. J. AND MATTOS, A. C. M., 1986, Avaliacao da efficiencia de uma escoria de aciaria como corretivo da acidez do solo. *R. Ceres.*, **33**:242-246.
- RICHMOND, K. E. AND SUSSMAN, M., 2003, Got silicon? The non-essential beneficial plant nutrient. *Curr. Opinion Plant Biol.*, **6**:268-272.

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- RIISE, G., VAN HEES, P., LUNDSTRÖM, U. AND STRAND, L. T., 2000, Mobility of different size fractions of organic carbon, Al, Fe, Mn and Si in podzols. *Geoderma*, 94(2):237-247.
- RIOTTE, J., MARECHAL J. C., AUDRY, S., KUMAR, C., BEDIMO, J. P., RUIZ, L., SEKHAR, M., CISEL, M., CHITRA TARAK, R., VARMA, M. R. R., LAGANE, C., REDDY, P. AND BRAUN, J. J., 2014, Vegetation impact on stream chemical fluxes: Mule Hole watershed (South India). *Geochim. Cosmochim. Acta*, pp.1-10.
- ROCHA, L. C. M., PRADO, R. M. AND ALMEIDA T. B. F., 2011, Residual effect of slag as source of silicon for sorghum, *Magazine FZVA*. Uruguaiana, 18(2):101-115.
- RODRIGUES, F. A., MCNALLY, D. J., DATNOFF, L. E., JONES, J. B., LABBE, C., BENHAMOU, N., MENZIES, J. G. AND BELANGER, R. R., 2004, Silicon enhances the accumulation of diterpenoid phytoalexins in rice: A biochemical mechanism for blast resistance. *Phytopathology*, 94:177-183.
- ROMERO-ARANDA, M. R., JURADO, O. AND CUARTERO, J., 2006, Silicon alleviates the deleterious salt effect on tomato plant growth by improving plant water status. *J. Plant Physiol.*, **163**:847-855.
- RUCKERT, E., 1992, Na-bleichung und Tonzerstörung durch Ferrolysis n Stauwasserböden Baden-Württembergs? Hohenheimer Bodenkundliche Hefte, 3:1-178.
- SADIQ, M., BLEDSOE, B. E. AND ENFIELD, C. G., 1980, Solubility relationships of silica in soils. *Commun. Soil Sci. Plant Anal.*, **11**:317-326.
- SAHRAWAT, K. L., 1983, Nitrogen availability indexes for submerged rice soils. *Adv. Agron.*, **36**:415-451.
- SAHRAWAT, K. L., 2005 Fertility and organic matter in submerged rice soils. *Curr. Sci.*, **88**:735-738.
- SAHU, S. K., 1990, Effect of silica and phosphorus application on yield and phosphorus nutrition of rice. *IRRN*, **15**(1): 25.
- SAIGUSA, M., AKIKO, Y. AND KYOICHI, S., 2000, Change of Structure of Porous Hydrated Calcium Silicate by Dissolution in Paddy. *Soil Sci. Plant Nutr.*, **46**(1), 89-95.
- SANGSTER, A., HODSON, M. AND TUBB, H., 2001, Silicon deposition in higher plants. *Studies Plant Sci.*, **8**:85-113.
- SARTO, M. V. M., LANA, M. C., RAMPIM, L., ROSSET, J. S., WOBETO, J. R., ECCO, M., BASSEGIO, D. AND COSTA, P. F., 2014, Effect of silicate on nutrition and yield of wheat. *African J. Agri. Res.*, **9**(11):956-962.
- SASAKI, S. M., KEN, I. K., YUKA, S. AND ANDO, H., 2014, Effects of slag silicate fertilizer on silicon content of rice plants grown in paddy fields on the Shounai Plain, Yamagata, Japan, *Soil Sci. Plant Nutr.*, **60**:5708-721.
- SATTAR, A., MUMTAZ, A., CHEEMA, S. M. A., BASRA AND WAHID, A., 2013 Optimization of source and rate of soil applied silicon for improving the growth of wheat, *Pak. J. Agri. Sci.*, **50**(1):63-68.
- SAUER, D., SACCONE, L., CONLEY, D. J., HERRMANN, L. AND SOMMER, M., 2006, Review of methodologies for extracting plant-available and amorphous Si from soils and aquatic sediments. *Biogeochemistry*, **80**(1):89-108.
- SAVANT, A. S., PATIL, V. H. AND SOWRAT, 1994, Rice hull ash applied to seedbed reduces dead heart in transplanted rice. *Int. Rice. Res. Notes.*, 21-22.
- SAVANT, N. K., DATNOFF, L. E. AND SNYDER, G. H., 1997, Depletion of plant available silicon in soils: A possible cause of declining rice yields. *Commun. Soil Sci. Plant Anal.*, 28(13 & 14):1245-1252.
- SCHWANDES, L. P., SNYDER, G. H. AND WILKERSON, J., 2001, Plant-available silicon in selected alfisols and ultisols of Florida. *Soil Crop Sci. Soc. Florida Proc.*, **60**:57-59.
- SCHWER, P., 1994, Untersuchungen zur Modellierung der Bodenneubildungsrate auf Opalinuston des Basler Tafeljura. *Physiogeographica*, **18**:1-208.
- SCHWERTMANN, U., 1991, Solubility and dissolution of iron-oxides. *Plant Soil*, **130**:1-25.
- 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. *Geochem. Cosmochem. Acta*, **123**:120-133.
- SHARMA, Y. K., KAMATH, M. B. AND GOSWAMI, N. N., 1991, Phosphorus utilization by soybean from super phosphate and diammonium phosphate amended with silicate and biogas slurry. *J. Indian Soc. Soil Sci.*, **39**:710-714.
- SHEN, Y. Z., PAN, W. Q., XU, J. B. AND FU, C. C., 1994, Dynamic changes of soil available silicon over last decade in Yangzhou City and application of silicon fertilizers to rice. *Soil Fertil.*, **5**:6-23.

- SHUHEI, M., S., KEN-ICHI, K., SASAKI, Y. AND ANDO, H., 2013, Effect of slag silicate fertilizer on dissolved silicon in soil solution based on the chemical properties of Gleysols. *Soil Sci. Plant Nutr.*, 1-7.
- SILBER, A., LEVKOVITCH, I. AND GRABER, E. R., 2010, pH dependent mineral release and surface properties of corn straw biochar: Agronomic implications. *Environ. Sci. Technol.*, **44**:9318-9323.
- SINGH, K. K., RAGEVENDRA, S., YOGESHWAR, S. AND SINGH, C. S., 2006, Response of nitrogen and silicon levels on growth, yield attribute and nutrient uptake of rice (*Oryza sativa* L.). *Oryza*, **43**:220-223.
- SINGH, K. K. AND SINGH, K., 2005, Effect of N and Si on growth, yields attribute and yield of rice in alfisols. *IRRN*, **12**:40-41.
- SINGH, K. K., SINGH, K., SINGHL, R. S., RAGHAVENDRA, S. AND CHANDEL, R. S., 2005, Silicon nutrition in rice a review. *Agric. Rev.*, **26**(3):223-228.
- SISTANI, K. R., SAVANT, N. K. AND REDDY, K. C., 1997, Effect of rice hull ash silicon on rice seedling growth. *J. Plant Nutr.*, **20**(1):195-200.
- SISTANI, K. R., TORBERT, H. A., WAY, T. R., BOLSTER, C. H., POTE, D. H. AND WARREN, J. G., 2008, Broiler litter application method and runoff timing eff ects on nutrient and Escherichia coli losses from tall fescue pasture. *J. Environ. Qual.* 38:1216-1223.
- SNYDER, G. H., JONES, D. B. AND GASCHO, G. J., 1986, Silicon fertilization of rice on Everglades Histosols. Soil Sci. Soc. Am. J., 50:1259-1263.
- SOMMER, M., 2002, Biogeochemie bewaldeter Einzugsgebiete und ihr pedogenetischer Kontext. *Hohenheimer Bodenkundliche Hefte*, **65**:1-227.
- SOMMER, M., D., KACZOREK, Y. K. AND BREUER, J., 2006, Silicon pools and fluxes in soils and landscapes A review. J. Plant Nutr. Soil Sci., **169**:310-329.
- SORATTO, R. P., CRUSCIOL, C., CASTRO, G., COSTA., H. M. AND NETO, F. J., 2012, Leaf application of silicic acid to white oat and wheat. *Rev. Bras. Ci. Solo.*, **36**(5):1538-1544.
- STONESTROM, D. A., WHITE, A. F. AND AKSTIN, K. C., 1998, Determining rates of chemical weathering in soils – solute transport versus profile evolution. J. Hydrol., 209:331-345.
- STRUYF, E., ADRIAAN, S., STEFAN, V. D., PATRICK, M. AND DANIEL, J. C., 2009, The global biogeochemical silicon cycle. *Silicon*, **1**:207-213.

- SU, C., HARSH, J. B. AND BOYLE, J. S., 1995, Solubility of hydroxyaluminum interlayers and imogolite in a Spodosol. *Soil Sci. Soc. Am. J.*, **59**:373-379.
- SUBBIAH, A. Y. AND ASIJA, G. K., 1949, Available nitrogen: alkaline permanganate method. *Curr. Sci.*, **25**:254-260.
- SUBRAMANIAN, S. AND GOPALASWAMY, A., 1991, Effect of moisture, organic matter, phosphate and silicate on availability on silicon and phosphorus in rice soils. *J. Indian Soc. Soil Sci.*, **39**:99-103.
- SUKRISTIYONUBOWO, LAING, G. D. AND VERLOO, M. G., 2010, Nutrient balances of wetland rice fields for the Semarang district (Indonesia). J. Sust. Agric., 34(8):50-861.
- SUMIDA, H., 1991, Characteristics of silica dissolution and absorption in paddy soils: Application to soil test for available silica. *Japanese J. Soil Sci. Plant Nutr.*, 62:378-385. (Japanese language).
- TAKAHASHI, E., 1996. Uptake mode and physiological functions of silica in rice plant. *Food Agric.*, **2**:420-433.
- 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.
- TAKAHASHI, T. AND SATO, A., 2000, Silicon fertility of paddy fields in Hachirogata Reclaimed Land, Akita Prefecture. *Jpn. J. Soil Sci. Plant Nutr.*, **71**:881-883 (in Japanese).
- TAKAJIMA, Y., WIJAYARATHNA, H. M. S. AND SENEVIRATNE, C. J., 1970, Nutrient deficiency and physiological disease of low land rice in Ceylon. III. Effect of silicate fertilizers and dolomite for increasing yields. Soil Sci. Plant Nutr., 16:11-16.
- TALASHILKAR, S. G. AND CHAVAN, R., 1956, Effect of rice hull ash on yield and uptake of silicon and phosphorus by rice cultivars at different growth stages. *J. Indian Soc. Soil Sci.*, **44**:271-276.
- TALIBUDEEN, O., 1981, Cation exchange in soils John willey and Sons, New York. pp: 115-177.
- TAVAKKOLI, E., LYONS, G., ENGLISH, P. AND GUPPY, C. N., 2011, Silicon nutrition of rice is affected by soil pH, weathering and silicon fertilisation. *J. Plant Nutr. Soil Sci.*, **174**:437-446.

- THEODORE CHAPPEX AND KAREN SCRIVENER, L., 2012, The influence of aluminium on the dissolution of amorphous silica and its relation to alkali silica reaction. *Cement Concrete Res.*, **42**:1645-1649.
- TREGUER, P., NELSON, D. M., VAN BENNEKOM, A. J, DE MASTER, D. J., LEYNAERT, A. AND QUÉGUINER, B., 1995, The silica balance in the world ocean: A estimate. *Science*, **268**:375-379.
- TYNER, J. S., BROWN, G. O., VOGEL, J. R. AND GARBRECHT, J., 2000, Chloride mass balance to determine Water fluxes beneath KCl fertilized Crops. *Transactions Am. Soc. Agric. Eng.*, **43**(6):1553-1559.
- VAN HOEST, P. J., 2006, Rice straw, the role of silica and treatments to improve quality. *Animal Feed Sci. Tech.*, **130**:137-171.
- VAN ZWIETEN, L., KIMBER, S., DOWNIE, A., MORRIS, S., PETTY, S., RUST, J. AND CHAN, K. Y., 2010, A glasshouse study on the interaction of low mineral ash biochar with nitrogen in a sandy soil. *Australian J. Soil Res.*, 48(6-7):569-576.
- VANDEVENNE, F. I. L., BARAO, B. R., GOVERS, G., MEIRE, P., KELLY, E. F. AND STRUYF, E., 2015, Silicon pools in human impacted soils of temperate zones. *Global Biogeochem.*, *Cycles*, **29**:1-12.
- VEERHOFF, M., 1992, Silicatverwitterung und Veränderung des Tonmineralbestandes in Waldböden als Folge von Versauerungsvorgängen. *Bonner Bodenkundliche Abhandlungen*, **8**:1-249.
- VEERHOFF, M. AND BRUMMER, G. W., 1993, Bildung schlechtk- € ristalliner bis amorpher Verwitterungsprodukte in stark bis extrem versauerten Waldboden (Formation of poorly crystallized weathering products in strongly to extremely acid forest soils). Z. *Pflanzenernahr. Bodenk.*, **156**:11-17.
- WADA, K., 1989, Allophane and imogolite, Chap. 21, in Dixon, J. B., Weed, S. B. (eds.): Minerals in soil environments. SSSA Book series No.1, Madison, WI, pp. 1051-1088.
- WALKLEY, A. J. AND BLACK, C. A., 1934, An examination method for determination soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.*, **37**:29-38.
- WAN, X. S., HE, D. Y. AND LIAO, X. L., 1993, Silicon forms of soils in Hunan provence in relation to soil properties. *Soils*, **25:**51-146.
- WANG, W., LAI, D. Y. F., LI, S., KIM, P. J., ZENG, C., LI, P. AND LIANG, Y., 2014, Steel slag amendment reduces methane emission and increases rice productivity

in subtropical paddy fields in China. Wetlands Ecol. Manage. *Field Crops Res.*, **171**:146-156.

- WELCH, S. A. AND ULLMAN, W. J., 1993, The effect of organic acids on plagioclase dissolution rates and stoichiometry. *Geochim. Cosmochim. Acta*, **57**:2725-2736.
- WHITE, A. F. AND BRANTLEY, S. L., 1995, Chemical Weathering Rates of Silicate Minerals. Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C. 31: pp. 584.
- WICKRAMASINGHE, D. B. AND ROWEL, D. L., 2006, The release of silicon from amorphous silica and rice straw in Sri Lankan soils. *Biol. Ferti. Soils*, **42**:231-240.
- WILDING, L. P., HALLMARK, C. T. AND SMECK, N. E., 1979, Dissolution and stability of biogenic opal. *Proc. Soil Sci. Soc. Am.*, **43**:800-802.
- WINSLOW, M. D., 1992, Silicon, disease resistance and yield of rice genotypes under upland cultural conditions. *Crop Sci.*, **32**:1208-213.
- WINSLOW, M. D., OKADA, K., AND CORREA-VICTORIA, F., 1997, Silicon availability and response of rice and wheat to silicon in calcareous soils. *Commun. Soil Sci. Plant Anal.*, **25**:2285-2297.
- XIN, X., BAOLIANG, C. AND LIZHONG, Z., 2014, Transformation, morphology and dissolution of silicon and carbon in rice straw-derived biochars under different pyrolytic temperatures. *Environ. Sci. Technol.*, **48**:3411-3419.
- YAMATO, M., OKIMORI, Y., WIBOWO, I. F., ANSHIORI, S. AND OGAWA, M., 2006, Effects of the application of charred bark of acacia mangium on the yield of maize, cowpea and peanut, and soil chemical properties in south Sumatra, Indonesia. *Soil Sci. Plant. Nutr.*, **52**:489-495.
- YOSHIDA, S., NAVESER, S. A. AND RAMIREZ, E. A., 1969, Effect of silicon on nitrogen supply on some leaf characters of rice plant. *Plant Soil*, **31**:48-56.
- YOSHIDA, S., OHNISHI, Y. AND KITAGISHI, K. 1962, Histochemistry of silicon and the adaptation of tropical rice ecotypes. *Plant Soil*, **188**:239-248.
- YU, Q. Y., LI, X. L. AND ZANG, Y. L., 1998, available silicon distribution and affecting factors in paddy soils of Anhui provence. *J. Anhui Agrotech. Coll.*, **12**:5-9.
- ZENG, L., 1998, Available silicon content and its distribution in cultivated soils in Anhui province. *Chin. J. Soil Sci.*, 29:**8**-126.

- ZHANG, F. S., SHEN, A. L. AND LIU, C. Z., 1996, A preliminary study of the effect of silicon application to rice in the rice growing area along the Haunghe River. J. *Henan Agri. Sci.*, 10:14-15.
- ZHANG, H. L., 1987, A preliminary study on changes in soil available silicon content. *Soils*, **19**:5 -123.
- ZHENG, H., WANG, Z., XIA, D., ZHAO, J., LUO, Y., NOVAK, J., STEPHEN, H. AND XING, B., 2013, Characteristics and nutrient values of biochars produced from giant reed at different temperatures. *Bioresour. Technol.*, **130**: 463-471.
- ZHONGQIU, Z., YONGGUAN, Z. AND YUNLONG, C., 2005, Transport and transformation of cadmium in soil –plant systems and the influence factors. *Ecol. Env. Sci.*, **14**:282-286.
- ZHU, J. K., WEI, G. Q., LI, J., QIAN, Q. Q. AND YU, J. Q., 2004 Silicon alleviates salt stress and increases antioxidant enzymes activity in leaves of salt-stressed cucumber (Cucumis sativus L.). pp.26-32.
- ZHURAVLEV L.T., 2000, The surface chemistry of amorphous silica. Zhuravlev model. Colloids and Surfaces A: Physicochem. *Eng. Aspects*, **173**:1-38.
- ZIEGLER, K., CHADWICK, O. A., BRZEZINSKI, M. A. AND KELLY, E. F., 2005, Natural variations of δ30Si ratios during progressive basalt weathering, Hawaiian Islands. *Geochim. Cosmochim. Acta*, **69**:4597-4610.
- ZYSSET, M., BLASER, P., LUSTER, J. AND GEHRING, A. U., 1999, Aluminum solubility control in different horizons of a Podzol. *Soil Sci. Soc. Am. J.*, **59**:373-379.

