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INVITED ARTICLE

Silicon as Fertilizing Agent Improves Climate Resilience in Rice

Silicon is often termed as beneficial element either due to its abundance or its inert nature. Evidence of increasing importance in the perspective of soil and plant health is as an upcoming element is published from world over. The modern tools, it's ubiquitous presence, role in biotic as well as abiotic systems all molecular systems from transporters to aquaporins, and mutation studies resulting in the increasing role of the mysterious element silicon. The present short review is an attempt high lighting the role of silicon studies carried in India at IIRR and AICRIP trials on rice.

Planet earth evolved due to constant geological changes such as lightening reacted with the natural elements or nutrient in the gaseous atmosphere resulting in the formation of simple glycine molecule, which in turn resulted in the formation of various amino acids, building blocks such as proteins and nucleic acids, and finally to various biological forms. In the industries, synthetic process of nitrogen conversion to utilizable form as fertilizer is not only expensive but also causes considerable environmental pollution is well known at present day. It is also interesting to note that, biological systems can fix through symbiotic association without spending much energy in case of nitrogen is well known. Prevalence of the chemical process at normal atmospheric conditions happen in soils is an amazing phenomenon, the natural medium on which crop plants grow and produce yields. Developing fertilizer responsive genotypes, particularly rice made it possible to overcome the food security after the great Bengal famine period through green revolution. Sustainable agriculture food production with the natural calamities and underlying the climate vagaries in the adverse situations due to crop yields reaching plateau, (Subramanyam et al 2011) excess fertilizer application, poor soil health, etc is a greater challenge across the world.

Normally fertilizers are recommended to meet the crop demand based on three approaches viz., deficiency to determine the need, sufficiency to build the nutrient levels and luxurious application to derive yield response curves and to determine the economic benefits of the crop yields. The type of fertilizers, mode of application quantity varies for instance, liquid, semi-liquid, solid, and application methods such as soil, spray, solution etc., while, considering several of these variables, balancing the major known fertilizer such as

Dr. SR.VOLETI,
Director, Indian Institute of Rice Research,
Rajendranagar, Hyderabad-30

Dr. Voleti did his Post graduate and Doctoral studies in plant physiology from Haryana Agricultural University, Hissar and Indian Agricultural Research Institute, New Delhi respectively.

Dr. Voleti having a rich experience of 35 years as ARS Scientist at CPCRI, Kasaragod, NRRI, Cuttack, IARI New Delhi and IIRR Hyderabad. Major areas of interest stress physiology, physiology of flowering Post harvest process of flowers. For the past 15 years he is working on plant nutrition aspects in relation to development of rice genotypes suitable for climate change.Nitrogen, phosphorus use efficiencies, role of boron, and biofortification in rice with special reference to Zn and Fe are few to mention the significant contributions made in plant nutrition area. His work on Silicon is unique in multidisciplinary mode, not only attracting the scientists and research scholars, but also catching attention by the private industries also. Handled several externally funded projects includes DST, DBT, ICAR, BBSRC UK, IRRI etc., About 45 students worked for Post Doctoral, Doctoral and Master degrees under his guidance and are working in International and national laboratories.

Dr. Voleti Authored more than 150 original research contributions in National and International Journals, include, Journal of Experimental Botany, Nature Scientific Reports , Agric Meteorology and Forest Ecology, Crop science, PLos One, 3 Biotech, Frontiers Journals of Genetics, Nutrition, Journal of Applied Entomology, Fields Crop Research, Crop Protection, Biologia Plantarum, Oleagineux, Rice, Rice Science, Genes, Molecular Breeding, Indian Journal of Plant Physiology,. etc.,

He is a Life member of Societies like Indian Plant Physiology, Soc. For Biochemistry Biotechnology, Society for Ornamental Horticulture, Indian Science Congress association, etc.,

Dr. Voleti is a recipient of ICAR JRF, SRF, CSIR, and Post Doctoral visiting fellowship of INSA, Prof RD Asana Gold Medal, Prof GV Joshi memorial award and Geospatial award for the team work on Disaster risk management using remote sensing and spatial technologies.

Nitrogen, phosphorus and potassium, using other essential micro nutrients is common as farming practice. It is interesting to note that, balancing fertilizer using beneficial elements (as their essential criteria are not met) is another "emerging concept" in recent times. This would sometimes help to correct the excess of the major nutrient or the essential nutrients and make it in available to maintain soil fertility for future years. In this context, the research work is taken up.

One such element is silicon which is reported to be ubiquitous, can provide economic as well as ecological benefits to plant growers being non-corrossive, non-pollutive, and not detrimental to plants even when applied in excess. Hence, concerted efforts in the area of silicon research can lead to its accelerated and improved application in the form of fertilizer for sustainable agriculture. Silicon (Si) is next to oxygen (O) in quantity on earth's crust. Silicon in combination with oxygen forms silicon dioxide (SiO_2) which is also known as silica. About 87% of the earth's surface is made up of silica. However, lower solubility and detection are two major constraints in understanding the role of silicon played in the plants. The solubility also depends upon the pH, acidity and alkalinity and soil types and soil microbiota present therein. The efficiency of Silicon solubility and availability can be enhanced by addition of carrier molecules or by direct means of application such as sodium, potassium silicates. All these factors not only influence solubility but their uptake as well. Plants vary in their ability to absorb silicon. Plants that can absorb and accumulate silicon in their tissues are known as silicon accumulators, e.g. horsetail and wetland grasses. These plants can accumulate up to 4-7% of silicon in their foliage. In contrary, the silicon non-accumulators can only absorb and store 0.5-1.5% of silicon. In general, dicotyledonous plants contain low quantity of silicon. Rice exhibits the greatest uptake of silicic acid in the grass family. With the application of large quantity of silicon fertilizers, rice can accumulate silicon in the stem and leaves up to 10-15% of its dry weight. Research findings from China reveal that rice yield of 7.5 ton/ha require 750-500 kg of silica. On an average, 1,125 kg of silica is required to achieve that yield.

