

**STUDIES ON SILICON POOLS IN RICE SOILS OF
SELECTED AGRO CLIMATIC ZONES OF
KARNATAKA**

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**DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL
CHEMISTRY
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GKVK, BENGALURU-560065**

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Thesis submitted to the

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in

SOIL SCIENCE AND AGRICULTURAL CHEMISTRY

BENGALURU

OCTOBER, 2017



Affectionately Dedicated
to
My Beloved Parents

**DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL
CHEMISTRY
UNIVERSITY OF AGRICULTURAL SCIENCES
GKVK, BENGALURU- 560 065**

CERTIFICATE

This is to certify that the thesis entitled “STUDIES ON SILICON POOLS IN RICE SOILS OF SELECTED AGRO CLIMATIC ZONES OF KARNATAKA” submitted by Ms. PALLAVI, T., ID No. PALB 5322 in partial fulfilment of the requirements for the award of degree of MASTER OF SCIENCE (Agriculture) in SOIL SCIENCE AND AGRICULTURAL CHEMISTRY to the University of Agricultural Sciences, Bengaluru, is a 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 for the award of any degree, diploma, associateship, fellowship or other similar titles.

BENGALURU

OCTOBER, 2017


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Major Advisor

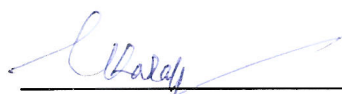
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(PALLAVI, T.)

STUDIES ON SILICON POOLS IN RICE SOILS OF SELECTED AGRO CLIMATIC ZONES OF KARNATAKA

PALLAVI, T.

ABSTRACT

In order to study the different pools of Si in soils and their contribution to rice, two surface soil samples were collected from each of four agro climatic zones of Karnataka with distinct climatic features. Five major pools of silicon (Si) such as mobile Si, adsorbed Si, organic matter bound Si, occluded Si in pedogenic oxides/hydroxides and amorphous Si were extracted from these soils using a sequential extraction method. The different pools of Si extracted from soils were in the order of amorphous Si > occluded Si > organic Si > adsorbed Si and mobile Si. The mobile Si and adsorbed Si pools were the smallest pools of Si and ranged from 14.45 to 44.60 mg kg⁻¹ and 4.90 to 89.40 mg kg⁻¹, respectively. Irrespective of the soils, amorphous Si was found to be the largest pool of Si ranging from 8,019 to 16,667 mg kg⁻¹. Pot culture experiment conducted using the bulk soil samples of these zones with rice as test crop revealed that there was a significantly higher Si content and uptake in Bellatha (southern dry zone) and Honnavile soil (southern transition zone), respectively and lower in Brahmavara soil (coastal zone). Better correlation and regression coefficients were recorded between Si pools, plant available Si in soils and Si content and its uptake by rice when only three soils (one each from low, medium and high content of plant available Si) were considered among the eight selected soils. The occluded, mobile and adsorbed pools of Si showed significantly higher correlation and regression with Si content and its uptake by rice and hence considered as major contributors of Si to rice.

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ಕರ್ನಾಟಕದ ವಿವಿಧ ಕೃಷಿ ಹವಾಮಾನ ವಲಯಗಳ ಭತ್ತದ ಮಣ್ಣುಗಳಲ್ಲಿ ಸಿರಿಕಾನ್ ವಿಭಜನೆಗಳ ಅಧ್ಯಯನ

ಪಲ್ಲವಿ, ಟಿ.

ಪ್ರಬಂಧದ ಸಾರಾಂಶ

ಸಿರಿಕಾನಿನ ವಿವಿಧ ವಿಭಜನೆಗಳು ಹಾಗೂ ಭತ್ತದ ಸಿರಿಕಾನಿನ ಅಂಶ ಮತ್ತು ಅದರ ಹೀರುವಿಕೆಗೆ ಅವುಗಳ ಕೊಡುಗೆಯನ್ನು ಅಭ್ಯಸಿಸುವ ಸಲುವಾಗಿ ಕರ್ನಾಟಕದ ನಾಲ್ಕು ವಿಶಿಷ್ಟ ಕೃಷಿ ಹವಾಮಾನ ವಲಯಗಳಿಂದ (ಪ್ರತಿ ವಲಯದಿಂದ ಎರಡು ಮಣ್ಣಿನ ಮಾದರಿಗಳಂತೆ) ಎಂಟು ಭತ್ತದ ಮಣ್ಣಿನ ಮಾದರಿಗಳನ್ನು ಸಂಗ್ರಹಿಸಿ, ಸಿರಿಕಾನಿನ ಐದು ಪ್ರಮುಖ ವಿಭಜನೆಗಳಾದ ಚಲನ ಸಿರಿಕಾನ್, ಅಂಟಿಕೊಂಡ ಸಿರಿಕಾನ್, ಸಾವಯವ ಸಿರಿಕಾನ್, ಅಕ್ಲೂಡೆಡ್ ಹಾಗೂ ಅಸ್ಪಟಿಕ ಸಿರಿಕಾನ್ ವಿಭಜನೆಗಳನ್ನು ಅನುಕ್ರಮವಾಗಿ ಹೊರತೆಗೆಯಲಾಯಿತು. ವಿವಿಧ ಸಿರಿಕಾನಿನ ವಿಭಜನೆಗಳ ಪ್ರಮಾಣವು ಅಸ್ಪಟಿಕ ಸಿರಿಕಾನ್ > ಅಕ್ಲೂಡೆಡ್ ಸಿರಿಕಾನ್ > ಸಾವಯವ ಸಿರಿಕಾನ್ > ಚಲನ ಸಿರಿಕಾನ್ > ಅಂಟಿಕೊಂಡ ಸಿರಿಕಾನ್ ಕ್ರಮದಲ್ಲಿ ಇರುವುದಾಗಿ ಕಂಡುಬಂದಿರುತ್ತದೆ. ಅಭ್ಯಸಿಸಿದ ಎಲ್ಲಾ ಮಣ್ಣುಗಳಲ್ಲಿಯೂ, ಚಲನ (೧೪.೪೫- ೪೪.೬೦ ಮಿ. ಗ್ರಾಂ ಪ್ರತಿ ಕೆ.ಜಿ) ಹಾಗೂ ಅಂಟಿಕೊಂಡ ಸಿರಿಕಾನ್ (೪.೯೦- ೮೯.೪೦ ಮಿ. ಗ್ರಾಂ ಪ್ರತಿ ಕೆ.ಜಿ) ವಿಭಜನೆಯು ಕಡಿಮೆ ಪ್ರಮಾಣದಲ್ಲಿರುವುದಾಗಿಯೂ ಮತ್ತು ಅಸ್ಪಟಿಕ (೮,೦೧೯- ೧೬,೬೬೭ ಮಿ. ಗ್ರಾಂ ಪ್ರತಿ ಕೆ.ಜಿ) ವಿಭಜನೆಯು ಹೆಚ್ಚಿನ ಪ್ರಮಾಣದಲ್ಲಿರುವುದಾಗಿಯೂ ಕಂಡುಬಂದಿರುತ್ತದೆ. ಪ್ರಸಕ್ತ ಮಣ್ಣಿನ ಮಾದರಿಗಳನ್ನು ಬಳಸಿ ನಡೆಸಿದ ಮಡಕೆ ಪ್ರಯೋಗದಿಂದ, ಅತಿ ಹೆಚ್ಚು ಸಿರಿಕಾನಿನ ಅಂಶ ಮತ್ತು ಅದರ ಹೀರುವಿಕೆಯು ಅನುಕ್ರಮವಾಗಿ ಬೆಳ್ಳತ್ತ (ದಕ್ಷಿಣ ಒಣ ವಲಯ) ಹಾಗೂ ಹೊನ್ನವಿಲೆ (ದಕ್ಷಿಣ ಅರೆಮಲೆನಾಡು ವಲಯ) ಮಣ್ಣಿನಲ್ಲಿ ಬೆಳೆದ ಭತ್ತದಲ್ಲಿ ಮತ್ತು ಅತಿ ಕಡಿಮೆ ಸಿರಿಕಾನಿನ ಅಂಶ ಮತ್ತು ಅದರ ಹೀರುವಿಕೆಯು ಬ್ರಹ್ಮಾವರ ಮಣ್ಣಿನಲ್ಲಿ (ಕರಾವಳಿ ವಲಯ) ಬೆಳೆದ ಭತ್ತದಲ್ಲಿ ಕಂಡುಬಂದಿರುತ್ತದೆ. ಅಭ್ಯಸಿಸಿದ ಎಂಟು ಮಣ್ಣುಗಳಲ್ಲಿ ಸಸ್ಯಕ್ಕೆ ಲಭ್ಯವಿರುವ ಸಿರಿಕಾನಿನ ಅಂಶವನ್ನು ಆಧರಿಸಿ ಕೇವಲ ಮೂರು ಮಣ್ಣುಗಳನ್ನು ಪರಿಗಣಿಸಿದಾಗ ಸಿರಿಕಾನಿನ ವಿಭಜನೆಗಳು, ಸಸ್ಯಕ್ಕೆ ಲಭ್ಯವಿರುವ ಸಿರಿಕಾನಿನ ಅಂಶ ಹಾಗೂ ಭತ್ತದ ಸಿರಿಕಾನಿನ ಅಂಶ ಮತ್ತು ಅದರ ಹೀರುವಿಕೆಯೊಂದಿಗೆ ಉತ್ತಮ ಸಹಸಂಬಂಧ ಹಾಗೂ ಹಿಂಚಲನಾ ಗುಣಾಂಕವನ್ನು ಹೊಂದಿರುವುದಾಗಿ ತಿಳಿದುಬಂದಿರುತ್ತದೆ. ಆದಾಗ್ಯೂ ಅಕ್ಲೂಡೆಡ್, ಚಲನ ಹಾಗೂ ಅಂಟಿಕೊಂಡ ಸಿರಿಕಾನ್ ವಿಭಜನೆಗಳು ಗಮನಾರ್ಹ ಧನಾತ್ಮಕ ಸಹಸಂಬಂಧ ಹಾಗೂ ಹಿಂಚಲನಾ ಗುಣಾಂಕವನ್ನು ಹೊಂದಿರುವುದರಿಂದ ಈ ಸಿರಿಕಾನ್ ವಿಭಜನೆಗಳನ್ನು ಭತ್ತದ ಸಿರಿಕಾನಿನ ಅಂಶ ಮತ್ತು ಅದರ ಹೀರುವಿಕೆಗೆ ಉಪಯುಕ್ತವಾದುವು ಎಂದು ಪರಿಗಣಿಸಲಾಗಿರುತ್ತದೆ.

ಅಕ್ಟೋಬರ್, ೨೦೧೭

ಮಣ್ಣು ವಿಜ್ಞಾನ ಮತ್ತು ಕೃಷಿ ರಸಾಯನ ಶಾಸ್ತ್ರ ವಿಭಾಗ
ಕೃಷಿ ವಿಶ್ವವಿದ್ಯಾನಿಲಯ
ಗಾಂಧಿ ಕೃಷಿ ವಿಜ್ಞಾನ ಕೇಂದ್ರ, ಬೆಂಗಳೂರು- ೫೬೦೦೬೫

(ಎನ್. ಬಿ. ಪ್ರಕಾಶ್)
ಮುಖ್ಯ ಸಲಹೆಗಾರರು



Contribution of silicon from soils of different agro-climatic zones of Karnataka for paddy

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Introduction

Silicon (Si) is the second most abundant element on the surface of the earth. Silicon dioxide comprises 50 - 70 per cent of the soil mass. Consequently, all plants rooting in soil contain some Si in their tissues.

The availability of Si in soil for crop uptake depends on the form in which it exists in soil and rate of solubility. The weathering and mineral neo-formation processes create a great variety of Si- fractions in soil. Solubility and bioavailability of soil Si mainly depends on the surface properties like pH, parent material, extent and type of clay minerals.

In soils, Si may be retained in the soil solution as dissolved silicic acid or may be adsorbed by the soil particles. Silicon can be occluded in sesquioxides, bound to organic matter and can also exist in amorphous form (biogenic and minerogenic). However, the knowledge about native Si in Indian soils and their contribution to plant uptake is limited.

Rice (*Oryza sativa* L.) is a typical silicon accumulating plant requires large amounts of silicon for vigorous growth and high production. Application of Si is known to increase the dry matter production and yield of paddy.

The present experiment was conducted to know the influence of native Si in soils on growth attributes, Si content and uptake by Paddy.

Objective

- To assess the contribution of Si from soils of different agro-climatic zones for growth, Si content and uptake by Paddy.

Material and Methods

- Location** : Green house, Dept. of SS&AC
- No. of Agro-climatic zones** : 04
 - Central dry zone : CDZ
 - Southern dry zone : SDZ
 - Southern transition zone : STZ
 - Coastal zone : CZ
- No. of soils** : 8 (2 from each zone)
- Test crop** : Rice
- Variety** : IR-64
- No. of treatments** : 05
- No. of replications** : 03
- Design** : FCRD
- Moisture level** : Submergence
- Crop duration** : 60 days

Treatment details :

- T1:** 100% Quartz sand (control)
- T2:** 25% Soil + 75% Quartz sand
- T3:** 50% Soil + 50% Quartz sand
- T4:** 75% Soil + 25% Quartz sand
- T5:** 100% Soil

Results

Table.1. Physico- chemical properties of soils of different agro-climatic zones (ACZ)

ACZ	SOIL	pH	EC (ds m ⁻¹)	CC Si (mg kg ⁻¹)	AA Si (mg kg ⁻¹)	Dominant minerals (XRD)
CDZ	Kathalagere	6.0	0.62	21.65	58.12	Quartz, feldspar,
	Kamalapura	6.6	1.28	40.73	179.18	Quartz, vermiculite
SDZ	Mandya	6.0	0.27	17.12	32.5	Quartz, feldspar, amphibole
	Chamarajanager	6.1	0.31	36.41	82.25	Quartz, feldspar, chlorite
STZ	Honnave	5.4	0.47	17.70	40.00	Quartz, feldspar, amphibole
	H.N.Pura	5.2	0.25	12.86	30.37	Quartz, feldspar, vermiculite
CZ	Brahmavara	5.6	0.18	8.99	28.37	Quartz, vermiculite, gibbsite
	Mandharthi	5.3	0.13	15.48	48.43	Quartz, vermiculite, kaolinite

* CC Si- CaCl₂ extractable Si AA Si- Acetic acid extractable Si

Table. 2: Effect of different proportion of soils of different agro-climatic zones with quartz sand on growth, Si content and uptake by shoots of paddy

Treatments	Plant height (cm)	Shoot Biomass (g pot ⁻¹)	Si Content (mg kg ⁻¹)	Si uptake (mg pot ⁻¹)
T1: 100% quartz sand (control)	40.40	0.27	4.24	11.79
T2: 25% soil + 75% quartz sand	67.82	1.10	4.75	51.59
T3: 50% soil + 50% quartz sand	75.04	1.41	5.26	73.05
T4: 75% soil + 25% quartz sand	77.79	1.58	5.47	85.50
T5: 100 % soil	78.68	1.66	5.64	91.23
S.E.m ±	0.71	0.04	0.06	2.58
CD at 5 %	2.01	0.12	0.19	7.27

Irrespective of the soils studied, increase in proportion of soil increased the growth parameters, Si content and uptake by shoots of paddy.

Treatment with only soil showed 94.75% increase in plant height and 514% increase in shoot biomass over control. Si content and uptake were increased by 33 % and 673% respectively over control (Table. 2).

In treatments with 100 % soil, maximum plant height was recorded in Kathalagere soil (85.5 cm) and lowest in Mandharthi soil (64.6 cm). Honnavale soil showed higher shoot biomass of 2.2 g pot⁻¹ and was lowest in Mandharthi soil (0.9 g pot⁻¹) (Fig-1).

The Si content in shoots recorded maximum in Chamarajanagar soil (6.9 mg kg⁻¹) and was minimum in Brahmavara soil (2.6 mg kg⁻¹). Higher Si uptake by shoots was observed in Honnavale (132.6 mg pot⁻¹) and minimum in Brahmavara soil (52.7 mg pot⁻¹).

The CaCl₂ and acetic acid extractable Si content in the initial soils showed a positive correlation with Si content and uptake in shoots of paddy but was found to be non-significant (Fig-2 and 3).

Discussion

The treatments with 100 % soil, recorded higher values for growth attributes, Si content and uptake by shoots of paddy which might be due to maximum availability of Si and other nutrients for growth of paddy.

All the soils in the study noticed significantly varied growth attributes, Si content and uptake by shoots of paddy over control which may be attributed to the influence pH, clay content, organic matter, available nutrients and other factors.

Better correlation between CaCl₂ extractable Si with plant uptake than acetic acid extractable Si can be attributed to better extractability of CaCl₂ Si in acidic soils.



Plate 1: General view of pot culture experiment

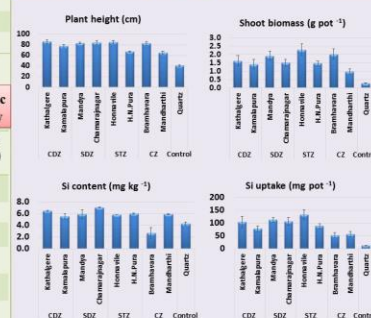


Fig-1: Effect of soils of different ACZ on growth attributes, Si content and uptake by paddy of paddy

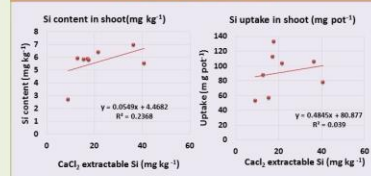


Fig 2 Effect of CaCl₂ extractable Si in soil on Si content and uptake of paddy

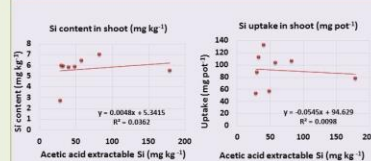


Fig 3 Effect of acetic acid extractable Si in soil on Si content and uptake of paddy

Summary

- ✓ Use of graded levels of soils corresponded to graded level application of Si as a growth media to the crop.
- ✓ The quantification of different pools of Si in soils would provide better understanding of their contribution to crop uptake.

Advisory committee

Chairman : Dr. N. B. Prakash

Members : Dr. G. G. Kadalli
Dr. G. B. Mallikarjuna
Dr. H. M. Jayadeva

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I INTRODUCTION

Rice- a symbol of cultural identity and global unity, is the world's most popular food. It shapes religious observances, festivals, customs, cuisine and celebrations. Rice is the staple food for over half the world's population. Approximately 480 million metric tons of milled rice is produced annually (Sumithra *et al.*, 2014). Rice cultivation is the principal activity and source of income for about 100 million households in Asia and Africa. For more than half of the humanity rice is life. As population increases, global demand for rice in the next decade is expected to expand at around one percent per year. Feeding these people will require the greatest effort in the history of agriculture. Farmers will have to grow an extra 3.7 million tons every year - at the very time that rice land is decreasing, and the remaining fields seem to be wearing out. 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).

India is an important centre of rice cultivation, covering about one-fourth of the total cropped area and providing food to about half of the Indian population. It is in fact the dominant crop of the country. In India, rice is grown in an area of 44 million ha with a production of 107 million tons and productivity of 2424 kg per hectare. In Karnataka, rice is grown under a variety of soils and wide range of rainfall and temperature. In Karnataka, total area under rice is 11.69 lakh hectares with a production of 28.05 lakh tons (Anon., 2015). It is highly challenging for the researchers to work with the problems of rice cultivation because of diversified agro climatic situation, amount and distribution of rainfall, soil type and prevailing agricultural practices. 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).

Rice (*Oryza sativa* L.) is a typical silicon (Si) accumulating plant and requires large amounts of Si for vigorous growth and high production. Application of Si is known to increase the dry matter production and yield of paddy.

Silicon is the second most abundant element on the surface of the earth. Silicon dioxide comprises 50 - 70 per cent of the soil mass. Consequently, all plants rooting in soil contain some amount of Si in their tissues.

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). In-situ measured Si concentration of soil solutions range from 0.4 to 2000 $\mu\text{mol L}^{-1}$. Most important factors for Si concentrations in soil solutions seem to be parent material, stage of soil development, temperature and residence time of pore water.

The major Si phases in soil are primary minerals inherited from parent material and secondary minerals resulting from soil formation. The latter are subdivided into crystalline phases (mainly clay minerals) and microcrystalline to poorly ordered phases (Monger and Kelly, 2002). Transformation between those phases is controlled by pH, temperature, presence of cations, and organic compounds with water as the main medium for Si fluxes in terrestrial biogeosystems (Gerard *et al.*, 2002).

Although Si is one of the fundamental elements, it has received relatively little attention in soil science compared to other elements (Sommer *et al.*, 2006). Nevertheless, the benefits of Si fertilization to crop production are too significant to be overlooked, and in some agricultural areas, fertilization with Si is the common agronomic practice. The benefits of Si fertilization on crop yields and quality has been studied extensively in Si accumulating crops like paddy (Snyder *et al.*, 1986). There are many sources of Si in use like K and Na silicates, liquid formulations, calcium silicates, steel slags, rice hull, rice hull biochar etc.,

In soil, Si occurs in various fractions which includes soil solution Si, adsorbed Si forms (monosilicic and polysilicic acids), amorphous forms (phytoliths and silica nodules), poorly crystalline and microcrystalline forms (allophane, immogolite and secondary quartz), and crystalline forms (primary silicates: quartz, feldspars, secondary silicates: clay minerals) (Cornelis *et al.*, 2011).

However, the knowledge about Si availability in Indian soils is limited (Prakash, 2002). Hence, there is a need for evaluation of simple and rapid extractants for determination of different pools of Si in Indian soils.

Unlike other nutrients such as N, P, K, secondary and micronutrients, a sequential extraction procedure to identify the various Si pools is very much lacking. The sequential extraction method fractionates and analyses various pools of Si, from the most mobile to immobile pools in soils. The sequential extraction allows differentiation of soluble, adsorbed, organic, amorphous and crystalline silicon, so that the different Si-pools can be analysed. There is no specific information about the silicon pools and dynamics. The lack of knowledge to the basic magnitudes of the Si-release is partly due to the fact that no standard technique is available for quantitative extraction of different pools of Si in soils.

In view of this, “Studies on silicon pools in rice soils of selected agro climatic zones of Karnataka” was conducted with the following objectives:

- To quantify the silicon pools of selected rice soils.
- To assess the contribution of different silicon pools for rice.
- To determine the relationship between different silicon pools and the properties of rice soils.

II REVIEW OF LITERATURE

The present investigation was undertaken to study “Silicon pools in rice soils of selected agro climatic zones of Karnataka”. The available reviews related to the present investigation are presented under following headings.

2.1 Silicon in agriculture with special reference to rice

2.2 Status of silicon in soil

2.3 Pools of silicon in soils

2.4 Extractability of different pools of silicon

2.5 Bioavailability of different pools of silicon

2.1 Silicon in agriculture with special reference to rice

2.1.1 Importance of Silicon

Silicon is considered as a useful element for a large variety of plants (Nakata *et al.*, 2008). Crop production removes large quantities of Si from soil. On a global perspective, the estimated amount of Si removed annually by different agricultural crops is between 210 and 224 million tons. Larger removal rates are estimated from high Si accumulator crops such as wheat, sugarcane, and rice. Sugarcane removes approximately $300 \text{ kg ha}^{-1} \text{ y}^{-1}$, whereas rice is as much as $500 \text{ kg Si ha}^{-1} \text{ y}^{-1}$ (Makabe *et al.*, 2009). These amounts are much higher than the removal rates of primary essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K).