## **ANNEXURE I**

## Zone wise sampling area, geographical location, altitude and cropping system in soil

| Sl. No.  | Sampling Area        | Village Name     | Latitude (N-S) Longitude (E –W) | Altitude | Cropping system |
|----------|----------------------|------------------|---------------------------------|----------|-----------------|
| North Ea | stern Dry Zone (NED2 | <u>Z)</u>        |                                 |          |                 |
| Raichur  |                      |                  |                                 |          |                 |
| 1.       | Deodurga             | Joladagadagi     | N 16°29'24.3", E 076°55'49.8"   | 390m     | Rice            |
| 2.       | Deodurga             | Bunkaladoddi     | N 16°22'04.8", E 076°41'22.7"   | 385m     | Rice            |
| 3.       | Deodurga             | Chinchodi        | N 16°22'53.5", E 076°43'27.3"   | 395m     | Rice            |
| 4.       | Deodurga             | Jaalahalli       | N 16°22'04.1", E 076°47'25.5"   | 410m     | Rice            |
| 5.       | Manvi                | Neeramanavi      | N 16°02'06.5", E 077°05'23.3"   | 363m     | Rice            |
| 6.       | Manvi                | Hokrani cross    | N 16°06'21.7", E 077°10'27.4"   | 372m     | Rice            |
| 7.       | Manvi                | Kappagal         | N 16°03'04.1", E 077°07'25.0"   | 355m     | Rice            |
| 8.       | Manvi                | Manvi            | N 16°00'09.2", E 077°03'41.5"   | 363m     | Rice            |
| 9.       | Manvi                | Nandihaala       | N 15°59'08.0", E 076°59'37.7"   | 380m     | Rice            |
| 10.      | Manvi                | Kavithala        | N 15°57'32.3", E 076°56'43.3"   | 389m     | Rice            |
| 11.      | Raichur              | Hunishihaalahuda | N 16°11'47.8", E 077°15'02.6"   | 413m     | Rice            |
| 12.      | Raichur              | Kasbe camp       | N 16°09'37.7", E 077°14'59.0"   | 400m     | Rice            |
| Yadgir   |                      |                  |                                 |          |                 |
| 13.      | Shahpur              | Saavooru         | N 16°33'54.2", E 076°52'44.8"   | 378m     | Rice            |
| 14.      | Shahpur              | Khanapura        | N 16°42'45.5", E 077°00'59.6"   | 383m     | Rice            |
| 15.      | Shahpur              | Kongoddi         | N 16°35'05.2", E 076°51'55.8"   | 392m     | Rice            |
| 16.      | Shahpur              | Hattiguru        | N 16°35'38.9", E 076°52'14.5"   | 417m     | Rice            |
| 17.      | Shahpur              | Hattiguru        | N 16°35'32.2", E 076°51'54.6"   | 427m     | Rice            |

| 18.      | Shorapur           | Mandagali        | N 16°34'22.3", E 076°50'27.8" | 405m | Rice |
|----------|--------------------|------------------|-------------------------------|------|------|
| 19.      | Shorapur           | Krishnapura      | N 16°33'36.9", E 076°49'32.5" | 387m | Rice |
| 20.      | Yadgir             | Gurushinigi      | N 16°44'04.4", E 077°04'55.8" | 376m | Rice |
| 21.      | Yadgir             | Ramasamudra      | N 16°46'31.9", E 077°13'27.4" | 422m | Rice |
| 22.      | Yadgir             | Mylapura         | N 16°45'23.7", E 077°14'07.0" | 432m | Rice |
| 23.      | Yadgir             | Hosalli          | N 16°43'09.7", E 077°14'35.6" | 400m | Rice |
| Northern | Dry zone (NDZ)     |                  |                               |      |      |
| Raichur  |                    |                  |                               |      |      |
| 24.      | Lingasugur         | Karadakal        | N 16°09'33.2", E 076°30'23.4" | 472m | Rice |
| 25.      | Lingasugur         | Lingasuru        | N 16°10'01.1", E 076°31'31.5" | 494m | Rice |
| 26.      | Lingasugur         | Gowduru          | N 16°17'00.2", E 076°38'06.8" | 455m | Rice |
| 27.      | Sindhunur          | Badignuru        | N 15°54'07.6", E 076°51'59.8" | 372m | Rice |
| 28.      | Sidhanuru          | Thayamma camp    | N 15°47'49.5", E 076°46'45.8" | 420m | Rice |
| Bellary  |                    |                  |                               |      |      |
| 29.      | Siruguppa          | Imranpura        | N 15°39'34.2", E 076°54'08.2" | 433m | Rice |
| 30.      | Sandur             | Bandri           | N 14°58'48.0", E 076°27'02.2" | 618m | Rice |
| 31.      | Sandur             | Kurekuppa        | N 15°12'21.8", E 076°39'15.0" | 442m | Rice |
| 32.      | Hospete            | Dhanapura        | N 15°09'42.3", E 076°21'53.1" | 515m | Rice |
| 33.      | Hospete            | Nandibandigrama  | N 15°08'39.4", E 076°19'06.9" | 513m | Rice |
| 34.      | Bellary            | Eethalbayi       | N 15°06'35.7" ,E 076°54'10.3" | 418m | Rice |
| 35.      | Hagaribommanahalli | Upanayakanahalli | N 15°07'33.1", E 076°15'26.0" | 502m | Rice |
| 36.      | Kudligi            | Ramadurga        | N 14°50'45.6", E 076°33'08.1" | 674m | Rice |
| 37.      | Kudligi            | Gudekote         | N 14°49'46.6", E 076°36'59.5" | 616m | Rice |

| Корра  | 1                |                   |                               |       |      |
|--------|------------------|-------------------|-------------------------------|-------|------|
| 38.    | Koppal           | Boodugunda        | N 15°23'58.3", E 076°19'14.6" | 509m  | Rice |
| 39.    | Koppal           | Jabbalagudda      | N 15°25'41.6", E 076°21'49.9" | 516m  | Rice |
| 40.    | Gangavati        | Karatagi          | N 15°35'41.8", E 076°39'26.5" | 475m  | Rice |
| 41.    | Gangavathi       | Siddhapura        | N 15°32'48.1", E 076°38'17.9" | 466m  | Rice |
| 42.    | Gangavathi       | Chikkabanakal     | N 15°26'01.4", E 076°25'47.3" | 492m  | Rice |
| Centra | l Dry Zone (CDZ) |                   |                               |       |      |
| Davana | agere            |                   |                               |       |      |
| 43.    | Davanagere       | Mallenahalli 1    | N 14°19'29.9", E 076°00'40.0" | 626 m | Rice |
| 44.    | Davanagere       | Mallenahalli 2    | N 14°19'29.4", E 076°00'39.5" | 613 m | Rice |
| 45.    | Davanagere       | Kabburu           | N 14°19'29.1", E 076°00'38.7" | 613 m | Rice |
| 46.    | Davanagere       | Athigere 1        | N 14°19'25.8", E 076°00'00.2" | 603 m | Rice |
| 47.    | Davanagere       | Athigere 2        | N 14°19'24.5", E 075°59'59.7" | 602 m | Rice |
| 48.    | Davanagere       | Chikkathogalare   | N 14°21'08.7", E 075°58'44.6" | 617 m | Rice |
| 49.    | Harihar          | Doddabathi 1      | N 14°28'30.5", E 075°51'52.5" | 570 m | Rice |
| 50.    | Harihar          | Doddabathi 2      | N 14°28'32.4", E 075°51'54.8" | 567 m | Rice |
| 51.    | Harihar          | Malebennur        | N 14°20'39.5", E 075°44'14.4" | 635 m | Rice |
| 52.    | Harihar          | Nittur 1          | N 14°22'08.5", E 075°46'45.2" | 587 m | Rice |
| 53.    | Harihar          | Nittur 2          | N 14°21'30.4", E 075°45'38.0" | 591 m | Rice |
| Chitra | durga            |                   |                               |       |      |
| 54.    | Hiriyur          | Vanivilasa sagara | N 13°53'58.6", E 076°29'33.3" | 632 m | Rice |
| 55.    | Hiriyur          | Hucchehalli       | N 13°56'22.9", E 076°30'39.4" | 661 m | Rice |
|        |                  |                   |                               |       |      |

| Tumku  | ır               |                    |                               |       |                        |
|--------|------------------|--------------------|-------------------------------|-------|------------------------|
| 56.    | Tiptur           | Nonavina kere 1    | N 13°09'45.6", E 076°34'58.8" | 815 m | Rice                   |
| 57.    | Tiptur           | Nonavinkere 2      | N 13°09'48.1", E 076°33'58.6" | 816 m | Rice                   |
| 58.    | Sira             | Kalambella         | N 13°09'45.6", E 076°34'58.8" | 726 m | Rice                   |
| Easter | n Dry Zone (EDZ) |                    |                               |       |                        |
| Kolar  |                  |                    |                               |       |                        |
| 59.    | Mulbagal         | Avani 1            | N 13°09'48.1", E 076°33'58.6" | 819m  | Rice – ragi            |
| 60.    | Mulbagail        | Avani 2            | N 13°09'45.6", E 076°34'58.8" | 819m  | Rice – fodder maize    |
| 61.    | Mulbagal         | Devarayanasamudra  | N 13°09'48.1", E 076°33'58.6" | 809m  | Rice                   |
| 62.    | Mulbagal         | Keelaholeli        | N 13°09'45.6", E 076°34'58.8" | 805m  | Rice – tomato          |
| Tumku  | ır               |                    |                               |       |                        |
| 63.    | Tumkur           | Heggaraevada       | N 13°09'48.1", E 076°33'58.6" | 789 m | Rice-Ragi              |
| 64.    | Gubbi            | Bayachanahalli     | N 13°09'45.6", E 076°34'58.8" | 784 m | Rice                   |
| Chikka | aballapur        |                    |                               |       |                        |
| 65.    | Bagepalli        | Mugachinapalli – 2 | N 13°09'48.1", E 076°33'58.6" | 751 m | Rice-Maize-Potato      |
| 66.    | Bagepalli        | Mugachinapalli – 1 | N 13°09'45.6", E 076°34'58.8" | 755 m | Rice-Potao-onion-Maize |
| 67.    | Gudibande        | Krishnarajapura    | N 13°09'48.1", E 076°33'58.6" | 730 m | Rice-Chilly            |
| 68.    | Gudibande        | Chidamanahalli     | N 13°09'45.6", E 076°34'58.8" | 817 m | Rice                   |
| 69.    | Gauribidanur     | Banderamanhalli    | N 13°09'48.1", E 076°33'58.6" | 762 m | Rice-Brinjal-Maize     |
| 70.    | Gauribidanur     | D. palya           | N 13°09'45.6", E 076°34'58.8" | 705 m | Rice-Maize-onion       |
| Ramar  | nagar            |                    |                               |       |                        |
| 71.    | Ramanagara       | Nagohalli          | N 12°40'33.4", E 077°19'40.6" | 678 m | Rice - ragi            |
| 72.    | Kanakapura       | Cheelooru          | N 12°38'50.7", E 077°24'52.8" | 666 m | Rice                   |
| 73.    | Kanakapura       | Chikahalabalu      | N 12°39'05.1", E 077°24'46.6" | 653 m | Rice – Ragi            |
|        | =                |                    |                               |       | -                      |

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| 74.    | Kanakapura         | Mudavadi           | N 12°37'56.8",E 077°23'20.6"  | 674 m  | Rice –Ragi  |  |
|--------|--------------------|--------------------|-------------------------------|--------|-------------|--|
| 75.    | Magadi             | Kaalerikaavalu     | N 13°00'03.4",E 077°10'17.5"  | 866 m  | Rice        |  |
| Southe | ern Dry zone (SDZ) |                    |                               |        |             |  |
| Mandy  | a                  |                    |                               |        |             |  |
| 76.    | Mandya             | Banakanahalli      | N 12°31'15.9", E 076°51'46.2" | 730 m  | Rice        |  |
| 77.    | Mandya             | V C Farm           | N 12°34'10.2", E 076°48'31.0" | 735 m  | Rice        |  |
| 78.    | Mandya             | Holalu             | N 12°32'44.8", E 076°50'38.1" | 703 m  | Rice – Ragi |  |
| 79.    | Nagamangala        | Thiruganahalli     | N 12°45'54.0", E 076°37'21.6" | 1022 m | Rice        |  |
| 80.    | Krishnarajpet      | Thendekere 1       | N 12°36'03.0", E 076°33'14.0" | 1088 m | Rice        |  |
| 81.    | Krishnarajpet      | Thendekere 2       | N 12°36'04.8", E 076°33'12.8" | 1051 m | Rice        |  |
| 82.    | Pandavapura        | K Betahalli        | N 12°29'30.5", E 076°38'17.2" | 751 m  | Rice        |  |
| 83.    | Pandavapura        | Kennahalu          | N 12°28'20.2", E 076°40'55.0" | 727 m  | Rice        |  |
| 84.    | Srirangapatna      | Mandya koppalu     | N 12°23'51.4", E 076°48'11.9" | 682 m  | Rice        |  |
| 85.    | Srirangapatna      | Chikka palya       | N 12°24'35.5", E 076°45'59.6" | 675 m  | Rice        |  |
| 86.    | Malavalli          | Thamadahalli       | N 12°24'09.3", E 077°03'30.6" | 626 m  | Rice        |  |
| 87.    | Malavalli          | Malavalli11        | N 12°23'33.2", E 077°03'27.2" | 627 m  | Rice        |  |
| 88.    | Malavalli          | Malavalli 2        | N 12°23'33.9", E 077°03'28.5" | 627 m  | Rice        |  |
| 89.    | Maddur             | Uppinakere         | N 12°34'29.2", E 077°01'57.2" | 691 m  | Rice        |  |
| 90.    | Maddur             | Huligere pura 1    | N 12°32'31.0",E 077°02'54.8"  | 715 m  | Rice        |  |
| 91.    | Maddur             | Huligere pura 2    | N 12°32'30.6", E 077°02'53.5" | 669 m  | Rice        |  |
| 92.    | Maddur             | Chikka Arasinakere | N 12°29'58.0", E 077°02'07.4" | 641 m  | Rice        |  |
| Mysor  | e                  |                    |                               |        |             |  |
| 93.    | Krishnarajanagar   | K R Nagar 1        | N 12°27'12.3", E 076°23'08.2" | 792 m  | Rice        |  |
| 94.    | K R nagara         | K R Nagar 2        | N 12°27'11.8", E 076°23'07.4" | 780 m  | Rice        |  |

|   | 95.     | Mysore            | Halekesere      | N 12°21'35.2", E 076°39'59.6" | 733 m | Rice         |
|---|---------|-------------------|-----------------|-------------------------------|-------|--------------|
|   | 96.     | Mysore            | Hosahundi       | N 12°14'55.9", E 076°39'43.5" | 715 m | Rice         |
|   | 97.     | Nanjangud         | Chikayanachakra | N 12°09'19.6", E 076°40'48.9" | 722 m | Rice         |
|   | 98.     | Nanjangud         | Basavanapura    | N 12°08'20.9", E 076°41'01.9" | 698 m | Rice         |
|   | 99.     | T. Narsipur       | Basavanahalli   | N 12°21'01.0", E 076°53'59.2" | 692 m | Rice –Cowpea |
|   | 100.    | T. Narsipur       | Santhe mala     | N 12°21'23.3", E 076°50'26.9" | 677 m | Rice         |
|   | 101.    | T. Narsipur       | Aalagudu        | N 12°11'37.7", E 076°54'59.4" | 660m  | Rice         |
|   | Hassan  |                   |                 |                               |       |              |
|   | 102.    | Hassan            | Naralakoppalu   | N 12°58'59.3", E 076°05'09.5" | 938 m | Rice         |
|   | 103.    | Channarayanapatna | Cholenahalli    | N 12°51'46.7", E 076°23'28.1" | 845 m | Rice- Sesame |
| 2 | Tumkur  |                   |                 |                               |       |              |
| : | 104.    | Turuvekere        | Tavarekere 1    | N 13°10'39.5", E 076°40'17.8" | 787 m | Rice         |
| 1 | 105.    | Turuvekere        | Tavarekere 2    | N 13°10'38.0", E 076°40'22.0" | 786 m | Rice         |
|   | 106.    | Turuvekere        | Tavareker 3     | N 13°10'37.0", E 076°40'24.1" | 785 m | Rice         |
| 1 | 107.    | Turuvekere        | Doddagatta 1    | N 13°09'41.2", E 076°36'27.8" | 810 m | Rice         |
|   | 108.    | Turuvekere        | Doddagatta 2    | N 13°09'40.3", E 076°36'28.4" | 814 m | Rice         |
|   | 109.    | Kunigal           | Lalaapura       | N 12°59'47.1", E 077°00'14.7" | 769 m | Rice - ragi  |
|   | Chamara | ijanagar          |                 |                               |       |              |
|   | 110.    | Yelanduru         | Honnuru         | N 12°04'56.6", E 077°01'03.5" | 676 m | Rice         |
|   | 111.    | Yelanduru         | Uppinamole      | N 12°02'33.6", E 077°02'39.9" | 671m  | Rice         |
|   | 112.    | Yelanduru         | Duggahatti      | N 12°01'47.8", E 077°00'22.1" | 708m  | Rice         |
|   | 113.    | Yelanduru         | Yariyuru        | N 12°03'50.2", E 077°03'06.8" | 702m  | Rice         |
|   | 114.    | Kollegal          | Mudhuvanahalli  | N 12°09'37.7", E 077°09'50.2" | 658m  | Rice         |
|   | 115.    | Kollegal          | Shankarapura    | N 12°09'13.9", E 077°05'26.7" | 644m  | Rice         |

| 116.                | Kollegal                              | Moogooru         | N 12°07'25.6", E 076°58'02.1" | 666m   | Rice |
|---------------------|---------------------------------------|------------------|-------------------------------|--------|------|
| <b>a</b> . <b>a</b> |                                       | -                |                               |        |      |
| Souther             | rn Transition Zone (ST                | <u>Z)</u>        |                               |        |      |
| Shimog              | a a a a a a a a a a a a a a a a a a a |                  |                               | (00)   | D.   |
| 117.                | Shimoga                               | Malgoppa         | N 13°54′22.8″, E 075°36′38.5″ | 608 m  | Rice |
| 118.                | Shimoga                               | Navile           | N 13°53'29.8", E 075°38'47.1" | 601 m  | Rice |
| 119.                | Badravathi                            | Barandur         | N 13°48'12.5", E 075°43'01.1" | 601 m  | Rice |
| 120.                | Badravathi                            | Bommanahalli     | N 13°47'09.4", E 075°43'24.5" | 603 m  | Rice |
| 121.                | Shikaripur                            | Hulinakoppa      | N 14°24'59.0", E 075°18'12.5" | 659 m  | Rice |
| Davana              | ngere                                 |                  |                               |        |      |
| 122.                | Channagiri                            | ARS Kathlagare   | N 14°21'30.4", E 075°45'38.0" | 590 m  | Rice |
| 123.                | Channagiri                            | Kareganuru       | N 14°17'54.3", E 075°50'40.1" | 561 m  | Rice |
| 124.                | Honnalli                              | Kulambi          | N 14°17'39.1", E 075°47'42.3" | 594 m  | Rice |
| Hassan              |                                       |                  |                               |        |      |
| 125.                | Honnalli                              | Kalivada         | N 14°18'06.5", E 075°45'46.8" | 614 m  | Rice |
| 126.                | Alur                                  | Byalapura        | N 12°57'02.4", E 075°58'18.0" | 916 m  | Rice |
| 127.                | Belur                                 | Bommadahalli     | N 13°06'13.5", E 075°51'47.3" | 1000 m | Rice |
| 128.                | Arakalagud                            | Gorur            | N 12°49'07.0", E 076°03'44.8" | 878 m  | Rice |
| 129.                | Arakalagud                            | Vaddarahalli     | N 12°48'37.4", E 076°03'37.6" | 877 m  | Rice |
| 130.                | Holenarasipura                        | Mandikoppalu     | N 12°38'31.6", E 076°19'05.7" | 832 m  | Rice |
| Mysore              | 2                                     |                  |                               |        |      |
| 131.                | Holenarasipura                        | Yadaegowdanhalli | N 12°38'54.0", E 076°19'05.2" | 854 m  | Rice |
| 132.                | Hunsur                                | Nallurapala      | N 12°15'00.0", E 076°15'57.8" | 797 m  | Rice |
| 133.                | Heggadevanakote                       | Irge             | N 12°06'08.1", E 076°22'20.3" | 713 m  | Rice |

| UIIKKa   | magaiore              |                |                               |       |               |
|----------|-----------------------|----------------|-------------------------------|-------|---------------|
| 134.     | Tarikere              | Taralabalu     | N 13°43'22.1", E 075°47'02.7" | 673 m | Rice          |
| 135.     | Tarikere              | Bhavikere      | N 13°43'19.1", E 075°43'12.7" | 680 m | Rice          |
| 136.     | Tarikere              | Rangenahalli   | N 13°42'16.3", E 075°41'22.3" | 648 m | Rice          |
| Northe   | rn Transition Zone (N | NTZ)           |                               |       |               |
| Haveri   |                       |                |                               |       |               |
| 137.     | Haveri                | Sangura 1      | N 14°46'29.5", E 075°18'16.7" | 542 m | Rice – Chilly |
| 138.     | Haveri                | Sangura 2      | N 14°46'30.5", E 075°18'16.5" | 543 m | Rice – Chilly |
| 139.     | Hirekerur1            | Hirekerur 1    | N 14°27'21.7", E 075°24'25.5" | 658 m | Rice          |
| 140.     | Hirekerur2            | Hirekerur 2    | N 14°27'27.9", E 075°24'20.4" | 584 m | Rice          |
| 141.     | Ranibennur            | Nituvalli      | N 14°27'47.3", E 075°39'21.0" | 558 m | Rice          |
| 142.     | Ranibennur            | Hanumanahalli  | N 14°30'32.3", E 075°41'42.1" | 554 m | Rice          |
| 143.     | Ranibennur            | Holeanhaveri   | N 14°29'41.6", E 075°41'02.4" | 558 m | Rice          |
| 144.     | Shiggaon              | Shadhambhi     | N 15°04'03.8", E 073°09'27.9" | 631m  | Rice          |
| Belgaur  | n                     |                |                               |       |               |
| 145.     | Belgaum               | Macche         | N 15°46'25.8", E 074°29'14.1" | 693m  | Rice          |
| 146.     | Belgaum               | Peeranvadi     | N 15°48'22.6", E 074°29'02.1" | 722m  | Rice          |
| 147.     | Belgaum               | Basavanakudchi | N 15°51'30.6", E 074°33'14.3" | 725m  | Rice          |
| Hilly Zo | one (HZ)              |                |                               |       |               |
| Shimog   | a                     |                |                               |       |               |
| 148.     | Soraba                | Bommanahalli   | N 14°28'35.3", E 075°04'45.9" | 596 m | Rice          |
| 149.     | Soraba                | Thavanadi      | N 14°26'40.1", E 075°05'03.7" | 625 m | Rice          |
| 150.     | Sagara                | Hiralemaruru   | N 14°12'33.5", E075°06'12.1"  | 607 m | Rice          |
| 151.     | Hosanagar             | Huvinakotae    | N 14°00'16.4", E 075°08'53.2" | 629 m | Rice - Ginger |
|          |                       |                |                               |       |               |