Rice is able to accumulate Si up to 10% of dry weight in the shoots; this concentration is several-fold higher than those of the essential macronutrients, including nitrogen, phosphorus and potassium. High accumulation of Si is required for maximal sustainable rice production.

Problem identification: Basic and strategic aspect

Mostly the work carried out on silicon is of recent origin. At plant level variation in terms of accumulation, uptake identification of aquaporins, transporters on cell membranes also has been reported recently. The genes, molecular mechanisms, transcriptomics, metabolomic responses, transport, localization and distribution were widely reported (Ma et al 2006: 2007 and Deshmukh, Ma and Belangir 2020). However, its abundance presence in nature, difficulties in detection and lower solubility are the factors for attention of researchers not drawn on silicon research. Wide variation of silicon accumulation in some of the rice lines has been reported from IIRR (Volet et al 2012). Silicification is a process of formation of strong structures such as shells in sea animals as protective structures and sometimes referred as murals also. In plants also a similar process is noticed on various surfaces of rice plant such as leaves, husk which could be due indicating the process of rice evolution from ocean may not be surprising.

Basic Concept and model mechanism

Most of the beneficial effects of Si are realized through Si deposition in cell walls which may happen along the three modes i.e., paramural silicification, spontaneous and directed cell wall depositions. Si is taken up in the form of silicic acid and translocation from the roots to the shoots in the same form. It is finally deposited in the cell wall materials as a polymer of hydrated amorphous silica, forming silica-cuticle double layers and silica-cellulose double layers in the shoot. Deposition of Si enhances the strength and rigidity of cell walls and thus increases the resistance of plants to various stresses. To overcome the low solubility**,** basic research on enhancing the solubility and releasing the monosilicilic acid, i.e the active form of silica in IIRR in collaboration with Indian Institute of Chemical Technology, Hyderabad initiated laboratory research as early as 2006 (Ranganathan et al 2006). Carrier molecules solubilizing silica such as Pyrridine –N _Oxide, Morpholino – N Oxide two synthetic compounds were identified. Based on the properties observed as they might lead to soil pollution identification of environmental friendly carrier molecules search was undertaken. Awareness of silicon and slowly industrial manufacturing of silicon as beneficial amendment has increased during this period in India. This has motivated us to look into the chemistry of solubilization in the compounds particularly the structures having similarity and led to identification of imidazole and other simple aminoacids. To the surprise imidazole and aminoacids shown capability to act as carrier molecule which are also present in soils due to soil microbial interactions, were identified (Voleti et al 2011). In a trail conducted in farmer fields at KVK, Mehboobnagar and observed that, imidazole when applied as solid on direct contact with leaf surface produced burning symptoms hence changed the course of application mode into liquid for the convenience of the application. Simultaneously, the mechanism of solubilization due to ably forming monosilicilic acid in different proportions by these compounds a “Sand Witch Model” mechanism has been proposed (Ranganathan et al 2011). Rice husk ash alone and in combination with imidazole to improve the efficacy was initiated as often rice husk is considered as waste product but rich in silicon. The biotic stress tolerant trials at IIRR resulted in the observation that, damage of incisors and mandibles of yellow stem borer larvae also has been established utilizing the rice husk ash alone and in combination with imidazole as silicon solubilizers (Jeer et al 2016 : Jeer et al 2018). Silicon rich fertilizers are generally slags, and of mineral origin such as diatomaeceous earth and are soluble like sodium and potassium silicates as described in led to identification of the microbial association of a Rhizobium isolate (IIRR-1) has been reported recently (Chandrakala et al 2019). This isolate colonized on rice root seedlings was shown to solubilize silica from insoluble silicates by acidolytic dissolutions. Thus weathering process to increase bioavailability of silica is present in the soils albeit at low concentrations has been shown.

Biotic and abiotic stress tolerance initial Station trails

Detection utilizing modern tools as well as biochemistry principles for silicilic acid determination by ammonium molybdenum yellow method (Satio et al 2005) simultaneously fluorescence (Ranganathan et al 2006), Si NMR and energy dispersive x ray micro analysis (Padmakumari et al 2008) in has been shown as confirmative evidences of solubilization and quantification. The biochemical responses, and also the extent of biotic stress resistance offered by monosilicilic acid against yellow stem borer, blast (Ranganathan et al 2006), and beneficial effects on various crops and diseases in brief has been reviewed (Voleti et al 2012 and Voleti 2018). Also abiotic stress tolerance studies were carried out at IIRR, Hyderabad wherein the concept of silicon accumulation under aerobic stress on five rice varieties at station trial and the physiological responses such as leaf rolling, membrane stability were studied utilizing the imidazole and other aminoacids compounds which solubilize silica (Sujatha et 2013).

Encouraging results of this concept further exemplified and extended on similar lines as reported for boron studies in different soil (Rao et al 2013) by undertaking approximately at 300 trials (10 locations x10 rice genotypes x 3 replications) from 2012 to 2019 under All India Co-Ordinated Rice Improvement Program (AICRIP) through multi location testing across the India.

Methods of application

Five hybrids and 5 varieties were used in the experiments at locations. Initial trials were conducted using imidazole (solid) and Na, K silicate (liquid) formulations at vegetative and flowering stages in three replications. Later trials conducted in split-plot design with following treatments with the objective to study the effect of silicon (Silixol - commercial product also) @400ml in 200 litres/acre (as spray) were used at active tillering, panicle initiation, and 50% flowering. The experimental lay-out was split-plot with three replications and also under imposed stress treatments. Phenology, photosynthesis parameters, silica accumulation, yield and its components were recorded and all the results obtained are summarized for the brevity. (AICRIP Vol 3: Crop Production 2012-2019).

APPLICATION: MULTILOCATION FIELD TRIALS

Application of silicon had no significant effect on the days to 50% flowering. However, significant differences were observed amongst the varieties. The interaction between the treatment x location was found to be non-significant and the interaction between Variety x location is significant. However, the interaction between Treatment x Varieties x location was also significant. At TTB centre application of imidazole or siloxol reduced the days taken for 50% flowering (Fig 1).

