Environment and Ecology 42 (4B) : 1912—1925, October—December 2024
Article DOI: https://doi.org/10.60151/envec/UANW2908
ISSN 0970-0420

Effect of Nitrogen Management and Silicon Fertilization on Crops

Sujay Kumar Paul, Ganesh Chandra Malik, Mahua Banerjee,
Sumit Ray, Sitabhra Majumder, Sapparapu Sai Sivani,
Tanmoy Shankar, Duvvada Sarath Kumar

Received 22 August 2024, Accepted 12 November 2024, Published on 16 December 2024

ABSTRACT

Nitrogen management has a substantial impact on crop growth stages and yields. Split nitrogen administration at specific growth stages improves nutrient utilization, reduce losses and increase yield. Several studies have shown that applying nitrogen in fractions throughout the life cycle improves nutrient uptake efficiency while minimizing environmental contamination. Proper judicious nitrogen application impacts soil properties by affecting nutrient availability. Nitrogen management based on the Leaf Color Chart (LCC) is successful in terms of optimizing nitrogen delivery and enhancing yield characteristics. Silicon fertilization has shown encouraging outcomes in terms of plant growth, yield, and stress tolerance across a variety of crops. Silicon also improves the soil features such as nutrient availability and pH regulation, resulting in increased plant nutrient uptake. The interaction effects of silicon with other nutrients show synergistic effects that improve nutrient absorption and yield. Silicon interacts with nitrogen, phosphorus, potassium, and other nutrients, which promotes crop performance and nutrient efficiency. Application of nitrogen and silicon management strategies can boost crop yield, nutrient efficiency, and sustainability in agricultural systems. However, additional research is needed to understand the intricate mechanisms behind the interactions of nitrogen, silicon, and other nutrients in crop-soil systems to develop more effective nutrient management strategies. This review deals with different aspects of nitrogen fertilization in crops and simultaneous silicon application and interaction among both. The aspects of growth parameters, yield attributes, yield, economics, soil characteristics and efficiency studies have been assessed.

Keywords Agricultural management, LCC, Nitrogen, Silicon.

INTRODUCTION

Nutrient management has been a crucial factor in

Sujay Kumar Paul[1]*
[1]Research Scholar, Department of Agronomy, Palli Siksha Bhavana (Institute of Agriculture), Visva Bharati, Sriniketan, West Bengal, 731236, India

Present Affiliation: Assistant Professor, Department of Agronomy and Agroforestry, M. S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha, 761211, India

Ganesh Chandra Malik[2], Mahua Banerjee[3], Duvvada Sarath Kumar[8]
[2]Head of Department, [3]Associate Professor, [8]PhD Research Scholar Palli Siksha Bhavana (Institute of Agriculture), Visva Bharati, Sriniketan, West Bengal, 731236, India

Sumit Ray[4], Sitabhra Majumder[5], Tanmoy Shankar[7]
[4,5]PhD Research Scholar, [7]Head of Department
Department of Agronomy and Agroforestry, M. S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha, 761211, India

Sapparapu Sai Sivani[6]
[6]PhD Research Scholar, SR University, Anantasagar, Hasanparthy, Warangal, Telangana, 506371, India

Email : sujay.paul39@gmail.com
*Corresponding author

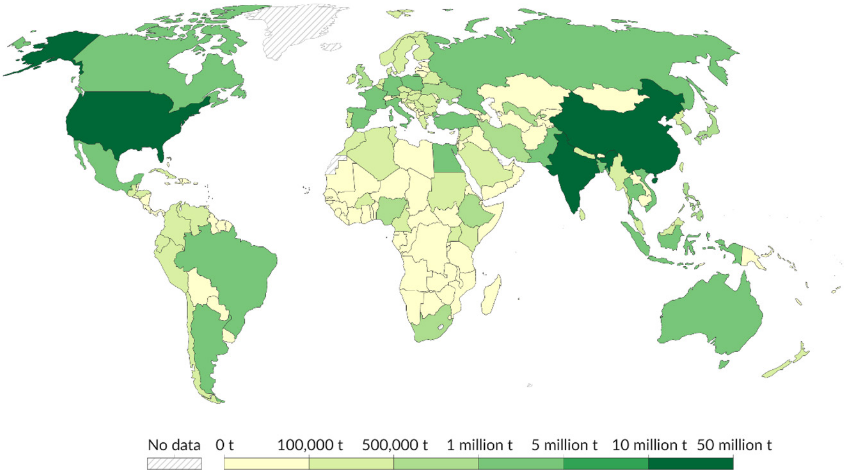

Fig. 1. Annual input of nitrogen fertilizers in crop fields (West *et al.* 2014).

agricultural production and its sustainability. Nutrient applied has direct role on crop growth and development, yield attributes and yield due to its relation with nutrient content of plant and nutrient uptake. With average growth rate of 1.1%, to feed the increasing population in a sustainable manner, choosing proper nutrient management practices plays an indispensable role. Proper nutrient management strategies based on maximizing resource utilization can be a way forward towards sustainability.

Fertilizer in most of the cultivated regions are managed using some blanket recommendations common for a vast area. In many countries across the world over use of nitrogen fertilizers is a burning issue which generally leads to little output gain but higher losses (Fig. 1). The excessive use of nitrogen fertilizers without much improvement in crop yield have been illustrated in the Fig. 2. This kind of nutrient management especially nitrogen leads to excess amount of fertilizer application and environmental pollution in return.

Leaf color intensity is directly related to chlorophyll content of leaf, which in turn is related to leaf nitrogen (N) status. Leaf color chart (LCC) is a high

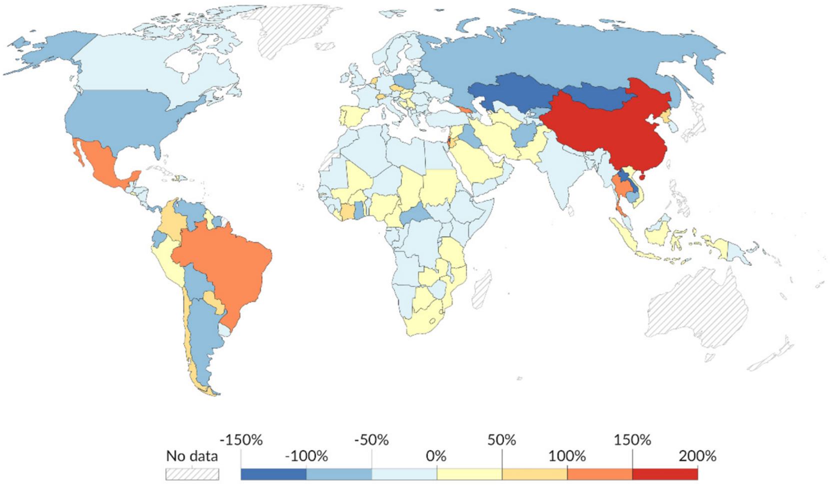

Fig. 2. Gap between nitrogen over-applied without gains in yield (Wuepper *et al.* 2020). Color from yellow and red indicate countries over applying nitrogen without yield gains.