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| 152.    | Thirthahalli      | Aargagate           | N 13°44'42", E 075°12'38.7"   | 640 m | Rice                  |
|---------|-------------------|---------------------|-------------------------------|-------|-----------------------|
| Chikka  | magalore          |                     |                               |       |                       |
| 153.    | Koppa             | Kudaregombi         | N 13°33'08.7", E 075°25'29.9" | 667 m | Rice                  |
| 154.    | Sringeri          | Marigaebayalu       | N 13°28'17.0", E 075°12'55.5" | 647 m | Rice                  |
| 155.    | Sringeri          | Gandagatta          | N 13°25'10.8", E 075°12'36.0" | 667 m | Rice                  |
| 156.    | Mudigere          | Jannapura           | N 13°04'54.7", E 075°41'35.4" | 890 m | Rice                  |
| 157.    | Narasimharajnagar | K. Kanabur          | N 13°44'47.0", E 075°29'14.2" | 621 m | Rice                  |
| 158.    | Chikkamagalur     | Mugalavalli         | N 13°16'26.1", E 075°49'40.8" | 996 m | Rice                  |
| Hassan  |                   |                     |                               |       |                       |
| 159.    | Sakleshpur        | Chikkanayakanahalli | N 12°56'34.3", E 075°54'08.6" | 990 m | Rice                  |
| 160.    | Sakleshpur        | Kadabanahalli       | N 12°58'34.1", E 075°47'43.0" | 900 m | Rice                  |
| Haveri  |                   |                     |                               |       |                       |
| 161.    | Hangal            | Singapur 1          | N 14°46'41.5", E 075°17'03.0" | 550 m | Rice                  |
| 162.    | Hangal            | Singapur 2          | N 14°46'42.8", E 075°17'02.7" | 551 m | Rice                  |
| 163.    | Hangal            | Singapur 3          | N 14°46'45.5", E 075°17'00.3" | 547 m | Rice                  |
| 164.    | Hangal            | Singapur 4          | N 14°46'31.6", E 075°16'27.8" | 529 m | Rice                  |
| 165.    | Hangal            | Singapur 5          | N 14°46'34.0", E 075°16'26.2" | 528 m | Rice – S.cane- Cotton |
| Dharwa  | nd                |                     |                               |       |                       |
| 166.    | Kalghatgi         | Thadasa             | N 15°07'49.3", E 075°07'30.3" | 638m  | Rice                  |
| 167.    | Kalghatgi         | Honnali             | N 15°09'18.8", E 075°03'11.9" | 578m  | Rice                  |
| 168.    | Kalghatgi         | Sangameshwara       | N 15°11'00.0", E 074°53'06.0" | 520m  | Rice                  |
| 169.    | Kalghatgi         | Huliyala            | N 15°11'00.4", E 074°55'06.8" | 534m  | Rice                  |
| Belgaun | n                 |                     |                               |       |                       |
| 170.    | Kanpur            | Khanapura           | N 15°38'03.5", E 074°30'28.0" | 608m  | Rice                  |
|         |                   |                     |                               |       |                       |

| Ottal IS | amaua        |               |                               |      |      |
|----------|--------------|---------------|-------------------------------|------|------|
| 171.     | Yallapura    | Idagundi      | N 14°55'19.9", E 074°39'29.2" | 446m | Rice |
| 172.     | Sirsi        | Sonda         | N 14°44'02.2", E 074°49'15.5" | 460m | Rice |
| 173.     | Siddapura    | Thyagal       | N 14°27'21.0", E 074°52'27.9" | 535m | Rice |
| Kodagu   | L            |               |                               |      |      |
| 174.     | Virajapete   | Kaarmadu      | N 12°13'42.7", E 075°52'28.2" | 874m | Rice |
| 175.     | Virajapete   | Thaknuru      | N 12°13'07.1", E 075°46'59.5" | 870m | Rice |
| 176.     | Virajapete   | Kakotporchi   | N 12°15'00.4", E 075°45'48.1" | 872m | Rice |
| 177.     | Madikeri     | Kandana kolli | N 12°28'21.8", E 075°46'54.7" | 988m | Rice |
| 178.     | Madikeri     | Mekeri        | N 12°24'04.4", E 075°44'38.7" | 970m | Rice |
| 179.     | Madikeri     | Kaggodu       | N 12°22'50.3", E 075°45'18.9" | 888m | Rice |
| 180.     | Somavarapete | Kudige        | N 12°29'55.8", E 075°57'11.4" | 854m | Rice |
| 181.     | Somavarapete | Madalapura    | N 12°30'17.5", E075°56'02.0"  | 853m | Rice |
| Coastal  | zone(CZ)     |               |                               |      |      |
| Uttar K  | annada       |               |                               |      |      |
| 182.     | Kumta        | Dhareshwara   | N 14°22'25.8", E 074°24'39.1" | 4m   | Rice |
| 183.     | Ankola       | Thorke        | N 14°33'27.8", E074°21'05.6"  | 8m   | Rice |
| 184.     | Karvar       | Thendye       | N 14°46'09.0", E 074°10'36.8" | 11m  | Rice |
| 185.     | Bhatkala     | Shiruru       | N 13°53'47.6", E 074°36'53.9" | 24m  | Rice |
| 186.     | Bhatkala     | Bengre        | N 14°02'23.8", E074°31'19.2"  | 1m   | Rice |
| 187.     | Honnavara    | Royalkeri     | N 14°17'42.4", E 074°26'21.7" | 3m   | Rice |
| Udupi    |              |               |                               |      |      |
| 188.     | Udupi        | Hiriyadaka    | N 13°21'03.3", E 074°50'15.0" | 49m  | Rice |
| 189.     | Brahmavara   | Upporu        | N 13°24'14.5", E 074°44'46.3" | 25m  | Rice |
|          |              |               |                               |      |      |

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| 190.    | Kundapura   | Thalluru        | N 13°38'58.9", E 074°42'18.3" | 33m  | Rice |
|---------|-------------|-----------------|-------------------------------|------|------|
| 191.    | Kolluru     | Chittoru        | N 13°43'46.6", E 074°45'50.3" | 53m  | Rice |
| 192.    | Kolluru     | Idooru kunchadi | N 13°45'20.6", E 074°47'01.7" | 36m  | Rice |
| 193.    | Karkala     | Sanuru          | N 13°12'02.7", E 074°59'44.7" | 100m | Rice |
| 194.    | Karkala     | Byluru          | N 13°17'09.2", E 074°54'41.2" | 71m  | Rice |
| Dakshir | na Kannada  |                 |                               |      |      |
| 195.    | Sulya       | Bellare         | N 12°39'19.3", E 075°22'14.0" | 114m | Rice |
| 196.    | Puttur      | Kodimbadi       | N 12°48'41.2", E 075°12'53.0" | 79m  | Rice |
| 197.    | Belthangady | Karaya          | N 12°51'28.0", E 075°14'35.8" | 82m  | Rice |
| 198.    | Belthangady | Korinja         | N 12°52'59.9", E 075°14'47.8" | 92m  | Rice |
| 199.    | Bantwala    | Karimaneelu     | N 13°01'05.6", E 075°07'32.9" | 91m  | Rice |
| 200.    | Mudabidre   | Hosangady       | N 13°02'15.8", E 075°05'16.3" | 102m | Rice |

# ANNEXURE II

| Physi | icochemica | l properties | s of soil sa | mples of | different agro | climatic zones | of Karnataka |
|-------|------------|--------------|--------------|----------|----------------|----------------|--------------|
|-------|------------|--------------|--------------|----------|----------------|----------------|--------------|

|         | 11                 | E.C.                         | CCSi   | AASi                 | Sand   | Silt   | Clay   |                 | CEC                          |
|---------|--------------------|------------------------------|--------|----------------------|--------|--------|--------|-----------------|------------------------------|
| Sl. No. | рН<br>(1:2.5water) | ( <b>dSm</b> <sup>-1</sup> ) | (m     | g kg <sup>-1</sup> ) |        | (%)    |        | Textural class  | (cmol(p+) kg <sup>-1</sup> ) |
| 1       | 8.022              | 0.941                        | 15.194 | 165.181              | 62.288 | 14.701 | 23.011 | Sandy clay loam | 35.000                       |
| 2       | 9.536              | 0.416                        | 44.635 | 87.888               | 72.887 | 7.499  | 19.613 | Sandy loam      | 77.391                       |
| 3       | 8.517              | 0.310                        | 20.645 | 123.969              | 51.961 | 44.091 | 3.948  | Sandy clay      | 70.435                       |
| 4       | 6.173              | 0.111                        | 24.654 | 28.019               | 80.443 | 0.000  | 19.557 | Sandy loam      | 22.000                       |
| 5       | 6.631              | 0.149                        | 27.305 | 40.056               | 76.855 | 14.063 | 9.082  | Sandy loam      | 30.000                       |
| 6       | 8.422              | 0.274                        | 41.576 | 126.931              | 37.483 | 59.409 | 3.109  | Silty loam      | 40.000                       |
| 7       | 8.817              | 0.258                        | 12.770 | 111.781              | 71.553 | 24.964 | 3.483  | Sandy clay      | 94.348                       |
| 8       | 7.488              | 0.224                        | 24.665 | 58.681               | 83.349 | 12.766 | 3.885  | Loamy sand      | 48.000                       |
| 9       | 8.452              | 1.350                        | 14.888 | 93.963               | 56.166 | 39.004 | 4.829  | Sandy loam      | 43.478                       |
| 10      | 8.463              | 0.602                        | 22.110 | 251.413              | 49.790 | 46.714 | 3.496  | Sandy loam      | 72.826                       |
| 11      | 8.267              | 0.274                        | 41.868 | 77.150               | 61.277 | 32.584 | 6.139  | Sandy loam      | 75.652                       |
| 12      | 8.261              | 0.225                        | 13.775 | 58.313               | 35.232 | 58.955 | 5.813  | Silty loam      | 108.043                      |
| 13      | 8.394              | 0.272                        | 23.143 | 109.838              | 50.095 | 48.010 | 1.895  | Sandy loam      | 101.739                      |
| 14      | 7.807              | 0.306                        | 13.633 | 131.775              | 64.324 | 29.238 | 6.438  | Sandy loam      | 19.000                       |
| 15      | 8.857              | 0.407                        | 42.857 | 111.638              | 45.752 | 16.304 | 37.944 | Sandy clay      | 32.174                       |
| 16      | 8.198              | 0.492                        | 32.489 | 41.219               | 39.774 | 55.384 | 4.842  | Silty loam      | 78.696                       |

| 17 | 8.544 | 0.395 | 25.777 | 51.681  | 43.465 | 51.723 | 4.811  | Silty loam      | 75.217 |
|----|-------|-------|--------|---------|--------|--------|--------|-----------------|--------|
| 18 | 8.736 | 0.407 | 21.057 | 106.488 | 54.147 | 41.042 | 4.812  | Sandy loam      | 55.217 |
| 19 | 8.374 | 0.355 | 30.058 | 90.619  | 44.484 | 50.714 | 4.801  | Silty loam      | 85.000 |
| 20 | 8.203 | 0.694 | 23.215 | 52.250  | 46.415 | 40.771 | 12.814 | Loam            | 84.783 |
| 21 | 8.214 | 0.243 | 25.668 | 105.050 | 69.560 | 8.050  | 22.390 | Sandy clay loam | 31.087 |
| 22 | 7.248 | 0.095 | 37.325 | 85.163  | 74.821 | 17.898 | 7.281  | Sandy loam      | 22.000 |
| 23 | 9.237 | 0.233 | 21.254 | 91.788  | 37.705 | 0.000  | 62.295 | Clay            | 15.652 |
| 24 | 8.231 | 0.311 | 61.782 | 99.281  | 89.186 | 0.772  | 10.042 | Sand            | 98.478 |
| 25 | 8.520 | 0.206 | 41.315 | 55.025  | 64.084 | 30.895 | 5.020  | Sandy loam      | 18.478 |
| 26 | 8.084 | 0.319 | 10.272 | 97.819  | 73.170 | 21.021 | 5.808  | Sandy loam      | 25.600 |
| 27 | 8.628 | 0.510 | 11.958 | 135.213 | 44.230 | 53.235 | 2.535  | Silty loam      | 25.652 |
| 28 | 8.504 | 0.338 | 34.408 | 80.225  | 34.007 | 60.083 | 5.910  | Silty loam      | 97.826 |
| 29 | 8.230 | 0.995 | 24.918 | 75.413  | 77.275 | 14.068 | 8.657  | Sandy loam      | 26.087 |
| 30 | 7.725 | 0.196 | 34.755 | 65.181  | 81.853 | 11.641 | 6.506  | Sand            | 41.000 |
| 31 | 8.822 | 0.429 | 35.161 | 64.731  | 67.663 | 26.210 | 6.127  | Sandy loam      | 37.609 |
| 32 | 8.683 | 0.584 | 29.609 | 102.675 | 68.281 | 31.719 | 0.000  | Sandy loam      | 12.174 |
| 33 | 7.124 | 0.393 | 57.810 | 123.581 | 90.453 | 3.182  | 6.364  | Sand            | 21.000 |
| 34 | 8.353 | 0.282 | 62.919 | 135.075 | 70.742 | 21.013 | 8.246  | Loamy sand      | 28.696 |
| 35 | 8.603 | 0.504 | 48.760 | 96.619  | 79.922 | 14.456 | 5.622  | Loamy sand      | 31.304 |
| 36 | 7.953 | 0.189 | 32.486 | 91.431  | 67.047 | 26.719 | 6.234  | Sandy loam      | 25.000 |
| 37 | 8.362 | 0.225 | 29.886 | 87.856  | 77.917 | 16.492 | 5.591  | Loamy sand      | 28.913 |

| 38 | 8.245 | 0.391 | 30.083 | 95.238  | 61.432 | 33.782 | 4.786  | Sandy loam      | 26.957 |
|----|-------|-------|--------|---------|--------|--------|--------|-----------------|--------|
| 39 | 8.492 | 0.365 | 25.287 | 50.000  | 51.770 | 27.403 | 20.826 | Loam            | 40.652 |
| 40 | 8.848 | 0.527 | 21.561 | 44.606  | 71.650 | 5.505  | 22.845 | Sandy clay loam | 54.565 |
| 41 | 8.415 | 0.390 | 47.893 | 52.344  | 68.049 | 29.841 | 2.110  | Sandy loam      | 29.565 |
| 42 | 8.541 | 0.497 | 23.535 | 122.569 | 71.877 | 28.123 | 0.000  | Loamy sand      | 54.130 |
| 43 | 5.268 | 0.081 | 13.580 | 18.160  | 78.913 | 5.272  | 15.815 | Sandy loam      | 17.600 |
| 44 | 4.879 | 0.082 | 17.110 | 13.840  | 81.348 | 4.789  | 13.863 | Sandy loam      | 14.200 |
| 45 | 5.307 | 0.052 | 23.420 | 16.110  | 82.108 | 13.035 | 4.856  | Loamy sand      | 14.700 |
| 46 | 6.041 | 0.176 | 26.100 | 44.620  | 44.675 | 14.132 | 41.193 | Sandy clay loam | 33.800 |
| 47 | 6.239 | 0.238 | 27.970 | 71.370  | 39.108 | 42.252 | 18.640 | Loam            | 33.700 |
| 48 | 8.170 | 0.498 | 24.270 | 135.560 | 68.619 | 10.997 | 20.384 | Sandy clay loam | 21.400 |
| 49 | 7.439 | 0.137 | 28.980 | 133.940 | 71.010 | 3.829  | 25.161 | Sandy clay loam | 20.200 |
| 50 | 7.097 | 0.191 | 32.710 | 100.110 | 72.224 | 3.401  | 24.375 | Sandy clay loam | 21.800 |
| 51 | 8.223 | 0.187 | 14.110 | 69.630  | 76.347 | 8.942  | 14.711 | Sandy loam      | 37.174 |
| 52 | 5.702 | 0.066 | 23.850 | 42.870  | 65.539 | 3.733  | 30.728 | Sandy clay loam | 20.800 |
| 53 | 7.890 | 0.710 | 35.140 | 88.310  | 78.742 | 16.637 | 4.621  | Loamy sand      | 28.400 |
| 54 | 9.119 | 0.487 | 24.720 | 63.270  | 57.568 | 14.548 | 27.884 | Sandy clay loam | 38.261 |
| 55 | 8.260 | 0.089 | 54.400 | 280.040 | 42.961 | 18.499 | 38.540 | Clay loam       | 70.000 |
| 56 | 7.768 | 0.165 | 21.940 | 160.480 | 62.620 | 7.314  | 30.067 | Sandy clay loam | 18.500 |
| 57 | 7.779 | 0.147 | 28.470 | 121.360 | 55.239 | 9.469  | 35.292 | Sandy clay      | 38.900 |
| 58 | 9.013 | 0.280 | 31.910 | 122.310 | 76.266 | 6.657  | 17.077 | Sandy loam      | 16.348 |

| 59 | 6.658 | 0.122 | 37.050 | 42.140  | 82.980 | 5.403  | 11.617 | Loamy sand      | 11.500 |
|----|-------|-------|--------|---------|--------|--------|--------|-----------------|--------|
| 60 | 7.722 | 0.240 | 41.150 | 105.750 | 73.867 | 4.126  | 22.007 | Sandy clay loam | 14.600 |
| 61 | 6.277 | 0.092 | 31.300 | 64.710  | 54.097 | 5.485  | 40.418 | Sandy clay      | 19.200 |
| 62 | 5.069 | 0.129 | 14.550 | 19.410  | 85.518 | 4.418  | 10.064 | Loamy sand      | 12.000 |
| 63 | 6.741 | 0.093 | 56.180 | 85.380  | 70.176 | 5.247  | 24.577 | Sandy clay loam | 14.100 |
| 64 | 7.024 | 0.184 | 34.370 | 97.300  | 66.642 | 9.124  | 24.234 | Sandy clay loam | 22.600 |
| 65 | 6.237 | 0.095 | 35.740 | 64.430  | 83.155 | 1.685  | 15.161 | Sandy loam      | 16.000 |
| 66 | 6.213 | 0.159 | 32.580 | 60.260  | 82.337 | 3.896  | 13.767 | Loamy sand      | 11.100 |
| 67 | 6.855 | 0.506 | 36.100 | 75.350  | 80.444 | 4.314  | 15.242 | Sandy loam      | 12.000 |
| 68 | 6.107 | 0.117 | 23.660 | 35.090  | 73.206 | 11.908 | 14.885 | Sandy loam      | 13.900 |
| 69 | 8.050 | 0.142 | 52.630 | 166.040 | 65.285 | 12.007 | 22.708 | Sandy clay loam | 17.500 |
| 70 | 8.135 | 0.731 | 42.600 | 117.440 | 70.693 | 14.409 | 14.898 | Sandy loam      | 14.600 |
| 71 | 7.922 | 0.280 | 26.710 | 123.830 | 66.965 | 14.567 | 18.468 | Sandy loam      | 20.100 |
| 72 | 8.087 | 0.293 | 27.430 | 65.070  | 80.877 | 2.569  | 16.554 | Sandy loam      | 17.200 |
| 73 | 8.479 | 0.229 | 27.680 | 62.810  | 80.659 | 12.124 | 7.217  | Loamy sand      | 20.000 |
| 74 | 6.267 | 0.045 | 17.350 | 22.380  | 93.942 | 0.288  | 5.769  | Sand            | 10.300 |
| 75 | 7.752 | 0.113 | 52.710 | 138.850 | 73.948 | 20.955 | 5.097  | Sandy loam      | 13.400 |
| 76 | 8.384 | 0.236 | 79.660 | 124.720 | 74.751 | 1.540  | 23.710 | Sandy clay loam | 39.130 |
| 77 | 8.019 | 0.162 | 32.950 | 136.220 | 78.293 | 12.714 | 8.993  | Sandy loam      | 23.300 |
| 78 | 7.148 | 0.130 | 47.540 | 92.990  | 81.514 | 4.201  | 14.285 | Sandy loam      | 21.900 |
| 79 | 4.962 | 0.055 | 27.740 | 20.690  | 86.150 | 2.173  | 11.678 | loamy sand      | 17.000 |