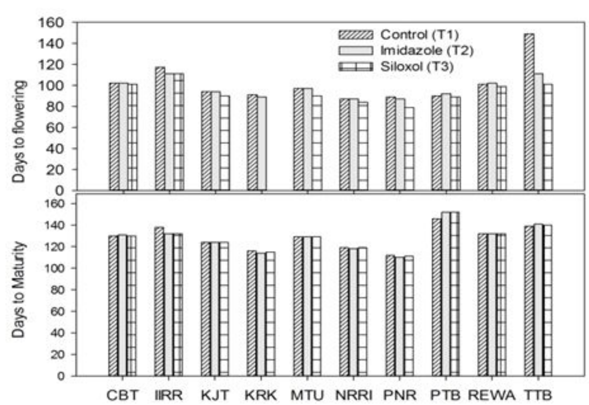

Fig1: Influence of silicon application on mean days to flowering and days to maturity for all the varieties at different AICRIP centers during Kharif-2015

Leaf area index, leaf and culm weights

Tiller stage

At tiller stage, experimental means for leaf area index (LAI), leaf and culm weights recorded were 2.78, 131 (g) and 191 (g) respectively. With the application of silicate as well as carrier molecules there was an increase in the mean leaf area from 2.67 to 2.86. However, the increase in leaf and culm the treatment effects were found to be negligible though, location and genotypic significances were noticed. For instance, all the five hybrids had better initial vigour and treatments resulted in enhancing the LAI and leaf weights but the same was not true with reference to the varietal response. Thus, a mean LAI at tiller stage in control was 2.61 which increased to 2.86 with carrier application was evidenced. The mean increase in LAI was relatively more in hybrids compared to the varieties and is significant at MTU, PNR and REWA locations.

At Flowering stage

Naturally an increase in the LAI, leaf and culm weights would be forecasted but the degree of treatment and genotypic variations were with reference to the these parameters was found to be significant. The experimental mean in LAI reached to 5.71 while in control it was 5.55 only. Carrier molecule application had significant influence relative to silicate application (5.85 and 5.72 respectively). Once again, the consistently significant influence was recorded at the same three locations viz., MTU, PNR and RWA. The influence was concomitant with increases in leaf and culm weights respectively. Interestingly, the initial vigour exhibited by hybrids appears to be reducing with time where as varieties catching up and expanded the leaf area more vigorously there by the mean differences were not to be varying between the two groups. Also, at this stage treatment influence was more prominent on culm weight preparing the crop towards maturity. However, the growth response due to silicate seems to be as good as that of carrier molecule treatment (Table1).

Analysis of variance revealed that the treatments had no significant influence on mean stem weight. However, the interaction between Location x Treatment was statistically significant ($p<0.01$) indicating that the effect of treatment on stem weight varied across the locations. The mean stem weight (all genotypes and treatment) varied from 499 g m^{-2} (NRRI) to a maximum of 1361 g m^{-2} at PTB centre. The treatments (silicon, WS+Silicon+WS) had no significant impact on mean stem weight at CBT, IIRR, KJT, RANCHI and TTB centres (Fig2). Application of silicon had resulted in a minor but non-significant increase (3% over control) in mean stem weight (Fig.2). Imposition of water stress (T4) resulted in >17% reduction in mean stem weight. However, under T3 (Silicon +WS), application silicon to water stressed crop had resulted in amelioration of stem weight reduction.

The interaction between Treatment x Variety was found to be non-significant. However, significant ($p<0.01$) differences were observed among the varieties. The mean stem weight was highest in KRH-4 with 1065 g m^{-2} and minimum mean stem weight was recorded in Sahabhagidhan (695 g m^{-2}). Silicon application (T2) had a positive effect on mean stem weight. The positive response is more pronounced in case of US-312 (15% increase over control) followed by HRI-174 (>7% increase over control). However, PA-6129 showed a marginal reduction in mean stem weight (mean of all locations) (Fig.2).

Leaf Photosynthesis (Pn)

Leaf photosynthesis was measured using LICOR 6400 at CBT and DRR. The mean Pn at both the locations were comparable ranged between 20-24. At both the locations silicon application improved Pn rate. At DRR the Pn rate was associated with variety, while at CBT treatment application was also significant. Similar trend with reference to other parameters i.e., stomatal conductance and transpirations were recorded were found to be at these locations. At DRR, internal carbon concentration and also intrinsic water use efficiencies were also studied and found to be influenced by silicon treatment. It was interesting to note that carrier molecule application has relative advantage on leaf photosynthetic characteristics compared to the Na, K silicate and improving the general crop health (Table 2).

Leaf Silicilic acid content

The mean silicon content was 0.334 µmol (control). Both the treatments resulted in increased silicilic acid content in the leaf tissues confirmed uptake irrespective of treatment. However, application of Na, K silicate had superior silicilic acid content compared to the carrier molecule in the leaf tissues (0.434 and 0.398 respectively). Among the five locations, at PTB internal Silicilic acid content was significantly lower (0.099) while it was highest at DRR (0.841). The mean silicilic acid uptake was 100 µmol and 64 µmol per 100 ml cell sap by Na, K silicate and carrier molecules respectively. Genotypic variation with reference to the silicilic acid in the leaf tissues was apparent in the present study. Treatment resulted in superior tissue level silicilic acid content recorded in Hybrids, PA 6444, KRH-2 and varieties Nagarjuna, and Sampada (Table 3). On the contrary, hybrids, PA 6201, PHB-71 and varieties AK Dhan and Varadhan did not respond to external silicon treatment. In general, hybrids had lower silicilic acid content and may require higher doses of external application.