In the early 1900s, Si was recognized as one of the 15 elements needed for plant life (Halligan, 1912). Silicon plays a significant role in imparting biotic, abiotic stress resistance and enhancing crop productivity (Savant *et al.*, 1997). It is also crucial in preventing or minimizing lodging in cereal crops, a matter of great importance in agricultural productivity.

Silicon increases the erectness of the leaves of rice; it strengthens the air canal, leading to more efficient oxygen supply to roots and to the limited loss of water by

evapotranspiration. Silicon is a structural element in diatoms and a cell wall component in rice and other grasses, which also occurs in vegetative tissues in lesser amounts. Si in plants contributes to the compression resistance and rigidity of cell walls, which in turn improve light interception and drought resistance and photosynthetic efficiency (Epstein, 1999).

Considerable damages to plants caused by abiotic stresses such as drought, salinity, heavy metal stresses and nutrient imbalance, as well as biotic stresses like insect pests and pathogens and even herbivorous attacks, have been reported to be reduced significantly by silicon application.

Silicon is not an essential nutrient because most plants can complete their reproductive cycle when grown in nutrient solutions lacking Si in their formulation. Nutrient culture studies show that plants accumulate some silica even in carefully controlled studies to exclude its presence in growth solutions. Of all the “non-essential” elements assimilated by plants, Si alone is consistently present at concentrations similar to those of the macro and secondary nutrients. Si concentrations range from 0.1 per cent (similar to that of P and S) to more than 10 per cent of whole plant dry matter (Epstein, 1999). When accumulated Si typically represents more than 1 per cent of dry mass, a species is considered a Si-accumulator (Epstein, 1994).

Ma and Takahashi (2002) reported that plants are considered as Si “accumulators” when the tissue Si concentrations is $>10 \text{ g kg}^{-1}$ or a Si concentration over 1 per cent and a $[\text{Si}]/[\text{Ca}]$ ratio >1 . As “excluders” when the Si concentrations is $<5 \text{ g kg}^{-1}$ or below 0.5 per cent and a $[\text{Si}]/[\text{Ca}]$ ratio <0.5 . Those plants that do not meet these criteria are called “intermediates”. The critical value of 0.5 per cent is considered to be the Si concentration obtained in a plant which would absorb 0.5 L of a solution containing 10 mg Si L^{-1} and produce 1 g of dry matter.

Silicon is taken up by the roots in the form of silicic acid $[\text{Si}(\text{OH})_4]$, an uncharged monomeric molecule, when the solution pH is below 9. The occurrence of Si within the plant is a result of its uptake, in the form of soluble $\text{Si}(\text{OH})_4$ or $\text{Si}(\text{OH})_3\text{O}_2$, from the soil

and its controlled polymerization at a final location. However, the ability of a plant to accumulate Si varies greatly between species (0.1 – 10 % of shoot dry weight) and extensive analysis of Si uptake in plants has been carried out (Hodson *et al.*, 2005). The difference in Si accumulation between species has been attributed to differences in the Si uptake ability of the roots.

Silicon is assimilated by plant roots as monosilicic acid (H_4SiO_4) where it accumulates in leaves and other plant tissue primarily as amorphous silicates or phytoliths. Once deposited in this form, Si is immobile and is not redistributed within the plant (Ma *et al.*, 1989). Hydrated, amorphous silica is deposited in cell lumens, cell walls, and intercellular spaces. It also accumulates in external layers below and above the cuticle of leaves. Silicon is present in roots, leaves, and the inflorescence bracts of cereals, especially in rice, wheat, oats and barley (Epstein, 1999). The uptake of Si by rice and other plants is not well understood, but appears to be influenced by a number of soil and climatic factors.

Silicon is taken up by plants from soil solution either passively with the mass flow of water or actively, e.g., by rice plants (Ma *et al.*, 2001). Plants show Si contents ranging from 0.1 to 16 wt per cent dry matter (Marschner, 1995; Datnoff *et al.*, 2001).

Increasing Si availability in the soil is usually accompanied by increased Si content in the plant. This may result in increased growth and productivity in several grasses, especially rice (Berthelsen *et al.*, 2003).

Among the cereals, rice responds more to Si and magnitude of yield advantage due to silicon application reached 20-30 per cent (Kalyan Singh *et al.*, 2006).

2.1.2 Silicon and Rice

Rice (*Oryza sativa* L.) is a typical silicon accumulating plant requiring large amounts of silicon for vigorous growth and high production. It has been considered as a necessary nutrient for rice (Ma *et al.*, 2001). It is the only element known that does not

damage plants upon excessive accumulation. High accumulation of Si in rice has been demonstrated to be necessary for healthy growth and high stable production.

Rice is known to accumulate high amount of silicon approximately 10 per cent of its dry weight. The rice plant uptake the soil silicon along with the essential elements such as nitrogen, phosphorus and potassium. The endogenous Si has been known to improve the plant growth and mitigates environmental stresses (Parveen and Hussain, 2008; Kim *et al.*, 2011).

Adequate Si uptake promotes rice growth by increasing its tolerance to both biotic and abiotic stresses. Silicon is still not considered as an essential nutrient, its beneficial effects on plant growth and yields have been repeatedly demonstrated in rice (Savant *et al.*, 1999).

Silicon deposited in the leaves, stem and husk improves the light-interception ability by plants and increases erectness of leaves resulting in increased photosynthesis. It also minimizes transpiration losses and improves water usage by the plants.

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). Accumulated silicon in rice tissues enhances resistance against insects and diseases, alleviates lodging and other abiotic stress and decreases toxicity of heavy metals such as Al, Mn, Fe, Cd, Pb and Zn (Nakata *et al.*, 2008).

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).

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⁻¹ SiO₂ 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. Silicon induces dehydration tolerance at tissue or cellular levels by improving the water status and hence, facilitates the plant to access photosynthates (Mukthar *et al.*, 2013).

2.2 Si status in soils

Silicon (Si) is ubiquitous in the earth's crust, it is the second most abundant element after O₂ and is ~ 28 per cent by weight (Singer and Munns, 1999; Wedepohl, 1995). Silicon exclusively found in the form of silicon dioxide (SiO₂) in association with a wide array of Si-bearing minerals in crystalline, poorly crystalline, and amorphous phases (Sommer *et al.*, 2006). It does not occur free as an individual element in nature but rather as a complex in oxides and silicates (Gascho, 2001). However, despite the relative abundance of Si in soils, plant-available Si is often limited in most soil-type.

In soil solutions, silicon is found mostly as uncharged monomeric silicic acid at concentrations from about 0.1 mM to 0.6 mM, or up to about 0.8 mM at equilibrium when the solution pH is below 9 (Ma and Takahashi, 2002). Silicon concentrations in soil solution have been reported to range from 0.01 to 2.0 mM (Karathanasis, 2002) but are commonly in the range of 0.1 to 0.6 mM (Epstein, 2001). Concentrations of Si in soil solution range between 0.1 and 2 mmol L⁻¹, depending on soil type, CO₂ partial pressure and complexing organic acids (Marschner, 1995). At high pH (> 9) silicic acid dissociates to form H₃SiO₄ and H₃SiO₄⁻, above pH 11 to H₂SiO₄²⁻.

Most Si in the soil is in an inert form, and only a small fraction is soluble and available for plant uptake, whereas most Si in mineral soils is held in the crystalline structure of sand, silt, and clay particles, a Si form unavailable for plant uptake. In soil solutions, the prevailing Si form is silicic acid Si(OH)₄.

Soils vary significantly in their ability to supply plant-available Si. In general, soils in which Si fertilization will likely increase crop yields are typically highly weathered, leached tropical soils with low pH, base saturation, and silica-sesquioxide

ratios. Soils that are less weathered or geologically young have the capacity to supply higher amounts of plant-available Si than highly weathered soils.

In general, Si concentration in soil solution decreases with increasing soil development (Karathanasis, 2002). As a result, the soluble Si content of tropical soils, such as Ultisols and Oxisols, is generally 5–10 times less than that of most temperate soils (Foy, 1992).

The main determinant of concentrations of Si in soil solution is the solubility of primary and secondary minerals. The concentration of Si in soil solution depends on the solubility of primary and secondary Si compounds in soils.

Silicon fluxes in soils and terrestrial biogeosystems are mainly mediated through water. Si solubility in soils decreases with increasing pH. Thus, if adsorption reactions are the major factor determining soil solution Si concentrations, then Si solubility and availability will decrease with increasing pH (Hingston and Raupach, 1967).

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. Also soil type, soil texture, soil pH, soil Eh, organic matter, and accompanying ions (Struyf *et al.*, 2009)

Amounts of Si in soils also depends on reflecting pedogenic processes at pedon and landscape scale. They vary from less than 1 mass per cent Si in Histosols to up to 45 mass per cent Si in Podzols (Sommer *et al.*, 2006).

Monosilicic acid (H_4SiO_4), behaves as a very weak acid, and even in pH 7, only 2 mg kg⁻¹ 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⁻³ SiO₂ (Raven, 2003) and depended on clay content (Raij and Camargo, 1973), iron and aluminium oxides and pH (Beckwith and 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.*, 1968).

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 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⁻¹ soil covered about 43.7 per cent of the total area followed by the class 800 to 1000 mg kg⁻¹ 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.

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 SiO₂ Kg⁻¹. 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 SiO₂ kg⁻¹ and 50 per cent of those contained available Si less than 150 mg SiO₂ kg⁻¹.

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⁻¹ with an average of 700 kg ha⁻¹ (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⁻¹ and considered to be highly deficient. The plant available soil Si (mean) extracted by 1 N NaOAc (pH 4.0) in soils of Orissa and Andhra Pradesh were 139 and 278 mg kg⁻¹, respectively.

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⁻¹ respectively.

2.3 Different pools of Si in soil

Soil contains various Si fractions, since weathering and mineral neo-formation processes create a great variety of Si- fractions in soils. 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. 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).

The mineral Si pools are developed from rocks or sediment sands and mainly composed of primary crystalline silicates such as quartz, feldspar, mica and secondary

silicates, especially clay minerals. Si pools of biogenic origin includes phytoliths, diatoms and sponge spicules and pedogenic amorphous silica (Drees *et al.*, 1989).

Danilova *et al.* (2010) by sequential extraction on a soil catena in the Black forest in SW-Germany indicated that, most of the Si (98-99%) is bound in primary and secondary silicates. Up to 1 per cent of Si originates from the abiotic amorphous phase or from organic matter.

A large variety of silicon fractions may occur in soils. Silicic acid also dissolved in soil solution with some part of the silicic acid absorbed to soil minerals, particularly iron and aluminium oxides /hydroxides (Dietzel, 2002). It may also occur as bound to organic matter. Amorphous silica exists in the form of biogenic (e.g. phytoliths) and minerogenic opal (e.g. silica cutans). Moreover, Si in the form of dissolved silicic acid is retained in the soil solution. Finally, many primary and secondary crystalline silicates (e.g. quartz, feldspar, micas, clay minerals) are generally found in soils. While the knowledge about quantification of crystalline minerals is advanced than their Si fractions such as Si in amorphous silica. (Danilova *et al.*, 2010)

Soils contain soluble and adsorbed Si, primarily as monomeric orthosilicic acid, with lesser amounts of polysilicic acids and organo-silicon compounds (Matichencov and Bocharnikova, 2001). In general, Si released during weathering of primary silicates can be leached or consumed in the formation of secondary silicates, or it may precipitate as pedogenic silica from the soil solution (McKeague and Cline, 1963a). Silica precipitates may form amorphous coatings on mineral grains (Veerhoff and Brümmer, 1993) or mixtures with crystalline substances (Follett *et al.*, 1965).

When dissolved Si (DSi) concentrations in soils become over-saturated (defined as 2.1 mm for amorphous silica at 25 °C), dissolved Si can precipitate as ASi, forming pedogenic opal. Finally, DSi in soil solution can sorb on the surface of aluminium and iron oxy/hydroxides according to their type, size and degree of crystallinity (Cornelis *et al.*, 2011). Together, these non-biogenic forms in soil constitute the ‘pedogenic Si pool’.

The Si pool in soils not only comprises crystalline silicates such as quartz, plagioclase, feldspar, orthoclase and clay minerals but also includes an amorphous fraction (Sauer *et al.*, 2006). Amorphous silica (ASi) consists mainly of biogenic silica (BSi), produced by plants as phytoliths, with a variable contribution of a non-crystalline inorganic fraction (ISi), such as Si included in iron oxides/hydroxides and Si in inorganic alumino-silica coatings. There is still little knowledge regarding the size of the ASi pool and as a result, there is a growing interest in selecting a chemical extraction method that can give reliable and reproducible estimates. This is a critical step as ASi dissolution rates are faster than the dissolution rates of silicate minerals (Bartoli and Wilding, 1980).

The solubility of amorphous Si ranges between 1.8 and 2 mM compared with quartz's 0.10 to 0.25 mM Si (Monger and Kelly, 2002). Biogenic silica also contributes to the concentration of Si in soil solution, and with solubility 17 times higher than quartz, this contribution to the dynamics of plant-available Si in soil solution is rather significant (Frayse *et al.*, 2006).

The largest proportion of amorphous silica in most soils is represented by bio-opal (Drees *et al.*, 1989) in the form of phytoliths, siliceous sponges and diatoms. Some authors assume that biogenic silica is a major source of dissolved Si in soil solution (Cornelis *et al.*, 2010, Derry *et al.*, 2005 and Miretzky *et al.*, 2001). Alexandre *et al.* (1997) estimate that Si release from bio-opal is two to three times as great as that from silicate weathering. This implicates a high turnover of this fraction.

Phytoliths are regarded as the major component of the biogenic silica pool in soils followed by diatoms and sponge spicules. In the plant, monosilicic acid precipitates forming amorphous Si particles known as 'phytoliths'. Phytogenic Si precipitates with a size of 51 nm to 200 nm, probably contribute the major part of biogenic Si in soils. Phytolith content in soils ranges from 0.01 wt. per cent up to 50 wt. per cent (1 to 30 mg g⁻¹) of fine earth (<2 mm) (Clarke, 2003).

Vegetation stores Si as amorphous biogenic silica (ASi) in biomass, mostly in phytoliths, in the form of hydrated amorphous silicon dioxide (SiO₂.nH₂O) (Piperno,

1988), which have greater solubility than silicate minerals (Frayse *et al.*, 2009). After plant decay, phytoliths return to the soil (Meunier *et al.*, 1999).

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_4SiO_4 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 soil-to-plant transfer of Si was however poorly investigated though plant-BSi has been reported to vary depending on soil type (Schwandes *et al.*, 2001).

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 $\text{pH} < 8$.

2.4 Extractability of different Si pools in soils

Since plants remove Si from soil, it is important to understand its forms and reactions in soils. Silicon forms may be defined in terms of total, extractable, and soluble pools. Total Si comprises all forms of Si that may be present and can be solubilized by strong alkali-fusion or acid-digestion bomb methods. Extractable Si represents those forms removed by less severe dissolution agents, such as sodium dithionite, ammonium oxalate, and sodium pyrophosphate (Sauer *et al.*, 2006). These extractants remove Si of intermediate stability that is often found associated with crystalline or amorphous soil

components. Soluble Si represents the most labile form in soils and consists primarily of monomeric silicic acid. Plant available Si is influenced by several factors, such as pH, clay, and organic matter content, type of Al and Fe oxides, parent material, and the chosen extraction method.

Different methods dissolve different amounts of Si, which is not only due to the strength of the extractant used, but also to the variability of Si distribution in the soil type and horizon. Different soil tests for plant-available Si have been developed for crops which are sensitive for Si nutrition, mainly rice, and sugarcane in the USA, Japan, and Australia (de Lima Rodrigues *et al.*, 2003), but no experiences have been reported for pasture crops. The use of 0.5 M ammonium acetate (pH 4.8) is very common for determination of soluble Si on sugarcane fields in Hawaii (Fox *et al.*, 1967). As a solution of 0.01 M CaCl_2 reflects the ionic strength and pH of soil solution in agricultural soils, it is a promising candidate for assessing plant-available Si. It has also been used for studying the chemical kinetics of Si release from soils. Korndorfer *et al.* (1999) concluded that among the extractants tested, the 0.5 M acetic acid gave the best results for the available Si in soils with rice cultivation.

Plant available soil Si levels need to be considered from three aspects: ‘intensity’ (concentration of Si in the soil solution available for immediate plant use); ‘capacity’ (the reserve supply of Si present as solid phases in the soil); and ‘buffer capacity’ the factors that affect the sorption/desorption reaction in the soil (ability of the solid phase to replenish the soil solution following depletion through leaching or plant use). The difference in Si obtained using different extractants has led many researchers to suggest using two methods of extraction. The first in water or a dilute salt solution to provide a solution concentration near equilibrium with the soil system (an ‘intensity’ factor), and the second, using a stronger extractant such as phosphate acetate, citric acid and 0.005 M H_2SO_4 , to provide an index of the adsorbed soil Si (a ‘capacity’ factor) (Khalid *et al.*, 1978).

Berthelsen *et al.* (2001) reported that the weakest extractant after water is CaCl_2 , CaCl_2 extracted easily water-soluble Si; acetate, acetic acid, and phosphate acetate

dissolved some of exchangeable Si; and citric acid and sulfuric acid extracted specifically adsorbed Si.

Haysom and Chapman (1975) compared 0.01 M CaCl_2 , 0.5 M ammonium acetate, and 0.005 M sulfuric acid for their ability to extract plant-available Si from soils and found that Si extracted by CaCl_2 showed the highest correlation to sugar cane yield ($r = 0.82$). It can be used as an estimate of DSi availability for plants.

Snyder (1991) reported an acetic acid extraction, which is used at the soil testing laboratory at the University of Florida Everglades Research and Education Center (EREC) as a standard method to analyse plant available Si in rice growing soils.

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)

Silicon in soil organic matter (SOM) can be obtained through destruction of SOM. Concentrated H_2O_2 solution is widely used for oxidizing SOM (Blume *et al.*, 2011). Whereas, according to Bartlett *et al.* (1937) and Tessier *et al.* (1979), diluted H_2O_2 -solution does not completely oxidize SOM. Alternatively, acid (Tessier *et al.*, 1979) or alkaline (Shuman and Hargrove, 1985) treatments have been proposed. However, such treatments may attack other Si phases in soil samples (e.g., amorphous silica and clay minerals), which is unacceptable in a Si-fractionation procedure. Hence, the effect of concentrated H_2O_2 -solution at 85 °C (Blume *et al.*, 2011) was tested on selected soil compounds (kaolin, smectite, microcline, quartz powder, silica gel) in order to find out whether hot H_2O_2 -extraction attacks these substances. 1 g of the test material was first treated with 20 ml of 17.5 per cent H_2O_2 -solution and kept for 1 hr at room temperature. Then 10 ml of 35 per cent H_2O_2 -solution were added obtaining a solid to solution ratio of 1:30. The samples were shaken in a water bath at 85 °C and 90 rpm for 7 h. Then, the samples were cooled down in a cold-water bath for 15 min and centrifuged at 3000 rpm for 15 min. The extract was filtered and Si was measured by ICP-OES.

Extraction by 1 % Na_2CO_3 followed by a correction for crystalline Si (De Master, 1981) has recently become widely used and is proposed as the standard technique for quantifying amorphous silica (ASi) pools in soil and continental aquatic sediments.

Two approaches are currently used to quantify ASi. The first approach is based on a physical extraction using heavy liquid flotation (Cornelis *et al.*, 2010). This non-destructive method was first applied for analysing phytolith morphology. Several drawbacks have been pointed out when using physical extraction: poor reproducibility (Herbauts *et al.*, 1994); ASi dissolution when using dispersing agent (Zhao and Pearsall, 1998) and underestimation following clay separation that may contain a significant ASi fraction (Saccone *et al.*, 2007). The second approach is based on a wet-alkaline digestion. Two extractants are generally used: NaOH (Koning *et al.*, 2002) and Na_2CO_3 (Sauer *et al.*, 2006).

The method of DeMaster (1981) therein referred to as the 1 % Na_2CO_3 method, consists of a Na_2CO_3 kinetic extraction of ASi, that considers the crystalline contribution is easy to implement and is now widely used. The 1% Na_2CO_3 method was originally proposed for the quantification of amorphous silica pools in marine sediments that were mostly made of diatom frustules (Metzer *et al.*, 2010).

The most common extractants to dissolve amorphous silica from soils and aquatic sediments are NaOH and Na_2CO_3 , but both also dissolve crystalline silicates to varying degrees. In soils, moreover Tiron is used to dissolve amorphous silica, while oxalate is used to dissolve allophones and imogolite-type materials. Most techniques analyzing for biogenic silica in aquatic environments use a correction method to identify mineral derived Si. By contrast, in the soil sciences no correction methods are used although pedologists are well aware of the overestimation of amorphous silica by the NaOH extraction, which is most commonly used to extract silica from soils. It is recommended that soil scientists begin to use the techniques developed in the aquatic sciences, since it seems impossible to extract amorphous Si from soils completely without dissolving some of the crystalline silicates. (Sauer *et al.*, 2006).

The quantification of the phytolith pool in soils is based on the physical and chemical properties of amorphous opal A. Other biogenic amorphous silica particles can be found in soils such as diatoms frustules and the camoebian testates (Cary *et al.* 2005). Depending on the target (biogenic silica, plant-available Si or amorphous Si as a whole) the aim of the study and the scientific discipline, different approaches have been developed to identify and quantify amorphous silica in soils. The gravimetric method (Kelly, 1990) separates particles of amorphous silica from the rest of the soil using heavy liquid flotation, allows for the observation and quantification of amorphous silica particles and phytoliths.

Jones and Handreck (1963) observed 1–2 per cent of phytoliths in grassland soil, while soil horizons resulting from phytolith accumulation have also been described. An alternative technique to quantify the phytoliths in soil is by solubilization. Contrary to the gravimetric method, this is a destructive method so that the proportion of phytoliths vs. other amorphous silica particles cannot be assessed. Saccone *et al.* (2007) used alkaline extractions (NaOH and Na₂CO₃) originally used to quantify diatoms in marine sediments.

Other non-alkaline extractants do not solubilize phytoliths and usually dissolve less than the alkaline ones but, they may be used to quantify immediately plant-available Si in specific soils (Liang *et al.*, 1994). The depth of soil phytoliths distribution is variable, but generally, the highest concentrations are found in the topsoils of undisturbed soils (Saccone *et al.*, 2007; Sommer *et al.*, 2006) and decrease with depth. This distribution reflects the equilibrium between the rate of phytoliths input via litterfall and the rate of phytolith output via dissolution.

Klotzbucher *et al.* (2015) used three different extraction methods to assess Si forms that contribute to the pool of readily-soluble Si in soils. Firstly, sodium acetate extraction which assesses soluble and adsorbed Si from soils (Imaizumi and Yoshida 1958). Secondly, ammonium-oxalate extraction, a commonly used method to determine amorphous Fe and Al oxides (Schwertmann, 1964). The method also dissolves poorly crystalline aluminosilicates, i.e., allophane and imogolite type materials (Sauer *et al.*, 2006). In these soils Si of aluminosilicates may contribute to a larger portion to oxalate-

extractable Si. In the other soils Fe/Al-ratios ranged from 2.5 to 8.8 and assumed that oxalate primarily extracted Si adsorbed onto and occluded in Fe-oxides. The acetate and oxalate extraction methods hardly dissolve any amorphous Si such as phytoliths and pedogenic amorphous Si dioxides, due to the low pH values of extractants (Saccone *et al.*, 2007). Third, the sodium carbonate extraction method, primarily extracts amorphous Si from soils. The Si concentrations in carbonate extracts were determined after 1, 2, 3, 4, and 5 hours of extraction. Here, the correction proposed by DeMaster (1981) was used to estimate the contribution of amorphous Si forms to carbonate extractable Si. The correction assumes that most of the amorphous Si forms completely dissolve after 2 hours, while clay minerals dissolve at a slower rate and linearly over time. This commonly applied correction does not consider that carbonate extraction may also extract poorly crystalline aluminosilicates (Cornelis *et al.*, 2011).