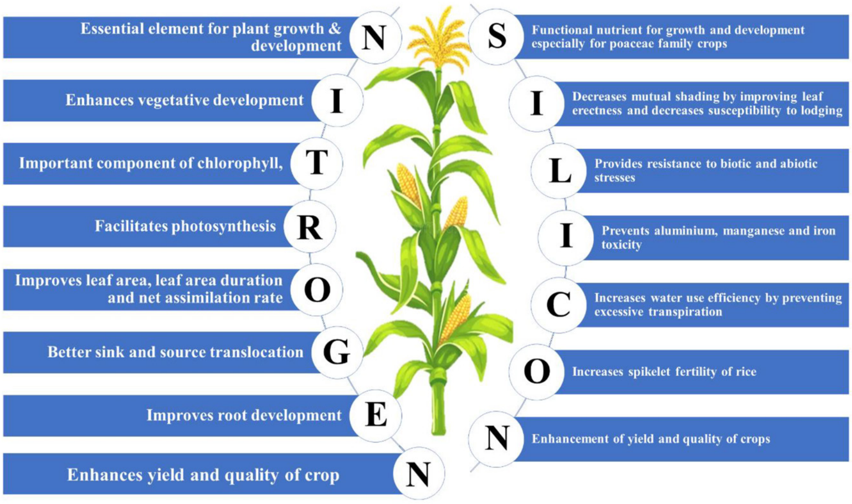

Fig. 3. Advantages of nitrogen and silicon in crop.

quality plastic strip with shades light yellowish green to dark green. Japan developed first LCC. However, International Rice Research Institute (IRRI) developed the latest and well evaluated version of LCC. It has four panels of rice leaf color. LCC is monitored every 7–10 day starting from 15 days after transplanting or 21 days after sowing till initiation of flowering and prescribed amount of fertilizer N is applied whenever the color of rice leaves falls below the critical LCC score (Thind and Gupta 2010). Scheduling of fertilizer N is the main target behind LCC. Farmers can use the LCC as a visual indicator of the rice crop nitrogen status of the crop. Then, they can easily manage the N fertilizer application. This will lead to appropriate nitrogen management reducing nutrient loss and environmental pollution. Oxygen is the most abundant element in earth's crust and silicon lies just after that. But, it has low availability in soil because of its low solubility from soil source (Lindsay 1979). Si is recognized as a "quasi-essential" or "agronomically essential" and "functional" element for rice present in much higher concentration than macronutrients nitrogen, phosphorus and potassium (Savant *et al.* 1996, Ma and Takahashi 2002). Rice accumulates silicon in its system and tends to accumulate Si in its tissue in concentrations of 5% or higher (Epstein 1999). Si responds well in the poaceae family of crops like rice, wheat, barley, oat, sorghum. Silicon in rice under unstressed conditions by favors remobilization of amino acids during grain development to support increased nitrogen demand (Detmann *et al.* 2012). With intensive rice production in the range of 5 t/ha of grain yield, rice crop removes 230–470 kg of Si from the soil without Si fertilization leading to decline or stagnation of yield in many countries (Savant *et al.* 1997). Si generally improves the concentration of N in rice plant tissues (Singh *et al.* 2006b). The advantages of nitrogen and silicon in crop plants are illustrated in Fig. 3.

However, information on the usefulness of different sources of Si and nitrogen management are still a debatable topic to consider (Prakash 2002). In this review, we included nitrogen management in aspects of split application and LCC based application along with silicon fertilization in different crops. The review is sub divided into different effects in growth, yield, soil and efficiency parameters.

Nitrogen fertilizer management

Nitrogen (N) fertilizer has been crucial in raising rice yields (Majumder *et al.* 2023), and the global amount of nitrogen used in rice farming has been steadily rising (Yogendra *et al.* 2014). Nitrogen plays a direct role in electron transmission, protein synthesis, and chloroplast pigmentation, so farmers see the visible effect of nitrogen fertilization much more prominently. Hence, most farmers go for blanket recommendations or sometimes imbalanced application of nitrogen fertilizers in the crops. Nitrogen, generally applied in ample concentrations, is lost and finds its way to water bodies and groundwater, causing pollution. Judicious nitrogen management is notably crucial for this reason. Efficient nutrient management following the principles of "4R", i.e. the right dose, right time, right source and right place, can help increase nutrient use efficiency. Following the recommended dose of fertilizers or using LCC can play an efficient role in this regard.

i) *Effect of nitrogen management on the growth of crop*

According to Mahapatra *et al.* (1990), for a given amount of N, applying N in fractions that correspond to the growth stages of robust absorption and effective N assimilation by the plant may produce better outcomes than administering the N dose as basal. Similar results were noted by Kondo *et al.* 2005, that applying nitrogen as per the demand of rice after active tillering, significantly enhances N-recovery. Geetha and Balasubramanian, 2016 also noted that applying nitrogen in splits at transplanting, active tillering and panicle initiation have positive effect on growth characters like tiller number, root growth and dry matter accumulation.