Yield components

Number of panicles, grain. Panicle^{-1} ,1000 grain weight were studied under normal and treated situation in rice. No. of panicles m^{-2} is one of the important yield contributing trait. The data revealed that, interaction between Location x Treatment is highly significant ($p<0.01$) indicating that the treatment effect varied from location to location. The mean (mean of all treatments) varied from 478 (IIRR) to 191 (KJT). The differences between the genotypes for mean No. of panicles m^{-2} was non-significant. However, the interaction between Location x Genotype was significant ($p<0.01$) implying that the genotype response varied from location to location. Nevertheless, mean (mean of all treatment) of No. of panicles m^{-2} varied from 321 (KRH-4) to a minimum of 299 (US-312). Silicon application (T2) showed positive influence on No. of panicles m^{-2} in HRI-174 (>8% increase over control) and US-312 (>7% increase). However, in case of Shahabaghidhan >11% reduction in No. of panicles m^{-2} was observed. The response in the remaining varieties is negligible *(Fig3).*

Imposition of water stress (T4) during reproductive stage resulted in reduction in No. of panicles m^{-2}. The mean No. of panicles m^{-2} (Mean of all varieties) was reduced by >9% over control treatment (T4). Maximum reduction (>20% over control) was noticed in Sahabhagidhan followed by KRH-4 and PA-6129 (>9% over control). Silicon application to crop undergoing water stress (T3) could partially reverse the reduction in No. of panicles m^{-2} by water stress (*Fig3)*.

Panicle weight m^{-2} is an important yield trait which was significantly ($p<0.01$) affected by the imposed treatments. Application silicon (T2) had significantly ($p<0.01$) increased the mean (mean of all varieties and locations) Panicle weight m^{-2} by >16% over control treatment (T1). Similarly, imposition of water stress (T4) resulted in significant reduction (>16% over control). Silicon application on crop undergoing water stress (T3) had resulted in significant recovery from the negative effect of water stress imposition. Significant varietal differences were noticed *(Fig.4.)*

The interaction between Location x Treatment was found to be significant ($p<0.01$). The mean (mean of all varieties and treatments) varied between 1525 g (PNR) to 442 g (Ranchi) with a mean of 774 g. The extent of treatment effect varied between the locations. At CBT, IIRR centres the effect is only marginal. Silicon application (T2) had resulted in an increase in Panicle weight (g), the effect was more pronounced at PNR and Ranchi where the increase is >20% over T1. Moderate increase in panicle weight was observed at NRRI (>18%), PTB and TTB. The change is negligible in case of CBT, IIRR and KJT (*Fig.4B)*. Varieties also differ in their response to silicon application, the change in panicle weight due to silicon application is maximum in US-312 (28% over control) followed by HRI-174 (22% over control) in all the remaining varieties the increase is >10% over control (T1).

Grains per panicle: (Location and varieties)

Silicon application significantly ($p<0.05$) influenced the number of grains per panicle. The mean Number of grains per panicles for all the tested varieties increased by 4.9% and 2.8% over control treatment by the application of Imidazole and Siloxol, respectively (Fig. 5). With the exception of KRK and NRRI centres the silicon treatments had a positive effect on the grain numbers. A non-significant reduction was observed at both the centres. The effect was high at CBT and REWA centre. At CBT the silicon solubilizer (Imadiazole) application resulted in maximum increase where as at REWA siloxol application had resulted in maximum increase in mean number of grains per panicles for all varieties (Fig 6).

Filled grains per panicle

Number of filled grains per panicle (GNP) is very important yield related trait which show significant change. Application of silicon had resulted in marginal improvement in mean GNP (mean of all locations and varieties). Imposition of water stress (T3) significantly reduced the GNP (>15% reduction in comparison with control). Application of silicon to water stressed crop (T4) significantly reversed negative effects of water stress. The interaction between Treatment x Location is significant ($p<0.01$) indicating that the treatment effect is not uniform across the locations. Maximum number of GNP were recorded at PNR, CHN and Ranchi followed by MTU (Fig 7).

Influence of silicon and stress on TDM and grain yield during 2019

Grain yield/m^2 and total dry matter production reported from all the 9 locations was found to be significantly influenced by silicon treatment. However, the response was also dependent on the genotype and location. The grain yields were at par CBT, PNR and IIRR locations with values in between 691 to 807 g/ m2. Silicon application significantly ($p<0.05$) increased the TDM and grain yield (g m^{-2}) across the locations, the mean grain yield for all varieties and centres show 6.6 and 9.54% improvement with imidazole and silixol application, respectively over control treatment (Fig.8).

Table 1. LAI at flowering under the influence of silica treatment.