Investigation of the different methodologies confirmed that oxalate, acetate and citrate extractions are not adequate to dissolve amorphous Si (ASi) in soils compared with alkaline methods. A 0.094 M Na₂CO₃ extraction works well for some soil samples, for example soils consisting primarily of ASi in phytolith. For more complex samples the relatively low pH and the limited number of sample points used to determine the intercept or ASi concentration, led to inaccurate corrections and large errors and thus hindered the findings. The automated NaOH method with mineral correction is therefore the preferred method to extract ASi from soils.

The high pH of the NaOH extractant compared with Na₂CO₃ ensures that all ASi is extracted from a soil sample. The entire dissolution-curve overtime is recorded, thus allowing for an accurate correction for the contribution of Si extracted from the lithogenic fraction of the soils. However, when an automated method is not available, and a manual method has to be used, a time-course sampling must be made to ensure that all ASi is extracted, with sufficient sample points to allow for a reliable extrapolation.

Cornellis *et al.* (2011) opined that extraction by means of an alkaline solution appears to be an accurate method, even when the proportion of amorphous silica is low in comparison with crystalline silicates. Depending on the soil development stage, oxalate

extraction could be used to estimate the silicic acid content adsorbed onto and occluded into amorphous Fe oxides, and the short-range ordered allophane and imogolite contents, which are not amorphous but are likely to be included in the Si_{alk} pool. In our samples, the readily soluble Si pool integrates mainly biogenic opal (phytoliths) and Si adsorbed onto amorphous pedogenic Fe oxides. The alkaline dissolution method provides a measurement of the amorphous, but presumably also of the non-amorphous Si fractions such as ‘plant-available Si’, Si adsorbed onto pedogenic oxides and Si included in short-range ordered aluminosilicates.

Georgiadis *et al.* (2013) developed a method for sequential extraction of Si fractions from soils, based on numerous series of extraction experiments using well-characterized isolated soil compounds and selected soil samples. The procedure has been developed by first improving and further developing existing specific extraction methods before implementing them as subsequent steps into the sequential procedure. The sequential extraction of Si introduced here extracts step by step various Si-fractions, from the most mobile to the most immobile Si fraction in fine earth. The sequential extraction procedure for Si in soils allows for the first time estimates of the sizes of most conceptually known Si fractions in soils. This is an important prerequisite for further investigating interactions between these fractions and thus Si dynamics in soils. In turn, this will allow contributing to the understanding of Si cycling at different spatial scales. The procedure was successfully tested on soils of humid temperate climate.

Georgiadis *et al.* (2017) applied for the first time a sequential Si extraction scheme to three floodplain soils to separate six Si fractions: mobile Si, adsorbed Si, Si bound to organic matter, Si included in pedogenic oxides and hydroxides, biogenic as well as minerogenic amorphous silica. The highest Si proportion apart from the residual fraction (Si bound in primary and secondary silicates) was found in minerogenic amorphous silica (up to 5.6 % of total Si), followed by Si occluded in pedogenic oxides and hydroxides (up to 0.7 % of total Si). Silicon from biogenic amorphous silica amounted to 0.02–0.6 per cent of total Si. The smallest proportion of Si was found in the mobile Si fraction and made up about 0.01 per cent of the total Si. The results of this study demonstrate the importance of the soil water budget (here periodic flooding with

prolonged water saturation) on the accumulation of easy-to-mobilise Si, Si occluded in pedogenic oxides and hydroxides and amorphous minerogenic as well as biogenic silica. Reductive dissolution of Fe and Mn oxides may induce Si release into the soil solution, subsequent oxidizing conditions may induce Si accumulation by adsorption, co-precipitation and occlusion of Si on/with newly formed Fe and Mn oxides.

2.5 Bioavailability of different Si pools

Solubility and bioavailability of soil Si mainly depends on the surface properties like pH, soil constituents and type of soil. Struyf *et al.* (2009) reported that 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 $\text{H}_2\text{SiO}_4^{2-}$.

So far, the role and rate of Si uptake by higher plants, as well as its dependence on environmental factors like, pH of soil solution, is almost unknown (Ma and Takahashi, 2002). Evaluation of the effect of pH on Si availability in soil is crucial as it plays an important role for several pedogenic processes including weathering and formation and disintegration of secondary clay minerals, as well as Si solubility.

Makabe *et al.* (2009) evaluated the relationship between the amount of available Si in paddy soils and their mineral properties on the Shounai Plain in Japan. 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 $\text{SiO}_2/\text{Al}_2\text{O}_3$ 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_2O and K_2O concentrations of silt, the K_2O 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 $\text{SiO}_2/\text{Al}_2\text{O}_3$ 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 $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio, clay fraction contents contributed approximately 50 per cent to the amount of available Si in the soils.

Elghawary and Lindsay (1972) measured the solubility of Si on two soils in which equilibrium was approached from both under-saturation and supersaturation over a 50-day period. In this study, 0.02 M CaCl_2 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^{-1} of Si in solution while the calcareous soil supported 25 mg kg^{-1} . These levels are intermediate between the solubility of quartz (2.8 mg kg^{-1} Si) and amorphous silica (51 mg kg^{-1} Si) and lie very near the level predicted for equilibrium between kaolinite and montmorillonite.

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_{alk} (extracted by alkali) concentration decreased from the humus layer to 15 cm depth and then slightly increased until a depth of 75 cm. Below 7.5 cm, the Si_{alk} content did not differ significantly between tree species and the Si_{ox} (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.

Klotzbucher *et al.* (2015) studied the forms and fluxes of Si in paddy fields and resulted Si storage in plants at harvest was $0.73 \pm 0.12 \text{ Mg ha}^{-1}$ (>78 % in straw) and not related to different Si forms in topsoils. Large stocks of carbonate-extractable Si ($2\text{--}29 \text{ Mg ha}^{-1}$) suggested an accumulation of ‘phytoliths’ in topsoil due to irrigation.

Obihara and Russell (1972) reported that 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. Other anions and soil pH also influence the reactions.

Georgiadis *et al.* (2014) in their study on different pools of Si found that, most of the Si (~86–99 %) in the soils was bound in primary and secondary silicates (residual Si). In the mineral soil horizons, Si in the minerogenic amorphous phase contributed the second largest amount of Si to the total Si, making up ~0.1–1.5 per cent of total Si. In some organic horizons, this phase was exceeded by Si from the biogenic amorphous phase. Silicon from minerogenic amorphous silica exhibited maxima in the organic layers, in or below the lower Bs horizon of the Podzols, in the Bt horizons of the Luvisol, and in the Cg horizons of the Stagnosol. Silicon from biogenic amorphous silica reached maximum values in the organic layers. Silicon in pedogenic oxides and hydroxides and Si in soil organic matter each exhibited value usually amounting to 0.1–0.2 per cent of total Si. The E horizon of the Luvisol showed a slight minimum and its Bt horizons a slight maximum of Si occluded in pedogenic oxides and hydroxides. The depth curve of Si in soil organic matter (SOM) in the Podzols was similar to that of Si in minerogenic amorphous silica, but at an overall lower level of Si content. The proportions of mobile and adsorbed Si fractions both made up <0.01 per cent of the total Si in most samples. These two fractions reached their highest values in the Bt horizons of the Luvisol and the Cg horizons of the Stagnosol.

Georgiadis *et al.* (2013) in their study on pools of Si revealed Si extracted from bio-opal decreased with depth in the soil profiles and was positively correlated with Soil organic matter (SOM) content ($r = 0.479^{**}$). The amounts of bio-opal Si were positively correlated with amounts of Si from minerogenic amorphous silica ($r = 0.599^{**}$). A major part of residual Si was related to the sand fraction ($r = 0.577^{**}$). The second-highest amounts of Si are found in precipitates of minerogenic amorphous silica; in the organic layers. However, biogenic amorphous silica may contribute the second-greatest proportion of Si. The amount of Si in the form of biogenic amorphous silica depends on the vegetation present and can be up to 14 per cent of the total Si content in Oa horizons

of the studied soils. Clayey horizons (subsoil horizons of a Luvisol and a Stagnosol) accumulate minerogenic amorphous silica. The lowest Si amounts are found in the mobile and adsorbed Si fractions. They depend on the contents of clay, sesquioxides and amorphous silica in the soil. Correlations of these fractions with soil pH and SOC were not observed.

There is a variety of methodologies used in soil sciences for extracting different forms of Si from sediments and soils. However, a comparison of the published extraction techniques is lacking.

A standardized sequential extraction procedure is required to identify the various Si fractions in soils and to quantitatively separate mineral and biogenic Si pools in soils. Quantification gives relative proportions, magnitude, stability, and dynamics of different Si pools in various soils under differed climatic situation which is needed for improving our understanding of biogeochemical processes involving Si cycle in the plant–soil system.

III MATERIAL AND METHODS

The present investigation was undertaken to study “Silicon pools in rice soils of selected agro climatic zones of Karnataka”. A pot culture experiment was conducted in green house at Department of Soil Science and Agricultural Chemistry, GKVK, UAS, Bengaluru. The details of materials used, and the methodologies adopted during the investigation are presented below.

3.1 Quantification of silicon pools of selected rice soils

3.1.1 Soil sampling

Karnataka state has been divided into ten distinct agro climatic zones based on climatic conditions, rainfall pattern, topography, soil characteristics and cropping pattern. The surface soil samples were collected at a depth of 15 cm from four agro climatic zones viz. central dry zone, southern dry zone, southern transition zone and coastal zone. Two soil samples were collected from each agro-climatic zone. Soil samples were shade dried, powdered and sieved through 2mm mesh size sieve, then subjected for pH, EC, CaCl_2 extractable silicon, acetic acid extractable silicon and other nutrient analysis. The details of soil sampling locations are given in Table 1.

Table 1: List of agro climatic zones and locations selected for soil sampling

Sl. No.	ACZ No.	Agro climatic zones	Locations	Latitude	Longitude
1	4	Central dry zone	1. AHRS, Kathalgere, 2. Kamalapura, Davanagere	14 ⁰ 16' 01.2" 14 ⁰ 26'19.2"	75 ⁰ 49'43.5" 75 ⁰ 43'32.5"
2	6	Southern dry zone	1. V.C. Farm Mandya, 2. Bellatha, Chamarajanagara	12 ⁰ 34'05.6" 11 ⁰ 57'17.5"	76 ⁰ 49'49.7" 77 ⁰ 05'24.3"
3	7	Southern transition zone	1. Honnavile, Shimoga 2. Tattekere, H.N. Pura	13 ⁰ 54'13.1" 12 ⁰ 48'13.1"	75 ⁰ 40'07.8" 76 ⁰ 16'38.0"
4	10	Coastal zone	1. Seed fram, Brahmavara 2. Mandharthi, Brahmavara	13 ⁰ 25'59" 13 ⁰ 29'46.3"	74 ⁰ 44'09.0" 74 ⁰ 49'20.9"

3.1.2 Characterization of soils for physico-chemical properties.

To know the different of physico-chemical properties soils collected from different agro- climatic zones, the analysis of pH, EC, OC, CEC, particle size distribution, acetic acid (AASi) and calcium chloride extractable Si (CCSi), available nutrients were under taken in the present investigation. The procedures employed for analysis of these parameters are given in Table 2.

3.1.3 Fractionation of silicon pools of selected rice soils

A large number of silicon fractions may occur in soils. Soil particles may adsorb dissolved silicic acid from the soil solution. Si may be retained in the soil solution as dissolved silicic acid or may be adsorbed by the soil particles. Silicon can be occluded in sesquioxides, bound to organic matter and can also exists in amorphous form (biogenic and minerogenic forms). The availability of Si in soil for crop uptake depends on the form in which it exists in soil and rate of solubility.

Quantification of the different pools of Si in soils is required for better understanding of their contribution to the crop uptake. A sequential extraction method was adopted to study various Si fractions in soil as outlined by Georgiadis *et al.* (2013)

3.1.3.1 Sequential extraction of Si pools from soil

Sequential extraction is an analytical procedure involving sequential chemical extractions for partitioning of different fractions of Si. Sequential extraction method is operationally defined on the basis of reactivity of a particular phase in a given extractant. Here, the method extracts stepwise, various Si fractions, from the most mobile to the most immobile fractions. The sequentially extracted Si pools include: (1) mobile Si (extracted by CaCl_2 solution) (2) adsorbed Si (extracted by acetic acid) (3) Si bound to soil organic matter (extracted by H_2O_2) (4) Si occluded in pedogenic oxides and hydroxides (extracted by NH_4 -oxalate under UV radiation); (5) amorphous Si (extracted by NaOH extraction).

Table 2: Methods of soil analysis

Sl. No.	Parameter	Procedure	Method and Reference
1	Particle size analysis	Soil was pre-digested with H ₂ O ₂ and dispersed with sodium hexametaphosphate. Sand was separated with decantation procedure. Silt and clay in the suspension was measured after pipetting with Robinson pipette	International pipette method, Jackson (1973)
2	Cation exchange capacity	Sample was leached with 1N (pH 7) ammonium acetate followed by washing with alcohol and ammonium in the leachate was determined by distillation method.	Distillation method Page <i>et al.</i> (1982)
3	Soil reaction	Soil: water suspension (1:2.5) was measured for pH using potentiometer after standardising with appropriate buffers.	Potentiometry, Jackson (1973)
4	Electrical conductivity	Soil: water extract (1:2.5) was measured for EC using conductivity bridge	Conductometry Jackson (1973)
5	Organic carbon	Soil was digested with K ₂ Cr ₂ O ₇ and Conc. H ₂ SO ₄ . The unutilized K ₂ Cr ₂ O ₇ was back titrated against ferrous ammonium sulphate using diphenyl amine indicator.	Wet oxidation, Walkley and Black (1934)
6	Available nitrogen	Soil was oxidized and distilled with alkaline potassium permanganate and then titrated against standard acid using mixed indicator.	Subbaiah and Asija (1949)
7	Available phosphorus	Soil was extracted with Brays-I extractant and estimated by chloromolybdate acid method using spectrophotometer and intensity of blue color was measured at 660 nm.	Brays and Kurtz (1945)

Sl. No.	Parameter	Procedure	Method and Reference
8	Available potassium	Soil was extracted with 1 N (pH 7) ammonium acetate and estimated with flame photometer.	Flame photometry, Jackson (1973)
9	Available silicon	Soil was extracted with 0.1M Calcium chloride, the Si was determined using UV- visible spectrophotometer at 820 nm.	Haysom and Chapman (1975)
		Soil was extracted with 0.5 M Acetic acid; the Si was determined using UV- visible spectrophotometer at 630 nm.	Korndorfer <i>et al.</i> (2001)
10	Exchangeable Calcium and Magnesium	Extracted the soil with 1 N (pH 7) ammonium acetate and Ca and Mg were estimated by complexometric titration method.	Baruah and Barthakur (1997)
11	DTPA extractable micronutrients	Soil was extracted with DTPA and micronutrients were determined using Atomic Absorption Spectrophotometer	Lindsay and Norvell (1978)

3.1.3.2 Procedure for sequential extraction of Si pools from soil

Step 1: Extraction of mobile Si fraction

One gram of air dried soil was taken in a plastic centrifuge tube and treated with 5 ml of 0.01 M CaCl_2 solution with a soil to solution ratio of 1:5, to extract mobile fraction of Si. The tubes were kept for shaking on a horizontal shaker for 24 hours for only 1min hr^{-1} . The samples were centrifuged at 3000 rpm for 3 min. Then filtered and analysed for Si concentration. The samples were rinsed with distilled water to remove the residual extractant of previous step.

Step 2: Extraction of adsorbed Si fraction

A 10 ml of 0.01 M acetic acid extractant was added to the residual soil with a soil to solution ratio of 1: 10 in order to extract adsorbed Si fraction. The tubes were kept for shaking on a horizontal shaker for 24 hrs for only 1min hr^{-1} . The samples were centrifuged at 3000 rpm for 3 min. Then filtered and analysed for Si concentration. The samples were rinsed with distilled water to remove the residual extractant of previous step.

Step 3: Extraction of organic matter bound Si

To extract Si organic matter bound Si, H_2O_2 was used as extractant with a soil to solution ratio of 1:30. First the residual soil was treated with 20 ml of 17.5 % H_2O_2 and manually shaken for 4–6 times and kept for 1 hour at room temperature. Then, 10 ml of 35 % H_2O_2 was added and the samples were kept in water bath at 85°C , with 90 rpm for 7 hours (Plate 1). Then samples were cooled in a cold-water bath for 15 min and centrifuged at 3000 rpm for 15 min and filtered. The samples were rinsed with distilled water to remove the residual extractant of previous step.

Step 4: Extraction of Si occluded in pedogenic oxides and hydroxides

This fraction was extracted with 0.2 M ammonium oxalate and 0.2 M oxalic acid under UV-light. First, the extractant was applied at daylight and room temperature for 8 h, using a soil to solution ratio of 1:50. Then, the suspensions were irradiated with UV

light (30W) overnight with a distance between the sample and the UV lamp of approx. 20 cm (Plate 2). During the whole time, the samples were shaken horizontally for 1 min hr⁻¹. The samples were rinsed with distilled water to remove the extractant of previous step.

Step 5: Extraction of amorphous Si

The amorphous Si was extracted with 0.2 M sodium hydroxide solution for 168 hours at room temperature, using a sample to solution ratio of 1:400, and preferably shaking slowly over the whole time. An aliquot of 7 ml was pipetted from the supernatant solution after 5, 24, 48, 72, 120, 144 and 168 hours, filtered and analysed for Si to determine the plateau concentration.

The filtered extracts at each step were analysed for Si with ICP-OES at 250.690, 251.611 and 288.158 nm wavelength. The mean value of the three wavelengths was taken as one value and expressed in mg kg⁻¹.

3.3 Assessment of contribution of different silicon pools for rice

3.3.1 Pot culture experiment

The pot culture experiment was conducted to know the effect of graded levels of soil on growth and yield of rice using eight different soils from different agro- climatic zones of Karnataka.

3.3.2 Experimental set up

The present study was conducted by taking 2.5 kg capacity plastic pots and filled with calculated proportions of quartz and soil on volume basis. After filling 2/3rd of the pot, soil solution sampler (rhizon) was placed horizontally at 10 cm depth of the pot and remaining 1/3rd was filled and kept undisturbed. Rhizon sampler consisted of a 5cm long porous part, with an outside diameter of 2.5 mm and pore size of 0.15 microns (Plate 3). The samplers were supplied with coextruded tubing (PE inside / PVC outside) 1 mm internal diameter with connector and protective cap (Supplier – Eijkelkamp Agriresearch equipment: www.Eijkelkamp.com). Sampler end was connected with an extension tube to draw the soil solution connected to a syringe (20 ml). After installation of rhizons, the



Plate 1: Hot water bath with horizontal shaker for extraction of organic Si pool



(a)



(b)

Plate 2: Horizontal shaker with UV-light (a) covered with lid (b) for extraction of occluded Si pool



a) Rhizon unit



b) Syringe



c) Rhizon sampler unit

Plate 3(a- c): A complete set of rhizon samplers used for soil solution sampling



Plate 4: Overview of pots installed with rhizon samplers

pots were brought to submerged condition and then two seedlings of 21 days old were transplanted to each pot and submergence was maintained throughout the experimental period by adding distilled water. Solution samples were extracted by creating vacuum through syringe and were collected in tarsons plastic vials of 20ml capacity at 0, 7, 15, 30, 45, 60 days after transplanting and analysed for dissolved Si content.

Observations such as plant height, number of tillers per pot were recorded at 30 and 60 days after transplanting. The shoot biomass and root biomass were recorded at 60 days after transplanting. After the harvest of the plants, the shoot and root samples were oven dried at 65 °C for 72 hours, powdered and samples were subjected for silicon analysis by adopting standard procedures.

3.3.3 Experiment details:

No. of Agro-climatic zones	:	4
No. of soils (each zone)	:	2
No. of treatments	:	5
No. of replications	:	3
Design	:	CRD and Factorial CRD
Moisture level	:	Submergence
Test crop	:	Rice
Variety	:	IR-64
Date of transplanting	:	14 th July 2016
Date of harvest	:	12 th September 2016

3.3.4 Treatment details:

- T1 : 100 % Quartz sand
- T2 : 75 % Quartz sand + 25 % Soil
- T3 : 50 % Quartz sand + 50 % Soil
- T4 : 25 % Quartz sand + 75 % Soil
- T5 : 100 % Soil

3.3.5 Analytical methods for soil samples

3.3.5.1 Extraction and estimation of plant available silicon in soil by 0.01 M CaCl₂ extractant

Two grams of soil was taken in a 50 ml centrifuge tube and added 20 ml of 0.01 M CaCl₂. After continuous end to end shaking in a mechanical shaker for sixteen hours, 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 added 2.5 ml of 0.5 M sulfuric acid and 2.5 ml of ammonium molybdate solution (pH 7). After 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 30 minutes following addition of the reducing agent, absorbance was measured at 820 nm using UV visible spectrophotometer (Shimadzu). Simultaneously Si standards (0, 0.5, 1, 2, 3, 4, 5 and 6 mg L⁻¹) prepared in the same matrix were also measured using UV visible spectrophotometer (Haysom and Chapman, 1975).

3.3.5.2 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, 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-naphthol-4-sulfonic acid - ANSA) was added. After 5 minutes, but not later than 30 minutes following addition of the reducing agent, absorbance was



Plate 5: General view of pot culture experiment

measured at 630 nm 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.

3.4.5 Determination of silicon in plant samples

3.4.5.1 Preparation of plant samples for digestion

The collected plant samples of rice from the pot culture experiment were separated into shoot and roots. Both samples were initially washed in tap water followed by distilled water to remove any surface contaminants and were dried in the hot air oven at 65 °C for 72 hours. The dried plant samples were cut into smaller pieces and powdered in a ball mill.

3.4.5.2 Plant sample digestion

The powdered plant 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 HNO₃ (70 %), 2 ml of H₂O₂ (30 %) and 1 ml of HF (40 %) using microwave digestion system (Milestone-start D) at 150 °C with following steps: 1200 watt for 15 minutes with a ramping rate of 7 °C per minute and 1200 watt for 10 minutes at holding temperature of 150 °C and venting for 10 minutes. The digested samples were diluted to 50 ml with 4 per cent boric acid (Ma and Takahashi, 2002).

3.4.5.3 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 which 3.75 ml of 0.2 N HCl, 0.5 ml of 10 per cent ammonium molybdate ((NH₄)₆Mo₇O₂) and 0.5 ml of 20 per cent tartaric acid and 0.5 ml of reducing agent (Amino naphthol sulphonic acid - ANSA) was added and the volume was made up to 12.5 with distilled water. After one hour, the absorbance was measured at 600 nm with a UV-visible spectrophotometer (Ma and Takahashi, 2002). Similarly, standards (0, 0.2, 0.4, 0.8 and 1.2 ppm) were prepared by following the same procedure.

3.5 Determination of relationship between different silicon pools and properties of rice soils

The initial parameters of soils viz., pH, EC, OC, CEC and clay content were correlated with different pools of Si using statistical method. The Si content and uptake by plants were also correlated with the different pools of Si extracted by different extractants to assess their contribution on growth and performance of rice.

3.6 Statistical analysis

Data generated were statistically analysed using CRD and FCRD, Pearson's correlation analysis and regression analysis were also carried out as per procedure outlined by Rangaswamy, 2010.