Reduced organic matter concentration (less than 10 g/kg soil) in the soils of South Asian countries is the primary reason of low nitrogen contents in the soil (Lal 2004). Therefore, to increase the use-efficiency of nitrogen in agricultural fields we have to adhere to the government's recommendation to apply split doses of nitrogenous fertilizers and site-specific nitrogen management techniques like LCC. The leaf color chart is commonly used as a visual indicator of the crop's need for nitrogen fertilizer since the color intensity of LCC is highly correlated with the leaf's chlorophyll content and nitrogen status (Reddy and Pattar 2006). Bhavana *et al.* (2020) found significantly taller mature plants, more tillers, higher leaf area index, higher SPAD value, and increased dry matter accumulation in treatment of LCC-4 at 150 kg N/ha. Compared to the suggested split applications, Maiti *et al.* (2004) and Lone *et al.* (2017) indicated also found comparable results of higher growth characteristics and panicle number in LCC-4 treatments. The results of a field experiment by Jayanthi *et al.* (2023) showed that that growth characteristics, yield attributes and yield of rainfed rice improved when the recommended dose of nitrogen was applied in more splits at a critical value of LCC 3 (20 kg N/ha). When nitrogen fertilizers were supplemented further in vegetative and reproductive stages in addition to the basal application of nitrogen, rice responded favorably and gave better results in terms of plant height, dry matter accumulation and leaf area index.

ii) *Effect of nitrogen management on yield attributes and yield of crop*

Crop output and yield attributes improved when nitrogen was supplied in split doses and while advocating site-specific or real time nutrient management. Yield and yield characteristics were significantly higher when 100 kg N/ha was applied in three splits—one-third at transplanting, one-third at tillering, and one-third at panicle initiation—as compared to N application in a single dose (Geetha & Balasubramanian 2016). Singh *et al.* (2005b) also observed that while considering total spikelets per panicle, total tillers, and productive tillers, split nitrogen application of N outperformed foliar application of nitrogen. The longest panicle length and higher number of spikelets were linked to split nitrogen application during flowering and panicle initiation (Singh *et al.* 2015).

When the rice plant's flag leaf color was less intense than LCC 3, 30 kg N/ha was applied, this produced a greater yield than when 80 and 120 kg N/ha were applied in four equal split doses at predetermined periods (Singh *et al.* 2006b). According to research by Porpavai *et al.* (2000), in direct seeded rice, the LCC 3-based nitrogen-applied plots had the highest yield during the dry season, which was at par with SPAD-32, SPAD-35, and LCC 4. The experiment conducted at the Agricultural Research Station in Mugad, Karnataka, showed that N management based on LCC 3 considerably boosted grain yield and yield attributes such panicles per meter row length and full grains per panicle when compared to the recommended dose and check (Premalatha 2001). Singh *et al.* (2006a) reported that grain yield of rice in nitrogen management by LCC 4 was found at par to blanket application of 120 kg N/ha in three equal splits. Using a leaf color chart (LCC), Premalatha and Angadi (2005) assessed how well direct dry-seeded rainfed rice responds to crop-need-based N control. They found that in addition to having more panicles, panicle weight, filled grains per panicle, and test weight, treatment LCC 3 gave highest grain yield which was 15.5% more than the treatment where 100% recommended N fertilizer was applied.

iii) *Effect of nitrogen fertilization on soil characteristics*

LCC-based N management may be the best option for farmers to preserve soil fertility and conserve N fertilizer because there have been significant differences in soil-accessible nutrients between LCC-based treatments and typical blanket N treatment (Gunasekhar *et al.* 2007). According to Arvind *et al.* (2006), reported significant reduction in NO_3-N in soil profile (45-105 cm) depth when nitrogen application in field was done through LCC 5 (160 kg/ha), LCC 4 (120 kg/ha) and LCC 3 (90 kg/ha) to apply recommended nitrogen (120 kg/ha) and farmers practice (150 kg/ha). A leaf color chart was used to evaluate the quantity of available nitrogen in the soil after bread wheat was harvested in order to assess the amount of nitrogen applied. It was found that LCC 3 (90 kg N/ha) and LCC 4 (90 kg N/ha) had considerably lower levels of available nitrogen (128.86 and 170.34 kg/ha) in their soil than LCC 5, which had the highest quantity (197.26 kg/ha) as compared to LCC 4, LCC 3 and recommended application of nitrogen (120 kg N/ha) (Dinesh Kumar 2010). Srinivasagam and Stephan (2013) found that at various phases of rice growth, the maximum available N and P were found when nitrogen was applied in six splits using LCC 5 (140 kg N/ha). Achieng *et al.* (2023) studied the changes in pH, N, P and K depending on nitrogen fertilizer rates and split applications. They observed that splitting the nitrogen rate raised the amount of nitrogen in the soil, maintained the pH levels within a suitable range, showed no discernible changes in phosphorus levels, and only caused a change in potassium levels because of the variety's higher uptake rate. Study regarding how different nitrogen fertilization rates affect crop productivity and soil characteristics in banana farming was done by Sun *et al.* (2020). The findings revealed higher quantities of available potassium, phosphorus, and nitrogen as well as an enhanced rate of enzymes like urease and invertase. They concluded that plant physiological activity is positively impacted by both soil enzymatic activity and nutrient availability, which was again decided by the application of nitrogen rates at different stages of crop growth.

iv) *Effect of nitrogen fertilization on economics*

Any technology must be technically and financially viable before it can be used in farmer fields, therefore, an economic analysis of the results is essential. LCC-based nitrogen management and split nitrogen application greatly increase nitrogen utilization and decrease nutrient losses. The most effective way to lower the quantity of fertilizer used for crops and increase economic returns is through LCC-based nitrogen management. In order to maximize productivity and profit from their small agricultural holdings, farmers need to consider the non-fixed inputs, like fertilizers, than fixed inputs and technical improvements. (Wang *et al.* 2017). Ramu (2008) found that while managing wheat crop, nitrogen management @ 100 kg N/ha in three splits—20 kg N as the basal dose + 30 kg N at 20 DAS + 50 kg N at 40 DAS—produced significantly higher gross returns, net returns and benefit-cost ratios than other levels and splits. When compared to farmers' fertilizer practices, nitrogen management techniques using leaf color charts greatly increased rice crop productivity and profit. Using LCC for N management increased average grain output in rice across villages and seasons by 0.1 to 0.7 t/ha without changing farmers' crop management or fertilizer dosages, which in return gave higher return from their crop (Alam *et al.* 2005). Pandu *et al.* (2022) noted that compared to merely administering the appropriate nitrogen dose, the nitrogen management through LCC 3 generated net returns and a Benefit: Cost ratio that were considerably higher. Sapkota *et al.* (2020) pointed out that rational N management is necessary to balance the systems' economic and environmental performance in order to sustainably boost the economic production of rice-wheat cropping systems on small and medium-sized farms.