Treat		Varieties	CBT	DRR	MTU	PNR	PTB	REWA	TTB	KJT	MEAN
Control	1	Akshayadhan	5.79	5.28	8.68	5.91	3.09	3.70	6.87	8.06	5.92
	2	Varadhan	5.29	4.15	5.63	6.03	3.37	4.20	3.70	7.99	5.04
	3	Nagarjuna	5.19	7.17	5.35	9.44	3.04	3.33	7.66	8.28	6.18
	4	Shanthi	4.79	5.41	7.34	4.93	3.43	3.93	5.56	7.68	5.38
	5	Sampada	4.49	5.97	8.45	7.28	2.73	3.23	6.11	9.04	5.91
	6	KRH-2	6.29	4.09	6.46	4.94	2.98	4.77	4.03	9.01	5.32
	7	PA-6129	6.39	4.32	6.09	7.89	3.03	5.33	3.33	8.22	5.58
	8	PA-6201	6.09	3.87	6.47	7.28	3.39	4.53	4.89	8.18	5.59
	9	PA-6444	6.29	4.42	6.63	5.14	3.18	5.60	4.26	8.77	5.54
	10	PHB-71	5.99	3.72	5.15	5.52	3.79	4.57	3.54	8.20	5.06
T-1	1	Akshayadhan	6.39	5.03	5.90	6.25	3.55	4.60	7.69	7.50	5.86
	2	Varadhan	6.09	4.92	6.91	7.21	3.72	5.40	4.37	9.22	5.98
	3	Nagarjuna	5.99	6.69	6.22	9.90	3.19	3.40	7.67	8.16	6.40
	4	Shanthi	5.59	5.18	6.39	4.93	3.45	4.50	6.07	7.88	5.50
	5	Sampada	5.19	5.78	9.55	7.44	3.18	3.33	6.88	8.70	6.26
	6	KRH-2	6.59	3.36	7.35	5.37	3.01	5.10	4.69	8.63	5.51
	7	PA-6129	6.49	4.07	5.10	6.63	2.98	5.57	4.29	8.04	5.40
	8	PA-6201	6.59	2.95	7.62	7.57	3.18	4.80	5.15	8.05	5.74
	9	PA-6444	6.79	5.02	3.98	5.12	3.11	5.80	4.58	7.76	5.27
	10	PHB-71	6.79	4.12	7.30	5.39	2.91	4.70	4.02	6.79	5.25
T-2	1	Akshayadhan	6.69	4.93	5.86	6.65	3.13	4.73	7.27	8.84	6.01
	2	Varadhan	6.39	5.30	7.84	7.11	4.12	5.17	3.89	8.31	6.02
	3	Nagarjuna	6.29	6.30	7.79	9.86	3.44	3.43	7.08	9.16	6.67
	4	Shanthi	5.89	5.22	6.17	5.32	3.62	4.63	5.66	8.40	5.61
	5	Sampada	5.49	6.59	9.07	7.70	3.24	3.27	6.27	8.04	6.21
	6	KRH-2	6.89	4.05	6.30	5.30	3.73	5.03	4.44	8.39	5.52
	7	PA-6129	6.79	3.73	7.26	6.28	3.42	5.30	3.78	7.85	5.55
	8	PA-6201	6.89	3.88	6.95	7.16	3.55	4.60	4.96	7.05	5.63
	9	PA-6444	6.69	4.92	8.55	5.58	3.28	5.23	4.37	8.96	5.95
	10	PHB-71	6.79	3.72	6.96	5.46	3.17	4.40	3.75	8.10	5.29
		Mean contorl	5.66	4.84	6.62	6.44	3.20	4.32	5.00	8.34	5.55
		Mean Imidaazole	6.25	4.71	6.63	6.58	3.23	4.72	5.54	8.07	5.72
		Mean Na, K silicate	6.48	4.86	7.28	6.64	3.47	4.58	5.15	8.31	5.85
		Expt. Mean	6.13	4.80	6.84	6.55	3.30	4.54	5.23	8.24	5.71
		CD(0.05)	0.00	0.90	0.38	0.18	NS	0.19	0.44	0.67	0.39
		CV(%)	0.04	19.91	5.85	2.85	13.57	4.32	8.94	8.60	8.01
		M and T	0.00	NS	0.65	0.30	NS	0.32	NS	NS	
		T and M	0.00	NS	0.63	0.30	NS	0.31	NS	NS	

Table 2. Photosynthetic and related charateristics under silicon treatment Kh 2013

	Means	Fv/fm	Pn (Mmols $.m^{-2}S^{-1}$	TRANS (mmol $m^{-2}S^{-1}$	Conductance (gs) $mol.m^{-2}S^{-1}$			
	Control	0.7	20.07	10.02	0.53			
CBT	Na,K Si	0.74	22.19	10.85	0.7			
	Carrier	0.76	23.87	11.14	0.72			
	T (0.5%)		20.2	11.91	0.501			
	V (0.5%)		21.13	12.53	0.473			
	T x V		20.46	11.28	0.427	Efficiencies		
						Transpiration	IWUE	Carboxylation
	Control		20.2	11.91	0.501	1.7	40.48	0.072
DRR	Na,K Si		21.13	12.53	0.473	1.69	45.46	0.078
	Carrier		20.46	11.28	0.427	1.84	48.58	0.075
	T (0.5%)		NS	0.73	0.04	0.11	4.6	NS
	V (0.5%)		2.08	1.19	NS	0.18	6.3	0.01
	T x V		3.6	2.07	0.098	0.31	10.91	0.015

Significant interaction ($p<0.01$) between treatment and centre was observed as striking differences were noticed across the locations. Application of silicon resulted in marked improvement in mean TDM and grain yield at PTB centre. Both imidazole and silixol application had resulted in 29.8 and 32.4% increase in the mean grain yield, respectively. Both the treatments are effective at CTB as mean grain yield for all varieties showed >16% improvement with imidazole and silixol application. At TTB centre also silicon application had a positive response with 10.7 and 9% increase over control in grain yield with imidazole and silixol, respectively. Silixol application was more effective at REWA (18% increase) and PNR (16% increase over control) centres. However, at MTU centre application of imidazole had resulted in marginally higher grain yield (12% increase against only 8% improvement with silixol over control treatment). However, at IIRR, and NRRI centers application of silicon had no positive effect on mean grain yield for all the varieties (Fig. 8). At KJT centre also grain yield was not significantly affected by silicon treatment.

Grain yield as influenced by the silicon treatments over the years

Grain yields vary from location to location and year to year. The grain yields from under the AICRIP conducted during 2012 to 2019 are summed up and presented from low to high grain yield (Fig 9). From this, it is evident that silicon irrespective of solubilizer or silixol has positive influence on grain yield. Field trials during these years at 10 locations and 114 times were conducted. The treatment influence was at 89 times i.e., 78% silicon solubilizer and or silicon based fertilizer has influenced the grain yield. In this both the treatments were found to be effective at all the locations (Fig 10). Maximum of 9% yield advantage was realized in these experiments. The yield increase could be through the balancing influence as silicon is known to counter act the excessive nitrogen effects such as drooping of leaves to erect position there by helping the photosynthesis as shown above.

Future Leads

Few important leads that arose from these studies include, Rice husk ash is a rich source of silicon and can be utilized as silicon source which is otherwise used as fuel. Alternative to, rice straw of rice burning is feasible and can be utilized by developing the industrial silicon manufacture which has several utilities such as silicon chips other than mulching, improving soil health. Silicon though has been considered as beneficial element might serve as a balancing fertilizer to correct the soil deficiency of various other elements thereby alleviating the biotic and abiotic stresses. Soil microbiota contributing to the silicon solubilization one of the significant factor in understanding the process of silicilic acid is first of its kind report.