IV EXPERIMENTAL RESULTS

The present investigation was undertaken to study the “Silicon pools in the rice soils of selected agro climatic zones of Karnataka”. In this investigation, soil samples were collected from rice ecosystems from four different agro climatic zones of Karnataka. The results of the investigation are presented in this chapter.

4.1 Quantification of silicon pools of selected rice soils

In the present investigation, the rice soils of four agro climatic zones of Karnataka were subjected for quantification of different pools of Si. Soil samples were collected from two locations in each of selected zone viz central dry zone (CDZ), southern dry zone (SDZ), southern transition zone (STZ) and coastal zone (CZ). The samples were analysed for pH, EC, cation exchange capacity, particle size analysis (sand, silt, clay) and plant available silicon (0.01 M Calcium chloride extractable Si – CCSi and 0.5 M acetic acid extractable Si - AASi) and available nutrient content. The results are presented in the Table 3 and 4.

4.1.1 Physico- chemical properties of soils

4.1.1.1 Soil pH (1: 2.5 water) and Electrical Conductivity (dS m^{-1})

The results revealed that pH of the soil samples used in this study were found to be acidic except Kamalapura soil (neutral). The pH of different soils ranged from 5.29 to 6.67. The EC (ds m^{-1}) of different soils under study varied from 0.13 to 1.28 dS m^{-1} . The maximum EC observed in Kamalapura soil (1.28 dS m^{-1}) and the lower EC was recorded in Mandharthi soil (0.13 dS m^{-1}).

4.1.1.2 Organic Carbon (g kg^{-1})

Among all the soils, the organic carbon content ranged from 1.9- 11.7 g kg^{-1} . The organic carbon content was high in Mandharthi, Kathalgere, Honnavile, Bellatha soils and medium in Kamalapura soil. The soils of V. C. Farm, Mandya and H.N. Pura recorded lower organic carbon content.

Table 3: Physico-chemical properties of selected rice soils

ACZ	Soil	pH	EC (dS m ⁻¹)	OC (g kg ⁻¹)	CEC (cmol (p ⁺) kg ⁻¹)	Sand %	Silt %	Clay %	Textural class
CDZ	AHRS, Kathalgere	6.02	0.62	10.10	37	59.62	14.19	26.19	Sandy clay loam
	Kamalapura, Davanagere	6.67	1.28	7.10	36	36.84	15.35	47.81	Clay
SDZ	V.C. Farm, Mandya	6.02	0.27	2.00	31	85.57	0.86	13.57	Loamy sand
	Bellatha, Chamarajanagara	6.15	0.31	7.70	37	54.21	12.68	33.11	Sandy clay loam
STZ	Honnavile, Shimoga	5.44	0.47	8.30	46	71.28	5.08	23.64	Sandy clay loam
	H.N. Pura, Thattekere	5.29	0.25	3.10	26	84.68	1.59	13.73	Loamy sand
CZ	Seed farm, Brahmavara	5.61	0.18	4.50	27	72.39	12.44	15.18	Sandy loam
	Mandharthi, Brahmavara	5.39	0.13	11.70	23	49.82	24.24	25.94	Sandy clay loam

*CDZ-Central dry zone SDZ-Southern dry zone STZ-Southern transition zone CZ- coastal zone

Table 4: Available nutrient status of selected rice soils

ACZ	Soils	CCSi	AASi	Avail. N	Avail. P ₂ O ₅	Avail. K ₂ O	Ca	Mg	Na	Zn	Mn	Fe	Cu
		mg kg ⁻¹			kg ha ⁻¹		cmol (p ⁺) kg ⁻¹			mg kg ⁻¹			
CDZ	AHRS, Kathalgere	21.66	58.13	211.40	38.09	151.87	5.45	2.55	0.16	1.41	11.77	14.65	5.19
	Kamalapura, Davanagere	40.74	179.19	162.40	25.14	278.88	14.85	4.55	0.39	2.39	11.00	14.32	5.01
SDZ	V.C. Farm, Mandya	17.13	32.50	215.60	329.32	66.53	2.71	0.97	0.10	5.11	3.90	17.55	1.57
	Bellatha, Chamarajanagara	36.41	82.25	197.40	23.21	77.28	7.71	4.44	0.17	1.40	11.73	16.67	5.41
STZ	Honnavile, Shimoga	17.70	40.00	183.40	38.73	109.54	4.00	0.93	0.12	1.01	11.69	16.84	2.88
	H.N. Pura, Thattekere	12.86	30.38	154.00	33.60	35.62	2.53	0.70	0.10	0.86	6.98	16.53	3.29
CZ	Seed farm, Brahmavara	8.99	28.38	183.40	383.95	67.20	2.06	0.14	0.08	1.29	1.55	16.17	2.09
	Mandharthi, Brahmavara	15.48	48.44	588.00	169.66	92.74	2.10	0.20	0.10	1.09	2.85	14.11	1.83

*CDZ-Central dry zone SDZ-Southern dry zone STZ-Southern transition zone CZ- coastal zone

* CCSi- Calcium chloride extractable Si * AASi- Acetic acid extractable Si

4.1.1.3 Cation exchange capacity ($\text{cmol (p}^+) \text{ kg}^{-1}$)

The results revealed that CEC of the soil samples ranged from 23 to 46 $\text{cmol (p}^+) \text{ kg}^{-1}$. Both Kathalgere and Kamalapura soils representing CDZ recorded CEC of 37 and 36 $\text{cmol (p}^+) \text{ kg}^{-1}$, respectively. Whereas V. C. Farm, Mandya and Bellatha soils from SDZ recorded CEC of 31 and 37 $\text{cmol (p}^+) \text{ kg}^{-1}$. The Honnavile and H.N. Pura soils from STZ recorded CEC of 46 and 38 $\text{cmol (p}^+) \text{ kg}^{-1}$, respectively. Brahmavara and Mandharthi soils representing CZ recorded comparatively lower CEC of 27 and 23 $\text{cmol (p}^+) \text{ kg}^{-1}$, respectively.

4.1.1.4 Particle size analysis

Among all the soils, higher sand content was noticed in V.C. Farm, Mandya soil (85.57 %) followed by H.N. Pura soil (84.68 %). The sand content was lower in Kamalapura soil (36.84 %). Sand content of 59.62, 54.21, 71.28, 72.39 and 49.82 per cent was recorded in Kathalgere, Bellatha, Honnavile, Brahmavara and Mandharthi soils, respectively.

The silt content ranged from 0.86 to 24.24 per cent. The silt content of different soils was in the order of Mandharthi (24.24 %) > Kamalapura (15.35 %) > Kathalgere (14.19 %) > Bellatha (12.68 %) > Brahmavara (12.44 %) > Honnavile (5.08 %) > H.N. Pura (1.59 %) > V. C. Farm, Mandya (0.86 %).

The clay content was higher in Kamalapura soil (47.81 %) followed by Kathalgere (26.19 %) and Mandharthi soil (25.94 %). The lower clay content was noticed in V.C. Farm, Mandya (13.57%) and H. N. Pura soil (13.73 %). The soils of Bellatha, Honnavile and Brahmavara recorded a clay content of 33.11, 23.64 and 15.18 per cent, respectively.

Based on the particle size analysis of selected soils, the textural class was determined. The soils of Kathalgere, Bellatha, Honnavile, Mandharthi were sandy clay loam while that of V.C. Farm, Mandya and H. N. Pura as loamy sand, Brahmavara soil as sandy loam and Kamalapura as clayey soil.

4.1.1.5 Plant available silicon (PAS)

Plant available silicon (PAS) content of the soil samples was estimated by extraction with 0.01M calcium chloride (CCSi) and 0.01 M acetic acid (AASi). The concentration of CCSi in the selected soils ranged from 8.9- 40.7 mg kg⁻¹. The higher CCSi content was recorded in Kamalapura soil and lower in Brahmapura soil. Whereas, the soils of Kathalgere, V.C. Farm, Mandya, Bellatha, Honnavile, H.N. Pura and Mandharthi recorded CCSi content of 21.6, 17.1, 36.4, 17.1, 12.86 and 15.48 mg kg⁻¹, respectively.

Acetic acid extractable Si concentration in the selected soils ranged from 28.38 to 179.19 mg kg⁻¹. The higher AASi content was recorded in Kamalapura soil and lower in Brahmapura soil. Whereas, the soils of Kathalgere, V.C. Farm, Mandya, Bellatha, Honnavile, H.N. Pura and Mandharthi recorded AASi content of 58.13, 32.50, 82.25, 40.0, 30.38 and 48.44 mg kg⁻¹, respectively.

4.1.2 Fractionation of different pools of silicon in soils

Eight soil samples, from selected agro climatic zones of Karnataka were subjected to fractionation of soil silicon by employing a standard sequential extraction procedure. The results are presented in the Table 5.

Mobile Si

The mobile Si content of different soils ranged from 14.5 to 44.6 mg kg⁻¹. Kamalapura soil recorded higher content of mobile Si (44.6 mg kg⁻¹) but, was on par with Bellatha soil (42.4 mg kg⁻¹). The lower content of mobile Si was recorded in Brahmapura soil (14.5 mg kg⁻¹). The content of mobile Si in soils of Kathalgere, V.C. Farm, Mandya, Honnavile and Mandharthi soils was 26.7, 25.3, 27.8 and 27.1 mg kg⁻¹, respectively and was found to be on par with each other.

Adsorbed Si

The adsorbed Si fraction in the soils under study ranged from 4.9 to 89.4 mg kg⁻¹. Significantly higher adsorbed Si pool was observed in Bellatha soil (89.4 mg kg⁻¹),

Table 5: Different pools of Si in selected rice soils

ACZ	Soil	Pools of Silicon				
		Mobile Si	Adsorbed Si	Organic Si	Occluded Si	Amorphous Si
		(mg kg ⁻¹)				
CDZ	AHRS, Kathalgere	26.7	61.7	425.2	1121.4	8798.5
	Kamalapura, Davanagere	44.6	28.4	619.2	1405.8	11927.2
SDZ	V.C. Farm, Mandya	25.3	23.6	313.6	381.5	5075.9
	Bellatha, Chamarajanagara	42.4	89.4	477.8	1740.4	16667.9
STZ	Honnavile, Shimoga	27.8	26.6	393.8	832.7	7482.2
	H.N. Pura, Thattekere	37.4	10.7	310.6	460.0	3342.4
CZ	Seed farm, Brahmavara	14.5	4.9	233.7	476.3	8019.8
	Mandharthi, Brahmavara	27.1	10.1	267.4	1405.5	20200.2
	SEm ±	0.8	1.7	7.2	134.6	569.7
	CD at 5 %	2.6	5.6	23.5	438.9	1857.9

*CDZ-Central dry zone SDZ-Southern dry zone STZ-Southern transition zone CZ- coastal zone

followed by Kathalgere soil (61.7 mg kg^{-1}) while the lower content was recorded in Brahmavara soil (4.9 mg kg^{-1}). The content of adsorbed Si pool in H. N. Pura soil (10.7 mg kg^{-1}) was on par with Mandharthi soil (10.1 mg kg^{-1}). While all other soils showed significant difference with respect to adsorbed Si pool.

Organic Si

A significantly higher organic Si pool was recorded in Kamalapura soil (619.2 mg kg^{-1}) compared to other soils. Whereas, Brahmavara soil recorded lower organic Si content of 233.7 mg kg^{-1} . A significant difference was also observed among different soils for organic Si pool.

Occluded Si

The occluded Si pool was in the range of 381.5 mg kg^{-1} (V.C. Farm, Mandya soil) to $1740.4 \text{ mg kg}^{-1}$ (Bellatha soil). Kamalapura ($1405.8 \text{ mg kg}^{-1}$) and Mandharthi ($1405.5 \text{ mg kg}^{-1}$) soils also showed higher content of occluded Si pool followed by Kathalgere, Honnavile, Brahmavara and H.N. Pura soils. The occluded Si content in V. C. Farm, Mandya and H.N. Pura soils was on par with each other. While, the rest of soils showed significant difference with respect to occluded Si content.

Amorphous Si

The amorphous Si pool was significantly higher in Mandharthi soil ($20200.2 \text{ mg kg}^{-1}$) and least in H.N. Pura soil ($3342.4 \text{ mg kg}^{-1}$). There was a significant difference in amorphous Si pool among the different soils under investigation.

4.1.3 Pearson's correlation between different pools of Si in the selected rice soils

The correlation between different pools of Si given in Table 6. The mobile Si had a positive correlation with adsorbed Si (0.458), occluded Si (0.582) and amorphous Si (0.234). The mobile Si pool was significantly positively correlated with organic Si pool (0.777*). The adsorbed Si pool was positively correlated with organic Si (0.560), occluded Si (0.641) and amorphous Si (0.313) pools. The organic Si pool showed significant positive relationship with occluded (0.617) and amorphous Si pools (0.187).

Table 6: Pearson's correlation for different pools of silicon in selected rice soils

Si pools	Mobile Si	Adsorbed Si	Organic Si	Occluded Si	Amorphous Si
Mobile Si	1				
Adsorbed Si	0.458	1			
Organic Si	0.777*	0.56	1		
Occluded Si	0.582	0.641	0.617	1	
Amorphous Si	0.234	0.313	0.187	0.857**	1

** Correlation is significant at the 0.01 level * Correlation is significant at the 0.05 level

A significant positive correlation was noticed between occluded and amorphous Si pools (0.857**). In general, there existed a positive relationship between all the different pools under study.

4.2 Assessment of contribution of different Si pools for rice

4.2.1 Dissolved Si (DSi) in the soil solution at different intervals of experimental period

The soil solution samples were collected at different intervals of experimental period using rhizons to know the dissolution pattern of native Si in different soils over time. The data is presented in Table 7.

Dissolved silicon (DSi) content of soil solution significantly varied between the different soils. The DSi content of different soils between intervals of 0 and 60 DAT ranged as follows. 6.34-3.75 mg L⁻¹ in Kathalgere, 8.86- 6.35 mg L⁻¹ in Kamalapura, 11.53- 3.10 mg L⁻¹ in V.C. Farm, Mandya, 9.92- 6.22 mg L⁻¹ in Bellatha, 8.44- 2.56 mg L⁻¹ in Honnavile, 11.06- 4.47 mg L⁻¹ in H.N. Pura, 6.04- 2.93 mg L⁻¹ in Brahmavara and 8.35- 4.64 mg L⁻¹ in Mandharthi soils.

At the initial interval (0 DAT), the highest DSi content was recorded in soils of V.C. Farm, Mandya (11.53 mg L⁻¹) followed by H. N. Pura (11.06 mg L⁻¹). While lowest DSi content was recorded in Brahmavara soil (6.04 mg L⁻¹). Irrespective of the soil, the DSi was found to be higher during initial period of crop growth and decreased significantly after 15 DAT in most of the soils. DSi content of all the soils at 30, 45 and 60 DAT were found to have no greater difference but DSi was significantly decreased at 60 DAT compared to 0 DAT.

In the present investigation, the concentration of dissolved silica in the soil solutions of submerged soils increased slightly after flooding and then decreased gradually and reached lower concentrations at the end of cropping period.

Table 7: Dissolved Si content (mg L⁻¹) in soil solution at different intervals of experimental period

ACZ	Soil	Days after transplanting					
		0	7	15	30	45	60
CDZ	AHRS, Kathalgere	6.34	8.47	4.82	3.94	3.20	3.75
	Kamalapura, Davanagere	8.86	8.47	8.43	6.77	6.05	6.35
SDZ	V.C. Farm, Mandya	11.53	13.65	9.64	5.66	2.90	3.10
	Bellatha, Chamarajanagara	9.92	10.50	4.88	7.13	6.06	6.22
STZ	Honnavile, Shimoga	8.44	3.66	3.23	3.28	2.85	2.56
	H.N. Pura, Thattekere	11.06	10.88	9.06	6.77	5.32	4.47
CZ	Seed farm, Brahmavara	6.04	5.65	2.56	2.62	1.40	2.93
	Mandharthi, Brahmavara	8.35	7.50	6.07	4.61	2.95	4.64
	SEm ±	0.41	2.55	1.41	0.57	0.45	0.55
	CD at 5 %	1.34	3.33	4.59	1.87	1.47	1.80

*CDZ-Central dry zone SDZ-Southern dry zone STZ-Southern transition zone CZ- coastal zone

4.2.2 Effect of application of graded proportions of soils of selected rice soils on growth, Si content and its uptake by rice

The data presented in Table 8 and 9 revealed the effect of different proportions of soils of selected agro climatic zones of Karnataka on growth, Si content and uptake by rice.

Plant height (cm)

The plant height in different zones under different treatments varied from 40.40 to 83.37 cm. Among the different treatments significantly lower plant height was recorded in control (40.40 cm). With respect to different proportions of soil viz. 25, 50, 75 and 100 per cent soil, plant height ranged from 71.25 to 81.75 cm, 66.92 to 83.37 cm, 68.35 to 79.07 cm and 64.77 to 73.53 cm in CDZ, SDZ, STZ and CZ, respectively. Irrespective of the zone, the treatment with 100 per cent soil recorded significantly higher plant height over control but was on par with 75 and 50 per cent soil treatments.

Shoot biomass (g pot⁻¹)

In the present study, shoot biomass ranged from 0.28 to 1.92 g pot⁻¹ in different zones. Among the five treatments, significantly lower shoot biomass was observed in control (100 % quartz) 0.28 g pot⁻¹. Shoot biomass under treatments with varied proportion of soil ranged from 1.21 to 1.92 g pot⁻¹ in CDZ, 0.96 to 1.72 g pot⁻¹ in SDZ, 1.27 to 1.88 g pot⁻¹ in STZ and 0.95 to 1.5 g pot⁻¹ in CZ. Irrespective of the zones, higher shoot biomass was recorded in 100 per cent soil treatment which showed on par results with 75 per cent soil treatment. Whereas, significant difference was noticed for the shoot biomass recorded under 25 and 50 per cent soil treatments in all the zones.

Root length (cm)

Irrespective of zones, root length of rice was in the range of 17.20 to 29.73 cm. The root length under treatments with different proportion of soil in CDZ, SDZ, STZ and CZ varied from 17.20 to 29.22 cm, 17.20 to 29.73 cm, 17.20 to 27.27 cm and 17.20 to 25.22 cm respectively. Among the treatments, 75 per cent soil treatment recorded significantly higher root length under CDZ, SDZ and CZ. Whereas in STZ, higher root

Table 8: Effect of application of graded proportions of selected rice soils on growth parameters of rice

Treatments	Growth Parameters															
	Plant height (cm)				Shoot biomass (g pot ⁻¹)				Root length (cm)				Root biomass (g pot ⁻¹)			
	CDZ	SDZ	STZ	CZ	CDZ	SDZ	STZ	CZ	CDZ	SDZ	STZ	CZ	CDZ	SDZ	STZ	CZ
100 % Q	40.40	40.40	40.40	40.40	0.28	0.28	0.28	0.28	17.20	17.20	17.20	17.20	0.05	0.05	0.05	0.05
75 % Q+25 % S	71.25	66.92	68.35	64.77	1.21	0.96	1.27	0.95	22.95	22.90	26.37	22.50	0.27	0.21	0.32	0.25
50 % Q+ 50 % S	78.27	74.23	76.40	71.25	1.53	1.26	1.66	1.20	27.07	23.07	27.27	24.22	0.34	0.24	0.37	0.33
25 % Q+ 75 % S	80.20	80.27	78.68	72.00	1.71	1.56	1.71	1.34	29.22	29.73	24.97	25.22	0.35	0.34	0.35	0.39
100 % S	81.75	83.37	76.07	73.53	1.52	1.72	1.88	1.50	20.77	17.03	22.47	19.88	0.13	0.12	0.18	0.20
SEm±	1.80	1.42	1.36	1.06	0.10	0.11	0.11	0.14	0.64	0.90	0.80	1.08	0.03	0.02	0.03	0.01
CD at 5 %	5.39	4.27	4.09	3.17	0.30	0.32	0.34	0.36	1.92	2.71	2.41	3.24	0.08	0.07	0.05	0.03

*Q- Quartz sand *S- Soil

Table 9: Effect of application of graded proportions of selected rice soils on Si content and its uptake by rice

Treatments	Si content (%)								Si uptake (mg pot ⁻¹)							
	Shoot				Root				Shoot				Root			
	CDZ	SDZ	STZ	CZ	CDZ	SDZ	STZ	CZ	CDZ	SDZ	STZ	CZ	CDZ	SDZ	STZ	CZ
100 % Q	4.24	4.24	4.24	4.24	1.22	1.22	1.22	1.22	11.79	11.79	11.79	11.79	0.19	0.19	0.19	0.19
75 % Q+25 % S	4.97	5.58	4.51	3.95	1.70	1.70	1.87	1.73	59.10	53.83	55.91	37.52	4.52	3.63	6.12	4.31
50 % Q+ 50 % S	5.53	5.69	5.16	4.68	2.41	2.38	2.76	2.03	83.97	71.79	82.95	53.49	8.20	5.85	10.45	6.93
25 % Q+ 75 % S	5.82	6.02	5.38	4.65	3.17	2.72	2.85	2.21	90.85	93.50	90.63	58.14	11.11	9.27	9.99	9.13
100 % S	5.98	6.44	5.87	4.28	1.82	1.83	1.95	1.71	99.72	109.07	110.14	54.86	2.32	2.15	3.43	3.92
SEm±	0.15	0.13	0.04	0.19	0.06	0.05	0.05	0.06	5.77	6.12	4.56	3.88	0.69	0.56	0.66	0.34
CD at 5 %	0.44	0.43	0.13	0.57	0.17	0.19	0.16	0.17	17.28	18.34	13.38	11.64	2.08	1.66	1.99	1.02

*Q- Quartz sand *S- Soil

length was recorded in treatment with 50 per cent soil but, statistically on par with 25 and 75 per cent soil treatments.

Root biomass (g pot⁻¹)

Root biomass in different treatments among all the zones varied from 0.05 to 0.39 g pot⁻¹. The lowest root biomass of 0.05 g pot⁻¹ was recorded in control (100 % quartz). Root biomass under different zones for different proportion of soils viz. 25, 50, 75 and 100 per cent soil varied from 0.13 to 0.35 g pot⁻¹ in CDZ, 0.12 to 0.34 g pot⁻¹ in SDZ, 0.18 to 0.37 g pot⁻¹ STZ and 0.20 to 0.39 g pot⁻¹ in CZ. The higher root biomass was recorded in 75 per cent soil treatment irrespective of all zones. The 50 per cent soil treatment showed on par results with 75 per cent soil treatment for root biomass under CDZ and STZ.

Si content in shoot (%)

The Si content in shoot in all zones ranged from 4.24 to 6.44 per cent under different treatments. The 100 per cent quartz treatment (control) recorded significantly lower Si content in shoot among the different treatments in all the zones. Whereas, Si content in 25, 50, 75 and 100 % soil treatments varied from 4.97 to 5.98, 5.58 to 6.44, 4.51 to 5.87 and 3.95 to 5.28 per cent in CDZ, SDZ, STZ and CZ, respectively. Irrespective of the zones, significantly higher Si content of shoot was recorded in 100 per cent soil treatment over control. In CDZ and SDZ, 50 per cent soil treatment showed on par results with 100 per cent soil treatment.