Silicon fertilizer application

Silicon treatment has a good effect on plant dry matter, height and yield and is an environmentally safe method of fostering plant development. Since silicon is non-corrosive and non-polluting to plants, even in excess, its application reduces a varied range of biotic and abiotic stresses (Kowalska *et al.* 2021). Growth characteristics such as plant height, number of leaves per plant, and dry matter in the roots and shoots increase when cucurbitaceous crops are treated with silicic acid (Alam *et al.* 2021). When water melon was fertilized with silicon, the number, weight, and overall production of fruits increased (do Nascimento *et al.* 2020). Additionally, Si is known to make plants more rigid and upright, which promotes improved nutrient translocation and photosynthetic activity, perhaps increasing growth characteristics and also dry matter accumulation (Sirisuntornlak *et al.* 2021). Through a number of mechanisms, such as osmotic adjustment, changed gas exchange characteristics, improved mineral absorption from soil and an enhanced antioxidant defence system, silicon has positive effects under water-deficit stress, including improved seed germination, higher dry matter accumulation, and a faster rate of photosynthetic reaction (Alam *et al.* 2021). Applying silicon to rice improves canopy photosynthesis, increases root oxidative power, preserves rice water balance and reduces water loss (Li *et al.* 2023).

i) ***Effect of silicon fertilization on growth and yield characteristics of crop***

Effect of silicon on variety of crops with respect to growth and yield characteristics have been tabulated in Table 1.

Silicon application in crops significantly effects the growth of crops. The application and absorption of silicon in plants, strengthens the stems and leaves, which may be contributing to growth enhancement (Jinger *et al.* 2023). Silicon fertilization is also linked with reduced chlorophyll destruction, higher root biomass, higher uptake, increased leaf area, increased photosynthetic activity which strengthens the carbon sink by increased dry matter accumulation, stem stiffness and better plant stand (Gerami *et al*. 2012, Naik *et al.* 2022 and Vasudevan and Thiyagarajan 2022). Applying silicon reduces stomata width, forms silica cuticles on leaves, maintains water balance, avoids vessel compression, and decreases water loss through transpiration, according to Othmani *et al.* (2021).

Maghsoudi *et al.* (2016) also reported that applying silicon typically boosted the levels of carotenoids, membrane stability, and chlorophyll a, b and total chlorophyll. Si deposition in plant stems has been reported to enhance the thickness of the cell wall, vascular bundles, and sclerenchyma content, all of which plays a positive role towards plants resistance to lodging (Jinger *et al*. 2023).

Silicon fertilization increased grain numbers per panicle as well as test weight of grains which has a positive impact on yield of crop (Li *et al.* 2023). An increased spike formation impacting weight and length of wheat is observed when silicon is applied in liquid form I soil or leaves of wheat (Kowalska *et al.* 2021). Silicon application improved the sunflower plants' ability to absorb CO_2, expanded their leaf area, and improved the number and quality of flowers (de MeloPeixoto *et al.* 2022). Because flag leaves have a high concentration of N, P, K and Si, hence application of Si to white oat increased its biomass production, number of grains per panicle, and grain yield, according to Othmani *et al.* (2021).

ii) ***Effect of Si fertilization on soil characteristics***

Although silicon is abundant in soil, but availability of silicon in soil solution is less, and the soil's capacity to provide available silicon to crops is the major factor behind silicon uptake and better crop growth (Jawahar and Vaiyapuri 2013). Silicon has a high affinity for collecting nitrogen in the nitrate and ammonium forms, which are then loaded into the xylem stream of the maize crops' shoot component with the help of transporter gene participation (Naik *et al*. 2022).

Prakash *et al.* (2019) inferred that the pH of acidic soil increased and the pH of alkaline soil decreased under both field capacity and submergence, irrespective of the Si doses in the form of diatomite. Silicon fertilizers contain calcium which helps in neutralizing acidic soils, which enhances crop growth (Sahrawat 2005). After 15 and 30 days of incubation, the soil's pH may have increased due to improved ionization and the dissolution of applied Si fertilizer material (Camargo *et al.* 2007).

The application of silicon (Si) improved the availability and efficiency of nitrogen in the soil, which progressively improved as silicon levels

Table 1. Effect of silicon on growth and yield characteristics of different crops.

Sl. No.	Crops	Observations	Literature cited
1	Maize	With application of seed priming with 1.5 mm of sodium meta silicate & foliar application of silicic acid @ 0.2% increase in plant height (7%), dry matter production (11%), cob length(7%), cob weight (8%), no. of grains/cob (13%), grain yield (11.3%), stover yield (2.1%) was observed as compared to control	Manoj Kumar *et al.* (2018)
		Silicon dose (1 mm) application increased in plant height (8.2%), leaf area (9.5%), cob length (10%), number of kernels per cob (47%), grain yield (g/plant) increased 12% as compared to control	Sirisuntornlak *et al.* (2021)
		With application of 1.8 mmol/l of silicic acid increased accumulated nitrogen in the plant shoots (31%), accumulated Si in the plant shoots mg per pot (90%), plant shoot dry mass (16.5%)	da Silva *et al.* (2021)
		Application of 150 kg silicon/ha increased dry matter production of shoot (11.3%), dry matter production of root (5%), silicon content in the shoot (15%), silicon content in the root (26%) when compared to control	Vasudevan and Thiyagarajan (2022)
		With application of silicon at 200 kg/ha increased plant height at harvest (25%), dry matter accumulation at harvest (63%), weight per cob (with husk) (63%), number of filled cobs per plant (16%) as compared to control	Naik *et al.* (2022)
2	Rice	Application of 250 kg/ha silicon (potassium silicate) resulted in maximum plant height (18.73%), the number of tiller (66.6%) and 1000 grain weight (47%), silicon content of stem (501%), leaves (421.5%) as compared to control	Hoseinian *et al*. (2020)
		There was an increment in plant height (14.7%), no. of tiller/m^2 (19.6%), no. of panicle/m^2 (22%), 1000-grain weight (17%), leaf area index (77%), grain yield (89.7%), straw yield (58.7%) as compared to control	Pati *et al.* (2016)
		With application of silicon 15% increased in panicle length (2.5%), no. of spikelets/panicle (18%), no. of grains/panicle (9.8%), 1000-grain weight (1.1%)	Jan *et al*. (2018)
		With application of Si dose 300 kg/ha increase in plant height (9%), shoot dry matter (8.5%), number of panicle/plant (58%), panicle length (8.6%), number of spikelet/panicle (12.7%), grain yield (40%), shoot silicon content (28%) as compared to control	Ullah *et al.* (2018)
3	Rice-wheat cropping system	Application of silicon doses 120 kg/ha increased available P (kg/ha) (29%), available Si (mg/kg) (8.1%), gross returns (INR/ha) (40%), net returns (INR/ha) (70%), B:C ratio (70%) as compared to control	Jinger *et al.* (2023)
4	Wheat	Increase in spike length (11%), spike weight (8.5%), number of grains per spike (16.2%), 1000 grains weight (12 %), grain yield (60.6%), photosynthetic rate (97%) by silicon application	Jeer *et al.* (2021)
5	French bean	With application of 5 g/kg of silicon increased plant height (130%), pod length (151%), pod yield/plant (122%) with application of 10 g/kg of silicon as compared	Kumar *et al.* (2020)
6	Mungbean	With application of 2 kg/ha of silicon significantly increased in plant height (10%), leaf area (36%), dry biomass (23%), seed yield (70%).	Mahmood *et al.* (2016)
7	Chickpea	With application of 1 mm silicon increased grain yield (6.7%), leaf number (11.7%), total dry matter (30%) as compared to control	Zamani *et al.* (2017)
8	Groundnut	Application of potassium silicate @ 0.4% increased plant height (4.45%), specific leaf area (2.29%), relative water content (7.46%), pod yield (89.86%)	Mikhina *et al*. (2019)
		Application of 100 mg/l silicon resulted significant increase in plant height (cm) (20%), no of pods per plant (45%), 100-seed weight (g) (25%), pods per plant (36%), pod yield (17%), dry matter (21%),oil content (3.44%) when compared to control	Khalaf *et al.* (2020)