| 2     |     |       |       |        |         |        |        |        |                 |        |
|-------|-----|-------|-------|--------|---------|--------|--------|--------|-----------------|--------|
| 19    | 80  | 8.605 | 0.269 | 21.710 | 55.390  | 56.777 | 31.800 | 11.423 | Sandy loam      | 19.913 |
|       | 81  | 8.716 | 0.302 | 33.460 | 115.530 | 53.694 | 37.910 | 8.396  | Sandy loam      | 47.174 |
|       | 82  | 6.618 | 0.174 | 42.440 | 79.540  | 65.355 | 8.791  | 25.854 | Sandy clay loam | 14.600 |
|       | 83  | 6.974 | 0.107 | 41.540 | 77.800  | 61.161 | 9.461  | 29.378 | Sandy clay loam | 9.200  |
|       | 84  | 6.455 | 0.111 | 33.990 | 54.960  | 85.098 | 8.884  | 6.018  | Loamy sand      | 14.100 |
|       | 85  | 7.186 | 0.182 | 27.390 | 63.510  | 57.177 | 12.772 | 30.051 | Sandy clay loam | 16.300 |
|       | 86  | 8.480 | 0.362 | 28.960 | 89.070  | 64.595 | 22.415 | 12.990 | Sandy loam      | 22.826 |
| San   | 87  | 8.336 | 0.385 | 25.400 | 103.670 | 79.967 | 13.156 | 6.877  | Loamy sand      | 26.565 |
| dhya  | 88  | 8.454 | 0.515 | 27.050 | 85.630  | 80.737 | 9.187  | 10.076 | Loamy sand      | 24.652 |
| , K., | 89  | 6.385 | 0.125 | 36.330 | 62.540  | 75.739 | 5.332  | 18.929 | Sandy loam      | 14.300 |
| Ph.I  | 90  | 8.397 | 0.250 | 13.300 | 56.280  | 75.675 | 10.703 | 13.622 | Sandy loam      | 16.435 |
| O     | 91  | 8.522 | 0.267 | 24.090 | 70.590  | 76.734 | 6.081  | 17.185 | Sandy loam      | 20.304 |
|       | 92  | 8.330 | 0.235 | 23.380 | 85.130  | 76.245 | 23.492 | 0.264  | Sand            | 21.217 |
|       | 93  | 7.495 | 0.474 | 75.750 | 106.200 | 83.011 | 16.728 | 0.261  | Loamy sand      | 13.400 |
|       | 94  | 7.334 | 0.281 | 44.610 | 110.280 | 74.654 | 23.554 | 1.792  | Loamy sand      | 19.900 |
|       | 95  | 8.358 | 0.332 | 33.400 | 162.430 | 47.366 | 11.124 | 41.511 | Sandy clay      | 55.217 |
|       | 96  | 8.376 | 0.348 | 18.610 | 75.980  | 73.314 | 12.231 | 14.455 | Sandy loam      | 26.087 |
|       | 97  | 5.800 | 0.048 | 32.320 | 55.210  | 66.941 | 13.075 | 19.983 | Sandy loam      | 19.700 |
|       | 98  | 5.965 | 0.071 | 49.280 | 67.060  | 58.180 | 13.038 | 28.782 | Sandy clay loam | 18.000 |
| N)    | 99  | 5.882 | 0.106 | 21.080 | 33.100  | 78.486 | 4.753  | 16.761 | Sandy clay      | 9.600  |
| 2016  | 100 | 6.633 | 0.089 | 23.750 | 25.730  | 76.935 | 0.530  | 22.534 | Sandy clay loam | 14.100 |
|       |     |       |       |        |         |        |        |        |                 |        |

| Bio    | 101 | 8.099 | 0.406 | 40.476 | 113.625 | 64.690 | 25.502 | 9.808  | Sandy loam      | 48.000  |
|--------|-----|-------|-------|--------|---------|--------|--------|--------|-----------------|---------|
| geoc   | 102 | 7.774 | 0.845 | 12.230 | 120.330 | 32.038 | 19.476 | 48.487 | Clay            | 18.300  |
| hem    | 103 | 6.068 | 0.057 | 26.790 | 48.390  | 77.458 | 3.259  | 19.283 | Sandy loam      | 14.600  |
| istry  | 104 | 7.023 | 0.092 | 23.280 | 76.760  | 74.230 | 0.879  | 24.892 | Sandy clay loam | 15.100  |
| of s   | 105 | 8.449 | 0.150 | 21.700 | 110.180 | 66.304 | 23.502 | 10.194 | Sandy loam      | 31.391  |
| ilico  | 106 | 7.904 | 0.134 | 13.360 | 70.380  | 77.266 | 1.850  | 20.884 | Sandy clay loam | 14.100  |
| n in ( | 107 | 7.213 | 0.305 | 23.950 | 91.080  | 66.667 | 4.638  | 28.696 | Sandy clay loam | 15.200  |
| diffe  | 108 | 6.947 | 0.128 | 35.060 | 111.560 | 58.559 | 11.051 | 30.390 | Sandy clay loam | 19.400  |
| rent   | 109 | 7.521 | 0.067 | 44.820 | 105.170 | 77.677 | 6.261  | 16.061 | Sandy loam      | 15.200  |
| rice ( | 110 | 8.456 | 0.315 | 37.351 | 87.563  | 66.828 | 7.526  | 25.645 | Sandy clay loam | 110.435 |
| ecosy  | 111 | 8.617 | 1.070 | 36.113 | 60.600  | 80.514 | 8.234  | 11.253 | Loamy sand      | 81.087  |
| ysten  | 112 | 8.710 | 0.349 | 27.407 | 106.000 | 50.436 | 40.725 | 8.839  | Loam            | 115.217 |
| n of   | 113 | 9.101 | 0.605 | 55.149 | 88.238  | 68.269 | 7.798  | 23.932 | Sandy clay loam | 81.522  |
| Karn   | 114 | 8.366 | 0.251 | 20.656 | 108.906 | 66.138 | 7.814  | 26.048 | Sandy clay loam | 105.870 |
| ıatak  | 115 | 8.524 | 0.473 | 32.740 | 137.150 | 53.799 | 13.569 | 32.631 | Sandy clay loam | 101.522 |
| а      | 116 | 8.300 | 0.181 | 15.965 | 107.200 | 56.323 | 25.594 | 18.083 | Sandy loam      | 122.826 |
|        | 117 | 6.389 | 0.175 | 24.080 | 45.640  | 73.650 | 6.862  | 19.488 | Sandy loam      | 16.900  |
|        | 118 | 4.985 | 0.082 | 16.860 | 35.890  | 86.096 | 10.945 | 2.958  | Sand            | 11.600  |
|        | 119 | 5.374 | 0.077 | 13.000 | 26.180  | 82.673 | 3.938  | 13.389 | Loamy sand      | 10.900  |
| 22     | 120 | 6.052 | 0.086 | 19.490 | 38.960  | 79.239 | 9.342  | 11.418 | Sandy loam      | 9.800   |
| 0      | 121 | 6.178 | 0.056 | 34.000 | 53.120  | 66.957 | 11.117 | 21.926 | Sandy clay loam | 17.700  |

| 122 | 6.659 | 0.062 | 23.430 | 63.020  | 65.368 | 11.263 | 23.370 | Sandy clay loam | 21.500 |
|-----|-------|-------|--------|---------|--------|--------|--------|-----------------|--------|
| 123 | 8.430 | 0.286 | 16.030 | 151.810 | 75.222 | 6.413  | 18.365 | Sandy loam      | 63.043 |
| 124 | 7.158 | 0.373 | 13.640 | 150.300 | 15.994 | 41.670 | 42.335 | Silty clay      | 38.800 |
| 125 | 7.585 | 0.237 | 36.840 | 203.350 | 64.577 | 8.789  | 26.634 | Sandy clay loam | 30.400 |
| 126 | 6.556 | 0.206 | 25.870 | 95.400  | 60.817 | 17.111 | 22.071 | Sandy clay loam | 22.500 |
| 127 | 5.150 | 0.077 | 24.780 | 30.290  | 81.942 | 1.667  | 16.391 | Sandy loam      | 12.900 |
| 128 | 5.369 | 0.069 | 17.120 | 21.010  | 79.161 | 7.780  | 13.059 | Sandy loam      | 15.200 |
| 129 | 5.581 | 0.124 | 32.390 | 34.760  | 35.459 | 30.154 | 34.387 | Clay loam       | 13.700 |
| 130 | 7.615 | 0.230 | 30.110 | 96.620  | 75.298 | 10.729 | 13.973 | Sandy loam      | 14.600 |
| 131 | 6.489 | 0.087 | 30.180 | 73.270  | 70.157 | 10.783 | 19.059 | Sandy loam      | 17.700 |
| 132 | 5.732 | 0.039 | 31.270 | 34.500  | 23.064 | 36.327 | 40.609 | Clay            | 19.700 |
| 133 | 8.490 | 0.325 | 9.280  | 22.810  | 55.812 | 16.973 | 27.215 | Sandy clay loam | 47.609 |
| 134 | 7.364 | 0.097 | 30.310 | 132.990 | 44.968 | 2.997  | 52.035 | Clay            | 33.100 |
| 135 | 5.376 | 0.062 | 11.350 | 20.400  | 32.521 | 33.740 | 33.740 | Clay loam       | 12.700 |
| 136 | 6.088 | 0.077 | 47.830 | 54.160  | 58.422 | 10.642 | 30.936 | Sandy clay loam | 24.200 |
| 137 | 7.979 | 0.403 | 40.450 | 161.740 | 60.297 | 38.156 | 1.547  | Sandy loam      | 25.800 |
| 138 | 8.352 | 0.238 | 35.280 | 160.130 | 41.843 | 56.015 | 2.143  | Silty loam      | 56.957 |
| 139 | 8.113 | 0.775 | 26.690 | 163.470 | 39.657 | 51.018 | 9.326  | Silty loam      | 38.700 |
| 140 | 8.489 | 0.378 | 22.830 | 188.790 | 48.104 | 36.784 | 15.113 | Loam            | 58.696 |
| 141 | 8.276 | 0.302 | 26.620 | 203.370 | 40.424 | 27.306 | 32.271 | Clay loam       | 64.783 |
| 142 | 8.359 | 0.527 | 20.680 | 153.640 | 57.244 | 32.601 | 10.154 | Sandy loam      | 52.391 |

| 143 | 8.420 | 0.385 | 25.840 | 167.170 | 62.996 | 35.423 | 1.581  | Sandy loam      | 53.261 |
|-----|-------|-------|--------|---------|--------|--------|--------|-----------------|--------|
| 144 | 6.723 | 0.078 | 43.732 | 161.500 | 32.948 | 20.853 | 46.198 | Clay            | 36.000 |
| 145 | 5.616 | 0.054 | 82.894 | 130.188 | 22.475 | 26.580 | 50.945 | Clay            | 45.000 |
| 146 | 7.063 | 0.192 | 49.109 | 327.081 | 61.795 | 17.209 | 20.995 | Sandy clay loam | 48.000 |
| 147 | 7.672 | 0.729 | 34.125 | 370.244 | 62.919 | 31.967 | 5.115  | Sandy loam      | 51.000 |
| 148 | 5.644 | 0.046 | 24.080 | 33.180  | 34.803 | 36.289 | 28.908 | Clay loam       | 14.300 |
| 149 | 5.985 | 0.097 | 34.910 | 38.420  | 72.009 | 13.854 | 14.137 | Sandy loam      | 20.100 |
| 150 | 5.688 | 0.035 | 24.450 | 29.680  | 70.733 | 7.445  | 21.822 | Sandy clay loam | 13.700 |
| 151 | 5.607 | 0.040 | 14.580 | 14.970  | 51.788 | 23.323 | 24.889 | Sandy clay loam | 12.100 |
| 152 | 4.960 | 0.064 | 12.110 | 32.960  | 56.409 | 21.372 | 22.218 | Sandy clay loam | 10.100 |
| 153 | 5.370 | 0.032 | 20.810 | 19.880  | 54.427 | 20.663 | 24.909 | Sandy clay loam | 12.900 |
| 154 | 5.361 | 0.041 | 12.460 | 21.270  | 61.955 | 7.416  | 30.629 | Sandy clay loam | 16.700 |
| 155 | 5.150 | 0.041 | 11.790 | 13.750  | 48.610 | 17.614 | 33.777 | Sandy clay loam | 14.300 |
| 156 | 6.255 | 0.057 | 33.460 | 36.880  | 86.376 | 0.534  | 13.090 | Loamy sand      | 10.300 |
| 157 | 6.170 | 0.053 | 23.820 | 31.810  | 37.006 | 23.512 | 39.482 | Clay loam       | 16.700 |
| 158 | 5.763 | 0.084 | 24.140 | 25.790  | 73.726 | 23.620 | 2.654  | Loamy sand      | 8.200  |
| 159 | 4.954 | 0.164 | 39.480 | 35.010  | 78.939 | 18.201 | 2.860  | Loamy sand      | 16.200 |
| 160 | 5.271 | 0.066 | 29.790 | 33.310  | 65.561 | 20.388 | 14.051 | Sandy loam      | 18.900 |
| 161 | 6.448 | 0.092 | 49.780 | 112.080 | 60.666 | 17.208 | 22.125 | Sandy clay loam | 42.200 |
| 162 | 6.541 | 0.084 | 55.060 | 112.650 | 48.952 | 37.914 | 13.134 | Loam            | 45.500 |
| 163 | 5.911 | 0.144 | 50.670 | 95.340  | 53.354 | 40.018 | 6.627  | Sandy loam      | 51.500 |

| 164 | 7.481 | 0.380 | 54.240 | 210.900 | 37.323 | 57.454 | 5.223  | Silty loam      | 45.100 |
|-----|-------|-------|--------|---------|--------|--------|--------|-----------------|--------|
| 165 | 8.404 | 0.287 | 43.180 | 276.320 | 60.417 | 22.396 | 17.187 | Sandy loam      | 73.696 |
| 166 | 6.517 | 0.457 | 29.400 | 129.575 | 56.980 | 12.376 | 30.644 | Sandy clay loam | 33.000 |
| 167 | 5.482 | 0.055 | 17.409 | 33.500  | 52.996 | 19.462 | 27.541 | Sandy clay loam | 41.000 |
| 168 | 6.706 | 0.044 | 18.158 | 106.619 | 45.180 | 11.378 | 43.442 | Clay            | 27.000 |
| 169 | 5.729 | 0.080 | 32.847 | 29.938  | 57.537 | 11.040 | 31.423 | Sandy clay loam | 44.000 |
| 170 | 5.611 | 0.061 | 38.434 | 78.488  | 61.117 | 11.665 | 27.218 | Sandy clay loam | 44.000 |
| 171 | 5.774 | 0.053 | 13.187 | 31.213  | 62.035 | 21.289 | 16.676 | Sandy loam      | 24.000 |
| 172 | 5.168 | 0.102 | 17.257 | 25.819  | 77.602 | 6.892  | 15.507 | Sandy loam      | 20.000 |
| 173 | 5.161 | 0.061 | 1.414  | 6.694   | 87.694 | 5.384  | 6.922  | Loamy sand      | 12.800 |
| 174 | 5.579 | 0.071 | 13.349 | 26.431  | 71.829 | 15.620 | 12.552 | Sandy loam      | 20.800 |
| 175 | 5.537 | 0.025 | 23.701 | 9.388   | 63.867 | 25.247 | 10.886 | Sandy loam      | 14.400 |
| 176 | 5.937 | 0.037 | 22.249 | 31.656  | 71.440 | 17.808 | 10.752 | Sandy loam      | 21.600 |
| 177 | 5.862 | 0.072 | 18.240 | 23.819  | 65.660 | 16.297 | 18.043 | Sandy loam      | 42.400 |
| 178 | 5.469 | 0.030 | 20.462 | 26.644  | 75.012 | 10.289 | 14.699 | Sandy loam      | 22.400 |
| 179 | 5.852 | 0.060 | 8.080  | 15.763  | 80.053 | 15.111 | 4.836  | Loamy sand      | 16.000 |
| 180 | 5.074 | 0.037 | 9.541  | 10.588  | 84.088 | 3.080  | 12.832 | Loamy sand      | 18.400 |
| 181 | 5.679 | 0.034 | 13.343 | 14.138  | 83.917 | 4.669  | 11.414 | Loamy sand      | 24.000 |
| 182 | 4.931 | 0.079 | 17.364 | 19.956  | 73.126 | 11.645 | 15.228 | Sandy loam      | 24.800 |
| 183 | 6.208 | 0.035 | 14.643 | 26.881  | 74.003 | 7.183  | 18.814 | Sandy loam      | 16.000 |
| 184 | 5.394 | 0.036 | 9.399  | 15.625  | 82.882 | 6.898  | 10.220 | Loamy sand      | 12.800 |

| 185 | 5.142 | 0.031 | 7.916  | 13.075 | 70.765 | 18.794 | 10.441 | Sandy loam      | 18.400 |
|-----|-------|-------|--------|--------|--------|--------|--------|-----------------|--------|
| 186 | 5.384 | 0.373 | 7.528  | 11.413 | 84.161 | 6.212  | 9.628  | Loamy sand      | 16.800 |
| 187 | 4.958 | 0.068 | 5.271  | 6.988  | 84.046 | 3.039  | 12.915 | Loamy sand      | 19.200 |
| 188 | 5.548 | 0.043 | 13.610 | 17.181 | 83.905 | 6.241  | 9.854  | Loamy sand      | 26.400 |
| 189 | 5.437 | 0.053 | 7.923  | 10.131 | 71.814 | 12.918 | 15.267 | Sandy loam      | 21.600 |
| 190 | 5.445 | 0.055 | 15.245 | 27.231 | 64.991 | 14.824 | 20.185 | Sandy clay loam | 27.200 |
| 191 | 5.274 | 0.031 | 6.457  | 16.213 | 83.549 | 3.850  | 12.601 | Loamy sand      | 28.800 |
| 192 | 5.188 | 0.023 | 26.786 | 29.531 | 56.076 | 27.573 | 16.351 | Sandy loam      | 26.400 |
| 193 | 5.041 | 0.023 | 9.165  | 15.844 | 80.756 | 7.530  | 11.714 | Sandy loam      | 17.600 |
| 194 | 5.660 | 0.058 | 7.394  | 12.400 | 75.882 | 10.294 | 13.824 | Sandy loam      | 28.800 |
| 195 | 5.189 | 0.045 | 13.035 | 12.138 | 62.708 | 13.318 | 23.973 | Sandy clay loam | 19.200 |
| 196 | 5.023 | 0.038 | 16.809 | 19.738 | 51.296 | 18.685 | 30.019 | Sandy clay loam | 23.200 |
| 197 | 5.350 | 0.082 | 6.611  | 17.788 | 71.540 | 14.230 | 14.230 | Sandy loam      | 28.800 |
| 198 | 5.061 | 0.029 | 26.130 | 13.894 | 59.391 | 17.783 | 22.826 | Sandy clay loam | 23.200 |
| 199 | 6.131 | 0.053 | 26.130 | 32.888 | 75.694 | 5.632  | 18.674 | Sandy loam      | 28.800 |
| 200 | 5.706 | 0.040 | 22.555 | 18.056 | 65.873 | 12.286 | 21.841 | sandy clay loam | 21.600 |