Si uptake by shoot (mg pot⁻¹)

The Si uptake in different treatments under the four zones varied from 11.79 to 110.14 mg pot⁻¹. Among the different treatments significantly lower Si uptake was recorded in control (11.79 mg pot⁻¹) irrespective of the zone. With respect to different proportions of soil viz. 25, 50, 75 and 100 per cent soil, Si uptake ranged from 59.10 to 99.72 mg pot⁻¹ in CDZ, 53.83 to 109.07 mg pot⁻¹ in SDZ, 55.91 to 110.14 mg pot⁻¹ in STZ and 37.52 to 64.86 mg pot⁻¹ in CZ. In all the zones, the treatment with 100 per cent

soil recorded significantly higher Si uptake over control. Whereas, 75 per cent soil treatment showed on par results with 100 per cent soil treatment in CDZ and SDZ.

Si content in root (%)

The Si content in root in different zones ranged from 1.22 to 3.17 per cent under different treatments. Irrespective of the zones, 100 per cent quartz treatment (control) recorded significantly lower Si content of 1.22 per cent in root among the different treatments. Whereas, Si content in 25, 50, 75 and 100 per cent soil treatments varied from 1.70 to 3.17 per cent, 1.70 to 2.72 per cent, 1.87 to 2.85 per cent and 1.71 to 2.21 per cent in CDZ, SDZ, STZ and CZ, respectively. Irrespective of the zone, significantly higher Si content of shoot was recorded in 75 per cent soil treatment over control. In CDZ and SDZ, 50 per cent soil treatment showed on par results with 100 per cent soil treatment. Si content in 100 per cent soil treatment was significantly lower than 25 per cent soil treatment.

Si uptake by root (mg pot⁻¹)

The Si uptake in different treatments under four zones varied from 0.19 to 11.11 mg pot⁻¹. Among the different treatments, significantly lower Si uptake was recorded in control (0.19 mg pot⁻¹) in all the zones. With respect to different proportions of soil viz. 25, 50, 75 and 100 per cent soil, Si uptake ranged from 2.32 to 11.11 mg pot⁻¹, 2.15 to 9.27 mg pot⁻¹, 3.43 to 10.45 mg pot⁻¹ and 3.92 to 6.93 mg pot⁻¹ in CDZ, SDZ, STZ and CZ respectively. Irrespective of the zone, the treatment with 75 per cent soil recorded significantly higher Si uptake over control. Whereas, in STZ Si uptake was recorded higher in 50 per cent soil treatment and was on par with 75 per cent soil treatment.

The data presented in the Table 10 revealed the effect of different soils on growth, Si content and uptake by rice.

Plant height

The plant height of rice in different soils ranged from 85.57 to 64.63 cm. The higher plant height was recorded in Kathalgere soil (85.57 cm). However, the soils of V.

C. Farm, Mandya, Bellatha, Honnavile and Brahnavara showed on par results with Kathalgere soil. The lower plant height was recorded in Mandharthi soil (64.63 cm) which was on par with H.N. Pura soil (67.33 cm).

Shoot biomass (g pot⁻¹)

Among the different soils, Honnavile soil recorded higher shoot biomass of 2.29 g pot⁻¹ which was on par with Brahnavara (2.03 g pot⁻¹) and V.C. Farm Mandya soils (1.93 g pot⁻¹). While, the shoot biomass in rest of the soils was non-significant. The least shoot biomass was observed in Mandharthi soil (0.97 g pot⁻¹).

Root length (cm)

Significant difference was observed with respect to root length among different soils. The root length in different soils ranged from 25.40 to 15.13 cm. The higher root length of 25.40 cm was noticed in Honnavile soil and it was statistically on par with the root length observed in Brahnavara soil (24.63 cm). Wherein, Mandharthi soil recorded the lower root length of 15.13 cm.

Root biomass (g pot⁻¹)

Significantly higher root biomass was recorded in Brahnavara soil (0.31 g pot⁻¹) followed by Honnavile soil (0.24 g pot⁻¹) and least was recorded in Mandharthi soil (0.09 g pot⁻¹). There was no significant difference observed between the rest of soils for root biomass.

Silicon content in shoot (%)

Among the different soils, the maximum Si content in shoot was recorded in Bellatha soil (6.98 %) followed by Kathalgere soil (6.43 %). Whereas the lower value for Si content in shoot was observed in Brahnavara soil (2.69 %). The other soils were statistically on par with each other with respect to Si content in shoot.

Table 10: Effect of selected rice soils on growth parameters, silicon content and its uptake by rice

ACZ	Soils	Growth parameters				Si content		Si uptake	
		Plant height	Shoot biomass	Root length	Root biomass	Shoot	Root	Shoot	Root
		(cm)	(g pot ⁻¹)	(cm)	(g pot ⁻¹)	(%)		(mg pot ⁻¹)	
CDZ	AHRS, Kathalgere	85.57	1.61	20.30	0.11	6.43	1.83	103.75	1.96
	Kamalapura, Davanagere	77.93	1.43	21.23	0.15	5.52	1.81	77.96	2.68
SDZ	V.C. Farm, Mandya	83.13	1.93	16.13	0.14	5.90	1.65	112.34	2.34
	Bellatha, Chamarajanagara	83.60	1.51	17.93	0.10	6.98	2.01	105.80	1.95
STZ	Honnavile, Shimoga	84.80	2.29	25.40	0.24	5.79	1.80	132.64	4.30
	H.N. Pura, Thattekere	67.33	1.47	19.53	0.12	5.95	2.11	87.64	2.57
CZ	Seed farm, Brahmavara	82.43	2.03	24.63	0.31	2.69	2.12	52.78	6.67
	Mandharthi, Brahmavara	64.63	0.97	15.13	0.09	5.86	1.29	56.94	1.16
	SEm ±	3.13	0.19	1.56	0.03	0.42	0.12	7.75	0.70
	CD at 5 %	9.23	0.55	4.60	0.09	1.25	0.36	22.85	2.07

*CDZ-Central dry zone SDZ-Southern dry zone STZ-Southern transition zone CZ- coastal zone

Silicon content in root (%)

The Si content in root under different soils ranged from 1.29 to 2.12 percent. The Si content in root was higher in Brahmavara soil (2.12 %) and it was on par with the Honnavile soil (2.11 %). Significantly lower Si content of root was noticed in Mandharthi soil (1.29 %). The rest of soils showed on par content of Si in root.

Silicon uptake by shoot (mg pot^{-1})

The maximum uptake of Si by shoot was noticed in Honnavile soil ($132.64 \text{ mg pot}^{-1}$) followed by V. C. Farm, Mandya soil ($112.34 \text{ mg pot}^{-1}$). The lower values were recorded in Brahmavara ($52.78 \text{ mg pot}^{-1}$) and Mandharthi ($56.94 \text{ mg pot}^{-1}$) soils. There was a significant difference among different soils for Si uptake by shoot.

Silicon uptake by root (mg pot^{-1})

Among the different soils, Brahmavara soil recorded significantly higher Si uptake by root (6.67 mg pot^{-1}) followed by Honnavile soil (4.30 mg pot^{-1}). The Si uptake by root was very low in Mandharthi soil (1.16 mg pot^{-1}). However, the rest of soils had no significant difference with respect to Si uptake by root.

4.2.3 Relationship between different silicon pools and growth parameters, Si content and its uptake by rice

4.2.3.1 Pearson's correlation between different silicon pools and growth parameters, Si content and its uptake by rice

The various pools of Si viz. mobile Si, adsorbed Si, organic Si, occluded Si and amorphous Si pools of different soils were correlated with growth parameters, Si content and uptake by rice using Pearson's correlation and presented in Table 11.

The mobile Si pool was positively correlated with Si content in shoot ($r = 0.651$) and root ($r = 0.106$), also with Si uptake by shoot of rice ($r = 0.219$). The mobile Si pool was negatively correlated with plant height, root length, shoot and root biomass and Si uptake by roots.

Table 11: Pearson's correlation between different silicon pools with growth parameters, Si content and its uptake by rice

Pools of silicon	Growth parameters				Si content		Si uptake	
	Plant height	Shoot biomass	Root length	Root biomass	Shoot	Root	Shoot	Root
Mobile Si	-0.189	-0.442	-0.246	-0.597	0.651	0.219	0.106	-0.559
Adsorbed Si	0.518	-0.066	-0.159	-0.451	0.639	0.481	0.184	-0.396
Organic Si	0.306	-0.122	0.104	-0.295	0.450	0.314	0.096	-0.300
Occluded Si	-0.038	-0.570	-0.273	-0.519	0.504	-0.049	-0.284	-0.520
Amorphous Si	-0.264	-0.600	-0.447	-0.386	0.245	-0.319	-0.523	-0.405

The adsorbed fraction of Si showed a positive correlation with plant height ($r = 0.518$), Si content in shoot ($r = 0.639$) and root ($r = 0.184$), also with Si uptake by shoot of rice ($r = 0.481$). Root length, shoot and root biomass, Si uptake by roots were negatively correlated with adsorbed Si pool.

The correlation of organic Si pool with growth parameters, Si content and uptake by rice was similar to the correlation exhibited by adsorbed pool of Si.

The occluded ($r = 0.504$) and amorphous pools ($r = 0.245$) of Si were positively correlated only with Si content in the shoots of rice. These pools showed negative correlation with plant height, root length, shoot and root biomass, Si uptake by shoot and root of rice.

However, all the pools of Si under the study showed a non-significant correlation with growth parameters, Si content and uptake by rice.

4.2.3.2 Regression analysis between different silicon pools in soil and Si content and its uptake by rice

In the present investigation, the functional relationship between different pools of Si in soils and Si content and uptake by rice was determined for the selected eight soils using regression analysis (Fig. 6a).

All the pools of Si were positively related with Si content and uptake by rice. The regression coefficients between different pools of Si and Si content of rice were in the order of mobile Si ($R^2 = 0.4224$) > adsorbed Si ($R^2 = 0.4081$) > occluded Si ($R^2 = 0.2539$) > organic Si ($R^2 = 0.2022$) > amorphous Si ($R^2 = 0.4224$). The regression coefficients between different pools of Si and Si uptake rice were in the order of adsorbed Si ($R^2 = 0.2315$) > amorphous Si ($R^2 = 0.1015$) > organic Si ($R^2 = 0.0988$) > mobile Si ($R^2 = 0.0478$) > occluded Si ($R^2 = 0.0024$). However, there was poor association for Si content and uptake by rice with different pools of Si.

Hence, one each from low, medium and high contents of PAS (as estimated by CaCl_2 and acetic acid extractants) out of eight different soils in the study such as

Brahmavara (CZ), Bellatha (SDZ) and Kamalapura (CDZ) soils, respectively were selected and subjected for regression analysis to determine the functional relationship between different pools of Si in soils and Si content and uptake by rice (Fig. 6 b)

For the selected three soils, the functional relationship of different pools of Si with Si content of rice was in the order occluded Si > amorphous Si > mobile Si > adsorbed Si > organic Si. Among the different pools of Si, greater association with Si content in rice was recorded by occluded pool of Si ($R^2 = 0.9931$) followed by amorphous Si pool ($R^2 = 0.9445$). The mobile and adsorbed Si pools recorded a regression coefficient of 0.8437 and 0.8234, respectively. The organic pool of Si recorded the least association ($R^2 = 0.5729$) with Si content in rice.

Among the different pools of Si in the study, amorphous Si pool ($R^2 = 0.9993$) recorded the greatest regression coefficient with Si uptake by rice, followed by adsorbed Si ($R^2 = 0.9513$) and occluded Si ($R^2 = 0.9159$). The mobile Si pool showed a functional relationship of $R^2 = 0.6645$, while the least was noticed with organic Si pool ($R^2 = 0.3636$).

4.2.4 Different pools of silicon in post-harvest soil samples

After the harvest of the crop, the soils of pot culture study were analysed for different pools of silicon through sequential extraction method in order to know the dynamics of different pools of Si after the cropping period. The results are presented in the Table 12.

Mobile Si

In general, the mobile Si pool in the post- harvest soil sample was higher than the mobile Si pool determined in the initial soil sample. The concentration of mobile Si pool in the post -harvest soil samples ranged from 93.5 to 204.1 mg kg⁻¹. The Kamalapura soil (204.1 mg kg⁻¹) recorded higher mobile Si pool which was on par with Bellatha soil (197.3 mg kg⁻¹). However, Brahmavara soil recorded lower mobile Si content of 93.5 mg kg⁻¹.

Table 12: Different pools of silicon in post -harvest soils of selected rice soils

ACZ		Soils	Pools of silicon				
			Mobile Si	Adsorbed Si	Organic Si	Occluded Si	Amorphous Si
CDZ	AHRS, Kathalgere	129.1	397.3	2942.9	617.8	6803.2	
	Kamalapura, Davanagere	204.1	1041.2	5138.6	1127.9	9592.7	
SDZ	V.C. Farm, Mandya	111.5	167.0	2260.1	305.5	4387.8	
	Bellatha, Chamarajanagara	197.3	469.9	3721.9	1009.0	12732.8	
STZ	Honnavile, Shimoga	144.1	160.0	2918.0	389.8	6142.3	
	H.N. Pura, Thattekere	108.0	105.9	2412.0	300.6	2773.7	
CZ	Seed farm, Brahmavara	93.5	89.3	1335.5	334.7	6987.7	
	Mandharthi, Brahmavara	130.5	130.9	1696.3	1151.7	19032.4	
	SEm±	15.4	27.5	143.8	70.6	21.4	
	CD at 5 %	50.3	89.7	469.0	230.4	69.6	

*CDZ-Central dry zone SDZ-Southern dry zone STZ-Southern transition zone CZ- coastal zone

Adsorbed Si

Among the post-harvest soil samples, the concentration of adsorbed Si pool ranged from 89.3 to 1041.2 mg kg⁻¹. The adsorbed Si pool was significantly higher in Kamalapura soil (1041.2 mg kg⁻¹). The lower value was recorded in Brahmavara soil (89.3 mg kg⁻¹). The soils of Bellatha and Kathalgere recorded on par content with respect to adsorbed Si pool. While in rest of the soils it was non-significant. All soils showed increased content of adsorbed Si pools than initial soil samples.

Organic Si

The organic Si pool in all the post-harvest soil samples was found to be higher than that of initial soil samples. The Kamalapura soil recorded significantly higher organic Si pool to an extent of 5138 mg kg⁻¹ over other soils. The least content of organic Si pool was observed in Brahmavara soil. Significant difference was noticed among the different soils for organic Si content in post-harvest soils.

Occluded Si

The content of occluded pool of Si in the post-harvest soil samples was less compared to initial soil samples. The occluded Si pool ranged from 300.6 to 1151.7 mg kg⁻¹. The higher content of occluded Si pool was noticed in Mandharthi soil (1151.7 mg kg⁻¹) followed by Kamalapura (1127.9 mg kg⁻¹) and Bellatha soil (1009.0 mg kg⁻¹). The lower content of occluded Si was recorded in H.N. Pura. (300.6 mg kg⁻¹). There was no significant difference between the rest of soils.

Amorphous Si

The amorphous Si pool was decreased in the post-harvest soil samples in comparison to respective initial soil samples. Mandharthi soil retained significantly higher amorphous Si (19032.4 mg kg⁻¹) followed by Bellatha soil (12732.8 mg kg⁻¹). The amorphous Si was recorded lower in H. N. Pura soil which was on par with the soils of V.C. Farm, Mandya, Honnavile and Brahmavara.

4.2.5 Pearson's correlation between different pools of silicon in initial and post-harvest rice soils

The various pools of Si quantified in the initial soil samples were correlated with the pools of Si in the post-harvest soil samples using Pearson's correlation analysis and the data is presented in the Table 13.

It was found that, the initial mobile Si pool showed a significant positive correlation with mobile ($r = 0.812^*$) and organic ($r = 0.832^*$) Si pools. Also, showed a positive correlation with adsorbed Si ($r = 0.692$), occluded Si ($r = 0.544$) and amorphous Si ($r = 0.134$) pools of post-harvest soils.

The adsorbed Si pool in initial samples had a positive correlation with mobile Si ($r = 0.613$), adsorbed Si ($r = 0.384$), organic Si ($r = 0.507$), occluded Si ($r = 0.350$) and amorphous Si pool ($r = 0.158$) of post-harvest soil samples.

The organic Si pool of initial samples recorded a highly significant positive correlation with mobile Si ($r = 0.899^{**}$), adsorbed Si ($r = 0.936^{**}$) and organic Si pools ($r = 0.991^{**}$) of post-harvest soils. It also showed positive correlation with occluded Si ($r = 0.536$) and amorphous Si ($r = 0.059$) pools of post-harvest soil samples.

A significant positive correlation was exhibited by occluded Si pool of initial soil samples with mobile Si ($r = 0.828^*$), occluded Si ($r = 0.922^{**}$), amorphous Si ($r = 0.768^*$) and positive correlation with adsorbed Si ($r = 0.594$), organic Si ($r = 0.573$) pools of post-harvest soils.

The initial amorphous Si pool had a positive correlation with mobile Si ($r = 0.384$), adsorbed Si ($r = 0.226$), organic Si ($r = 0.056$) and a significant positive correlation with occluded Si ($r = 0.864^{**}$) and amorphous Si pool ($r = 0.980^{**}$) of post-harvest soils.

Table.13 Pearson's correlation between different pools of silicon in initial and post-harvest rice soils

Pools of silicon in initial soil samples	Pools of Si in post-harvest soil samples				
	Mobile Si	Adsorbed Si	Organic Si	Occluded Si	Amorphous Si
Mobile Si	0.812*	0.692	0.832*	0.544	0.134
Adsorbed Si	0.613	0.384	0.507	0.350	0.158
Organic Si	0.899**	0.936**	0.991**	0.536	0.059
Occluded Si	0.828*	0.594	0.573	0.922**	0.768*
Amorphous Si	0.384	0.226	0.056	0.864**	0.980**

** Correlation is significant at the 0.01 level

* Correlation is significant at the 0.05 level

4.3 Determination of the relationship between different silicon pools in soil and the properties of rice soils

To determine the relationship between different pools of silicon with the soil properties like pH, EC, OC, CEC, sand, silt, clay and various available nutrient content of soil Pearson's correlation analysis was done. The results are presented in the Table 14 and 15.

4.3.1 Pearson's correlation between different silicon pools and physico-chemical properties of selected rice soils

Perusal of data presented in Table 14 revealed that there existed both significant and non-significant relationship between soil properties and different pools of Si.

Irrespective of the soils, the mobile Si pool showed a positive correlation with soil pH, EC, OC, CEC, silt and clay content. However, it was negatively correlated with sand content. The adsorbed pool of Si was positively correlated with soil pH, EC, OC, CEC, silt and clay content. But, with sand content it showed negative correlation.

A significant positive correlation was exhibited by organic Si pool with soil pH ($r = 0.816^*$), EC ($r = 0.885^{**}$) and clay content ($r = 0.889^{**}$). The organic Si pool also showed positive relationship with OC, CEC, silt content and showed negative correlation with sand content.

The occluded Si pool was positively correlated with pH, EC, CEC. A significant positive relation was noticed with OC ($r = 0.742^*$), silt content ($r = 0.713^*$) and clay content ($r = 0.817^*$). The occluded Si pool was significantly negatively correlation with sand content ($r = -0.879^{**}$).

The soil pH ($r = 0.087$), EC ($r = 0.041$), OC ($r = 0.790^*$), silt ($r = 0.928^{**}$) and clay ($r = 0.215$) contents were positively correlated with amorphous Si pool. However, there was a negative correlation exhibited by amorphous Si pool with sand content ($r = 0.776^*$).

Table. 14 Pearson's correlation between different silicon pools and physico-chemical properties of selected rice soils

Pools of silicon	Physico- chemical properties						
	pH	EC (dS m ⁻¹)	O.C (%)	CEC (cmol (p ⁺) kg ⁻¹)	Sand %	Silt %	Clay %
Mobile Si	0.489	0.543	0.076	0.250	-0.463	0.010	0.678
Adsorbed Si	0.503	0.182	0.305	0.528	-0.334	0.102	0.425
Organic Si	0.816*	0.885**	0.224	0.611	-0.659	0.128	0.889**
Occluded Si	0.454	0.354	0.742*	0.241	-0.879**	0.713*	0.817*
Amorphous Si	0.087	0.041	0.790*	0.215	-0.776*	0.928**	0.519

** Correlation is significant at the 0.01 level

* Correlation is significant at the 0.05 level

Table 15: Pearson's correlation between different silicon pools and available nutrient content in selected rice soils

Pools of silicon	Available nutrients in soils											
	CCSi	AASi	Avail. N	Avai. P ₂ O ₅	Avail. K ₂ O	Exch. Ca	Exch. Mg	Exch. Na	Zn	Mn	Fe	Cu
Mobile Si	0.701	0.809*	-0.205	-0.774	0.426	0.728*	0.771*	0.690	-0.063	0.640	-0.146	0.683
Adsorbed Si	0.279	0.652	-0.230	-0.506	0.144	0.396	0.752*	0.252	-0.038	0.709*	0.046	0.781*
Organic Si	0.897**	0.940**	-0.378	-0.677	0.816*	0.957**	0.927**	0.916**	-0.058	0.811*	-0.292	0.818*
Occluded Si	0.621	0.759*	-0.337	-0.570	0.478	0.593	0.707*	0.536	-0.301	0.511	-0.555	0.643
Amorphous Si	0.329	0.276	-0.823	-0.088	0.302	0.189	0.142	0.221	-0.259	-0.098	-0.713	0.034

** Correlation is significant at the 0.01 level

* Correlation is significant at the 0.05 level

4.3.2 Relationship between different silicon pools and available nutrient content in selected rice soils

4.3.2.1 Pearson's correlation between different silicon pools and available nutrient content in selected rice soils

The data given in Table 15 represents correlation of different pools of silicon with plant available Si (CCSi and AASi) and available nutrients in the soil.

The mobile Si pool was positively correlated with CCSi ($r = 0.701$) and acetic acid extractable Si ($r = 0.809^*$). The mobile Si was also positively correlated with available potassium ($r = 0.427$), exchangeable Ca ($r = 0.728^*$), exchangeable Mg ($r = 0.771^*$), Na ($r = 0.690$), Mn ($r = 0.640$) and Cu ($r = 0.683$). Whereas, available N ($r = -0.205$), P_2O_5 ($r = -0.774^*$), Zn ($r = -0.063$) and Fe ($r = -0.146$) contents were negatively correlated with mobile Si pool.

The adsorbed Si pool showed positive correlation with CCSi ($r = 0.279$), AASi ($r = 0.652$), available K ($r = 0.144$), exchangeable Ca ($r = 0.396$), Mg ($r = 0.752^*$), Na ($r = 0.252$), Mn ($r = 0.709^*$) and Cu ($r = 0.781^*$). The pool showed negative correlation with available N ($r = -0.230$), P_2O_5 ($r = -0.506$), Zn ($r = -0.038$) and Fe ($r = -0.046$).

The plant available Si was significantly and positively correlated with organic Si pool, CCSi ($r = 0.897^{**}$) and AASi ($r = 0.940^{**}$). Organic Si pool also exhibited significant positive correlation with available K_2O ($r = 0.817^*$), exchangeable Ca ($r = 0.957^{**}$), Mg ($r = 0.927^{**}$), Na ($r = 0.916$), Mn ($r = 0.811^*$) and Cu ($r = 0.818^*$). The pool was negatively correlated with available N ($r = -0.378$), P_2O_5 ($r = -0.677$), Zn ($r = -0.058$) and Fe ($r = -0.292$).

The occluded Si pool had a positive correlation with CCSi ($r = 0.621$), AASi ($r = 0.759^*$), available K_2O ($r = 0.478$), exchangeable Ca ($r = 0.593$), Mg ($r = 0.707^*$), Na ($r = 0.536$), Mn ($r = 0.511^*$) and Cu ($r = 0.643$). The available N ($r = -0.337$), P_2O_5 ($r = -0.570$), Zn ($r = -0.301$) and Fe ($r = -0.555$) showed negative correlation co-efficient with occluded Si.