Table 1. Continued.

Sl. No.	Crops	Observations	Literature cited
9	Sunflower	With application of 100 mg/kg of silicon there was a significant increase in head diameter (22–30%), leaf area (26%), higher achene yield (17–23%), achene weight (25%) and membrane stability index (28%), shoot dry weight (31%), head diameter (30%)	Hussain *et al.* (2018)
		Significant increase in leaf number (25%), total leaf area (21%), accumulated Si in leaf (782%), leaf N (13%) with application of 3.36 Si (g/l)	de MeloPeixoto *et al.* (2022)
10	Soybean	Foliar application of silicic acid @ 2 ml/l significantly increased haulm yield (85%), pod yield (79%), seed yield (89.6%) as compared to control	Shwetha Kumari and Prakash (2018)
11	Rapeseed	Foliar application of potassium silicate 4 g/l resulted in highest seed yield (kg/ha) (10%), oil yield (kg/ha) (9%) as compared to control	Moghadam *et al.* (2022)
		Foliar application of potassium silicate (3 g/l) significantly influenced silique per plant (16%), seed per silique (21%), 1000-seed weight (14%), oil content (2.6%) as compared to control	Shirani Rad *et al.* (2022)
12	Sesamum	Application of silicon 44 kg/ha increased plant height (7.3%), number of branches per plant (8.4%), number of capsules per plant (5.5%), biological yield (45%), seed yield (22%) as compared to control	Manaf *et al.* (2020)
13	Pearl millet	Application of 3.36 g/l of silicon significantly increased plant height (9%), leaf area (27%), stomatal conductance (44.6%), transpiration (101.3%), photosynthesis (76%), shoot dry matter production (15%) as compared to control	Flores *et al.* (2021)
		Application of 6 mg/l silicon increased seeds per ear (4%), 1000-seed weight (66%), ear length (26%), grain yield (10%), biological yield (33%) as compared to control	Wasaya *et al.* (2022)
14	Finger millet	With application of 3 g calcium silicate/kg soil there was a significant increase in plant height (54%), root fresh weight (144%), root dry weight (128%), shoot fresh weight (221%), shoot dry weight (157%), number of leaves per plant (14%)	Jadhao and Rout (2020)
		There was increment with application of 4 ml/l of silicon on grain yield (9%), straw yield (17%), test weight (3%), Si content in straw (23.3%) and grains (26%), Si uptake (54%) when compared with control	Sandhya *et al.* (2020)
15	Kodo millet	Application of 75 kg silicon/ha increased the plant height (43%), no. of tillers/hill (74%), dry matter production (145%), no. of panicles/hill (209%), number of filled grains per panicle (52%), grain yield (90%), straw yield (200%) as compared with no silicon application	Jawahar *et al.* (2022)
16	Grapes	Increased bunch weight (267%), berry length (4.6%), berries per bunch (90%), berry firmness (9.7%) with application of amorphous silica fertilizer as compared to control treatment	do Nascimento *et al.* (2023)
17	Tuberose	There was increment in plant height (90%), number of leaves/plant (60%), root length (43%), stalk length (54%), spike length/stalk (76%), floret number/spike (47%), floret length (14%), floret fresh weight (77%), bulb fresh weight (27%) with application of 150mg/l silicon as compared to control	Shahzad et al. (2021)

increased (Singh *et al.* 2005a). In acidic soil, the extractable Si level increased 30 days after incubation, decreased to 45.61 ppm at 90 days, and increased to 55.72 ppm Si at 120 days (Prakash *et al.* 2019).

Enhanced root exudation of organic acids like citrate and malate, as well as enhanced expression of the phosphorus transporter gene, are associated with phosphorus uptake (Naik *et al.* 2022). Applying 600 kg/ha of diatomite during submergence resulted in the highest Si concentration both in field capacity as well as in submerged conditions (Prakash *et al.* 2019). Application of Si increases phosphorus use efficiency due to increased phosphorus absorption by plants resulting from higher availability of phosphorus in soil as well as decreased phosphorus fixation in soil layers (Li *et al.* 2023 and Greger *et al.* 2018). When rice receives the proper doses of other fertilizers' and Si in a balanced manner, its total absorption of nitrogen, phosphorus, and potassium is greatly enhanced (Chanchareonsook *et al.* 2002).

iii) *Interaction effect of silicon with other nutrients*

Through a synergistic effect, applied Si can raise the optimum rate of nitrogen, potentially increasing yields through effective use of nitrogen fertilizers (Savant *et al.* 1997). Through amino acid biosynthesis, silicon may help green-pigmented cells produce nitrogen-bonded protein molecules in chlorophyll a and b and increase their metabolism (Jan *et al.* 2018). Applying silicon in sweet corn's @ 200 kg/ha increases yield, quality and nitrogen usage efficiency (Naik *et al.* 2022).