## ANNEXURE III

## List of samples (n=40) selected for extensive studies with their properties

| Sl. No. | Zone   | District       | Sampling location | Villagename       | pН   | E.C.                 | CCSi  | AASi     | Sand  | Silt  | Clay  | CEC                              | <b>0.C.</b> |
|---------|--------|----------------|-------------------|-------------------|------|----------------------|-------|----------|-------|-------|-------|----------------------------------|-------------|
|         |        |                |                   |                   |      | (dSm <sup>-1</sup> ) | (n    | ıg kg¹)- |       | perce | nt    | (cmol (p+)<br>kg <sup>-1</sup> ) | (%)         |
| 1.      | NEDZ-1 | Raichur        | Deodurga          | Bunkaladoddi      | 9.54 | 0.416                | 44.64 | 87.89    | 72.89 | 7.49  | 19.61 | 77.39                            | 0.27        |
| 2.      | NEDZ-2 | Raichur        | Deodurga          | Jalahalli         | 6.17 | 0.111                | 24.65 | 28.02    | 80.44 | 0     | 19.56 | 22.00                            | 0.36        |
| 3.      | NEDZ-3 | Raichur        | Manvi             | Manvi             | 7.49 | 0.224                | 24.67 | 58.68    | 83.35 | 12.76 | 3.89  | 48.00                            | 0.62        |
| 4.      | NEDZ-4 | Yadgir         | Shahpur           | Kongoddi          | 8.88 | 0.407                | 42.86 | 111.64   | 45.75 | 16.30 | 37.94 | 32.17                            | 0.59        |
| 5.      | NDZ -1 | Raichur        | Lingasagur        | Gowduru           | 8.08 | 0.319                | 10.27 | 97.82    | 73.17 | 21.02 | 5.81  | 25.60                            | 0.18        |
| 6.      | NDZ-2  | Bellary        | Hospete           | Nandibandigrama   | 7.12 | 0.393                | 57.81 | 123.58   | 90.45 | 3.18  | 6.36  | 21.00                            | 0.20        |
| 7.      | NDZ-3  | Koppal         | Gangavathi        | Karatagi          | 8.85 | 0.527                | 21.56 | 44.61    | 71.65 | 5.51  | 22.84 | 54.57                            | 0.27        |
| 8.      | CDZ-1  | Davanagere     | Davanagere        | Mallenahalli 1    | 5.27 | 0.081                | 13.58 | 18.16    | 78.91 | 5.27  | 15.81 | 17.60                            | 0.20        |
| 9.      | CDZ-2  | Davanagare     | Harihar           | Doddabathi 2      | 7.09 | 0.191                | 32.71 | 100.11   | 72.22 | 3.40  | 24.37 | 21.80                            | 0.71        |
| 10.     | CDZ-3  | Chitradurga    | Hiriyur           | Vanivilasa sagara | 9.12 | 0.487                | 24.72 | 63.27    | 57.57 | 14.55 | 27.88 | 38.26                            | 0.39        |
| 11.     | EDZ-1  | Kolar          | Mulbagal          | Keelaholeli       | 5.07 | 0.129                | 14.55 | 19.41    | 85.52 | 4.42  | 10.06 | 12.00                            | 0.29        |
| 12.     | EDZ-2  | Chikkaballapur | Gudibande         | Krishnarajapura   | 6.86 | 0.506                | 36.10 | 75.35    | 80.44 | 4.31  | 15.24 | 12.00                            | 0.06        |
| 13.     | EDZ-3  | Ramanagara     | Kanakapura        | Chikahalabalu     | 8.48 | 0.229                | 27.68 | 62.81    | 80.66 | 12.12 | 7.22  | 20.00                            | 0.68        |
| 14.     | SDZ-1  | Mandya         | Mandya            | VCFarm            | 8.02 | 0.162                | 32.95 | 136.22   | 78.29 | 12.71 | 8.99  | 23.30                            | 0.48        |
| 15.     | SDZ-2  | Mandya         | Pandavapura       | Kennahalu         | 6.97 | 0.107                | 41.54 | 77.80    | 61.16 | 9.46  | 29.38 | 9.20                             | 1.04        |
| 16.     | SDZ-3  | Mandya         | Maddur            | Huligere pura 2   | 8.52 | 0.267                | 24.09 | 70.59    | 76.73 | 6.08  | 17.18 | 20.30                            | 0.33        |
| 17.     | SDZ-4  | Mysore         | Nanjangud         | Chikayanachakra   | 5.80 | 0.048                | 32.32 | 55.21    | 66.94 | 13.07 | 19.98 | 19.70                            | 0.83        |
| 18.     | SDZ-5  | Tumkur         | Turuvekere        | Tavarekere 2      | 8.72 | 0.302                | 33.46 | 115.53   | 53.69 | 37.91 | 8.39  | 47.17                            | 0.36        |
| 19.     | SDZ-6  | Chamarajanagar | Yelanduru         | yaniyunu          | 9.10 | 0.605                | 55.15 | 88.24    | 68.27 | 7.79  | 23.93 | 81.52                            | 0.54        |
| 20.     | STZ-1  | Shimoga        | Shimoga           | Navile            | 4.99 | 0.082                | 16.86 | 35.89    | 86.09 | 10.94 | 2.96  | 11.60                            | 0.24        |
| 21.     | STZ-2  | Davanagere     | Honnalli          | Kalivada          | 7.58 | 0.237                | 36.84 | 203.35   | 64.57 | 8.79  | 26.63 | 30.40                            | 0.06        |
| 22.     | STZ-3  | Mysore         | Heggadevanakote   | Irge              | 8.49 | 0.325                | 9.28  | 22.81    | 55.81 | 16.97 | 27.21 | 47.61                            | 1.04        |

| 23. | STZ-4 | Hassan           | Arakalagudu       | Vaddarahalli        | 5.58 | 0.124 | 32.39 | 34.76  | 35.46 | 30.15 | 34.39 | 13.70 | 0.86 |
|-----|-------|------------------|-------------------|---------------------|------|-------|-------|--------|-------|-------|-------|-------|------|
| 24. | NTZ-1 | Haven            | Hirekerur2        | Hirekerur 2         | 8.49 | 0.378 | 22.83 | 188.79 | 48.10 | 36.78 | 15.11 | 58.69 | 0.33 |
| 25. | NTZ-2 | Belgaum          | Belgaum           | Macche              | 5.62 | 0.054 | 82.89 | 130.19 | 22,47 | 26.58 | 50.94 | 45.00 | 1.13 |
| 26. | NTZ-3 | Belgaum          | Belgaum           | Basavanakudchi      | 7.67 | 0.729 | 34.13 | 370.24 | 62.92 | 31.97 | 5.11  | 51.00 | 0.53 |
| 27. | HZ-1  | Chikkamagalore   | Narasimharajnagar | K. Kanabur          | 6.17 | 0.053 | 23.82 | 31.81  | 37.01 | 23.51 | 39.48 | 16.70 | 0.59 |
| 28. | HZ-2  | Hassan           | Sakleshpur        | Chikkanayakanahalli | 4.95 | 0.164 | 39.48 | 35.01  | 78.94 | 18.20 | 2.86  | 16.20 | 0.71 |
| 29. | HZ-3  | Haven            | Hangal            | Singapur 5          | 8.40 | 0.287 | 43.18 | 276.32 | 60.42 | 22.39 | 17.19 | 73.69 | 0.45 |
| 30. | HZ-4  | Chikkamagalore   | Sringeri          | Gandagatta          | 5.15 | 0.041 | 11.79 | 13.75  | 48.61 | 17.61 | 33.77 | 14.30 | 1.63 |
| 31. | HZ-5  | Dharwad          | Kalghatgi         | Huliyala            | 5.73 | 0.080 | 32.85 | 29.94  | 57.54 | 11.04 | 31.42 | 44.00 | 0.41 |
| 32. | HZ-6  | Uttar kannada    | Yallapura         | Idagundi            | 5.77 | 0.053 | 13.19 | 31.21  | 62.04 | 21.29 | 16.68 | 24.00 | 1.19 |
| 33. | HZ-7  | Uttar kannada    | Siddapura         | Thyagal             | 5.16 | 0.060 | 1.41  | 6.69   | 87.69 | 5.38  | 6.92  | 12.80 | 0.03 |
| 34. | HZ-8  | Kodagu           | Virajpete         | Kakotporchi         | 5.94 | 0.037 | 22.25 | 31.66  | 71.44 | 17.81 | 10.75 | 21.60 | 0.39 |
| 35. | HZ-9  | Kodagu           | Somavarapete      | Kudige              | 5.07 | 0.037 | 9.54  | 10.59  | 84.09 | 3.08  | 12.83 | 18.40 | 0.56 |
| 36. | CZ-1  | Uttar Kannada    | Kumta             | Dhareshwara         | 4.93 | 0.079 | 17.37 | 19.96  | 73.13 | 11.64 | 15.29 | 24.80 | 0.92 |
| 37. | CZ-2  | Udupi            | Udupi             | Hiriyadka           | 5.55 | 0.043 | 13.61 | 17.18  | 83.90 | 6.24  | 9.85  | 26.40 | 2.35 |
| 38. | CZ-3  | Udupi            | Kolluru           | Idooru kunchadi     | 5.19 | 0.023 | 26.79 | 29.53  | 56.08 | 27.57 | 16.35 | 26.40 | 2.97 |
| 39. | CZ-4  | Dakshina Kannada | Belthangady       | Karaya              | 5.35 | 0.082 | 6.61  | 17.78  | 71.54 | 14.23 | 14.23 | 28.80 | 1.99 |
| 40. | CZ-5  | Dakshina Kannada | Bantwala          | Karimanelu          | 6.13 | 0.053 | 26.13 | 32.88  | 75.69 | 5.63  | 18.67 | 28.80 | 1.55 |
|     |       |                  |                   |                     |      |       |       |        |       |       |       |       |      |

## Effect of Different Sources of Silicon Fertilizer on Dissolved Silicon (DSi) in Soil Solution and its Bioavailability for Rice Crop in Three Contrasted Soil

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#### ABSTRACT

The present investigation was conducted in green house to assess the effect of different sources of silicon on soil solution Si and its bioavailability for rice in three types of soil. Rate of dissolution and release of Si from Si fertilizers varied among different sources and types of soil. Bioavailability of Si increased significantly with application of Si fertilizer and its effectiveness varied among soils and fertilizers. Plant available Si content in post harvest soil decreased in presence of rice crop as evidenced by plant uptake.

SILICON (Si) is one of the most abundant elements in the earth's crust. Though, soils generally contain about 5 to 40 per cent Si, mainly as quartz and crystalline silicates, their contribution to the plant available Si (PAS) pool in soil is very little due to their poor solubility (Epstein, 1999). It has been well documented that monosilicic acid (H<sub>4</sub>SiO<sub>4</sub>) is the only form of dissolved Si present in the soil solutions readily absorbed by the plants (Jones and Handreck, 1965). Nevertheless, the measured concentrations of monosilicic acid in soil solutions were only 0.1 -0.6 mM (Drees et al., 1989). The main factors influencing the soil Si availability or Si supplying power includes types of soil and parent material, soil pH, soil texture, land use and other accompanying ions. Furthermore, DSi concentrations in soil solution are linked to soil temperature and pore water residence time in the soil (Struyf et al., 2009). Rice is considered as a silicon accumulator plant and tends to actively accumulate Si. Although Si has not been recognized as an essential element for plant growth, it helps in alleviating various abiotic stresses like metal toxicity, drought, radiation damage, nutrient imbalance and high temperature. Also, Si plays a crucial role in preventing or minimizing the lodging in cereal crops and biotic stresses, a matter of great importance in terms of achieving higher yield (Guntzer et al., 2012). These beneficial effects of Si can therefore result in increasing the production and productivity of rice. Extensive and repeated cultivation of rice can deplete available Si in soil (Prakash, 2002) and hence there is need for silicon fertilization.

A pot experiment was conducted to assess the effect of Si fertilizers on DSi and its bioavailability in

three soils with contrasting pH with and without rice crop. Acidic soil with pH 5.86, neutral soil with pH of 7.10 and alkaline soil with pH of 9.38 were collected from Hassan, Mandya and Hiriyur respectively. The texture of acidic and neutral soil was sandy loam and that of alkaline soil was clay loam as determined by standard pipette method. Bulk soil was collected from each location, air dried and sieved through two mm sieve and used for pot culture studies. Soils were analysed for PAS by extracting with 0.1M calcium chloride (CCSi) and 0.05M acetic acid (AASi). Si concentration of acidic, neutral and alkaline soil was found to be 43.10, 73.82, 109.46 ppm as extracted by 0.05M acetic acid and 30.58, 41.98, 46.18 ppm as extracted by 0.1M Calcium chloride, respectively. Three types of Si sources were used in this experiment viz., calcium silicate (CaSiO, -12% Si), diatomaceous earth (DE -63.7 % SiO<sub>2</sub>) and rice husk biochar (RHB -30% Si) and applied at 250 and 500 kg Si ha<sup>-1</sup>. The study was undertaken by filling 5 kg of each soil per pot and mixed thoroughly with graded levels of Si sources. A rhizon was inserted at a depth of 10cm laterally in each pot to collect the soil solution at different interval. There were four treatments viz., T.:  $Si_0 + RP_0, T_2$ :  $Si_0 + RP, T_3$ :  $Si_1 + RP_0, T_4$ :  $Si_1 + RP$  ( $Si_0$ = without silicon,  $RP_0$  = without crop,  $Si_1$  = with silicon, RP=with crop) and thereby 14 combinations of treatments for one type of soil. Two twenty one days old rice seedlings (Var. Thanu) were transplanted to each pot and moisture content was maintained at submergence. Recommended dose of P<sub>2</sub>O<sub>5</sub> (SSP), half dose of the recommended K<sub>2</sub>O (as MOP) and N (as Urea) were applied as basal dosage. Remaining nitrogen and potash were given as two splits at 30<sup>th</sup> and 60<sup>th</sup> day after transplanting. Water samples have been collected by using preinstalled soil solution samplers (Rhizon collector) at 0, 7, 15, 30, 60, 90 and 120 days after transplanting (DAT) and analysed for Si. Straw and grain samples of acidic and neutral soil and only straw samples (due to condensed growth) in alkaline soil were collected at harvest and analysed for Si content and computed for total Si uptake based on yield and content. Post harvest soil samples were collected and analyzed for CCSi and AASi.

There was a gradual decrease in DSi from 0 to 15 days and thereafter stabilized in acidic soil. CaSiO<sub>3</sub> and RHB treatment recorded significantly higher DSi than DE. During initial period of experiment (0 - 15 DAT), CaSiO<sub>3</sub> treatment recorded lower DSi but increased significantly in later part of experiment (30 - 120 DAT) whereas DE treatment recorded significantly higher during initial period later on it decreased. In neutral soil, silicon concentration decreased from 0-30 DAT but increased significantly at 60 DAT and then decreased at harvest stage and application of RHB and CaSiO<sub>3</sub> significantly increased the Si.



Fig. 1. Effect of Si fertilizer on DSi at different intervals with and without crop in a) acidic, b) neutral and c) alkaline soil ( $T_1$ : Si\_0 + RP\_0,  $T_2$ : Si\_0 + RP,  $T_3$ : RP\_0 + CaSiO\_3 @ 250 kg Si ha<sup>-1</sup>,  $T_4$ : RP\_0 + CaSiO\_3 @ 500 kg Si ha<sup>-1</sup>,  $T_5$ : RP\_0 + DE @ 250 kg Si ha<sup>-1</sup>,  $T_6$ : RP\_0 + DE @ 500 kg Si ha<sup>-1</sup>,  $T_7$ : RP\_0 + RHB @ 250 kg Si ha<sup>-1</sup>,  $T_8$ : RP\_0 + RHB @ 500 kg Si ha<sup>-1</sup>,

Si concentration increased during the period from 0 - 90 DAT and then slightly decreased at harvest and application of RHB and DE could increase the Si in alkaline soil (Fig. 1). When Si source is applied to soil, Si dissolves in the soil solution and part of the dissolved Si is adsorbed onto the soil solid phase and then desorbed and redissolved into soil solution (Suhei *et al.*, 2013). The variability in DSi by the application of three different Si sources may be dependent on reactivity based on the soil pH rather than total Si content (Haynes, 2014).

Irrespective of Si sources, Si uptake was higher in neutral soil followed by acidic and alkaline soil. Application of  $CaSiO_3$  significantly increased the uptake of Si in acidic and neutral soil whereas application of RHB recorded significantly higher uptake in alkaline soil (Fig. 2).



Fig. 2 Effect of different sources of Si on total Si uptake (straw + grain) in acidic, neutral and straw Si uptake in alkaline soil, respectively. (Alphabets indicates the significance level at P< 0.05 via Fisher test with XLSTAT).

It is obvious that application of different Si fertilizer could increase the Si uptake as evidenced by earlier studies (Kanto *et al.*, 2004) but efficiency of different source varied with the types of soil. Post harvest soil silicon decreased significantly in treatment with crop plants was mainly attributed to plant uptake (Table I) irrespective of Si sources. Calcium chloride extractable Si was higher in neutral and alkaline soil than acidic

#### TABLE I

| Treatments                                      | Acidic soil |             | Neutral soil |            | Alkaline soil |               |
|---|-------------|-------------|--------------|------------|---------------|---------------|
|   | CCSi        | AASi        | CCSi         | AASi       | CCSi          | AASi          |
| Ck – without crop                               | 31.8 (cd)   | 76.7 (def)  | 49.9 (ab)    | 81.4 (ef)  | 42.8 (d)      | 116.4 (d)     |
| Ck-with crop                                    | 28.3 (cdef) | 62.8 (f)    | 42.3 (cd)    | 80.3 (f)   | 44.9 (bcd)    | 115.2 (d)     |
| Without crop                                    |             |             |              |            |               |               |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 28.1(cdef)  | 105.2 (b)   | 45.8 (abcd)  | 112.0 (b)  | 44.3 (bcd)    | 143.1(ab)     |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 26.7(defg)  | 104.0 (a)   | 43.5 (abcd)  | 133.0 (a)  | 45.5 (bcd)    | 131.3 (abcd)  |
| DE @ 250 kg Si ha-1                             | 33.6 (bc)   | 78.1(def)   | 49.8 (abc)   | 87.2 (cde) | 41.2 (d)      | 122.5 (bcd)   |
| DE @ 500 kg Si ha-1                             | 33.8 (bc)   | 84.6 (cdef) | 51.8 (a)     | 88.0 (cde) | 43.3 (cd)     | 119.7 (cd)    |
| RHB @ 250 kg Si ha-1                            | 38.1(ab)    | 79.6 (cdef) | 53.0 (a)     | 88.7 (cd)  | 45.2 (bcd)    | 130.18 (abcd) |
| RHB @ 500 kg Si ha-1                            | 40.7 (a)    | 95.0 (bcd)  | 51.5 (a)     | 84.4 (def) | 48.4 (ab)     | 127.8 (abcd)  |
| With crop                                       |             |             |              |            |               |               |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 21.8 (g)    | 98.3 (bc)   | 37.7 (d)     | 108.7 (b)  | 44.0 (bcd)    | 146.4 (a)     |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 25.1(fg)    | 150.0 (a)   | 37.9 (d)     | 139.2 (a)  | 44.7 (bcd)    | 143.1(ab)     |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 26.3 (efg)  | 62.4 (f)    | 43.0 (bcd)   | 87.1(cde)  | 43.1(cd)      | 133.7 (abc)   |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 28.0 (cdef) | 72.4 (ef)   | 41.2 (cd)    | 91.4 (cd)  | 42.5 (d)      | 133.5 (d)     |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 31.6 (cde)  | 78.6 (cdef) | 41.9 (cd)    | 91.5 (cd)  | 47.7 (bc)     | 117.7 (cd)    |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 30.7(cde)   | 71.4 (ef)   | 51.2 (a)     | 92.2 (c)   | 52.4 (a)      | 121.1(cd)     |
| LSD @ 5 %                                       | 5.73        | 19.28       | 8.21         | 6.96       | 4.44          | 18.15         |

Silicon concentration in post harvest soil

(Ck – Check, Alphabets in parenthesis indicates the significance level at P< 0.05 via Fischer test with XLSTAT)

soil whereas acetic acid extractable Si was higher in alkaline soil than neutral and acidic soil. Plant available Si content of post harvest soil as estimated by acetic acid when treated with CaSiO<sub>3</sub> was found to be on par among the treatments with and without crop in both acidic and neutral soil.

DSi and its bioavailability varied among different soils and sources of Si fertilizer. CaSiO<sub>3</sub> and RHB performed better in acidic and neutral soil whereas DE and RHB in alkaline soil.

#### REFERENCES

- DREES, L.R., WILDING, L.P., SMECK, N.E., AND SANKAYI, A.L. 1989, Silica in soils: quartz and disordered silica polymorphs. *Soil Sci. Soc. Am.*, pp. 913-974.
- EPSTEIN, E. 1999, Silicon. Annu. Rev. Plant Physiol. Plant Mol. Biol., 50: 641-644.

GUNTZER, F., KELLER, C., POULTON, P. R., MCGRATH, S. P. AND MEUNIER, J. D. ,2012, Long-term removal of wheat straw decreases soil amorphoussilica at Broadbalk, Rothamsted. *Plant Soil*, **352**: 173-184.