Positive correlations for amorphous Si pool were noticed with CCSi ($r = 0.329$), AASi ($r = 0.276$), available K_2O ($r = 0.302$), exchangeable Ca ($r = 0.189$), Mg ($r = 0.142$) and Na ($r = 0.221$). whereas, a negative correlation was observed with N ($r = -0.823^*$), P_2O_5 ($r = -0.108$), Zn ($r = -0.307$), Mn ($r = -0.098$), Fe ($r = -0.292$) and Cu ($r = -0.034$).

4.3.2.2 Regression analysis between PAS and different pools of Si in selected rice soils

Functional relationship between the PAS (CCSi and AASi) content and the different pools of Si was determined for the selected eight soils using regression analysis (Fig. 7a).

All the pools of Si were positively related with CCSi and AASi content in the soil. The regression coefficients between different pools of Si and CCSi content order of organic Si ($R^2 = 0.883$) > mobile Si ($R^2 = 0.6553$) > occluded Si ($R^2 = 0.5755$) > adsorbed Si ($R^2 = 0.4246$) > amorphous Si ($R^2 = 0.0705$). The regression coefficients between different pools of Si and AASi content were in the order of organic Si ($R^2 = 0.8044$) > mobile Si ($R^2 = 0.4917$) > occluded Si ($R^2 = 0.3860$) > adsorbed Si ($R^2 = 0.0777$) > amorphous Si ($R^2 = 0.0211$).

When only three soils one each from low, medium and high contents of PAS were considered for regression analysis (Fig. 7b), the CCSi showed highest regression coefficient with mobile Si ($R^2 = 0.9963$) and least with adsorbed Si pool ($R^2 = 0.3853$). The organic, occluded and amorphous pools of Si recorded a regression coefficient of 0.9412, 0.8594 and 0.5798, respectively with CCSi content of soil. Whereas, AASi showed the highest regression coefficient with organic Si pool ($R^2 = 0.9034$) and least with adsorbed Si pool ($R^2 = 0.0118$). The mobile, occluded and amorphous pools of Si recorded a regression coefficient of 0.6607, 0.3428 and 0.0899 respectively with AASi content of soil.

V DISCUSSION

The results of the present investigation, “Studies on silicon pools in the rice soils of selected agro climatic zones of Karnataka” are discussed in this chapter under the following headings.

5.1 Quantification of silicon pools of selected rice soils

5.1.1 Physico- chemical properties of soils

5.1.1.1 pH and EC

Among the eight soils from selected agro climatic zones of Karnataka, highest soil pH and EC was recorded in Kamalapura soil sample representing central dry zone (CDZ) and lowest in Mandharthi representing coastal zone (CZ). The high pH and EC of Kamalapura soil may be attributed to dominance of basaltic - black soils which impart basic cations and other salts inturn contribute to higher soil pH and EC. Mandharthi soil of coastal zone, characterized with very high rainfall due to which most of basic cations or salts are leached from the soil and hence recorded low in soil pH and EC. Badrinath *et al.* (1995) reported that coastal and hilly zones of Karnataka were distributed with acidic soil which affects crop yields.

5.1.1.2 Organic carbon (g kg^{-1})

The higher organic carbon content was recorded in Mandharthi soil followed by soils of Kathalgere, Honnavile. The lower content of organic carbon was noticed in V.C. Farm, Mandya and H. N. Pura soils. The higher organic carbon content might be due to higher vegetation and litter fall which impart higher amounts of organic matter to the soils.

5.1.1.3 Cation exchange capacity ($\text{cmol (p}^+) \text{ kg}^{-1}$)

Among all the soils, higher CEC was recorded in soils of Honnavile, Bellatha, Kamalapura, Kathalgere and V. C. Farm, Mandya which might be attributed to the higher clay content due to dominance of black soils characterized by 2:1 clay minerals. Relatively very low CEC was noticed in soils of H.N. Pura, Seed farm-Brahmavara and

Mandharthi soils due to low clay content and leaching of basic cations due to high rainfall in the region.

5.1.1.4 Particle size analysis

The textural class of the soils under study was determined based on the particle size analysis: The soils of Kathalgere, Bellatha, Honnavile, Mandharthi were reported as sandy clay loam. Whereas the soils of V.C. Farm, Mandya and H. N. Pura as loamy sand, Brahmavara as sandy loam and Kamalapura as clay soil.

5.1.1.5 Plant available silicon (PAS)

The eight different soils of selected agro climatic zones of Karnataka, recorded low to medium in plant available Si (PAS) as extracted by both CaCl_2 and acetic acid extractants (medium range for CCSi, 20- 40 mg kg^{-1} and for AASi 40-100 mg kg^{-1}). Relatively, higher Si content was noticed in Kamalapura soil which might be attributed to higher clay content of the soil due to the dominance of black soils with 2:1 type of clay minerals. Relatively very low PAS was noticed in Brahmavara soil, which may be attributed to excessive leaching of soil colloids and silica besides basic cations due to heavy rainfall. These soils are porous and sandy in nature. Due to high rainfall, most of the Si is leached from the soil by the process called desilication and thereby recorded low PAS. Low Si soils are typically highly weathered, leached, acidic and low in base saturation (Foy, 1992).

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 (Korndorfer *et al.*, 2001).

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^- ions from solution and can

extract unrealistically large amount of Si (Haynes, 2014; Kato and Owa, 1996). Near neutral extractants such as 0.01 M CaCl₂ 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).

5.1.2. Fractionation of different silicon pools in soils

There was a significant variation in contents of different pools of Si in the soils under study (Table 5).

Mobile Si

This pool represents the readily soluble fraction of soil silicon. The higher content of mobile Si was recorded in Kamalapura soil followed by Bellatha soil and lower value recorded in Brahmavara soil. The Kamalapura and Bellatha soils containing higher content of clay content, recorded higher content of mobile Si pool. Wherein, Brahmavara soil having low clay content recorded lower mobile Si pool. This suggests that clay mineral surfaces are a major source of mobile Si. This is found to be true with findings of Georgiadis *et al.* (2013) and Vandevenne *et al.* (2015) who also reported a positive relationship between easily soluble Si and clay content. In our study, the mobile Si pool ranged from 14.45 to 44.6 mg kg⁻¹ (0.01- 0.04 mg g⁻¹) which is in accordance with the range noticed by Cornellis *et al.* (2010) and Georgiadis *et al.* (2013). Vandevenne *et al.* (2015) reported that the CaCl₂ extractable Si pool in the crop lands range between 8 and 52 mg kg⁻¹. Their findings are in accordance with the results obtained in the present investigation.

Adsorbed Si

The content of adsorbed Si pool ranged from 4.9 and 89.43 mg kg⁻¹. Higher adsorbed Si pool was recorded in Bellatha soil followed by Kathalgere and Kamalapura soils having higher clay content. Whereas, Brahmavara soil having low clay content recorded lower adsorbed Si content. Dietzel, (2002) reported that, adsorption of monosilicic acid takes place through a surface reaction between the monosilicic acid and the hydroxyl groups of the clay mineral surfaces. The high Si-adsorption capacity of soils

might be attributed to the dominance of 2:1 clay minerals (like smectite) on which the monosilicic acid may polymerize and adsorb to the mineral surfaces as polysilicic acid or precipitate (Chadwick *et al.*, 1987).

In the present investigation, the content of adsorbed Si pool was lower than the mobile Si pool. Our observation was in contrast to the hypothesis that acetic acid extracts higher Si than CaCl_2 extractant (Haynes *et al.*, 2013). In general, 0.5 M acetic acid is used at soil to solution ratio of 1:2.5 while extracting adsorbed Si from soils. Whereas in the present investigation, comparatively lower concentration of acetic acid (0.01 M) was used at a higher soil to solution ratio of 1:10 to extract adsorbed pool of Si, which might be the reason for lower content of adsorbed Si.

In the present study, adsorbed Si content of different soils varied between 0.005 and 0.08 mg g^{-1} which is very low when compared to the reports of Georgiadis *et al.* (2014) wherein, adsorbed Si was ranged from 1.2 to 39 mg g^{-1} . The mobile and adsorbed Si pools represent smallest fractions of Si among the different pools.

Organic Si

The organic Si is the fraction of Si in soil that is associated with organic matter. The organic Si pool was obtained through destruction of soil organic matter. The content of organic Si pool ranged from 233.7 to $619.18 \text{ mg kg}^{-1}$. The higher organic Si pool was observed in Kamalapura soil followed by Bellatha, Kathalgere and Honnavile soils. These soils were rich in clay content ($> 20 \%$) and organic carbon content. While Brahmavara soil characterized by comparatively high sand and low organic carbon hence evidenced a lower organic Si pool. This showed clearly the involvement of clay and organic carbon in retention of Si in the soils. Though the soil of Mandharthi recorded very high organic carbon content, the organic Si content was low. This might be due to protection of soil Si from higher content of organic matter for dissolution and at the same time prevented Si from adsorption by soils (Sadzawka and Aomine, 1977). These observations suggest that the role of soil organic matter in Si dissolution is rather complex and needs further clarification.

Amounts of Si released by H₂O₂ treatment exhibited no relationship to soil organic matter content. Georgiadis *et al.* (2014) reported, no correlation between organic Si pool and organic carbon content. This was interpreted due to partial release of Si from clay minerals and pedogenic oxidized-hydroxides in the hot concentrated H₂O₂ solution.

The organic Si pool in our study ranged from 0.2 to 0.6 mg g⁻¹ which is in accordance with results obtained by (Georgiadis *et al.*, 2014). They reported that silicon in soil organic matter ranged between 0.04 and 0.9 mg g⁻¹.

Occluded Si

The occluded Si pool was found to be higher in Bellatha soil followed by soils of Kamalapura and Mandharthi. A lower content of occluded Si was noticed in soils of V. C. Farm, Mandya, H.N. Pura and Brahmavara. The content of the pool ranged between 0.3 and 1.74 mg g⁻¹ in accordance with the findings of Georgiadis *et al.* (2014). They reported that amounts of oxalate-extractable Si (occluded Si) ranged between 0.01 and 1.7 mg g⁻¹ in fine earth. Obihara and Russell (1972) reported that 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 pedogenic oxides and hydroxides, other anions and soil pH also influence the reactions.

The occlusion of dissolved Si depends upon the chemical composition of soil solution, the mineral surface and also the nature of dissolved silica (Dietzel, 2002). Cornellis *et al.* (2010) reported that the oxalate extractable Si (occluded Si) represents 3.3 - 52.5 per cent of total alkaline extractable Si (total amorphous Si). This finding holds good in the present investigation where, the occluded Si pool corresponds to 5- 12 per cent of amorphous Si pool.

Amorphous Si

The amorphous Si pool includes both minerogenic and biogenic silica. The minerogenic silica corresponds to non-crystalline inorganic fraction, such as opal formed at supersaturated soluble Si levels, volcanic glasses, opal coatings on secondary minerals and biogenic silica comprises phytolith, diatoms and sponge spicule (Sauer *et al.*, 2006).

This fraction is assumed to play a major role in Si availability and cycling since it is more soluble than crystalline minerals (Alexandre *et al.*, 1997).

In the present investigation, the amorphous Si pool of different soils was in the range of 3 to 20 mg g⁻¹. Drees *et al.* (1989) reported that the amount of amorphous Si typically ranges from < 1 to 30 mg g⁻¹ on a total soil basis. According to Vandevenne *et al.* (2015) in crop land soils the alkaline extractable Si (amorphous Si pool) concentrations ranged from 4 to 8 mg g⁻¹.

The higher amorphous Si pool was recorded in the soil of Mandharthi followed by Bellatha and Kamalapura. The lower content of amorphous Si was observed in H. N. Pura soil followed by soil of V.C. Farm, Mandya. The variation in amorphous Si content might be attributed to the texture and organic matter content of the soils. In general, among the different soils, clay and sandy clay loam soils with higher organic matter content recorded higher amorphous Si. While, the soils of loamy sand with less organic matter content recorded lower amorphous Si content. This clearly establishes the fact that, the amorphous Si pool is well associated with clay content of the soils.

Among all the pools studied in the investigation, amorphous Si pool was found to be the largest Si pool in all the soils under study. This result is supported by the findings of Danilova *et al.* (2010) who reported that Si extracted by NaOH (amorphous Si) as the largest fraction of extractable Si in the soils of SW -Germany.

5.1.3 Pearson's correlation between different silicon pools in the selected rice soils

The correlation between different pools of Si is given in Table 6. The mobile Si had a positive correlation with adsorbed Si, occluded Si and amorphous Si pools. It was considered that Si adsorbed in soil can be released into soil solution when Si concentration in soil solution decreases. Obihara and Russell (1972) reported that the Si concentration in 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, other anions and soil pH also influence the reactions.

The readily soluble Si pool (mobile Si pool) in the soil is primarily influenced by the phytolith content (amorphous Si) and secondly, by the adsorbed Si pool. Thus, the rates of phytolith dissolution and stable phytolith translocation/preservation in each forest stand may strongly influence the readily soluble Si distribution (Vandevenne *et al.*, 2015).

In the present investigation, the mobile Si pool showed a significant positive correlation with organic Si pool. The adsorbed pool of Si also showed a positive relation with organic Si pool. But, the observations of Sadzawka and Aomine (1977) were contrast to our findings, who reported that humus associated with Si pool protected Si from dissolution and at the same time prevented Si from adsorption by soil.

A positive correlation was observed between the adsorbed and occluded pools of Si. This correlation obtained in our study is in accordance with Klotzbucher *et al.* (2015). They reported a positive correlation between the concentrations of acetate extractable Si and oxalate-extractable Si. The adsorbed pool was also in positive correlation with amorphous Si. However, correlation of adsorbed Si pool with organic, occluded and amorphous Si pools was non-significant.

The organic Si pool correlated positively with occluded and amorphous Si pools but was statistically non-significant. This relationship is supported by Georgiadis *et al.* (2014) who reported a significant positive correlation of H₂O₂-extractable Si and Si from both biogenic and minerogenic amorphous silica ($r = 0.826^{**}$ and 0.536^{**} , respectively). They revealed that, bio-opal decreased with depth in the soil profiles due to decreasing soil organic matter (SOM) and thus positively correlated with SOM. They also reported that, H₂O₂ and oxalate-extractable Si were positively correlated.

In the present investigation, a significant positive correlation was noticed between occluded and amorphous Si pools. Cornellis *et al.* (2010) reported that the oxalate extractable Si (occluded Si) represents 3.3 to 52.5 per cent of total alkaline extractable Si (total amorphous Si). This shows that the occluded and amorphous Si pools are associated with each other.

5.2 Assessment of contribution of different silicon pools for rice

5.2.1 Dissolved Si (DSi) in the soil solution during different intervals of experimental period

Dissolved silicon (DSi) content of soil solution significantly varied between the treatments at different intervals of experiment (Table.7). DSi was found to be higher during initial period of crop growth and decreased significantly.

The concentration of Si in the soil solutions of submerged soils increased slightly after submergence condition. Prasanta and Neue (2009) reported that the solubility of Si in soil significantly influenced by the increase in pH under submergence condition. Soil moisture dynamics seem to play an important role in determining the concentration of dissolved Si in soil solution (McKeague and Cline, 1963b).

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, sesquioxides, surface area, surface coatings, and overall soil solution dynamics. Organic compounds such as organic acid and amino acids may enhance the dissolution of soil Si. The particle size and surface area of applied silicon minerals also influences the dissolution rate of silicon in soils.

Irrespective of soils in the present investigation, the content of DSi in soil solution found to have only marginal differences up to 15 DAT and from 30 DAT reduced significantly recording lower concentrations at the end of cropping period (Fig. 1) which might be majorly attributed to Si uptake by the crop and adsorption on surfaces of clay colloids. Clays in the soil may adsorb excess silica, thus inhibiting the formation of silica polymorph from soluble silica (Williams and Crerar, 1985). This result depicts about the maximum utilization period of Si by the crop. The Si concentration in a soil was controlled by the dissolution of 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.

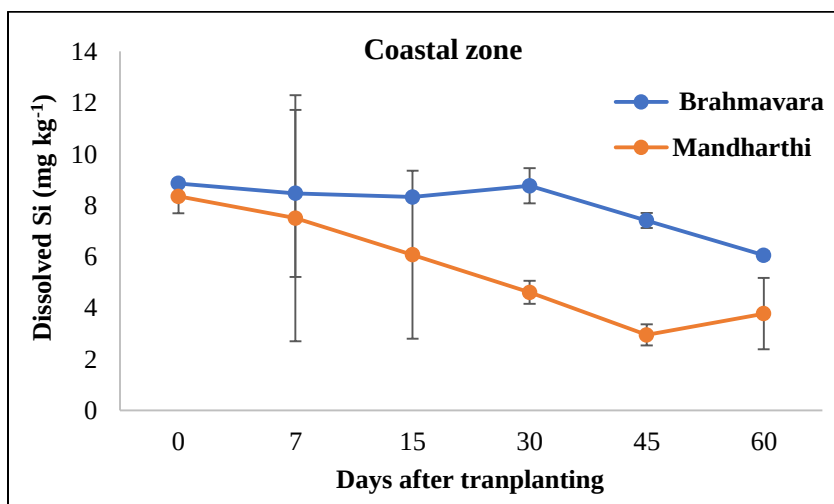
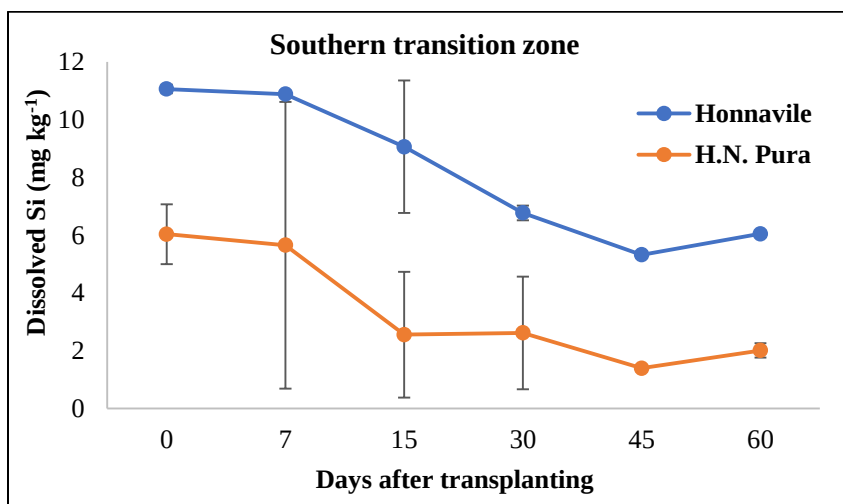
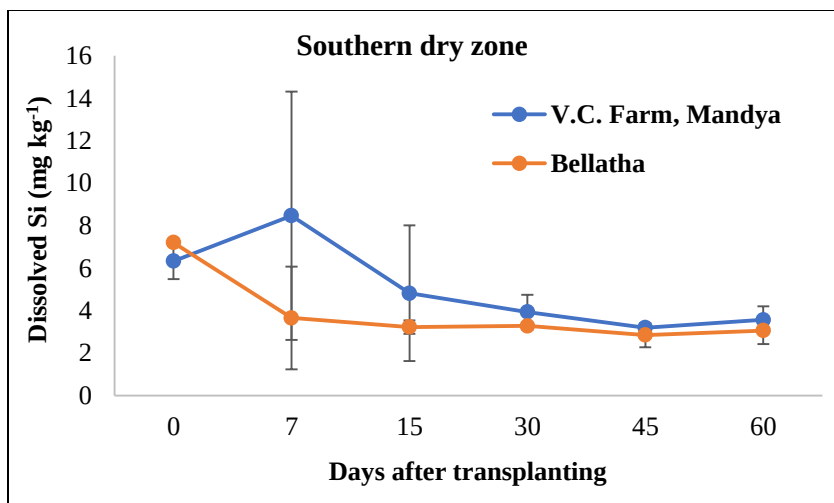
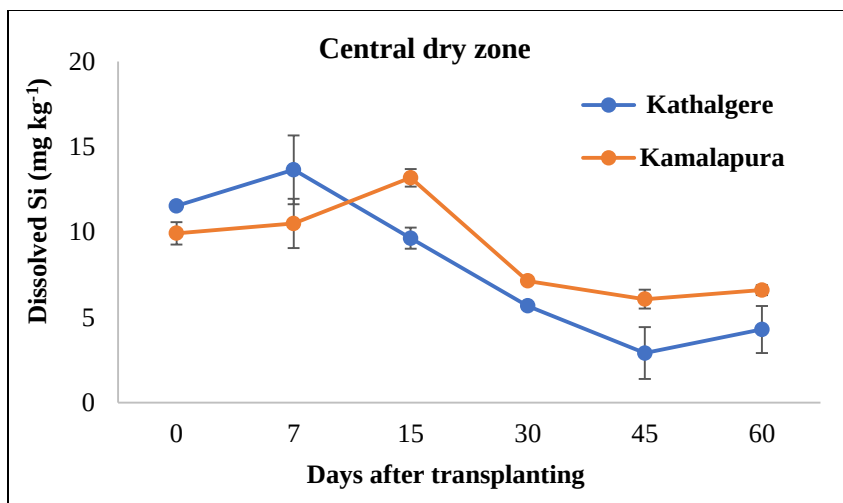


Fig. 1: Dissolved Si content in selected soils at different intervals of experimental period

In the present study, DSi content ranged from 1.4 to 13.65 mg L⁻¹ in soils at different intervals in general. A saturated solution of silica has 56 - 65 mg Si L⁻¹ as monosilicic acid (16 - 19 mg L⁻¹ as Si), although initially the concentration may be greater than this, which decreased to the equilibrium value reflecting polymerization in solution (Jones and Handreck, 1963; Bartoli, 1983). Savant *et al.* (1999) also reported that there is polymerization of plant-available Si to form a silica -gel if it exceeds a concentration of 65 mg L⁻¹ or if there is dehydration of the soil, which is reversible on dilution.

The concentration of silica in the solutions of submerged soils increased slightly after flooding and then decreased gradually and after few weeks of submergence the concentration may be lower than at the beginning of the study. The increase in concentration after flooding may be due to the release of silicon following (a) reduction of hydrous oxides of Fe (III) sorbing silica and action of CO₂ on aluminosilicates. The subsequent decrease may be the result of recombination with aluminosilicates, following decrease in partial pressure of CO₂ (Ponnamperuma, 1972).

Among the different soils under study, the highest content of DSi was recorded in V.C. Farm, Mandya soil followed by soils of H. N. Pura and Bellatha during initial period of study. These soils recorded significantly greater reduction in DSi content at the end of copping period.

In the present investigation, DSi content increased during some period and decreased at different stages of the experiment. In general, there was no definite trend in the DSi content in different soils at different intervals. This may due to phenomenon of adsorption and desorption process of Si in soil. A part of the adsorbed Si in the soil solid phase can then be desorbed and re-dissolved into soil solution (Kato *et al.*, 1996).

5.2.2 Effect of different proportions of selected rice soils on growth, Si content and its uptake by rice

The data presented in the Table 8 and 9 revealed the effect of different proportions of soils of selected agro climatic zones of Karnataka on growth, Si content and uptake by rice.

Irrespective of the soils studied under different zones, increase in proportion of soil increased the growth parameters, Si content and uptake by rice. Among different treatments with varied proportions of soil, 100 per cent soil treatment recorded higher plant height, shoot biomass, Si content and uptake by shoots of rice over control which might be due to maximum availability of Si and other nutrients for growth of rice. In general, root length and root biomass were maximum in 75 per cent soil treatment. Root length and root biomass reduced significantly in treatment with 100 per cent soil and were on par with control (100 % quartz). This might be due to compaction of soil and poor aeration that restricted penetration and development of roots. Soil compaction increases mechanical impedance, creates unfavourable growing conditions for roots and restricts oxygen, water and nutrients supply (Chen and Weil, 2010). A common response of the root system with increasing compaction is decreased root length, concentrating roots in the upper layer and reduced rooting depth (Lipiec *et al.*, 2003).