Silicon fertilization promotes a positive interaction between phosphorus and silicon enhancing the root growth which leads to higher vegetative growth, causing an increase in dry matter accumulation in rice (Gholami and Falah 2013). The intake of phosphorus increased due to Si fertilization in soil, resulting to enhanced uptake of phosphorus in grain and straw (Sreenivasan & Prakash 2017). Si and P fertilization work together to increase crop yield, water efficiency, and the economics of aerobic rice-wheat cropping systems (Li *et al.* 2023). Si alters the microbial community's dynamics, reduces P sorption by soil minerals because of P and Si competition, or raises the amount of P available in the soil by changing the pH (Li *et al.* 2023). Using a basal dose of 120 kg Si and 90 kg P_2O_5/ha in a rice-wheat cropping system improved soil health, crop yield, water productivity, profitability and reduced lodging (Jinger *et al.* 2023). Silicon have a positive interaction with potassium enhancing yield moreover concentration of silicon is found to be higher in plants as compared to nitrogen and potassium (Savant *et al.* 1997). Combined application of N and Si has been seen to boost nitrate reductase activity, dry matter accumulation and N and Si absorption in above-ground biomass (da Silva *et al.* 2021).

As more silicon was added to the soil, the concentration of zinc steadily dropped and deficiency symptoms of zinc due to deposition of zinc in the form of insoluble Zn_2SiO_4 (Jinger *et al.* 2022). Hence, symptoms of zinc deficiency may also be apparent in rice farming (Bokor *et al.* 2014). High Si accumulation in the root endoderm of rice plants prevented heavy metals from entering the apoplast by acting as a barrier and reducing the permeability of the cell walls of the inner root tissues (Jinger *et al.* 2022).

The quantities of nitrogen, potassium, iron, manganese and zinc in water melon's leaves increased linearly when silicon was added to the soil (do Nascimento *et al.* 2020). Wheat fertilized with Si increases the availability of calcium, magnesium, and phosphorus in soil as well as the absorption of nutrients in plants (Neu *et al*. 2017). Following soil fertilization with silicon, plants absorbed more S, Mg, Ca, B, Fe and Mn from the solution; N, Cu, Zn and K were less readily absorbed, while Cl and Mo were not absorbed (Greger *et al.* 2018).

iv) *Effect of silicon fertilization on economic output*

Application of silicon foliar sprays and giving farm yard manure the soil improved the wheat's growth and yield components as well as quality metrics, increasing the crop's gross returns, net returns, and Benefit-Cost ratio (Hellal *et al.* 2012 and Yadav *et al.* 2017). Jawahar and Vaiyapuri (2013) reported that adding S at 45 kg/ha along with Si at 120 kg/ha increased the rice crop's net return and return per rupee invested. This was due to rice's increased capacity to absorb silicon, which raised grain and straw yields. Rao *et al.* (2018) reported that a significant increase in net income, gross revenue, and the B:C ratio was the result of the inclusion of silicon sources such as rice husk ash (250 kg/ha) and fine silica (50 kg/ha). Yadav *et al.* (2017) reported that using 120 N kg/ha and 15% Si-based nutrient management, a higher B:C ratio and greater net returns (Rs 106107) were attained as a result of the improved grain and straw yield in rice due to increased uptake of silicon.

When 125% RDF, 25 kg/ha of silica GR (soil conditioner), and 12.5 kg/ha of a micronutrient combination were applied to the soil, the net return was higher than the other treatments, at Rs 87932/ha, and the benefit-to-cost ratio was 2.78 (Arigovindan

2022). The highest B:C was achieved when Si was given as a basal dosage due to the higher yield and lower expenses of intercultural activities (Jinger *et al.* 2023). Although the silicon application, which applied 120 kg Si/ha, produced the best gross returns, the net returns were similar to those of 80 kg/ha, which produced the highest B:C (2.02 and 1.96 in both years) (Arigovindan 2022). Lower cultivation costs and higher yield may have contributed to the maximum Benefit:Cost ratio in treatment where silicon was entirely treated as basal, which was followed by treatment 50% basal + 50% during the panicle-initiation stage (Singh *et al.* 2005a).

Effect of fertilization with nitrogen and silicon on nutrient uptake and use efficiency

Dobermann *et al.* (2000) found that site-specific nutrient management (SSNM) improved plant N utilization efficiency by 40% and enhanced plant absorption of N, P and K by 10% to 20%. Similar results was also confirmed by Sarnaik (2010) in wheat, who found applying 150 kg N/ha of nitrogen based on LCC 5 significantly boosted the absorption of potassium, phosphorus and nitrogen. Nitrogen applied in three splits at basal, active tillering, and panicle initiation or half at basal and half at panicle initiation boosts the amount of N, P and K nutrients that are absorbed by rice grain and straw (Geetha and Balasubramanian 2016). In field studies on wheat, maximum total nitrogen uptake (124.86 and 125.67 kg/ha) was noted when nitrogen was supplied @ 120 kg per ha in five splits but more available nitrogen in the soil (235.13 and 232.93 kg/ha) was recorded in the treatment where nitrogen was applied @ 120 kg per ha in four splits (Ramu 2008). Total nitrogen intake was higher in the Dodiga rice variety when LCC-3 nitrogen management was used because of the accumulation of the nutrients in plant parts such as leaves, panicles, grains (Pandu *et al*. 2022).

Up until 120 kg N/ha, agronomic efficiency increases greatly with an increase in N application rate; after that, agronomic efficiency dramatically decreases, according to Mahajan *et al.* (2012). While physiological efficiency increased up to 120 kg N/ha, agronomic usage efficiency and recovery efficiency (%) sharply decreased as the N dose increased from 30 to 150 kg/ha (Dar *et al.* 2000). Compared to complete basal nitrogen application, split nitrogen application reduced losses and enhanced uptake of nutrients of extra nitrogen in rice, demonstrating a higher nitrogen use efficiency (Majumdar *et al*. 2005). When compared to 0, 60 and 90 kg N/ha in wheat, Nasseri *et al.* (2009) found that applying 30 kg N/ha (three splits at planting, tillering, and stem elongation) resulted in a greater nitrogen consumption efficiency of 33.9 kg grain per kilogram of nitrogen. The best split application dose for increasing partial factor productivity of nitrogen was 10 kg N/ha applied every two weeks at LCC 3, as opposed to 20 and 30 kg N/ha (Jayanthi *et al.* 2023). Yields obtained in accordance with general principles suggest that real-time nitrogen management using an LCC can greatly lower fertilizer-N use and increase use efficiencies in rice crops, according to Thind *et al.* (2017).