- HAYNES, R. J., 2014, A contemporary overview of silicon availability in agricultural soils. J. Plant Nutr. Soil Sci., 177: 831-844.
- JONES, L. H. P. AND HANDRECK, K. A., 1965, Studies on silica in the oat plant.III Uptake of silica from soils by the plants. Plant Soil, 23: 79-96.
- KANTO, T., MIYOSHI, A., OGAWA, T., MAEKAWA, K. AND AINO, M., 2004, Suppressive effect of potassium silicate on powdery mildew of strawberry in hydroponics. J. Gen. Plant Pathol., 70: 207-211.

PRAKASH, N. B., 2002, Status and utilization of silicon in Indian rice farming. Second Silicon in Agriculture Conference, 1: 266-273.

- STRUYF, E., SMIS, A. DAMME, S. V., MEIRE, P. AND CONLEY, D. J., 2009, The global biogeochemical silicon cycle. Silicon, 1: 207-213.
- SUHEI, M. S., KEN, I. K., YUKA, S. AND ANDO, H., 2013, Effect of slag silicate fertilizer on dissolved silicon in soil solution based on the chemical properties of gleysols.Soil. Sci. Plant Nutr., 21:1-7.

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# Bioavailability of different sources of silicon and their effect on growth and yield of rice in acidic, neutral and alkaline soils of Karnataka, South India

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Bioavailability of different sources of silicon and their effect on growth and yield of rice in acidic, neutral and alkaline soils of Karnataka, South India

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#### ABSTRACT

Effect of three different sources of silicon (Si) on growth, yield and Si bioavailability for rice crop was studied in three contrasting soils of Karnataka in a pot experiment. Acidic (pH 5.86), neutral (pH 7.10) and alkaline (pH 9.38) soils collected from different locations were used for the study with rice as a test crop. Calcium silicate, diatomite and rice husk biochar was applied at 250 and 500 kg Si ha<sup>-1</sup> and maintained with and without rice crop under submerged condition. There were 14 treatment combinations with thrice replicated. There was a significant increase in the yield parameters such as panicle number pot<sup>-1</sup>, panicle length pot<sup>-1</sup>, straw dry weight pot<sup>-1</sup> and grain weight pot<sup>-1</sup> in acidic and neutral soil whereas only straw dry weight pot<sup>-1</sup> in alkaline soil with the application of Si sources over control. Higher nutrient content and uptake was noticed in neutral soil followed by acidic and alkaline soil. Although the application rate of different Si sources was 250 and 500 kg Si ha<sup>-1</sup>, there was a significant difference in the nutrient content and uptake by rice among the Si sources. Significant difference in plant available silicon status of the soil was noticed with the application of calcium silicate significantly increased the

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silicon status of the soil whereas rice husk biochar in alkaline soil. Plant available Si in soil decreased in the presence crop in acidic and neutral soil while increased in alkaline soil.

#### **KEYWORDS**

Silicon; rice; bioavailability; yield; types of soil

#### Introduction

Rice is life for most of the people living in Asia. Rice has shaped the cultures, diets and economics of thousands of millions of people (Gnanamanikam, 2009). Rice is a typical silicon (Si) accumulating plant requiring large amounts of Si for vigorous growth and high production. Silicon is absorbed by plants as monosilicic acid (H4SiO4) (Jones and Handreck, 1967) and Si can be taken up by rice at a rate as high as 500 kg Si ha<sup>-1</sup> year<sup>-1</sup> (Makabe *et al.* 2009). Production of 5 t ha<sup>-1</sup> of grain yield of rice is estimated to remove about 230 - 470 kg elemental Si from soil, depending upon soil and plant factors (Savant *et al.* 1997). Absorption of Si will be about 108 per cent more than the nitrogen content. Adequate supply of Si to rice from tillering to elongation stage increases the number of grains per panicle and the percentage of ripening (Korndorfer *et al.*, 2001). It is also suggested that the silicon plays a crucial role in preventing or minimizing the lodging incidence in the cereal crops, a matter of great importance in terms of agricultural productivity. These important factors mainly directed in many countries to include Si fertilization in agriculture.

Karnataka state located in South India represents a wide variety of geological, climatic, vegetational and physiographic features, which have influenced soil formation and thus has given rise to various types of soils. Accordingly, the different soils have distinct morphological and physico-chemical properties that have a bearing on plant growth and have influenced the
cropping pattern and availability of plant nutrients. The main factors influencing soil Si availability or Si supplying power include type of soil and parent material, historical land use change, soil pH, soil texture, soil Eh, organic matter, temperature and accompanying ions (Struyf *et al.*, 2009). Intensive cultivation and crop removal can reduce the concentration of potentially available Si to the extent that there is necessity of Si fertilization (Savant *et al.*, 1997; Meunier *et al.*, 2008).

It is evident from the fact that most of the traditional rice fields of the world are low in plant available Si and addition of Si is reported to improve the rice yield. This emphasize the need for identifying an ideal Si source/ sources for field application, which can improve soil Si status, plant available Si and sustain rice production. Silicon sources for agricultural use range from natural minerals to chemical products to byproducts of steel and iron industries. All these products are shown to be effective in improving crop growth and yield (Liang *et al.*, 2015). Solubility and bioavailability of native soil Si or applied Si fertilizers mainly depends on the surface properties like pH, soil constituents and soil reactivity rather than total Si content (Haynes, 2014). Struyf *et al.* (2009) reported the influence of pH on the dissolution of silicates can be neglected in the range of pH 2.5 to 8.5. However, in strong alkaline conditions (pH>9), part of the Si monomers transforms to polymers and DSi concentrations in soil solution increased almost exponentially with pH as a result of growing speciation to H<sub>3</sub>SiO<sub>4</sub><sup>-</sup> and H<sub>2</sub>SiO<sub>4</sub><sup>2-</sup>.

There are ranges of Si containing materials suitable for use as fertilizers (Gascho, 2001) but its availability depends on the reactivity in particular soil type. Slag fertilizers are very reactive in acidic condition (Berthelson *et al.*, 2003; Korndorfer *et al.*, 2005) whereas diatomaceous earth has limited solubility in acidic condition but its reaction increases as the soil pH increased from neutral to alkaline (Haynes, 2014). Xin *et al.* (2014) studied transformation

and dissolution of Si from Si rich biochar. Silicon dissolving rate and quantity are connected to pyrolysis temperature, which leads to variation in pH, structure, Si form and other properties of biochar.

For field application, an ideal Si source should possess attributes like local availability, cost effectiveness, easy to handle, improve plant available Si, environment friendly besides improving crop growth and yield. Also, for Si sources to be most effective as a fertilizer, it is essential to acquire knowledge of physical and chemical characteristics of Si sources and to understand the extent of bioavailability from sources for adequate plant uptake (Savant *et al.*, 1997). In this point of view, a pot experiment was conducted by using three different types of Si containing materials in three soil types (considered based on the varied soil pH) to assess the bioavailability of Si and its effect on growth and yield under rice wetland system.

#### Material and methods

A pot experiment was conducted at greenhouse, Department of Soil Science and Agricultural Chemistry, University of Agricultural Sciences, Bengaluru, Karnataka to assess the bioavailability of different sources of Si and their effect on growth and yield of rice in three types of soil.

#### Soil

Three soils with contrasting pH were used in this study. Acidic soil with pH 5.86 was collected from Hassan representing southern dry zone and taxonomically classified as *Rhodic Paleustalfs*. Neutral soil was collected with pH of 7.10 from Zonal Agricultural Researh Station, V. C. Farm, Mandya representing southern dry zone and taxonomically classified *as Typic Rhodustalfs*. Alkaline soil with pH of 9.38 was collected from Hiriyur representing central dry

zone and taxonomically classified as *Chromic haplusterts*. The texture of acidic and neutral soil was sandy loam and that of alkaline soil was clay loam. Bulk soil was collected from each location and soils were air dried, sieved through two mm sieve and used for the study. The soils were analysed for initial properties by following standard procedures and the data are presented in Table 1.

## Silicon sources

Three types of silicon sources used for the experiment were calcium silicate (CaSiO<sub>3</sub>), diatomaceous earth or diatomite (DE) and rice husk biochar (RHB). Calcium silicate is industrial slag by-product which contains around 12 per cent of Si, DE is a sedimentary rock having 30 per cent Si and RHB was produced at relatively lower temperature at around 400°C and contains 31per cent Si. All these sources were passed through 0.2 mm sieve and used for the greenhouse experiment. Compositions of Si sources are presented in Table 2.

#### 2.3 Experimental details

Study was undertaken by taking 5 kg of each soil per pot and thoroughly mixed with graded levels Si sources. Si sources were applied at 250 and 500 kg ha<sup>-1</sup> and experiment was conducted in presence (RP) and absence (RP<sub>0</sub>) of rice crop by maintaining the control (Ck). Hence, there were 14 treatment combinations *viz.*,  $Ck - RP_0$ ; Ck - RP;  $Si + RP_0 - CaSiO_3$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - CaSiO_3$  @ 500 kg Si ha<sup>-1</sup>;  $Si + RP_0 - DE$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - DE$  @ 500 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 500 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - DE$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - DE$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 500 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - DE$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - DE$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - DE$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>;  $Si + RP_0 - RHB$  @ 250 kg Si ha<sup>-1</sup>.

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One seedling of twenty one days old rice (*Var.* Tanu) was transplanted to each pot planned to rice crop and moisture was maintained at submergence for all 14 treatment pots. Recommended dose (100:50:50 kg NPK ha<sup>-1</sup>) of  $P_2O_5$  (SSP), half dose of the recommended K<sub>2</sub>O (as MOP) and N (as Urea) were applied as basal dosage to each pot. Remaining nitrogen and potash were applied as two splits at 30<sup>th</sup> and 60<sup>th</sup> day after transplanting (DAT).

Straw and grain yield parameters were recorded such as panicle number, panicle length, straw dry weight and grain weight for crops grown in acidic and neutral soil whereas only straw dry weight for crop grown in alkaline soil due to poor growth of the rice. Straw and grain samples were collected at harvest and analysed for Si content and Si uptake was computed. Soil samples after completion of the experiment was collected and analysed for parameters such as pH, EC, calcium chloride extractable Si (CCSi) and acetic acid Si (AASi).

## Analysis

#### Soil analysis

Soils collected from different locations were air dried and crushed to pass through 2mm sieve and used for analysis. Soil pH and EC was measured in a suspension of 1:2.5 water ratio. Soil textural class was determined by following International Pipette method (Jackson, 1973), available N was determined by alkaline potassium permanganate method (Subbiah and Asija, 1949). Estimation of available  $P_2O_5$  of acidic soil by Bray's method (Bray and Kurtz, 1945) and neutral and alkaline soil by Olsen method (Olsen, 1954). Available K and exchangeable Ca, Mg extracted by using 1N ammonium acetate. K was analyzed by using flame photometry (Jackson,

1973) and exchangeable Ca, Mg was determined by complexiometric titration method (Baruah and Barthakur, 1997).

#### 0.01M CaCl<sub>2</sub> extractable Si

Two grams of soil was taken in a 50 ml centrifuge tube and 20 ml of 0.01M CaCl<sub>2</sub> was added. After continuous end to end shaking in a mechanical shaker for sixteen hour, the solution was centrifuged at 2000 rpm for 10 minutes and then filtered.

Silicon in the extracting solution was determined by transferring 1 ml of filtrate into plastic centrifuge tube and then 2.5 ml of 0.5 M sulfuric acid and 2.5 ml of ammonium molybdate solution (pH 7) was added. After vortex stirring for 5 minutes, 1.25 ml of tartaric acid solution was added. After allowing for additional two minutes, 0.25 ml reducing agent (ANSA) was added. After 5 minutes, but not later than 30 minutes following addition of the reducing agent, absorbance was measured at 820nm using UV visible spectrophotometer (Shimadzu). Simultaneously Si standards (0, 0.5, 1, 2, 3, 4, 5 and 6 mg  $\Gamma^1$ ) prepared in the same matrix were also measured using UV visible spectrophotometer (Haysom and Chapman, 1975).

### 0.5 M acetic acid extractable Si

Available silicon in soil was extracted using 0.5 M acetic acid with the soil to extractant ratio of 1:2.5 as outlined by Korndorfer *et al.* (2001). After shaking continuously for a period of one hour, solution was centrifuged at 3000 rpm for 3 minutes and then filtered. The filtrate was then used for silicon determination. Silicon in the extracting solution was determined by adopting the procedure of Narayanaswamy and Prakash (2009).

An aliquot of 0.25 ml filtrate was taken into a plastic centrifuge tube and then added with 10.5 ml of distilled water, plus 0.25 ml of 1:1 hydrochloric acid, and 0.5 ml of 10 per cent ammonium molybdate solution. After allowing for 5 minutes, 0.5 ml of 20 per cent tartaric acid solution was added. After allowing for additional two minutes, 0.5 ml reducing agent (1-amino-2-napthol-4-sulfonic acid - ANSA) was added. After 5 minute, but not later than 30 minutes following addition of the reducing agent, absorbance was measured at 630nm using UV-visible spectrophotometer (SHIMADZU Pharma spec, UV-1700 series) with auto sample changer (ASC-5). Simultaneously Si standards (0, 0.2, 0.4, 0.8, 1.2 and 1.6 mg  $L^{-1}$ ) prepared in the same matrix were also measured using UV-visible spectrophotometer.

## Silicon analysis in plant sample (straw and grain)

The powdered grain and straw samples were dried in an oven at 70°C for 2-3 hrs prior to analysis. The sample (0.1g) was digested in a mixture of 7 ml of HNO<sub>3</sub> (70 %), 2 ml of H<sub>2</sub>O<sub>2</sub> (30 %) and 1 ml of HF (40 %) using microwave digestion system (Milestone-start D) with following steps: 1000 watt for 17 minutes, 1000 watt for 10 minutes and venting for 10 minutes. The digested samples were diluted to 50 ml with 4 per cent boric acid (Ma and Takahashi, 2002).

#### Estimation of silicon in plant samples

The Si concentration in the digested solution was determined as described below: 0.5 ml of digested aliquot was transferred to a plastic centrifuge tube, to this 3.75 ml of 0.2 N HCl, 0.5 ml of 10 per cent ammonium molybdate ( $(NH_4)_6Mo_7O_2$ ) and 0.5 ml of 20 per cent tartaric acid and 0.5 ml of reducing agent (Amino naphtholsulphonic acid - ANSA) was added and the volume was made up to 12.5 ml with distilled water. After one hour, the absorbance was

measured at 600 nm with a UV-visible spectrophotometer (Shimadzu) (Ma *et al.*, 2002). Similarly, standards (0, 0.2, 0.4, 0.8 and 1.2 ppm) were prepared by following the same procedure.

## Analysis of Si sources

Silicon content of CaSiO<sub>3</sub> and RHB was estimated by microwave digestion procedure. The remaining composition of the CaSiO<sub>3</sub> was estimated by following aqua regia leachable elemental method by taking 1 g of the sample into 250ml beaker adding 10 ml nitric acid and 20ml hydrochloric acid (1:1), and heating on an electric hot plate. The samples were digested with 5 - 10 ml H<sub>2</sub>O<sub>2</sub> and then the digest was diluted to 100 ml using double distilled water and filtered through whatmann filter paper and estimated with ICP-OES. Major elements of diatomite were determined by inductively coupled plasma optical emission spectrometer. Soil pH and EC of RHB was measured in a suspension of 1:2.5 water ratio.

#### Statistical analysis

Data generated were statistically analysed using XLSTAT software via one-way ANOVA by using Fisher test at  $p \le 0.05$ .

#### 1. Results and discussion

#### 3.1 Characteristics of studied soils

Three soils which were used for experiment was characterized by large variation in pH from acidic (5.86) to alkaline (9.38) and neutral soil (7..1)(Table 1). The electrical conductivity

(EC) of all three soil samples were in normal range (0.16 to 0.33 dsm<sup>-1</sup>). Based on the particle size distribution, acidic and neutral soils were sandy loam in textural class whereas, alkaline soil was clay loam in nature and all those soils were dominated with sand fraction (41.45 to 76.54 %) followed by clay fraction (16.90 to 28.15 %). Sand fraction was higher in neutral soil followed by acidic and alkaline soil while clay fraction was dominated in alkaline soil followed by acidic and neutral soil. Plant available Si as extracted by calcium chloride (CCSi) and acetic acid (AASi) was found to be higher in alkaline soil (CCSi – 46.18 and AASi – 109.47 mg kg<sup>-1</sup>) followed by neutral (CCSi – 41.98 and AASi – 73.82 mg kg<sup>-1</sup>) and acidic (CCSi – 30.58 and AASi – 43.10 mg kg<sup>-1</sup>) soil. The clay loam soil had the higher amount of native Si content compared to sandy clay soil. Neutral soil was having the higher amount all the nutrients compared to acidic and alkaline soil. Whereas Ca and Mg was found to be high in alkaline soil.

#### **Yield parameters**

The result on the effect of the Si sources on the yield parameters of rice crop revealed that panicle number pot<sup>-1</sup>, panicle length pot<sup>-1</sup>, straw dry weight pot<sup>-1</sup> and grain weight pot<sup>-1</sup> were increased with the application of Si sources in all three studied soils (Fig. 1 and Table 3). As there was poor growth of the crop under alkaline soil, only straw dry weight was reported.

## Panicle number pot<sup>-1</sup> and its length pot<sup>-1</sup>

Panicle number pot<sup>-1</sup> recorded on par with each other by the application of different sources of Si with an exception to CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup>( $2.33 \pm 0.58$ ) but all the treatments significantly higher compared to control ( $1.25 \pm 0.50$ ) in acidic soil. Panicle length pot<sup>-1</sup> recorded significantly higher by the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> ( $16.17 \pm 0.29$  cm) followed by RHB and DE. In neutral soil, panicle number pot<sup>-1</sup> recorded highest with application of CaSiO<sub>3</sub>

(*a*) 250 (1.67 ± 1.15) and 500 (2.33 ± 1.53) kg Si ha<sup>-1</sup>; and also by DE (*a*) 250 (2.33 ± 0.58) and 500 (2.33 ± 0.58) kg Si ha<sup>-1</sup> but on par with the control (1.25 ± 0.58) whereas significantly higher compared to RHB treatment, while significantly higher panicle length pot<sup>-1</sup> recorded with application of DE (*a*) 250 kg Si ha<sup>-1</sup> (17.44 ± 1.71 cm) and RHB (*a*) 500 kg Si ha<sup>-1</sup> (15.03 ± 0.06 cm). In general, application of silicon sources significantly increased the panicle number and panicle length in both soil types (Table 3). The efficiency of different Si sources in improving the panicle number and its length pot<sup>-1</sup> of rice varied with soils based on the reactivity of Si sources. Ma and Takahashi (2002) noticed higher panicle number and number of tillers of rice (Liang *et al.*, 1994) with Si fertilization. Kim *et al.* (2012) also reported that number of panicles per square meter was considerably increased by Si application compared to control in rice plants.

## Straw dry weight pot<sup>-1</sup> and Grain weight pot<sup>-1</sup>

Straw dry weight was found to be higher in the neutral soil followed by acidic and alkaline soil (Fig. 1). In acidic soil, straw yield was significantly higher with the application of CaSiO<sub>3</sub> (8.21 and 8.45 g pot<sup>-1</sup> respectively) followed by DE (6.18 and 5.89 g pot<sup>-1</sup> respectively) at both the rates of applied Si (250 and 500 kg Si ha<sup>-1</sup>) over control. A significantly higher straw dry weight was recorded with the application of DE at 250 and 500 kg Si ha<sup>-1</sup> (8.48 and 9.36 g pot<sup>-1</sup> respectively) followed by CaSiO<sub>3</sub> (7.60 and 7.83 g pot<sup>-1</sup> respectively) in neutral soil compared to control. In both types of soil RHB did not perform well and it was almost on par with the control at both rates of Si application. Grain yield of the rice under acidic and neutral soil has been reported but not for alkaline soil because of the poor growth of the crop. Application of CaSiO<sub>3</sub> (1.85± 0.40, 2.12± 0.34 g pot<sup>-1</sup> in acidic soil and 3.09 ± 0.10, 4.42± 0.14 g pot<sup>-1</sup> in neutral soil with 250 and 500 kg Si ha<sup>-1</sup> in acidic soil and 1.14± 0.09, 1.39 ± 0.04 g pot<sup>-1</sup> in acidic soil and 1.14± 0.09, 1.39 ± 0.04 g pot<sup>-1</sup> in acidic soil and 1.14± 0.09, 1.39 ± 0.04 g pot<sup>-1</sup> in acidic soil with 250 and

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500 kg Si ha<sup>-1</sup> respectively) and DE ( $1.12\pm 0.03$  in acidic soil and  $3.96\pm 0.07$ ,  $3.38\pm 0.16$  g pot<sup>-1</sup> in neutral soil with 250 and 500 kg Si ha<sup>-1</sup> respectively) recorded significantly higher grain yield compared to control ( $0.99\pm0.05$  g pot<sup>-1</sup> in acidic soil and  $2.74\pm0.46$  g pot<sup>-1</sup> in neutral soil) in both soils except with application of DE @ 500 kg Si ha<sup>-1</sup> ( $1.01\pm 0.01$  g pot<sup>-1</sup>) in acidic soil. Although significant difference recorded between Si applied and non applied pots there was no definite trend of increase in the grain yield with increased rate of Si application. Singh *et al.* (2005) also noticed, application of Si in rice increased grain yield with application of Si in rice. Application of calcium silicate as Si source significantly increased the grain and straw yield in acidic, neutral and alkaline soils of Karnataka (Narayanaswamy and Prakash, 2009). Pati *et al.* (2016) showed that application of diatomite as silicon source significantly increased grain and straw yield as well as other yield attributing parameters.