Socio-economic impact

In the context of present climate change and application of chemical fertilizers for biotic stress tolerance with an increase of B: C ratio from 1.16-1.32 than normal situation (Jeer et al 2018) has been brought out. The economics from the field studies realization of 5-10% rice yields and the water saving and the resultant benefits of the environmental friendly silicon immensely valuable for the society at large.

Table 3. Influence of Silica application Study Silica content µmols per 1000 µl cellsap at AICRIP locations Kh 2013

Treat	S.No.	Varieties	DRR	KJT	PTB	TTB	PNR	Mean
Control	1	Akshaya Dhan	0.783	0.671	0.088	0.162	0.149	0.371
	2	KRH-2	0.609	0.4	0.098	0.222	0.134	0.292
	3	Nagarjuna	0.729	0.48	0.085	0.182	0.14	0.323
	4	PA-6129	0.725	0.475	0.11	0.198	0.107	0.323
	5	PA-6201	0.654	0.611	0.084	0.235	0.208	0.358
	6	PA-6444	0.743	0.42	0.11	0.217	0.123	0.323
	7	PHB-71	0.839	0.495	0.055	0.226	0.159	0.355
	8	Sampada	0.629	0.644	0.094	0.226	0.099	0.339
	9	Shanthi	0.418	0.448	0.106	0.22	0.141	0.266
	10	Varadhan	1.016	0.547	0.029	0.23	0.149	0.394
		Mean	0.714	0.519	0.086	0.212	0.141	0.334
T1	1	Akshaya Dhan	1.143	0.469	0.127	0.194	0.317	0.45
	2	KRH-2	0.891	0.384	0.215	0.344	0.594	0.486
	3	Nagarjuna	1.06	0.601	0.138	0.341	0.251	0.478
	4	PA-6129	0.838	0.404	0.08	0.311	0.259	0.378
	5	PA-6201	0.903	0.473	0.091	0.273	0.227	0.394
	6	PA-6444	1.027	0.497	0.055	0.291	0.299	0.434
	7	PHB-71	0.759	0.666	0.102	0.243	0.189	0.392
	8	Sampada	0.951	0.628	0.084	0.263	0.435	0.472
	9	Shanthi	0.74	0.481	0.047	0.254	0.262	0.357
	10	Varadhan	1.077	0.64	0.088	0.311	0.37	0.497
		Mean	0.939	0.524	0.103	0.282	0.32	0.434
T2	1	Akshaya Dhan	1.103	0.397	0.109	0.222	0.321	0.43
	2	KRH-2	0.878	0.557	0.111	0.265	0.229	0.408
	3	Nagarjuna	1.005	0.397	0.103	0.257	0.206	0.394
	4	PA-6129	0.965	0.577	0.058	0.286	0.146	0.407
	5	PA-6201	0.768	0.491	0.127	0.298	0.123	0.362
	6	PA-6444	0.97	0.529	0.184	0.344	0.141	0.434
	7	PHB-71	0.794	0.557	0.036	0.24	0.226	0.371
	8	Sampada	0.582	0.666	0.088	0.266	0.176	0.356
	9	Shanthi	0.579	0.467	0.162	0.251	0.266	0.345
	10	Varadhan	1.052	0.628	0.106	0.23	0.159	0.435
		Mean	0.87	0.527	0.108	0.266	0.22	0.398
		Grand Mean	0.841	0.523	0.099	0.253	0.189	0.381
		LSD(Centre X Variety)	0.086	(P<0.01)				
		LSD(Centre x Treatment)	0.085	(P<0.01)				
		LSD (Centre x Treatment x Variety)	0.149	(P<0.01)				
		CV(residueal) %	16.393					

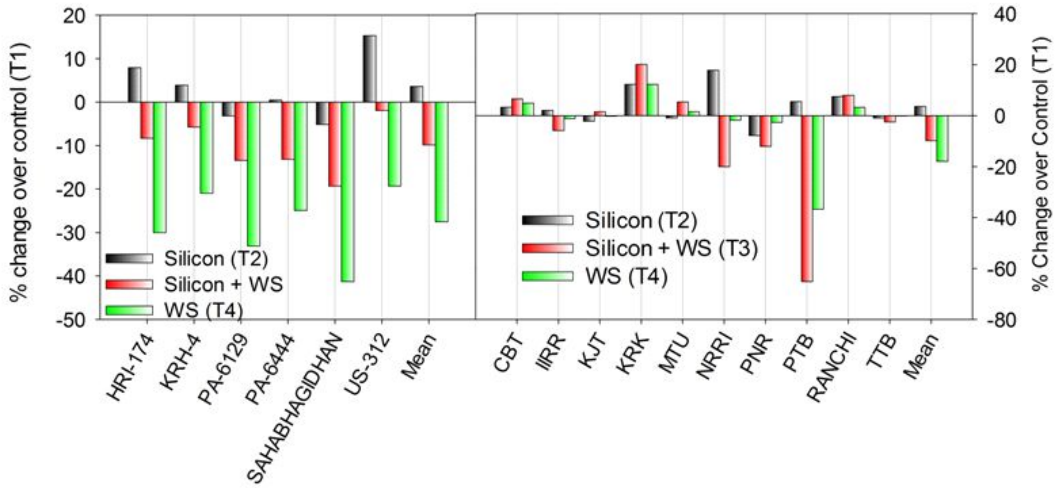

Fig. 2. Influence of silicon and water stress treatment on mean stem weight in selected rice variet ies. [A] Mean of genotypes irrespective of location [B] Mean of locations irrespective of genotypes. Each bar represents % change in stem weight over control treatment (T1)