The silicon-use-efficiency of rice under various rice establishment techniques was investigated by Sharma *et al.* (2021). They came to the conclusion that transplanted rice had a greater silicon efficiency than both dry bed and wet bed rice growth. Additionally, the transplanted rice absorbed silicon from fertilizer more readily. According to MalavJugal and Ramani (2017), silicon has an impact on rice's silicon and nitrogen concentrations as well as nitrogen use efficiency. The optimal quantity of N in terms of use-efficiency was found to be 100 kg N/ha. While physiological efficiency rose at 400 kg Si/ha, silicon reduced both agronomic efficiency and perceived N recovery. It was observed during rice harvest that both N and Si, as well as their interaction, had a considerable influence on the amount of accessible N and Si in the grain and straw.

CONCLUSION

The review emphasized how different farming practices have a major effect on crop productivity and soil health. The split application of nitrogen and the use of the LCC have been shown to enhance nitrogen use efficiency, resulting in improved crop growth and yield. These practices help in the precise timing and dosing of nitrogen, reducing losses and ensuring that crops receive adequate nutrition throughout their growth stages. Silicon (Si) fertilization, on the other hand, has demonstrated remarkable benefits in enhancing plant resilience to biotic and abiotic stresses. Silicon's role in strengthening plant structure, improving photosynthetic efficiency and mitigating the effects of pests and diseases contributes to better growth and yield attributes. Additionally, silicon improves soil characteristics by increasing the availability of essential nutrients and enhancing soil physical properties, which further supports plant health and productivity. When combined, the split application of nitrogen and silicon fertilization creates a synergistic effect that optimizes both growth and yield attributes of various crops. This combination not only boosts the overall yield but also improves the quality of the produce. The economic analysis of these practices indicates a positive return on investment, making them viable options for sustainable agricultural production.

Overall, integrating split nitrogen application and silicon fertilization into crop management strategies offers a promising approach to achieving higher efficiencies in nutrient use, enhancing soil health, and ensuring economic benefits for farmers. Future research should focus on fine-tuning these practices for different crops and environments to maximize their potential benefits and support sustainable agricultural development.

REFERENCES

Achieng GO, Owuor PO, Omondi CO, Abayo GO (2023) Variations in soil pH, N, P and K due to influence of rates, split applications of nitrogen fertilizer and ratoon crop of sugarcane varieties.

Alam A, Hariyanto B, Ullah H, Salin KR, Datta A (2021) Effects of silicon on growth, yield and fruit quality of cantaloupe under drought stress. *Silicon* 13 : 3153—3162.

Alam MM, Ladha JK, Khan SR, Foyjunnessa, Khan AH, Buresh RJ (2005) Leaf color chart for managing nitrogen fertilizer in lowland rice in Bangladesh. *Agronomy Journal* 97 (3) : 949—959.

Arigovindan K (2022) Effect of silicon on yield and economics of transplanted paddy under wetland ecosystem. *Research on Agricultural Sciences and Technology* 2 (1) : 1—3.

Arvind KS, Singh VK, Dwived BS, Sharmaj SK, Yogendra S (2006) Nitrogen use efficiencies using leaf color chart in rice (*Oryza sativa*) wheat (*Triticum aestivum*) cropping system. *Indian Journal of Agricultural Sciences* 76 (11) : 651—656.

Bhavana B, Laxminarayana P, Latha AM, Anjaiah T (2020) Leaf color chart-based nitrogen management-impact on soil properties and nutrient uptake of short duration transplanted rice. *International Journal of Chemical Studies* 8 (3) : 2071—2075.

Bokor B, Vaculík M, Slováková Ľ, Masarovič D, Lux A (2014) Silicon does not always mitigate zinc toxicity in maize. *Acta Physiologiae Plantarum* 36 : 733—743.

Camargo MSD, Pereira HS, Korndörfer GH, Queiroz AA, Reis CBD (2007) Soil reaction and absorption of silicon by rice. *Scientia Agricola* 64 : 176—180.

Chanchareonsook J, Suwannnarat C, Thongpae S, Chanchareonsook S, Thinyai P (2002) Effects of application of chemical fertilizer in combination with silicon on yield and nutrient uptake of rice in an acid sulfate soil. *In Symposium on 17th WCSS,* pp 14.

Dar SA, Bali AS, Shah MH (2000) Effect of different levels and time of nitrogen application on wet-seeded rice in Kashmir Valley. *Oryza* 37 (3) : 244—246.

da Silva ES, de Mello Prado R, Soares ADAVL, de Almeida HJ, dos Santos DMM (2021) Response of corn seedlings (*Zea mays* L.) to different concentrations of nitrogen in absence and presence of silicon. *Silicon* 13 : 813—818.

de MeloPeixoto M, Flores RA, do Couto CA, Pacheco HDN, de Mello Prado R, Souza-Junior JP, Castro-Netto JA, Graciano-Ribeiro D (2022) Silicon application increases biomass yield in sunflower by improving the photosynthesising leaf area. *Silicon* 14 (1) : 275—280. https://doi.org/10.1007/s12633-020-00818-2

Detmann KC, Araújo WL, Martins SC, Sanglard LM, Reis JV, Detmann E, Á Rodrigues F, Nunes-Nesi A, Fernie AR, DaMatta FM (2012) Silicon nutrition increases grain yield, which, in turn, exerts a feed-forward stimulation of photosynthetic rates via enhanced mesophyll conductance and alters primary metabolism in rice. *New Phytologist* 196 (3): 752—762.

Dinesh Kumar SP (2010) Nitrogen Management through leaf color chart in bread wheat (*Triticum aestivum* L.) and Emmer Wheat (*Triticum dicoccum* (Schrank.) Schulb) under irrigated condition. Thesis submitted to the University of Agricultural Sciences, Dharwad.

do Nascimento CWA, da Silva FBV, Lima LHV, Silva JR, de Lima, Veloso V, da Silva FL, de Freitas ST, dos Santos LF, dos Santos MA (2023) Silicon application to soil increases the yield and quality of table grapes (*Vitis vinifera* L.) grown in a semiarid climate of Brazil. *Silicon* 15 (4) : 1647—1658.

Dobermann A, Witt C, Robert PC, Larson WE (2000) SSNM concept for irrigated via system. *Proceedings of fifth International Conference on Precision Agriculture* 25 : 1—7.

do Nascimento CWA, de Souza Nunes GH, Preston HAF, da Silva FBV, Preston W, Loureiro FLC (2020) Influence of silicon fertilization on nutrient accumulation, yield and fruit quality of melon grown in Northeastern Brazil. *Silicon* 12 : 937—943.

Epstein E (1999) Silicon. *Annual Review of Plant Biology* 50 (1) : 641—664.