Under alkaline soil only straw yield (Fig. 1) was recorded due to poor plant growth. There was significantly higher straw dry weight pot<sup>-1</sup>( $0.67 \pm 0.10$  g pot<sup>-1</sup>) with application of RHB @ 250 kg Si ha<sup>-1</sup>, while others noticed on par but significantly higher compared to control. The straw yield was found to be higher in alkaline soil with application of RHB and attributed to higher dissolution rate of biochar under high pH soil (Xin *et al.*, 2014). Application of crop residues such as rice straw and rice hull has a beneficial effect on the build-up of organic matter and increased the N – supplying capacity of the wetland soils as there is a strong relationship between organic matter content and potentially mineralizable N as reported by Sahrawat (1983). Prakash *et al.* (2002) and recently Akshatha (2015) reported that application of 2 – 8 t ha<sup>-1</sup> of rice hull biochar recorded maximum straw and grain yield of rice. Xin *et al.* (2014) studied transformation and dissolution of Si from Si rich biochar. They reported that the release of Si from biochar produced at low temperature (200 - 400°C) increased the dissolution of Si linearly

with time. Similar observation was also made by Nguyen *et al.* (2014). Usually under salt stressed condition, plant growth will be reduced and nutrient ratio will be altered by the higher accumulation of salts. Salt stress causes both osmotic and ionic stress in the plant which affect the physiological activities of the plant and thereby plant growth and yield. Silicon is such elements which helps in reducing the salt stress in plants and enhances the growth of the plant and therefore application of Si source (CaSiO<sub>3</sub> or DE or RHB) improved the plant growth compared to control (Liang *et al.*, 2003; Ashraf *et al.*, 2010). The beneficial effects of Si under stress condition was mostly attributed to its deposition in cell walls of the roots, leaves and stems (Ma *et al.*, 2006). In general there was significant variation in the reactivity of the different sources of Si in different types of soil.

#### Silicon content and its uptake

A large variation for Si concentration in rice straw existed among the different sources of Si in three types of soil. In general, straw Si concentration was found to be higher in neutral soil followed by acidic and alkaline soil (Fig. 2). In acidic soil, application of RHB @ 500 kg Si ha<sup>-1</sup> could increase the straw Si (7.18 $\pm$  0.21%) significantly followed by DE and CaSiO<sub>3</sub> with an exception to CaSiO<sub>3</sub> @ 250 kg Si ha<sup>-1</sup> application which showed on par result with control (4.59 $\pm$  0.06%). However, straw Si uptake (527.49  $\pm$  39.15 mg pot<sup>-1</sup>) was found to be significantly higher with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> followed by DE and RHB. Application of CaSiO<sub>3</sub> significantly increased the straw Si concentration (7.98 $\pm$  0.94, 7.45 $\pm$  7.45% with application of 250 and 500 kg Si ha<sup>-1</sup> respectively) whereas other Si sources showed on par with control under in neutral soil. However, Si uptake was significantly increased with the application of Si sources over control with an exception to RHB @ 250 kg Si ha<sup>-1</sup>. In alkaline soil, straw Si concentration was significantly higher with the application of CaSiO<sub>3</sub> the straw Si uptake with the application of CaSiO<sub>3</sub> significantly higher with the application of Si sources over control with an exception to RHB @ 250 kg Si ha<sup>-1</sup>. In alkaline soil, straw Si concentration was significantly higher with the application of CaSiO<sub>3</sub> (5.89 $\pm$  0.57%) but its

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uptake was found to be significantly higher with the application of RHB ( $35.32\pm 4.60 \text{ mg pot}^{-1}$ ) than other sources. In acidic and neutral soil, application of calcium silicate influenced the nutrient uptake compared to other sources whereas RHB performed better in alkaline soil. The difference in effectiveness can be due to variation in reactivity of respective sources based on soil type. Although different Si sources were applied @ 250 and 500 kg Si ha<sup>-1</sup>, there was a significant difference in the Si content and uptake by rice among the Si sources. This result corroborates with the findings of Tavakkoli *et al.* (2011) who reported that Si uptake in rice was greatest in acidic to neutral soil. The uptake of Si by plant significantly increased to an extent of 60 per cent at the higher level of Si application as wollastonite @ 800 kg ha<sup>-1</sup> than 200 kg ha<sup>-1</sup> but it was contrasted in present study that there was no regular trend in increasing the Si uptake with increased rate of application or at higher level of Si application. The increase in the Si uptake was also noticed by Sahu (1990) who reported that significant increase in Si uptake by rice plant due to the application of rice hull as a source of Si. Deren *et al.* (1994) noticed increased Si concentration in plant tissue with increasing rate of Si fertilization. Similar results were also reported by Winslow (1992) and Winslow *et al.* (1997) in South America.

Grain Si content and uptake in acidic and neutral soil (Fig. 3) showed a significant difference with the application of Si sources over control. However, higher performance was recorded in neutral soil compared to acidic soil. A significantly higher Si content  $(0.92\pm 0.03, 0.75\pm 0.02 \%$  in acidic and neutral soil respectively) and its uptake  $(19.68\pm 3.72, 33.25\pm 0.16 \text{ mg pot}^{-1}$  in acidic and neutral soil respectively) was noticed with the application of CaSiO<sub>3</sub> @ 500 kg Si ha<sup>-1</sup> followed by DE and RHB. Although higher grain Si content was noticed in acidic soil, uptake was higher in case of neutral soil.

Irrespective of Si sources, linear regression for Si content and amount of Si added (Fig. 4) showed that straw Si content of rice grown in neutral ( $r^2=0.5984$ ) and alkaline ( $r^2=0.5558$ ) soil and grain Si content in neutral ( $r^2=0.772$ ) soil decreased as the rate of Si application increased from 250 to 500 kg Si ha<sup>-1</sup>. However, Si content ( $r^2=0.7368$  in rice straw;  $r^2=0.8867$  in grain) of rice grown in acidic soil increased at the increased with level of Si application.

## Soil parameters

In general, soil pH and EC was increased in presence of rice crop and varied among the different Si sources based on the soil type (Table 4). Plant available Si content (CCSi and AASi) was decreased in the presence of crop but there was no definite trend for rates of Si application (Table 5).

In acidic soil, there was a significant increase in soil pH and EC with application of calcium silicate @ 500 kg Si ha<sup>-1</sup> maintained without plant (7.01  $\pm$  0.08, 0.27  $\pm$  0.01 dSm<sup>-1</sup> respectively) or with plant (7.12  $\pm$  0.19, 0.26  $\pm$  0.01 dSm<sup>-1</sup> respectively) compared to control while other treatments were more or less on par with each other. A significant increase in the soil pH (7.81  $\pm$  0.15) and EC (0.27  $\pm$  0.04 dSm<sup>-1</sup>) with the application of calcium silicate @ 500 kg Si ha<sup>-1</sup> maintained with crop was noticed in neutral soil. Although, soil pH and EC was not greatly varied in alkaline soil, there was a significant increase in soil pH was noticed with application of calcium silicate @ 250 kg Si ha<sup>-1</sup> (9.19 $\pm$  0.01) and 500 kg Si ha<sup>-1</sup> (9.18 $\pm$  0.10) compared to other treatments but was on par with control (8.99  $\pm$  0.08). Soil EC was significantly high with the application of RHB @ 250 kg Si ha<sup>-1</sup> (0.37  $\pm$  0.08) but there was no definite trend observed among the treatments. The increase in the soil pH of the soil by the application of calcium silicate is in agreement with findings of others who reported that silicates

and slag pulverized to <1mm reported to be efficient in correcting the soil acidity and had great potential use in the agriculture as an environmentally by safe liming material (Correa *et al.*, 2007; Joulazadeh and Joulazadeh, 2010). Application of slags increased the pH and calcium content of the soil solution (Kato *et al.*, 1996; Kato and Owa, 1996). Increase in soil pH and thereby correcting soil acidity with the application of calcium silicate was reported by Bauera *et al.* (2011). The reactions involving silicate materials that occur in the soil could increase pH, neutralizing exchangeable Al and other toxic elements (Alcarde, 1992).

In general, Si extracted by calcium chloride and acetic acid significantly decreased in the presence of crop due crop uptake. The content of CCSi was significantly higher with the application of RHB @ 500 kg Si ha<sup>-1</sup> maintained without plant (40.79  $\pm$  0.21 mg kg<sup>-1</sup>) followed by DE applied at both rates. AASi content was significantly higher with application of calcium silicate and was on par between without (104.00  $\pm$  5.13 mg kg<sup>-1</sup>) and with plant (150.00  $\pm$  20.14 mg kg<sup>-1</sup>) in acidic soil.

In neutral soil, the content of CCSi was found to be significantly higher with the application of DE @ 500 kg Si ha<sup>-1</sup> (51.88  $\pm$  3.03 mg kg<sup>-1</sup>), RHB @ 250 kg Si ha<sup>-1</sup> (53.00  $\pm$  0.60 mg kg<sup>-1</sup>) and 500 kg Si ha<sup>-1</sup> (51.57  $\pm$  2.43 mg kg<sup>-1</sup>) maintained without crop and RHB @ 500 kg Si ha<sup>-1</sup> (51.27  $\pm$  10.64 mg kg<sup>-1</sup>) maintained with plant but was on par with each other. Acetic acid extractable Si content increased significantly with the application of calcium silicate @ 500 kg Si ha<sup>-1</sup> maintained with (139.25  $\pm$  4.84 mg kg<sup>-1</sup>) and without crop (133.00  $\pm$  0.35 mg kg<sup>-1</sup>) and was on par with each other whereas other treatments were nearly on par with each other but significantly higher compared to control. Increase in extractable Si with the application of silicates was also reported by Wang *et al.* (2014), Agarie *et al.* (1992) and Camargo *et al.* (2010).

Irrespective of the sources of Si, the plant available Si content was significantly higher in alkaline soil in the presence of rice crop compared to without crop. The CCSi content was significantly higher with the application of RHB @ 500 kg Si ha<sup>-1</sup> maintained with plant (52.46 $\pm$  6.26 mg kg<sup>-1</sup>). The AASi content was significantly higher with application of calcium silicate @ 250 kg Si ha<sup>-1</sup> (146.47  $\pm$  18.90 mg kg<sup>-1</sup>). Haefele *et al.* (2011) reported that biochar from rice residues can be beneficial in rice based systems but its effects on soil fertility depend on site specific conditions. Seyfferth *et al.* (2013) and Savant *et al.* (1997) suggested that recycling of crop residues like rice husk to soils provide a low cost, affordable means of Si fertilization and facilitates increase in plant available Si which is comparatively rapid.

Calcium chloride extractable Si concentration was decreased linearly (Fig. 5) with increased rate of Si application in acidic, neutral and alkaline soil with regression  $(r^2)$  value of 0.9952, 0.9758 and 0.9397 respectively. However, AASi content was increased linearly in case of neutral  $(r^2=0.9887)$  soil as the Si application rate increased but decreased trend was noticed in acidic  $(r^2=0.7157)$  and alkaline  $(r^2=0.0.3113)$  soil irrespective of the Si sources.

Effectiveness of the different sources of Si varied based on the type of soil, calcium silicate followed by RHB in acidic and neutral soil and RHB in alkaline soil performed better which can be due to variation in the reactivity of material based on the type of soil. Haynes (2014) also reported that usefulness of the Si sources depends on the reactivity rather than total Si content. Application of calcium silicate increased the PAS stock in soil as extracted by acetic acid in all soil which may be due to extraction of part of the Si adsorbed into the soil which might be useful for the succeeding crop. Empirical relationships between concentrations of acetate-extractable Si in soils (an estimate for amounts of Si adsorbed onto mineral surfaces) and the plant-Si-uptake suggested that adsorbed Si is also a major Si source for plants (Barbosa-

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Filho *et al.*, 2001; Narayanaswamy and Prakash, 2009). These results are in agreement with Shuhei *et al.* (2013) who revealed that when Si source was applied to soil, Si dissolves in the soil solution and part of the dissolved Si was adsorbed onto the soil solid phase and then desorbed and redissolved into soil solution.

Silicon concentration in the soil sample varied based on the extractants. Acetic Acid solution extracted greater Si compared to calcium chloride wherein the amounts of specifically adsorbed Si fraction differed with these two solutions (Fox *et al.* 1967; Korndorfer *et al.* 1999; Berthelsen, 2000).

#### Conclusion

The yield attributes of the rice crop was increased significantly with the application of three sources of Si compared to control in all three types of soil. Generally, application of calcium silicate followed by diatomite performed better in acidic and neutral soil whereas rice husk biochar was significantly performed better under alkaline soil. These results showed the reactivity and efficiency of different sources of Si in different types of soil rather than its total Si content. Bioavailability of Si from different sources also followed the same trend but varied based on the soil types.

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#### References

- Agarie, S., W. Dgata, Kubotah and P. S. Kaufonann. 1992. Physiological role of silicon in photosynthesis and dry matter production in rice plant. *Journal of Crop Science* 61: 200 208.
- Akshatha, M. K. 2015. Characterization of biochar, nutrient release and its effect on growth and yield of aerobic rice. M.Sc (Agri) Thesis, University of Agricultural Sciences Bengaluru, Karnataka, India.
- Alcarde, J. C. 1992. Corretivos da acidez dos solos, características interpretacoes tecnicas. Sao Paulo, ANDA. (Boletim Tecnico). pp: 6-9.
- Ashraf, M., H. Rahmatulla, M. Afzal, R. Ahmed, F. Mujeeb, A. Sarwar, and L. Ali. 2010. Alleviation of detrimental effects of NaCl by silicon nutrition in salt-sensitive and salttolerant genotypes of sugarcane (Saccharum officinarum L.). *Plant Soil*, 326: 381 - 391.
- Barbosa-filho, M. P., G. H. Snyder, C. L. Elliott and L. E. Datnoff. 2001. Evaluation of soil test procedures for determining plant available silicon. *Communications in Soil Science and Plant Analysis* 32: 1779–1792.
- Baruah, T. C. and H. P. Barthakur. 1997. A text book of soil analysis, pp: 142-190.
- Bauera, P., R. Elbaum and I. M. Weiss. 2011. Calcium and silicon mineralization in land plants: Transport, structure and function. *Plant Science* 180: 746–756.
- Berthelsen, S. 2000. An assessment of the Si status of soils in north Queensland, and the impact of sub-optimal plant available soil Si on sugarcane production systems. MSc thesis,

Tropical plant Sciences within the School of Tropical Biology, James Cook University, Townsville Queensland, Australia.

- Berthelsen, S., A. Noble, G. Kingston, A. Hurney, A. Rudd and A. Garside. 2003. Improving yield and ccs in sugarcane through the application of silicon based amendments. Final report on SRDC Project CL W009.
- Bray, R. H. AND L. T. Kurtz, 1945, Determination of total organic and available forms of phosphorus in soils. Soil Science 59: 39 – 45.
- Camargo, M. S. D., R. G. J. Alcides, W. Patricia and G. H. Korndorfer. 2010. Silicate fertilization in sugarcane: Effects on soluble silicon soil, uptake and occurrence of stalk borer (*Diatraea sacharalis*). 19<sup>th</sup> World Congress of Soil Science, 1 – 6<sup>th</sup> August, 259-262.
- Correa, J. C., L. T. Bull, C. A. C. Crusciol, R. Marcelino, and M. Mauad. 2007. Liming and ion mobility in an Oxisol under surface application of flue dust, aqueous lime, sewage sludge and limestone. *Pesquisa Agropecuaria Brasileira* 42: 1307–1317.
- Deren, C. W., L. E. Datnoff, G. H. Snyder and F. G. Martin. 1994. Silicon concentration, disease response and yield components of rice genotypes grown on flooded organic histosols. *Crop Science* 34: 733-737.
- Fox, R., L. J. Silva, A. O. R. Younge, D. L. Plucknett and G. D. Sherman. 1967. Soil and plant silicon and silicate response by sugarcane. *Procedure* of *Soil Science Society of America* 31:775-779.

- 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 B.V. Amsterdam, The Netherlands.
- Gnanamanikam, S. S. 2009. Biological Control of Rice Diseases. pp: 1-108.
- Haefele, S. M., Y. Konboon, W. Wongboon, S. Amarante, A. A. Maarifat, E. M. Pfeiffer and C. Knoblauch. 2011. Effects and fate of biochar from rice residues in rice-based systems. *Field Crop Research* 121: 430-440.
- Haynes, R. J. 2014. A contemporary overview of silicon availability in agricultural soils. *Journal* of Plant Nutrition and Soil Science 177:831–844.
- Haysom, M. B. C. and L. S. Chapman. 1975. Some aspects of the calcium silicate trials at Mackay. Proc. Qld. Society for Sugar Cane Technology 42:117-122.
- Jackson, M. L. 1973. Soil chemical analysis. Prentice Hall of India Pvt. Ltd. New Delhi.
- Jones, L. H. P., and K. A. Handreck. 1967. Silica in soils, plants and animals. Advances in Agronomy 19:107–149.
- Joulazadeh, M. H. and F. Joulazadeh. 2010. Slag; value added steel industry byproducts. Archieves of Metallurgy and Materials 35(4): 1138-1145.
- Kato, N. and N. Owa. 1996. Evaluation of Si availability in slag fertilizers by an extraction method using a cation exchange resin. *Soil Science and Plant Nutrition* 43: 351-357.

- Kato, N., H. Imori and N. Owa. 1996. The dissolution of calcium silicate slag fertilizers in flooded soil. Japanese Journal of Soil Science and Plant Nutrition 67: 640-647 (in Japanese with English summary).
- Kim, Y. H., A. L. Khan, Z. K. Shinwari, D. H. Kim, M. Waqas, K. Muhammad and L. Lee. 2012. Silicon treatment to rice (*Oryza sativa*) plants during different growth periods and its effects on growth and grain yield. *Pakistan Journal of Botany* 44 (3): 891-897.
- Korndorfer, G. H., M. N. Coelho, G. H. Snyder. and C. T. Mizutani. 1999. An evaluation of soil extractants for Si availability in upland rice. *Journal of Plant Nutrition* 23:101–06.
- Korndörfer, G. H., H. S. Pereira and A. Nolla. 2005. Silicon analysis in soil, plant and fertilizers. Brazil, GPSi/ICIAG/UFU.
- Korndorfer, G. H., G. H. Snyder, M. Ulloa and L. E. Datnoff. 2001. Calibration of soil and plant silicon for rice production. *Journal of Plant Nutrition* 24(7): 1071-1084.
- Liang, Y. C., T. S. Ma, F. J. Li and Y. J. Feng. 1994. Silicon availability and response of rice and wheat to silicon in calcareous soils. *Communications in Soil Science and Plant Analysis* 25: 2285 -2297.
- Liang, Y. C., Q. R. Shen and T. S. Ma. 2003. Effects of silicon on salinity tolerance of two barley cultivars. *Journal of Plant Nutrition* 19: 173-183.
- Liang, Y., M. Nikolic, R. Bélanger, H. Gong and A. Song. 2015. Silicon in Agriculture. Dordrecht: Springer. pp: 1-235.