The silicon content and uptake by shoots of rice were recorded significantly higher in 100 per cent soil treatment. There existed a positive correlation between Si concentration in the soil (PAS) and Si content of plant. Korndorfer *et al.* (1999) opined that in general where Si in soil was higher (soluble Si), the plant content of this element generally greater. However, a negative correlation between the Si concentration in soil and Si uptake by plant indicated that Si concentration in soil had no effect on Si uptake by plant in the study.

In 100 per cent quartz treatment (control), significant amount of Si content in plant was noticed. This might be attributed to dissolution of quartz used in the study, which might have imparted Si. Sommer *et al.* (2006) reported that quartz has a solubility of 36 to 250 $\mu\text{mol L}^{-1}$ in water depending on particle size and temperature. Holt and King

(1955) reported that quartz grains can adsorb dissolved silicic acid from the soil solutions. The rapidly-soluble material at the surface of quartz can adsorb silicic acid. Data of several of these examiners on the dissolution of silica from soil materials like quartz are consistent with the hypothesis that coatings of adsorbed monosilicic acid exists at the surfaces of particles which actually contributes to dissolution of silica from quartz.

Although, quartz supplemented small amount of Si to rice crop and its uptake, increased proportion of quartz did not increase the Si content in rice crop. However, irrespective of the soil in the present investigation increased proportion of soil increased the content and uptake of Si by crop. This emphasize that, soil type influenced the amount of Si which in turn influenced Si content and uptake. In the present investigation, use of graded levels of soils corresponded to graded level application of Si as a growth media to the crop, which in turn reflected as graded accumulation of Si in the above ground portion of the rice plant.

Data presented in the Table 10 revealed the effect of different soils under study on growth, Si content and uptake by rice (Fig. 2-5). Among the all soils, the highest plant height was recorded in Kathalgere soil and lowest in Mandharthi soil. The different soils under investigation did not show significant difference for plant height. With respect to shoot biomass, root length and root biomass, higher values were recorded in Honnavile soil which were on par with Brahmavara soil. Mandharthi soil recorded lower shoot biomass, root length and root biomass when compared to the rest of soils. This variation in growth parameters with respect to different soils under study might be attributed to the difference in soil properties like pH, CEC, clay content, available Si and other nutrients.

In the present investigation, Si content in shoots of rice under different soils ranged from 2.69 to 6.98 per cent and was in accordance with Epstein (1999), who reported that rice can accumulate amounts of Si up to 10 per cent of its dry weight.

The Si content in root under different soils was ranged from 1.29 to 2.12 per cent. Whereas Si uptake by shoot and root of rice was ranged from 52.7 to 132.6 mg pot⁻¹ and 1.16 to 4.3 mg pot⁻¹ respectively. Sandhya (2016), reported similar observations with

respect to Si content in root, Si uptake by shoot and root of rice in acidic soils. In their study, the Si content in shoot and root of rice recorded in the range of 3 to 5 and 1.7 to 2.6 per cent, respectively. Whereas, the Si uptake by shoot and root was ranged from 47 to 131 and 3 to 12 mg pot⁻¹, respectively.

Higher plants take up Si in the form of monomeric silicic acid and accumulate it primarily as amorphous silica. Variation in Si content and uptake by rice may be attributed to native Si content, PAS, soil pH and clay content. Increasing Si accumulation by plants is mainly attributed to increased Si supply of the soil. So far, the role of factors like pH of soil solution and its influence in Si uptake by crop is almost unknown (Ma and Takahashi, 2002)

5.2.3 Relationship between different silicon pools and growth attributes, Si content and its uptake by rice

5.2.3.1 Pearson's correlation between different silicon pools in soil and growth attributes, Si content and its uptake by rice

The relationship of different pools of Si with Si content and uptake by rice is represented in Table 11. Different pools of Si showed a negative correlation with plant height, shoot biomass, root length, root biomass and Si uptake by root. The Si content in shoot had a positive correlation with all the pools. While, a higher positive correlation was observed with mobile and adsorbed pools of Si. Whereas, the Si uptake by shoot and Si content in root were positively correlated only with mobile, adsorbed and organic pools of Si and had a negative correlation with occluded and amorphous Si. In the present investigation, a positive correlation for Si uptake in shoot and Si content in root was observed with mobile, adsorbed and organic pools of Si. This reason might be attributed to the ready solubility and availability of these pools over occluded and amorphous Si pools. However, the correlation between the different pools of Si and growth, Si content and uptake by rice were non- significant.

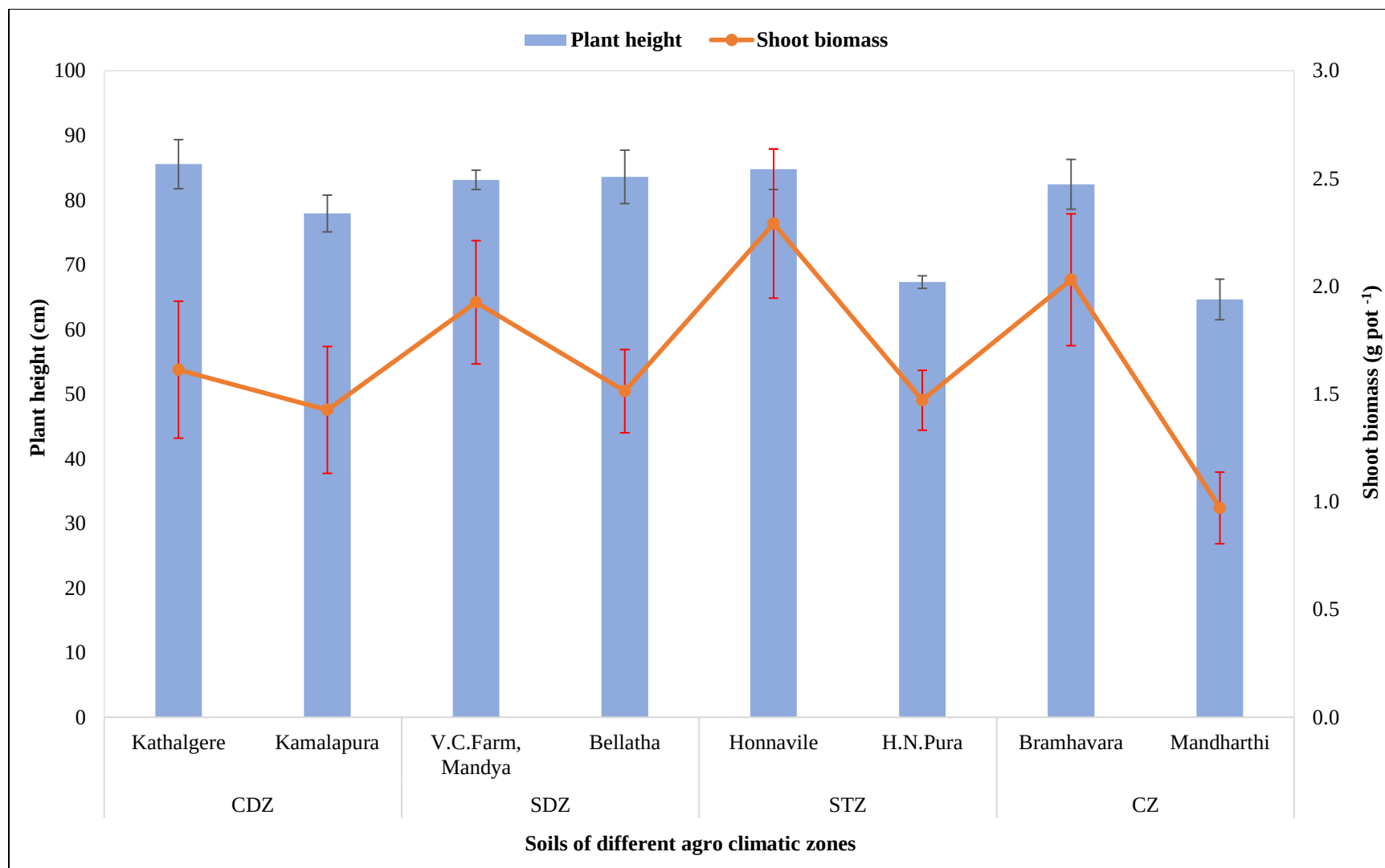


Fig. 2: Effect of selected rice soils on plant height and shoot biomass of rice

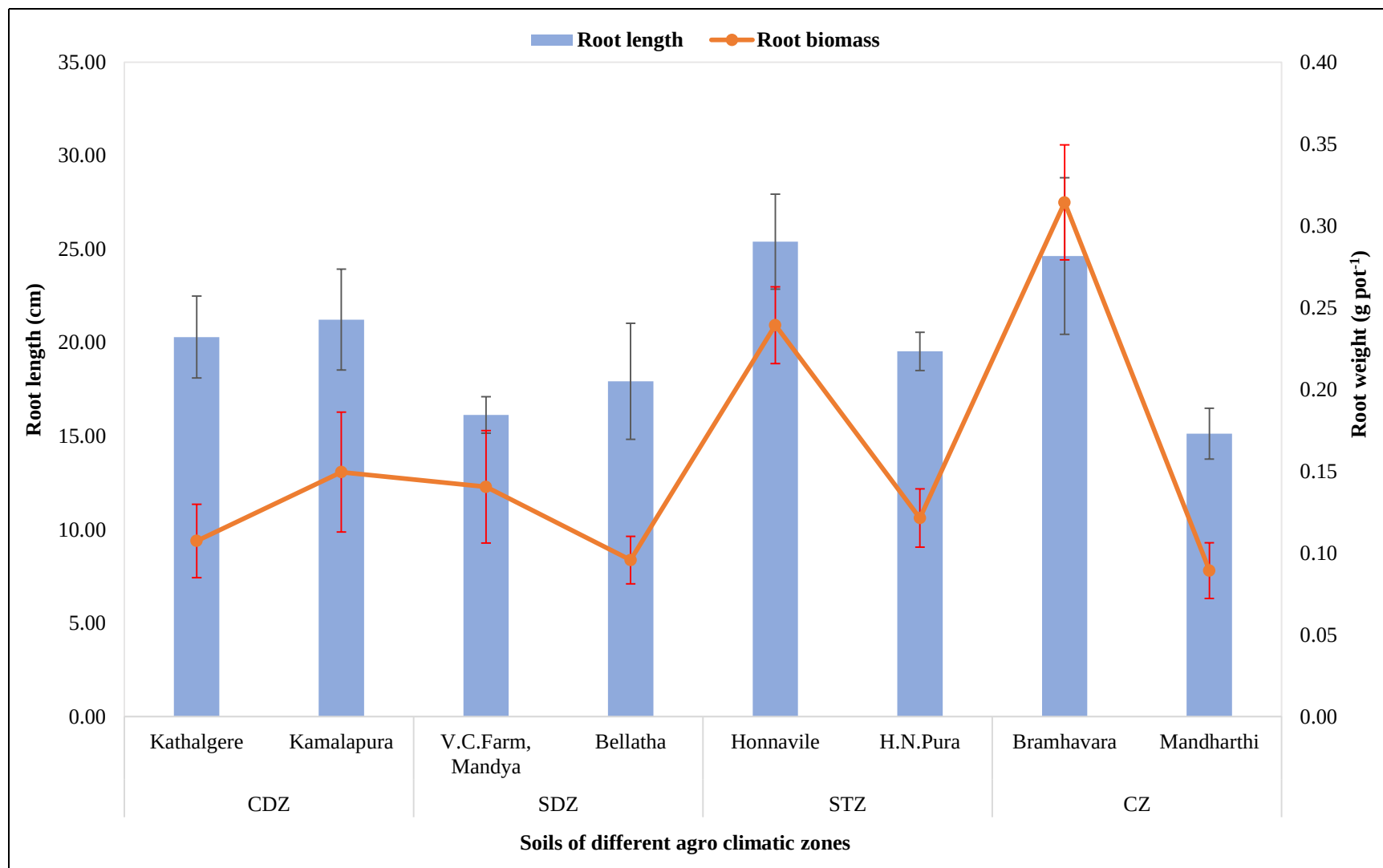


Fig. 3: Effect of selected rice soils on root length and root biomass of rice

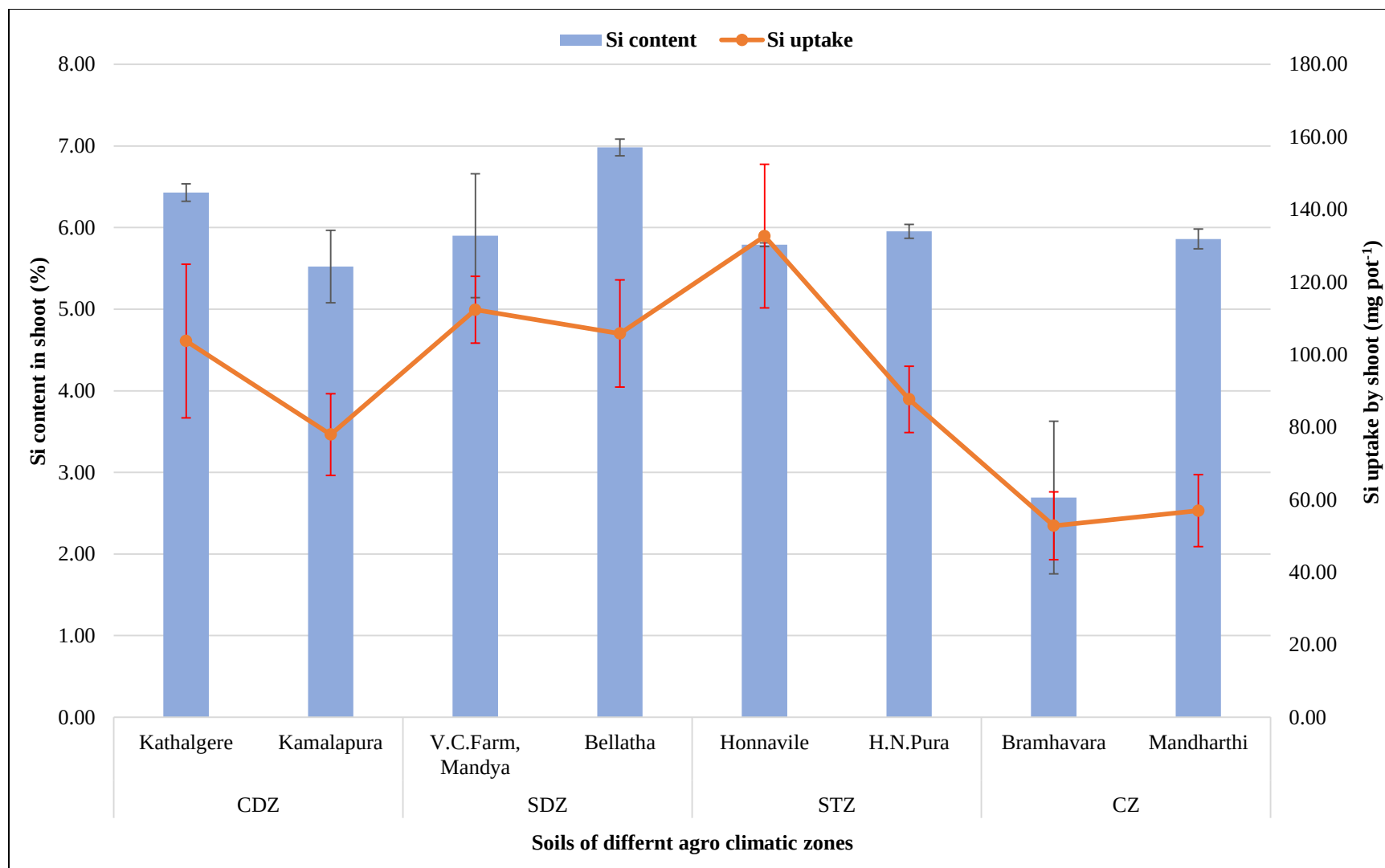


Fig. 4: Effect of selected rice soils on Si content and its uptake by shoots of rice

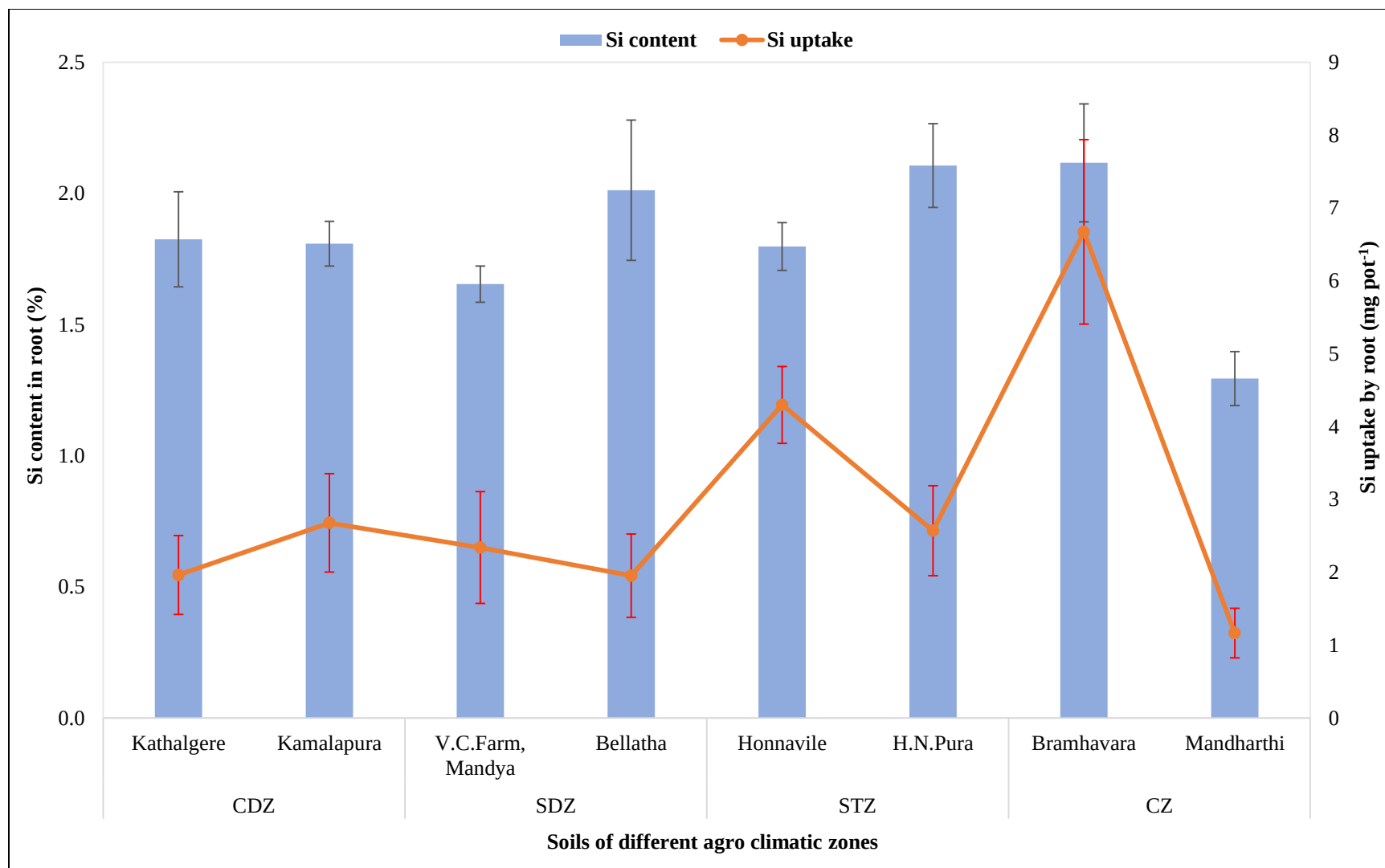


Fig. 5: Effect of selected rice soils on Si content and its uptake by roots of rice

5.2.3.2 Regression analysis between different silicon pools in soil and Si content and its uptake by rice

In the present investigation, the functional relationship between different pools of Si in soils and Si content and uptake by rice was determined for the selected eight soils using regression analysis (Fig. 6a) All the pools of Si were positively related with Si content and uptake by rice. However, there was poor association for Si content and uptake by rice with different pools of Si.

When only three soils one each from low, medium and high contents of PAS were considered for regression analysis, irrespective of the Si pools studied in the three soils, there existed a positive relationship with Si content of rice (Fig. 6b). However, the greatest regression coefficient was noticed by occluded Si pool followed by amorphous Si pool and least by organic Si pool. Hence, occluded pool of Si was considered to contribute maximum for Si content of rice followed by amorphous Si pool.

Irrespective of the Si pools studied in the three soils, there existed a positive relationship with Si uptake by rice. However, the greatest regression coefficient was noticed by amorphous Si pool followed by adsorbed and occluded Si pool and least by organic Si pool. Hence, amorphous pool of Si was considered to contribute maximum for Si uptake by rice followed by adsorbed and occluded pools of Si.

5.2.4 Different pools of Si in the post-harvest soil samples and its relationship with silicon pools of initial samples

The data presented in the Table 12 revealed that, the content of mobile, adsorbed and organic pools of Si were higher in the post-harvest samples compared to the initial soil samples. However, the content of occluded and amorphous Si pools reduced in the post-harvest soil samples. This might be attributed to the dissolution kinetics of Si pools under submerged conditions. A positive correlation was observed between the different pools of Si in initial and post-harvest soil samples (Table 13). Koltzbucher *et al.* (2015) reported that the various Si forms were continuously regenerated under submerged conditions, due to the dissolution of pools to a certain extent. Upon submergence the dissolution of the siliceous materials, Si associated with poorly crystallized iron and

aluminium oxides and hydroxides, undergoes dissolution due to the influence of pH, Eh and other factors (Kogel-Knabner *et al.*, 2010) and a part of amorphous Si which include diatoms, plant bound biogenic Si (phytoliths) and products of various binding processes, undergo dissolution and becomes available to plants as dissolved Si under reduced soil conditions upon flooding.

5.3 Determination of relationship between different silicon pools in soil and the properties of selected rice soils

5.3.1 Pearson's correlation between different silicon pools and the physico-chemical properties and available Si content of selected rice soils

The correlation of different pools of Si with soil properties is depicted in Table 14 and 15. Among the different pools of Si under study, the mobile, adsorbed, occluded and amorphous pools of Si exhibited a positive correlation with soil pH. While, the organic pool of Si showed significantly positive correlation with soil pH. Various studies reported that, there exists generally a positive relationship between pH and Si solubility and extractability (Oya *et al.*, 1989; Miles *et al.*, 2014). Korndorfer *et al.* (2005) and Camargo *et al.* (2007) further explained that the concentration of 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).