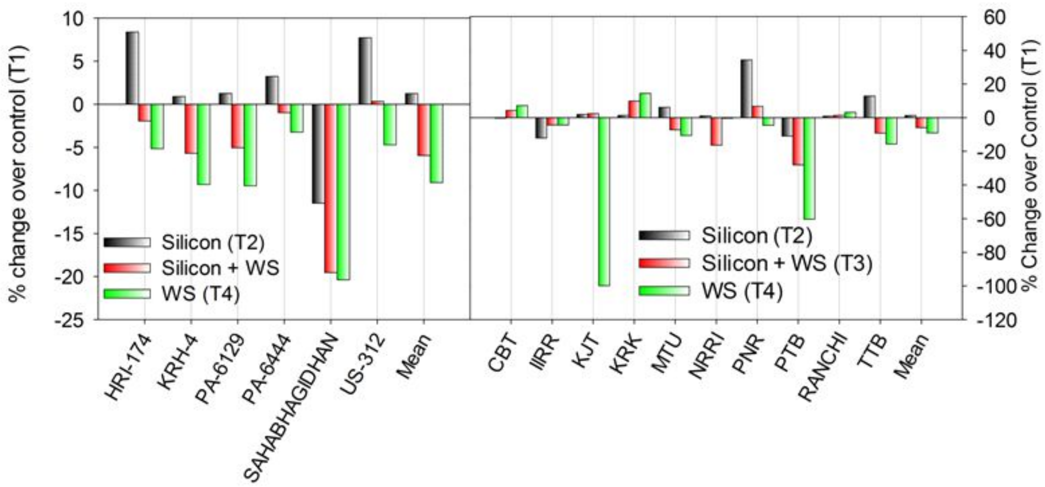

Fig 3. Influence of silicon application and water stress on No. of panicles m^{-2} [A] Mean of all locations [B] Mean of all varieties. Each bar represents % change over control treatment (T1)

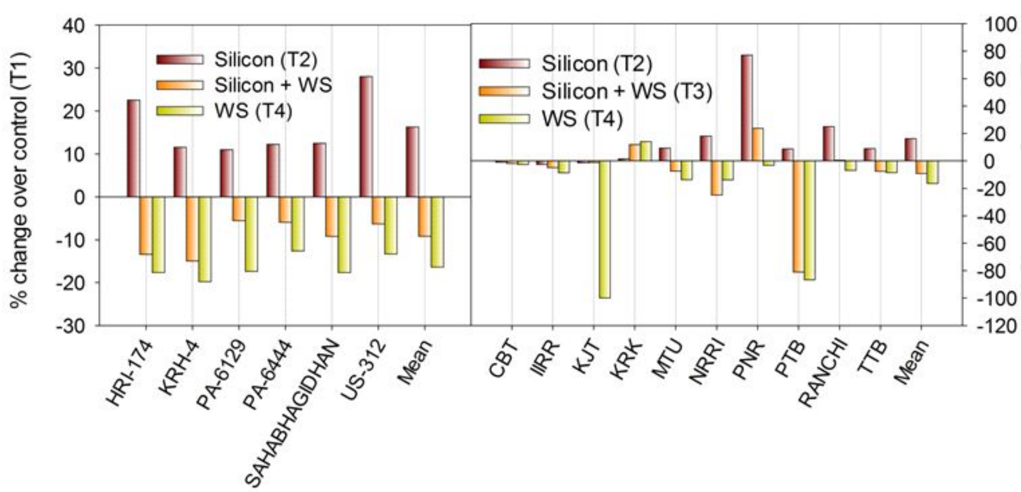

Fig 4. Influence of silicon application and water stress on Panicles weight(g) m^{-2} [A] Mean of all locations [B] Mean of all varieties. Each bar represents % change over control treatment (T1)

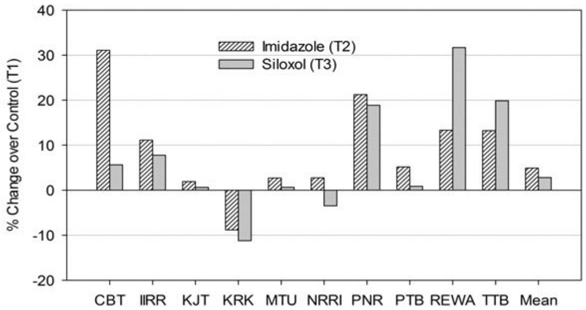

Fig 5. Influence of Imidazole (T2) and Siloxol (T3) application on mean No. of grains per panicle recorded at different AICRIP centres during kharif-2015 season.

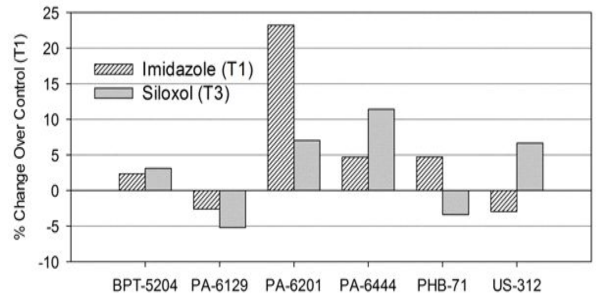

Fig 6. Influence of Imidazole (T2) and Siloxol (T3) application on mean No. of grains per panicle in different varieties. Each bar represents the mean of all the AICRIP centres during kharif-2015 season