- Ma, J. F. and E. Takahashi. 2002. Soil, fertilizer, and plant silicon research in Japan. Elsevier, Amsterdam.
- Ma, J. F., K. Tamai, M. Ichii and K. Wu. 2002. A rice mutant defective in active Si uptake. *Plant Physiology* 130: 211–217.
- Ma, J. F., K. Tamal, N. Yamaji, N. Mitani, S. Konishi, M. Katuhara, M. Ishiguro and M. Yano. 2006. A Si transporter in rice. *Nature* 440: 688-691.
- Makabe, S., K. Kakuda, S. Sasaki, T. Ando, H. Fujii and H. Ando. 2009. Relationship between mineral composition or soil texture and available silicon in alluvial paddy soils on the Shounai Plain, Japan. *Journal of Soil Science and Plant Nutrition* 55: 300–308.
- Meunier, J. D., F. Guntzer, S. Kirman and C. Keller. 2008. Terrestrial plant-Si and environmental change. *Mineralogical Magazine* 72(1):63–267.
- Narayanaswamy, C. and N. B. Prakash. 2009. Calibration and Categorization of Plant Available Silicon in Rice Soils of South India. *Journal of Plant Nutrition* 32(8): 1237 – 1254.
- Nguyen, M. N., S. Dultz and G. Guggenberger. 2014. Effects of pretreatment and solution chemistry on solubility of rice-straw phytoliths. *Journal of Plant Nutrition* and *Soil Science* 177: 349-359.
- Olsen. 1954. Determination of total organic and available forms of phosphorus in soils. Soil Science 59: 39 45.

- Pati, S., P. Biplab, B. Shrikant, Gora, C. Hazra and M. Biswapati. 2016. Effect of Silicon Fertilization on Growth, Yield, and Nutrient Uptake of Rice. *Communications in Soil Science and Plant Analysis* 47(3): 284-290.
- Prakash, N. B. 2002. Status and utilization of silicon in Indian rice farming. Japanese Society of Soil Science and Plant Nutrition 1: 266–273.
- Rajanna, M. P. 2013. Recent Rice Varieties and Hybrids of Karnataka. Zonal Agricultural Research Station, Mandya, Bangalore, India: University of Agriculture Science.
- Sahrawat, K. L. 1983. Nitrogen availability indexes for submerged rice soils. Advances in Agronomy 36: 415-451.
- Sahu, S. K. 1990. Effect of silica and phosphorus application on yield and phosphorus nutrition of rice. *IRRN*, 15(1): 25.
- Savant, N. K., L. E. Datnoff and G. H. Snyder. 1997. Depletion of plant available silicon in soils:
  A possible cause of declining rice yields. *Communications in Soil Science and Plant* Analysis 28 (13 & 14): 1245-1252.
- Seyfferth, A. L., B. D. Kocar, J. A. Lee and S. Fendorf. 2013. Seasonal dynamics of dissolved silicon in a rice cropping system after straw incorporation. *Geochem Cosmochem Acta* 123:120-133.

- Shuhei, M., S., K. Ken-ichi, Y. Sasaki and H. Ando. 2013, Effect of slag silicate fertilizer on dissolved silicon in soil solution based on the chemical properties of Gleysols. Soil Science and Plant Nutrition 1-7.
- Singh, K. K., K. Singh, R. S. Singhl, S. Raghavendra and R. S. Chandel. 2005. Silicon nutrition in rice a review. *Agricultural Rev*ieves 26 (3): 223 228.
- Struyf, E., S. Adriaan, V. D. Stefan, M. Patrick, J. C. Daniel. 2009. The global biogeochemical silicon cycle. *Silicon* 1:207–213.
- Subbiah, A. Y. and G. K. Asija. 1949. Available nitrogen: alkaline permanganate method. *Current Science* 25: 254 – 260.
- Tavakkoli, E., G. Lyons, P. English and C. N. Guppy, 2011, Silicon nutrition of rice is affected by soil pH, weathering and silicon fertilisation. *Journal of Plant Nutrition and Soil Science* 174: 437-446.
- Wang, W., D. Y. F. Lai, S. Li, P. J. Kim, C. ZENG, LI, P. AND LIANG, Y., 2014. Steel slag amendment reduces methane emission and increases rice productivity in subtropical paddy fields in China. Wetlands Ecol. Manage. *Field Crops Research* 171:146–156.
- Winslow, M. D., 1992, Silicon, disease resistance and yield of rice genotypes under upland cultural conditions. Crop Science 32: 1208-213.
- Winslow, M. D., K. Okada and F. Correa-Victoria. 1997. Silicon availability and response of rice and wheat to silicon in calcareous soils. *Communications in Soil Science and Plant Analysis* 25: 2285 -2297.

-----

Xin, X., C. Baoliang and Z. Lizhong. 2014. Transformation, morphology, and dissolution of silicon and carbon in rice straw-derived biochars under different pyrolytic temperatures. *Environmental Science and Technology* 48: 3411-3419.

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Fig. 2 Effect of different sources of Si on straw Si content and its uptake by rice crop.



Fig. 3 Effect of different sources of Si on grain Si content and its uptake by rice crop.



Fig. 4 Plot representing relationship between straw and grain Si content v/s addition of Si in acidic, neutral and alkaline soil (Each value represents average of three replication).



Fig. 5 Plot representing relationship between CCSi and AASi v/s addition of Si in acidic, neutral and alkaline soil (Each value represents average of three replication).

# Table 1. Initial properties of the soil

| Parameters                                | Acidic soil | Neutral soil      | Alkaline soil |
|---|-------------|-------------------|---------------|
| pH (1:2.5 water)                          | 5.86        | 7.10              | 9.38          |
| Location                                  | Hassan      | V.C. Farm, Mandya | Hiriyur       |
| $EC (dSm^{-1}) (1:2.5 water)$             | 0.16        | 0.22              | 0.33          |
| Particle size Distribution (%)            |             |                   |               |
| Sand                                      | 68.98       | 76.54             | 41.45         |
| Silt                                      | 8.60        | 6.56              | 30.40         |
| Clay                                      | 22.42       | 16.90             | 28.15         |
| Textural class                            | Sandy loam  | Sandy loam        | Clay loam     |
| CCSi (mg kg <sup>-1</sup> )               | 30.58       | 41.98             | 46.18         |
| AASi (mg kg <sup>-1</sup> )               | 43.10       | 73.82             | 109.47        |
| Available N (kg ha <sup>-1</sup> )        | 239.68      | 340.48            | 170.24        |
| Available $P_2O_5$ (kg ha <sup>-1</sup> ) | 53.73       | 203.66            | 21.16         |
| Available $K_2O$ (kg ha <sup>-1</sup> )   | 141.79      | 348.09            | 247.29        |
| Exch.Ca (cmol $(p^+)$ kg <sup>-1</sup> )  | 2.82        | 4.75              | 23.62         |
| Exch. Mg (cmol $(p^+)$ kg <sup>-1</sup> ) | 1.18        | 2.25              | 9.50          |

# Table 2: Composition of Si sources

|  |                    | DE    | DUD   |
|--|--------------------|-------|-------|
| Properties                                     | CaSiO <sub>3</sub> | DE    | КНВ   |
| pH (1:2.5 water)                               | 12.45              | 9.21  | 7.39  |
| $EC (dSm^{-1}) (1:2.5 water)$                  | n.d                | 0.72  | 1.62  |
| Cation exchange capacity $(cmol(p^+) kg^{-1})$ | n.d                | 52.00 | 38.63 |
| per cent                                       |                    |       |       |
| N  | n.d                | 0.03  | 0.78  |
| Р  | n.d                | 0.02  | 0.24  |
| K  | 0.076              | 0.40  | 0.96  |
| Si   | 12                 | 30.00 | 31.00 |
| Ca   | 5.33               | 2.70  | 0.36  |
| Mg   | 0.82               | 3.25  | 0.31  |
| S  | 0.05               | 0.17  | 0.05  |
| $Al_2O_3$                                      | n.d                | 15.30 | n.d   |
| mg kg <sup>-1</sup>                            | •                  |       |       |
| Fe   | 2.3                | 2.00  | 0.077 |
| Mn   | n.d                | 0.02  | 0.055 |
| В  | 7.7                | 6.00  | 8.36  |
| Zn   | 1.10               | 19.00 | 63.00 |
| Cu   | 0.10               | 20.00 | 31.00 |
| Мо   | 0.40               | 0.10  | n.d   |
| Se   | n.d                | 1.30  | n.d   |
| Cd   | < 0.01             | 0.50  | n.d   |

n.d. – Not determined

| T   | Acid  | ic soil               | Neutral soil                        |  |  |
|---|---|-----------------------|-------------------------------------|--|--|
| (With plant)                                    | Panicle Panicle length<br>number pot <sup>-1</sup> pot <sup>-1</sup> (cm) |                       | Panicle<br>number pot <sup>-1</sup> | Panicle length<br>pot <sup>-1</sup> (cm) |  |
| Ck  | 1.25± 0.50(b)   | 13.13± 0.85(d)        | 1.25± 0.58(a)                       | 14.23± 2.83(c)                           |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 1.67± 0.58(ab)  | 15.83± 0.76(ab)       | 1.67± 1.15(a)                       | $14.33 \pm 0.76$ (bc)                    |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>-1</sup> | 2.33± 0.58(a)   | 16.17± 0.29(a)        | 2.33± 1.53(a)                       | 14.79± 1.32(bc)                          |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 1.67±0.58(ab)   | 13.33±0.58(cd)        | 2.33±0.58(a)                        | 17.44±1.71(ab)                           |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 2.00± 1.00(ab)  | 13.50± 1.32(cd)       | 2.33± 0.58(a)                       | $15.33 \pm 1.53$ (bc)                    |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 1.33±0.58(ab)   | $14.50 \pm 0.87$ (bc) | 1.33± 0.58(ab)                      | $14.50 \pm 0.87$ (bc)                    |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 1.67± 0.58(ab)  | 15.03± 0.06(ab)       | 1.67± 0.58(ab)                      | 15.03± 0.06(ab)                          |  |
| S.Em±   | 0.36  | 0.38                  | 0.45                                | 0.87                                     |  |
| LSD (p≤0.05)                                    | 1.11  | 1.36                  | 1.49                                | 3.14                                     |  |

| Table | 3: | Effect | of S | si sources | on | yield | parameters | of | the | rice |
|-------|----|--------|------|------------|----|-------|------------|----|-----|------|
|       |    |        |      |            |    | •     |            |    |     |      |

 $\pm$  Value indicates the standard deviation.

Value having same alphabets does not differ significantly at p≤0.05.

# Table 4: Effect of different sources of Si on soil pH and EC of soil

|   | Acidic soil                |                               | Neut                                    | tral soil                                 | Alkaline soil                             |                               |  |
|---|----------------------------|-------------------------------|---|---|---|-------------------------------|--|
| Treatments  | pН                         | E. C.<br>(dSm <sup>-1</sup> ) | рН                                      | E. C.<br>(dSm <sup>-1</sup> )             | pH  | E. C.<br>(dSm <sup>-1</sup> ) |  |
| Ck - Without plant                                | 5.89± 0.11(d)              | 0.19± 0.01(cdef)              | 6.68± 0.07(d)                           | 0.24± 0.04(ab)                            | 8.99± 0.08(a)                             | 0.27± 0.01(cde)               |  |
| Ck – With plant<br>Without plant                  | $6.15{\pm}0.09(\text{cd})$ | 0.17± 0.03(ef)                | 6.98± 0.12(c)                           | $0.21{\pm}~0.02(bcd)$                     | 9.04±0.07(abcd)                           | $0.30{\pm}~0.01(bcde)$        |  |
| $C_{2}SiO_{2} @ 250 kg Si ha^{-1}$                | 6 51±0 05(bc)              | $0.20\pm 0.07$ (bodef)        | $7.34 \pm 0.01$ (b)                     | $0.22 \pm 0.04$ (bod)                     | $9.19\pm0.01(a)$                          | $0.28 \pm 0.01$ (ede)         |  |
| $CaSiO_3$ ( <i>a</i> ) 200 kg Si ha <sup>-1</sup> | $7.01 \pm 0.08(a)$         | $0.20\pm 0.01(a)$             | $7.3 \pm 0.01(0)$<br>$7.73 \pm 0.13(a)$ | $0.22\pm 0.04(bcd)$<br>$0.23\pm 0.01(ab)$ | $9.19 \pm 0.01(a)$<br>$9.18 \pm .0.10(a)$ | $0.23 \pm 0.01$ (de)          |  |
| DE @ 250 kg Si ha <sup>-1</sup>                   | $6.02 \pm 0.20(d)$         | 0.231±0.01(abcd)              | $6.75 \pm 0.17(d)$                      | 0.17± 0.00(d)                             | 9.19± 0.01(a)                             | 0.27± 0.01(de)                |  |
| DE @ 500 kg Si ha <sup>-1</sup>                   | 5.95±0.07(d)               | 0.19± 0.01(cdef)              | 6.68± 0.10(d)                           | 0.17± 0.02(cd)                            | 9.15± 0.01(ab)                            | 0.27± 0.01(de)                |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                  | 6.00± 0.01(d)              | 0.22± 0.01(abcde)             | $6.70 \pm 0.14(d)$                      | 0.22± 0.02(bc)                            | 9.11± 0.02(abc)                           | 0.30± 0.01(bcde)              |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                  | 5.92±0.01(d)               | 0.18± 0.00(def)               | 6.66± 0.02(d)                           | 0.25± 0.05(ab)                            | 9.11± 0.01(abc)                           | 0.29± 0.00(bcde)              |  |
| With plant  |                            |                               |   |   |   |                               |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup>   | 6.82±0.19(ab)              | 0.17± 0.01(ef)                | 7.49±0.05(b)                            | 0.24± 0.02(ab)                            | 9.06± 0.12(abcd)                          | $0.30 \pm 0.02$ (bcde)        |  |
| CaSiO <sub>3</sub> @ 500 kg Si ha <sup>1</sup>    | 7.12±0.19(a)               | 0.26± 0.01(a)                 | 7.81±0.15(a)                            | 0.27± 0.04(a)                             | 9.09± 0.09(abc)                           | $0.33{\pm}0.03(abcd)$         |  |
| DE @ 250 kg Si ha <sup>-1</sup>                   | $6.25{\pm}0.04(cd)$        | $0.15 \pm 0.01(f)$            | 7.07±0.07(c)                            | 0.22± 0.02(b)                             | 8.99± 0.17(cde)                           | $0.34 \pm 0.06 (ab)$          |  |
| DE @ 500 kg Si ha <sup>-1</sup>                   | $6.14 \pm 0.13$ (cd)       | $0.20\pm0.03(bcdef)$          | $7.08 \pm 0.03(c)$                      | $0.20 \pm 0.02$ (bcd)                     | 8.91± 0.06(e)                             | 0.33±0.04(abc)                |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                  | 5.89±0.70(d)               | 0.24± 0.02(abc)               | 6.98±0.05(c)                            | 0.23± 0.02(ab)                            | 8.94± 0.13(de)                            | 0.37±0.08(a)                  |  |
| $\rm RHB$ @ 500 kg Si ha $^1$                     | $6.14 \pm 0.05 (cd)$       | 0.19± 0.02(cdef)              | 7.03±0.07(c)                            | $0.21 \pm 0.01$ (bcd)                     | 8.99± 0.03(bcde)                          | $0.35{\pm}0.04(ab)$           |  |
| S.Em±   | 0.08                       | 0.007                         | 0.05                                    | 0.01                                      | 0.04                                      | 0.01                          |  |
| LSD (p≤0.05)                                      | 0.39                       | 0.03                          | 0.16                                    | 0.05                                      | 0.15                                      | 0.06                          |  |

 $\pm$  Value indicates the standard deviation.

Value having same alphabets does not differ significantly at  $p \le 0.05$ .

|   | Acio                    | lic soil              | Neutr                | al soil              | Alkaline soil         |                      |  |  |
|---|-------------------------|-----------------------|----------------------|----------------------|-----------------------|----------------------|--|--|
| Treatments                                      | CCSi* AASi**            |                       | CCSi                 | AASi                 | CCSi                  | AASi                 |  |  |
|   | (mg kg <sup>-1</sup> )  |                       |                      |                      |                       |                      |  |  |
| Ck - Without plant                              | 31.85± 2.93(cd)         | 76.71± 5.49(def)      | 49.90± 0.78(ab)      | 81.46± 2.27(ef)      | 42.89± 2.10(d)        | 116.46± 18.41(d)     |  |  |
| Ck – With plant<br>Without plant                | 28.32± 3.83(cdef)       | 62.84± 2.58(f)        | 42.33± 4.66(cd)      | 80.34± 5.02(f)       | 44.90± 1.20(bcd)      | 115.28± 7.90(d)      |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | -<br>28.16± 0.86(cdef)  | 105.25± 5.48(b)       | 45.84± 1.86(abcd)    | 112.00± 0.88(b)      | 44.38± 0.91(bcd)      | 143.12± 1.94(ab)     |  |  |
| $CaSiO_3$ (a) 500 kg Si ha <sup>-1</sup>        | 26.72± 0.28(defg)       | 104.00± 5.13(a)       | 43.52± 3.41(abcd)    | 133.00± 0.35(a)      | 45.55± 2.28(bcd)      | 131.37± 0.53(abcd)   |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 33.64± 1.29(bc)         | 78.18± 5.39(def)      | 49.81± 1.96(abc)     | 87.25± 4.60(cde)     | 41.20± 0.37(d)        | 122.50± 5.30(bcd)    |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | 33.841± 1.77(bc)        | 84.62±13.44(cdef)     | 51.88± 3.03(a)       | 88.06± 0.62(cde)     | 43.34± 2.11(cd)       | 119.75± 9.37(cd)     |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 38.17± 1.49(ab)         | 79.62± 2.83(cdef)     | $53.00 \pm 0.60(a)$  | 88.75± 5.66(cd)      | 45.27± 0.21(bcd)      | 130.18± 11.05(abcd)  |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 40.79± 0.21(a)          | 95.06±27.31(bcd)      | 51.57± 2.43(a)       | 84.43± 1.15(def)     | 48.49± 4.47(ab)       | 127.87± 6.01(abcd)   |  |  |
| With plant                                      | _                       |                       |                      |                      |                       |                      |  |  |
| CaSiO <sub>3</sub> @ 250 kg Si ha <sup>-1</sup> | 21.81± 4.89(g)          | 98.37±16.48(bc)       | 37.74± 2.38(d)       | 108.70± 3.13(b)      | $44.04 \pm 0.43(bcd)$ | 146.47± 18.90(a)     |  |  |
| ${\rm CaSiO_3}$ @ 500 kg Si ha $^1$             | 25.16± 2.46(fg)         | 150.00± 20.14(a)      | 37.98± 1.56(d)       | 139.25± 4.84(a)      | 44.75± 2.28(bcd)      | 143.12± 6.93(ab)     |  |  |
| DE @ 250 kg Si ha <sup>-1</sup>                 | 26.32± 2.74(efg)        | 62.45±2.70(f)         | 43.03± 7.69(bcd)     | 87.16± 2.67(cde)     | 43.17± 1.36(cd)       | 133.75±11.51(abc)    |  |  |
| DE @ 500 kg Si ha <sup>-1</sup>                 | $28.01 \pm 2.67$ (cdef) | $72.41 \pm 11.81(ef)$ | $41.27 \pm 4.62(cd)$ | $91.45 \pm 8.45(cd)$ | 42.59± 1.75(d)        | $133.54 \pm 6.66(d)$ |  |  |
| RHB @ 250 kg Si ha <sup>-1</sup>                | 31.67± 5.39(cde)        | 78.66± 4.27(cdef)     | 41.93± 2.64(cd)      | 91.54± 2.77(cd)      | 47.79± 1.95(bc)       | 117.70± 6.99(cd)     |  |  |
| RHB @ 500 kg Si ha <sup>-1</sup>                | 30.70± 2.26(cde)        | 71.45±13.57(ef)       | 51.27± 10.64(a)      | 92.20± 2.31(c)       | 52.46± 6.26(a)        | 121.16± 5.01(cd)     |  |  |
| S.Em±   | 1.38                    | 6.14                  | 2.08                 | 1.93                 | 4.98                  | 1.22                 |  |  |
| LSD (p≤0.05)                                    | 5.73                    | 19.28                 | 8.21                 | 6.96                 | 4.45                  | 18.16                |  |  |

Table 5: Effect of different sources of Si on plant available silicon content of soil

\*0.01M Calcium chloride extractable silicon.

\*\*0.5M Acetic acid extractable Si

 $\pm$  Value indicates the standard deviation.

Value having same alphabets does not differ significantly at p $\leq 0.05$