A positive correlation of mobile and adsorbed Si pool was observed with organic carbon content of the soils. He and Li (1995) stated that, the available Si supplying power of the soil can be attributed to organic carbon content of the soils and nature of the crop residues incorporated. There also existed a positive relationship between organic Si pool

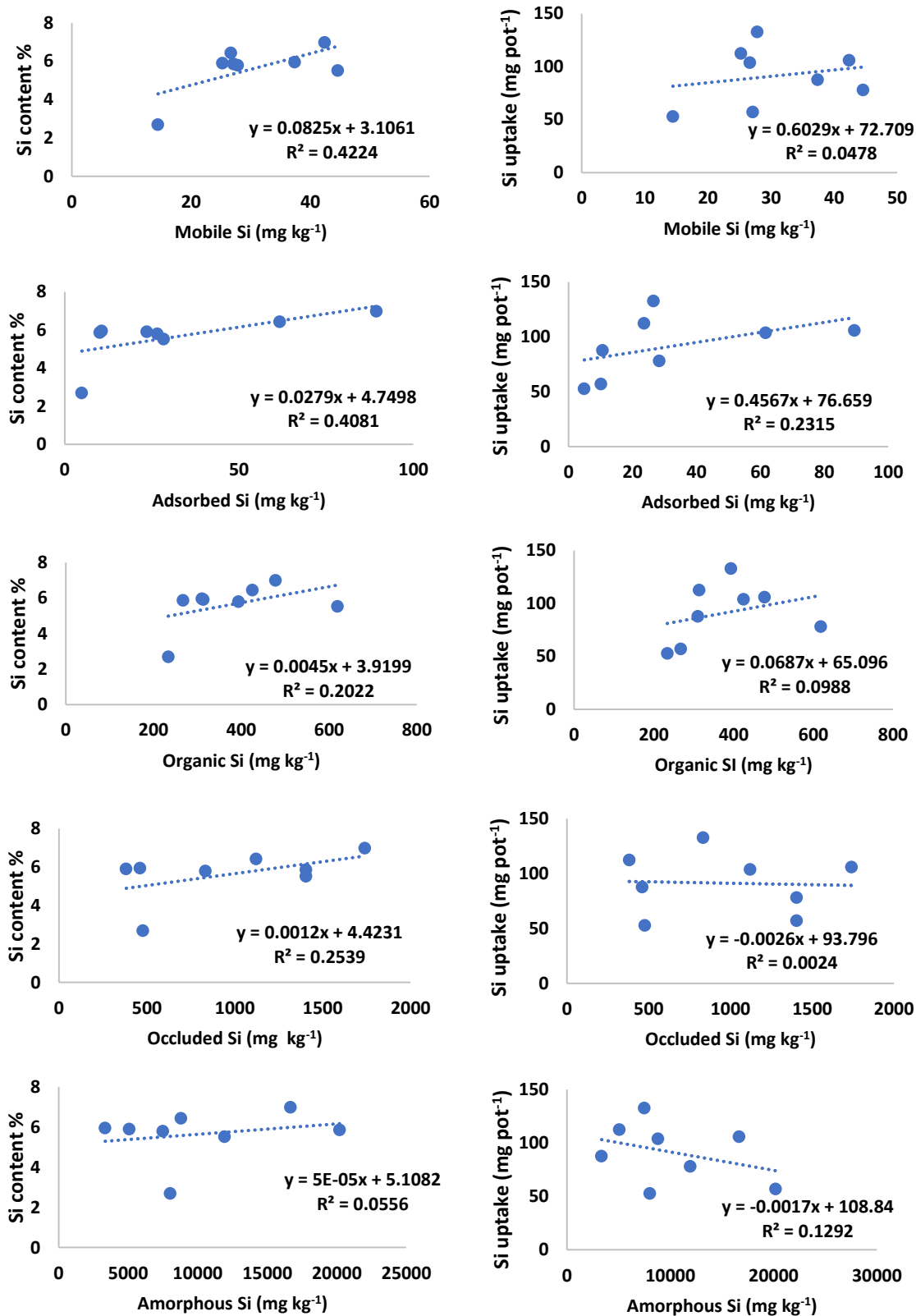


Fig. 6a: Regression relationship between different pools of Si in soil and Si content and its uptake by rice

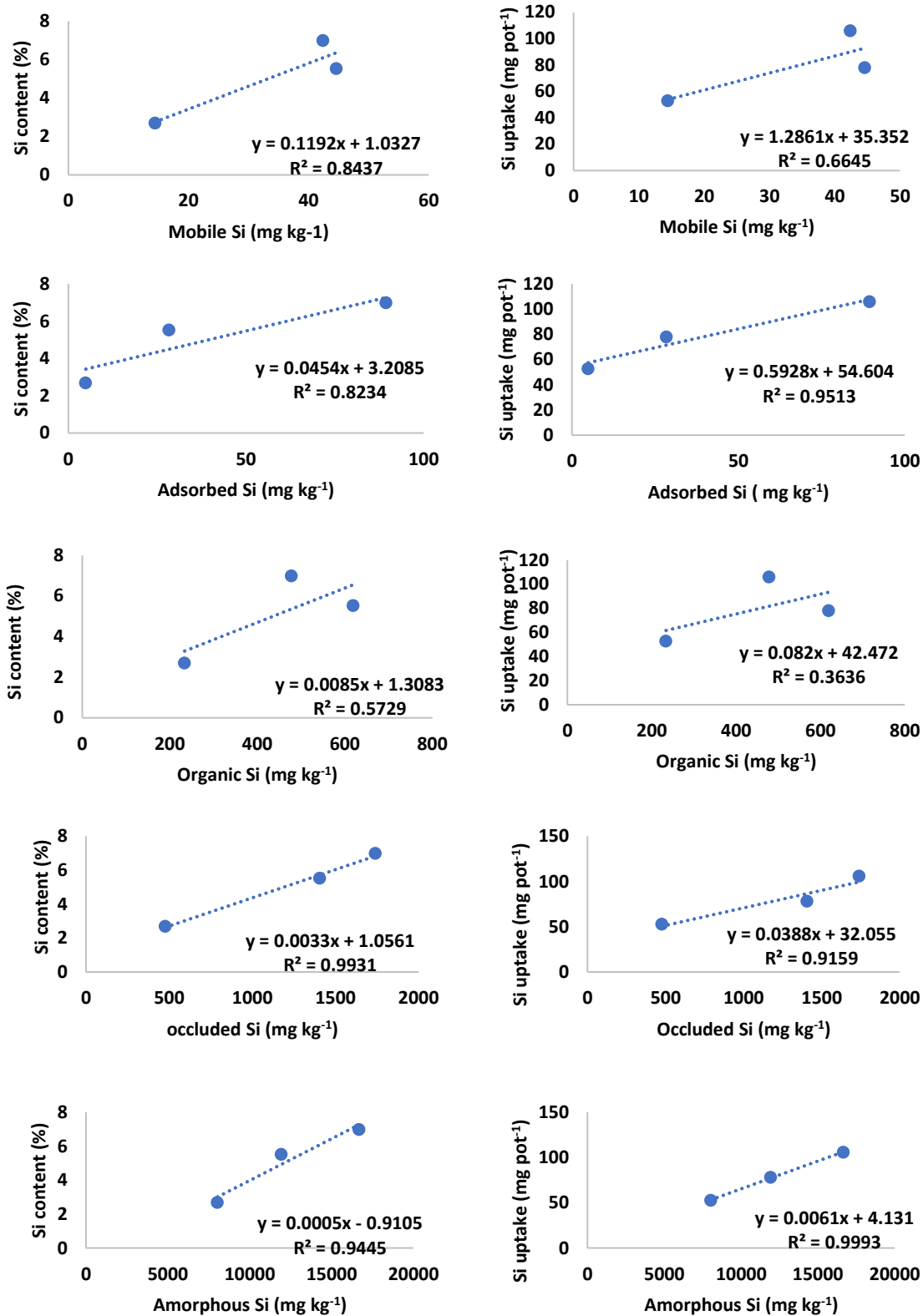


Fig. 6b: Regression relationship between different pools of Si in soil and Si content and its uptake by rice

and organic carbon content of the soil which is in contrast to the findings of Georgiadis *et al.* (2013) who reported that the amounts of Si released by H₂O₂ treatment (organic Si pool) exhibited no relationship to soil organic matter. The contents of occluded and amorphous Si in the present investigation were significantly and positively correlated with organic carbon content. The positive relation of amorphous Si pool with organic carbon content was supported by the findings of Georgiadis *et al.* (2013), who stated that bio-opal decreased with depth in the soil profiles and was positively correlated with SOM content.

The present investigation revealed a positive correlation between Si content of different pools with 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. 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.

It was also noticed, that all different pools of Si were negatively correlated with the sand content. While, occluded and amorphous Si pools showed a significant negative correlation. The amount of available Si (PAS) in the soil decreased with increase in the sand fraction. Sand consists basically of quartz minerals and in spite of having high SiO₂ 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 the 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 rice soil with higher pH and heavier soil texture contains high amount of Si.

A positive correlation existed between different pools of Si viz mobile Si, adsorbed and amorphous Si with clay content. There was a significant positive correlation of organic and occluded Si pools with the clay content. Georgiadis *et al.*

(2013) and Vandevenne *et al.* (2015) reported a positive relationship between easily soluble Si and clay concentration. Studies also indicated 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 rice soils in the Hachirogata Reclaimed Land area of Japan was positively correlated with the amount of clay when the clay fraction was $< 290 \text{ g kg}^{-1}$. 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 $< 150 \text{ g kg}^{-1}$. These reports indicate that the size of the clay fraction was also related to the amount of available Si in the soil.

A positive correlation was noticed between mobile, adsorbed, organic, occluded and amorphous Si pools with plant available Si. This might be attributed to dissolution of these pools under submergence. Plant available Si (PAS) content in soil mainly present in the form of amorphous or crystalline clay minerals and primary minerals and therefore are high in PAS content. The different Si fractions upon submergence undergo dissolution yielding plant available Si. Hence, the PAS in soils is continuously but very slowly regenerated by dissolution of adsorbed and organic Si pool. Additionally, from the release of Si that is occluded within poorly crystalline Fe oxyhydroxides. Part of this Si could become plant available when the Fe oxides dissolve under reduced soil conditions upon flooding of the paddies (Kogel-Knabner *et al.*, 2010). The dissolution of solid soil particles such as phytoliths also contributes to the PAS. Thus, all these pools have a positive influence on the concentration of available Si in soils.

5.3.2 Regression analysis between PAS and different pools of Si in soil

Functional relationship between the PAS (CCSi and AASi) content and the different pools of Si was determined for the selected eight soils (Fig. 7a) and also for three soils one each from low, medium and high contents of PAS as estimated by CaCl_2 and acetic acid extractants (Fig. 7b). Better functional relationship was noticed when regression analysis was done for only three soils than eight soils.

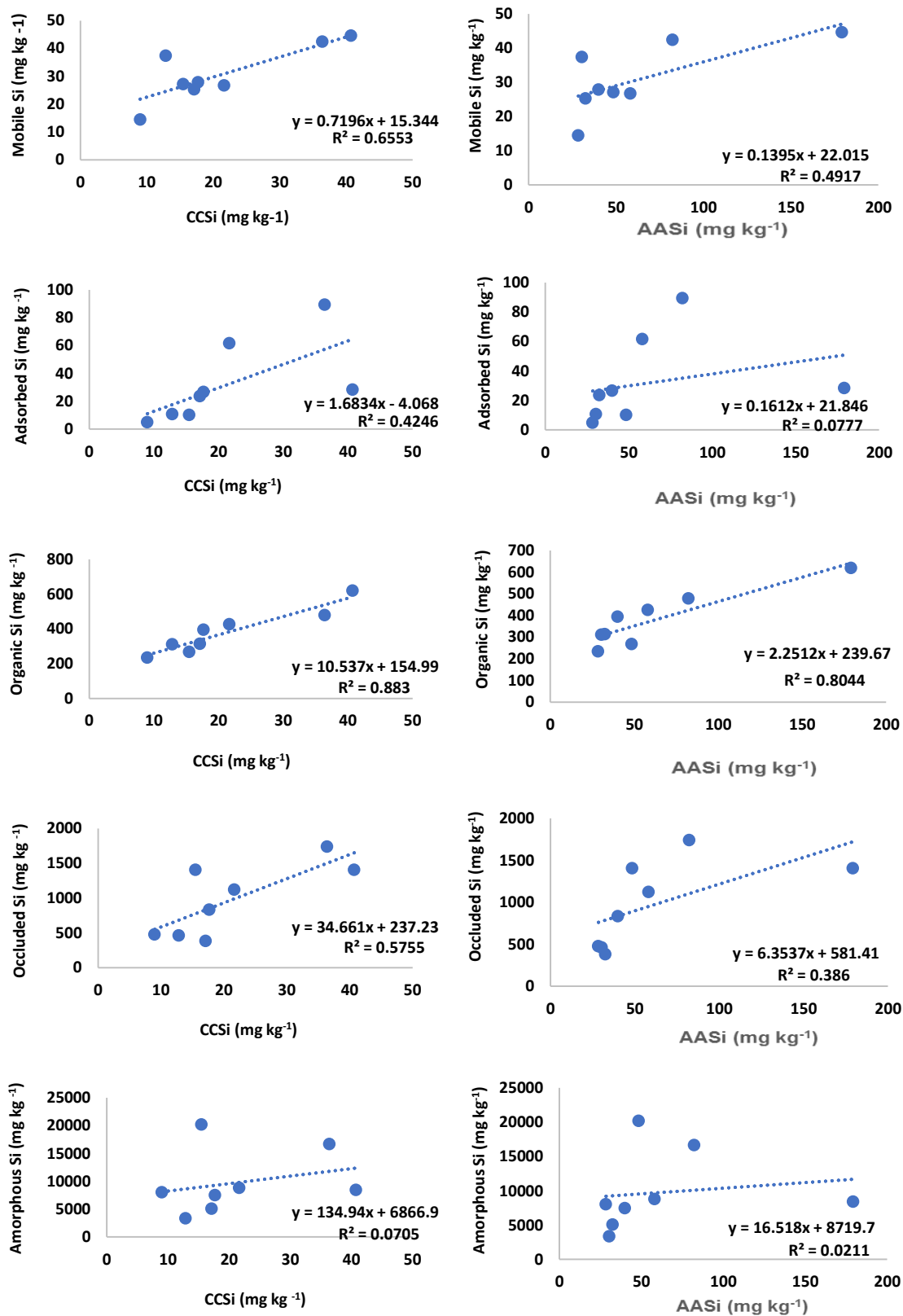


Fig. 7a: Regression relationship between plant available Si (CCSi and AASi) and different pools of Si in soil

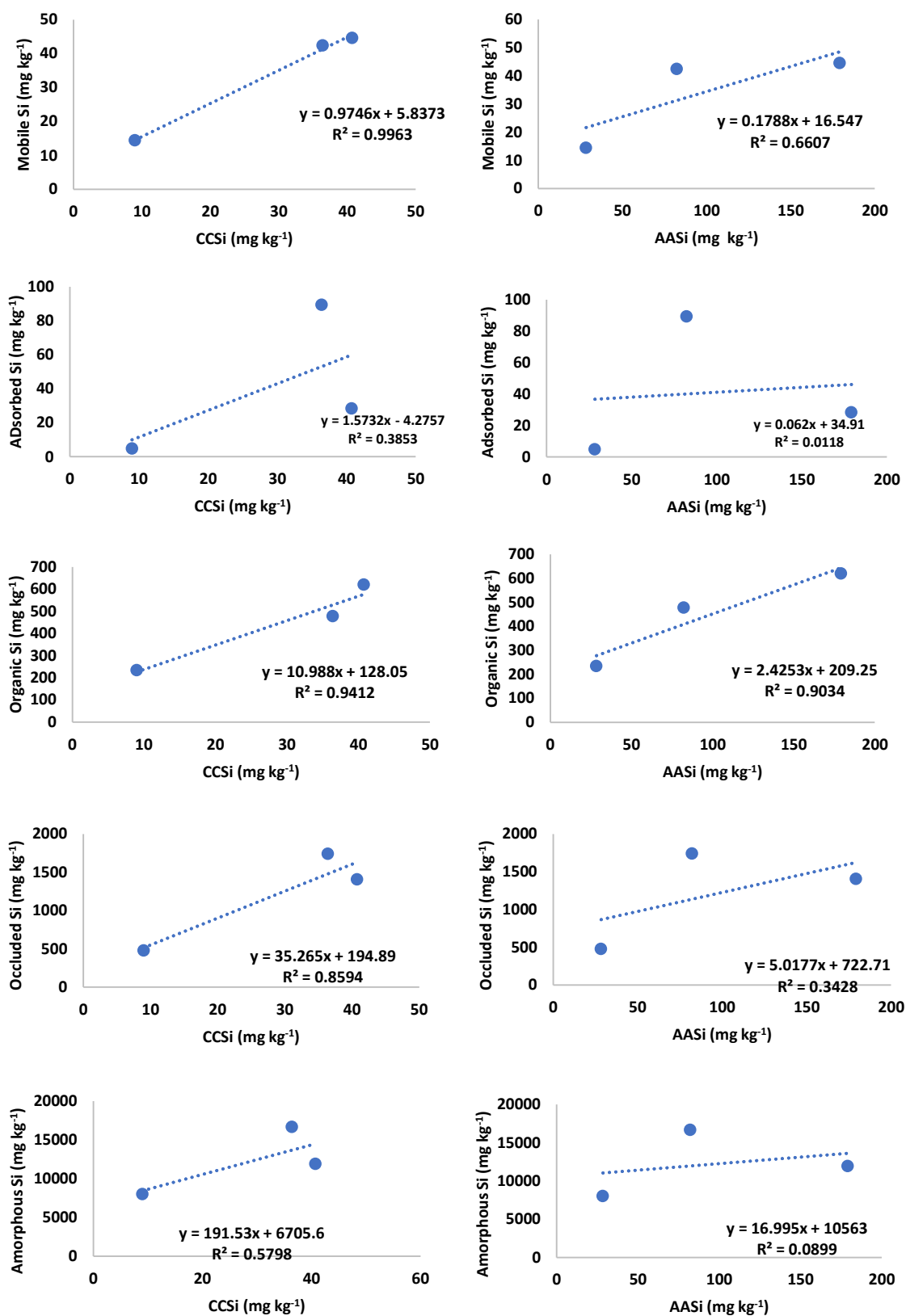


Fig. 7b: Regression relationship between plant available Si (CCSi and AASi) and different pools of Si in soil

Irrespective of the pools of Si, there existed a positive relationship with both CCSi and AASi. However, slightly higher regression coefficient was noticed between different pools of Si and CCSi than AASi which might be due to better extractability of CCSi in acidic soils than AASi. The CCSi had greater regression coefficient with mobile and organic Si pools. Hence these pools considered to be the major contributors to CCSi in soil. Whereas, AASi showed greater regression coefficient with organic Si pool and thus organic pool of Si was regarded as the major contributor to the AASi in the soil.

Future line of work:

- To conduct sequential extraction of Si pools in different soils of Karnataka and to determine their relationship with crop growth and yield.
- To separate and quantify biogenic and minerogenic fractions in amorphous Si pool and to assess their contribution to crop.

VI SUMMARY

The present investigation on “Studies on silicon pools in rice soils of selected agro climatic zones of Karnataka” was carried out with soils collected from different locations by conducting a pot culture experiment at Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bengaluru, Karnataka. The findings of this investigation are summarized below.

6.1 Quantification of different pools of Si in soils

- ✓ A significant difference was noticed among the different soils for various pools of Si.
- ✓ The mobile pool of Si in different soils ranged from 14.45 to 44.6 mg kg⁻¹. The highest content of mobile Si was recorded in Kamalapura soil and lowest in Brahmavara soil.
- ✓ Adsorbed Si pool varied from 4.9 to 89.43 mg kg⁻¹. Bellatha soil recorded higher adsorbed Si content while Brahmavara soil recorded the lowest.
- ✓ Organic Si pool of different soils recorded in the range of 233.7 to 619.2 mg kg⁻¹. The organic Si pool was higher in Kamalapura soil and was noticed least in Brahmavara soil.
- ✓ Occluded Si pool varied from 381 to 1740.35 mg kg⁻¹. V.C. Farm, Mandya soil recorded lower occluded Si content and higher in Bellatha soil.
- ✓ Amorphous Si pool in different soils ranged from 3342.40 mg kg⁻¹ in H.N. Pura soil to 20200 mg kg⁻¹ in Mandharthi soil.
- ✓ Among the different pools, amorphous Si was the largest pool and adsorbed pool of Si accounts to be the smallest pool of Si in the present investigation.
- ✓ Irrespective of the soils under study the Si content in different pools was in the order of Amorphous Si > Occluded Si > Organic Si > Mobile Si > Adsorbed Si.
- ✓ There existed a positive correlation between the different pools of Si in the study.

6.2 Assessment of contribution of different pools of Si for rice

- ✓ Significant difference was observed between the different soils under study with respect to DSi. The highest content of DSi was recorded in V.C. Farm, Mandya and lower DSi in Brahmavara soil.
- ✓ The DSi was higher at initial intervals and decreased significantly at the end of cropping period (60 DAT).
- ✓ In general, irrespective of the soils studied under different zones, increase in proportion of soil increased the growth parameters, Si content and uptake by paddy.
- ✓ Among different treatments comprising varied proportions (25, 50, 75, 100 %) of soil, 100 per cent soil treatment recorded significantly higher plant height, shoot biomass, Si content and uptake by shoots of paddy over control.
- ✓ The root length, root biomass, Si content and uptake by roots was found to be higher in 75 per cent soil treatment and was on par with control.
- ✓ The plant height under different soils, ranged from 64.43 to 85.57 cm. Higher plant height was recorded in Kathalgere soil which was on par with other soils and the lowest plant height was recorded in Mandharthi soil.
- ✓ There was a greater variation among the soils with respect to shoot biomass (0.97 to 2.29 g pot⁻¹), root length (15.13- 25.40 cm) and root biomass (0.09- 0.31 g pot⁻¹). Higher and on par shoot biomass, root length and root biomass were recorded in soils of Honnavile and Brahmavara, while lowest in Mandharthi soil.
- ✓ Si content in shoot under different soils ranged between 2.69 and 6.43 per cent in Brahmavara and Bellatha soil respectively.
- ✓ Si content in root among the soils ranged between 1.29 and 2.12 per cent in Mandharthi and Brahmavara soil respectively.
- ✓ The Si uptake by shoot of rice ranged from 52.78 to 132.64 mg pot⁻¹ and was recorded higher in Honnavile soil and lower in Mandharthi soil.

- ✓ Si uptake by root ranged from 1.16 mg pot⁻¹ in Mandharthi soil to 6.67 mg pot⁻¹ in Brahmavara soil.
- ✓ Different pools of Si showed a negative correlation with plant height, shoot biomass, root length, root biomass and Si uptake by root.
- ✓ The Si content in shoot had a positive correlation with all the pools of Si. However, it was non- significant.
- ✓ Si uptake by shoot and Si content in root were positively correlated with mobile, adsorbed and organic pools of Si and had a negative correlation with occluded and amorphous Si.
- ✓ The different pools of Si in the post -harvest soil samples were positively correlated with the various pools of Si in initial soil samples.
- ✓ The content of mobile, adsorbed and organic pools of Si were higher in the post-harvest samples compared to the initial soil samples. Whereas, the content of occluded and amorphous Si pools was lower in the post-harvest soil samples than initial samples.

6.3 Determination of relationship between different silicon pools and properties of rice soils

- ✓ All the pools of Si under the study showed positive correlation with soil properties viz pH, EC, organic carbon content, CEC, silt and clay content.
- ✓ The occluded and amorphous pools of Si showed a significant positive correlation with organic carbon content of soil.
- ✓ A significant positive correlation was exhibited by organic and occluded Si pools with clay content.
- ✓ Negative correlation was existed between the different pools of Si and sand content of soils.
- ✓ Irrespective of the soils, all pools of Si recorded a positive correlation with PAS.

- ✓ Irrespective of the pools of Si, positive regression was recorded with CCSi and AASi
- ✓ Mobile and Organic Si pools found to contribute maximum for CCSi content and likewise organic Si pool for AASi content in the soil.

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