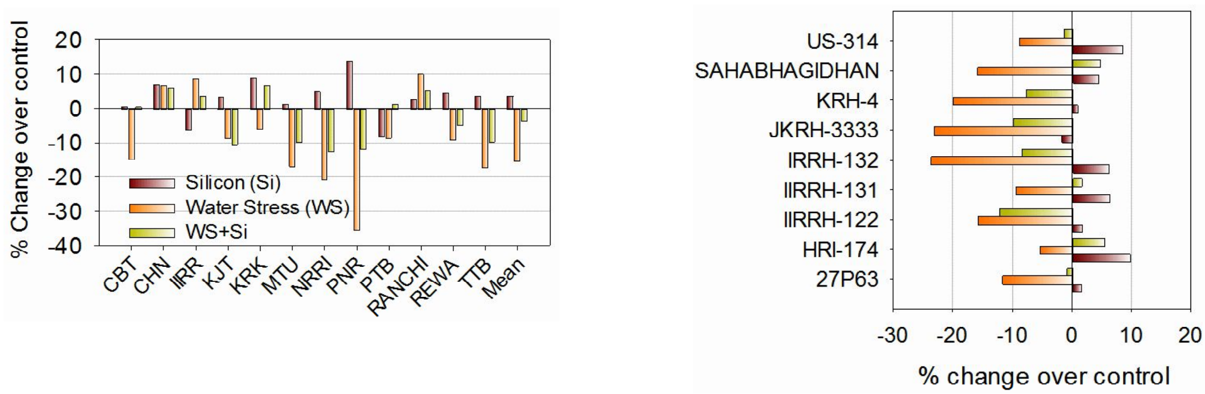

Fig 7. Influence of silicon (T2), water stress (T3) and WS+Si (T4) on number of filled grains per panicle in different rice varieties at different locations during kharif-2019

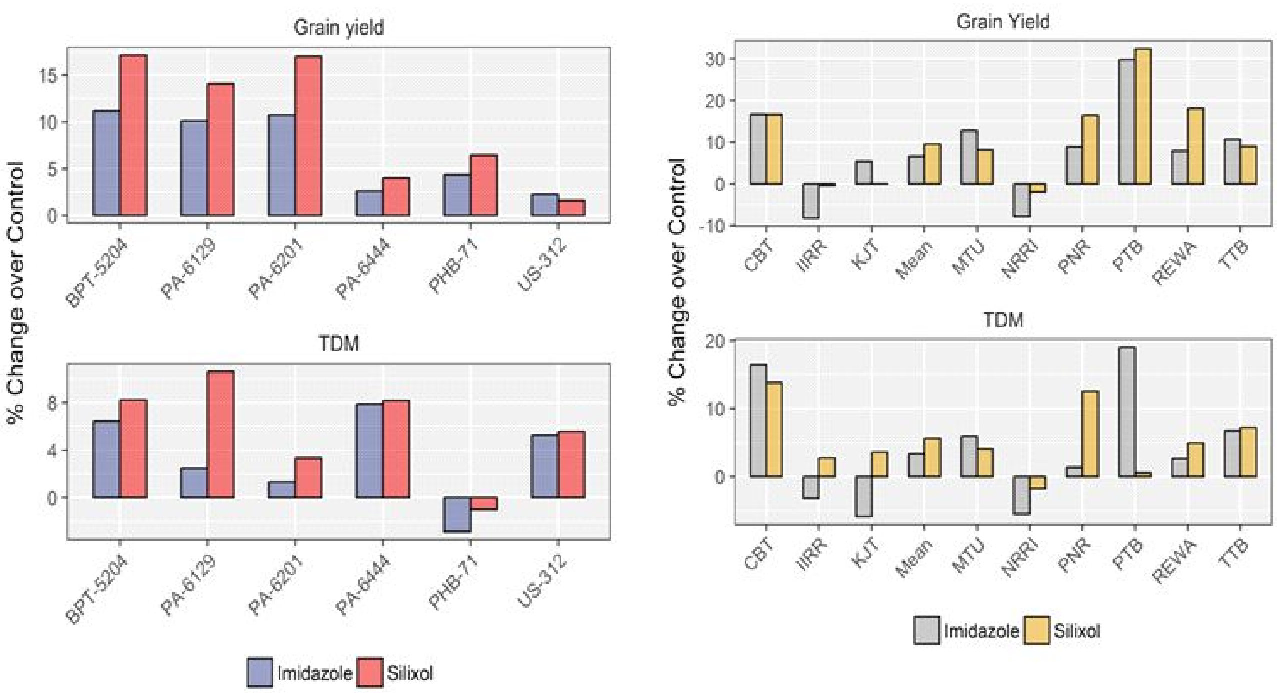

Fig 8. Influence of silicon treatments in alleviating effects on TDM and grain yield in rice grown at different locations and varieties.

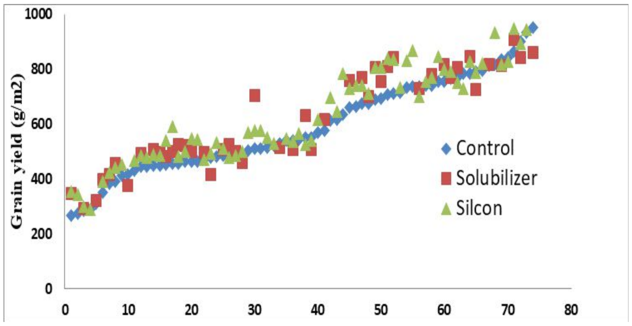

Fig 9. Mean grain yield under silicon treatments across 114 test locations and 89 locations had positively shown 9% increase in yield.

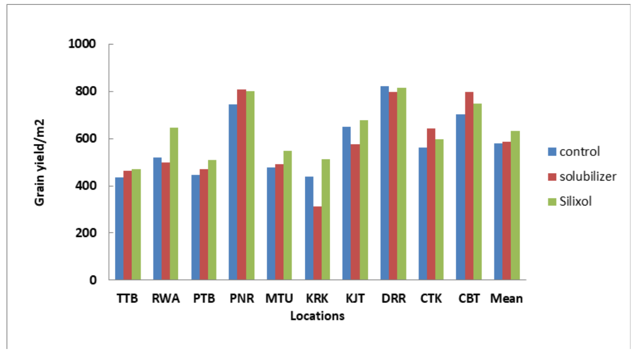

Fig 10. Mean grain yield as influenced by silicon treatments grain yield at different locations

Conclusions and important contributions

As described earlier, a new concept and mechanism of silicon solubilization in the soils using microbes is an important area and first report of Rhizobium culture. Mandibular wear of incisors of YSB under the influence of silicon and utilization of rice husk ash are the added knowledge in terms of evidence.

The decadal multilocation testing on abiotic stress tolerance studies, using silicon is favourably considered as AICRP recommendation for healthy rice crop and enhanced yields.

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