Flores RA, De Sousa MaP, Bueno AM, De Andrade AF, De Souza JP, Junior De Oliveira Abdala K, De Mello Prado R, Santos GG, Mesquita M (2021) Does foliar silicon application enhance the biomass yield of millet silage, and does it provide significant economic gains ? *Research Society and Development* 10 (4) : In press. e41610414232. https://doi.org/10.33448/rsd-v10i4.14232

Geetha P, Balasubramanian P (2016) Effect of varieties and nitrogen application on growth and yield of aerobic rice. *ORYZA-An International Journal on Rice* 53 (4) : 458—463.

Gerami M, Fallah A, Moghadam MK (2012) Study of potassium and sodium silicate on the morphological and chlorophyll content on the rice plant in pot experiment (*Oryza sativa* L.). *International Journal of Agriculture and Crop Sciences* 4 (10) : 658—661.

Gholami Y, Falah A (2013) Effects of two different sources of silicon on dry matter production, yield and yield components of rice, Tarom Hashemi variety and 843 Lines. *International Journal of Agriculture and Crop Sciences* 5 (3) : 227—231.

Greger M, Landberg T, Vaculík M (2018) Silicon influences soil availability and accumulation of mineral nutrients in various plant species. *Plants* 7 (2) : 41.

Gunasekhar N, Velu V, Malarvizhi P, Ramasamy S, Jayakumar B (2007) Relationship between index leaf nitrogen and leaf color chart (LCC) values in direct wet seeded rice (*Oryza sativa* L.). *Asian Journal of Plant Sciences* 6 (3) : 477—483.

Hellal FA, Zeweny RM, Yassen AA (2012) Evaluation of nitrogen and silicon application for enhancing yield production and nutrient uptake by wheat in clay soil. *Journal of Applied Sciences Research* (February), pp 686—692.

Hoseinian Y, Bahmanyar M A, Sadegh-Zade F, Emadi M, Biparva P (2020) Effects of different sources of silicon and irrigation regime on rice yield components and silicon dynamics in the plant and soil. *Journal of Plant Nutrition* 43 (15) : 2322—2335.

Hussain SA, Farooq MA, Akhtar J, Saqib ZA (2018) Silicon-mediated growth and yield improvement of sunflower (*Helianthus annus* L.) subjected to brackish water stress. *Acta Physiologiae Plantarum* 40 : 1—11.

Jadhao KR, Rout GR (2020) Silicon (Si) enhances the resistance in finger millet genotypes against blast disease. *Journal of Plant Pathology* 102 (4) : 985—1006.

Jan R, Bahar FA, Singh T, Lone R (2018) Effect of nitrogen and silicon on growth and yield attributes of transplanted rice (*Oryza sativa* L.) under Kashmir conditions. *Journal of Pharmacognosy and Phytochemistry* 7 (1) : 328—332.

Jawahar S, Prakash B, Arivukkarasu K, Elayaraja D, Kalaiyarasan C, Suseendran K (2022) Effect of silicon nutrition on growth, yield and economics of Kodomillet. *Indian Journal of Applied & Pure Biology* 37 (3) : 758—764.

Jawahar S,Vaiyapuri V (2013) Effect of sulfur and silicon fertilization on yield nutrient uptake and economics of rice. *International Research Journal of Chemistry* 1 : 34—43.

Jayanthi T, Basavaraja PK, Nagaraju RC, Mallesh BC, Prakash NB (2023) Nutrient use efficiency as influenced by fertigation of water-soluble fertilizers in aerobic rice. *The Pharma Innovation Journal* 12 (2) : 1175—1183.

Jeer M, Yele Y, Sharma KC, Prakash NB (2021) Exogenous application of different silicon sources and potassium reduces pink stem borer damage and improves photosynthesis, yield and related parameters in wheat. *Silicon* 13(3) : 901—910.

Jinger D, Dhar S, Dass A, Sharma VK, Jhorar P, Paramesh V, Gupta G, Parihar M, Kumar D, Singh S, Samal I, Bhoi TK, Jat RA (2023) Combined fertilization of silicon and phosphorus in aerobic rice-wheat cropping and its impact on system productivity, water use efficiency, soil health, crop resilience and profitability. *Silicon* 15 (17) : 7609—7620.

Jinger D, Dhar S, Dass A, Sharma VK, Paramesh V, Parihar M, Joshi E, Singhal V, Gupta G, Prasad D, Vijayakumar S (2022) Co-fertilization of silicon and phosphorus influences the dry matter accumulation, grain yield, nutrient uptake and nutrient-use efficiencies of aerobic rice. *Silicon,* pp 1—15.

Khalaf A, Hassan MS, Ismaeil HA, Awny A (2020) Impact of foliar application of silicon and selenium on growth characters, yield, physico-chemical characters, oil ingredients of peanut (*Arachis hypogaea* L.) variety Giza 6 under different planting dates. *Asian Journal of Advanced Agricultural Research* 12(1) : 21—28.

Kondo M, Singh CV, Agbisit R, Murty MVR (2005) Yield response to urea and controlled-release urea as affected by water supply in tropical upland rice. *Journal of Plant Nutrition* 28 (2) : 201—219.

Kowalska J, Tyburski J, Jakubowska M, Krzymińska J (2021) Effect of different forms of silicon on growth of spring wheat cultivated in organic farming system. *Silicon* 13 : 211—217.

Kumar V, Kumar P, Khan A (2020) Optimization of PGPR and silicon fertilization using response surface methodology for enhanced growth, yield and biochemical parameters of french bean (*Phaseolus vulgaris* L.) under saline stress. *Biocatalysis and Agricultural Biotechnology* 23 : 101—463.

Lal R (2004) The potential of carbon sequestration in soils of South Asia. In: Conserving soil and water for society: Sharing solutions, ISCO 2004 – 13th International soil conservation organization conference – Brisbane, July 2004, 134 pp 1—6.

Li C, He B, Zhang S, Du J, Teng Y, Yang L, Li Y, Geng Y (2023) Effect of silicon fertilizer on the morphology, yield and quality of rice. *Silicon*, pp 1—10.

Lindsay WL (1979) Chemical equilibria in soils. http://ci.nii.ac.jp/ncid/BA06871045

Lone NAH, Najar NGR, Ganie NMA, Mehmood NMA (2017) Nitrogen management in rice through leaf color chart under Kashmir conditions. *International Journal of Engineering Research and Technology* V6 (06) : 50—54. https://doi.org/10.17577/ijertv6is060045

Maghsoudi K, Emam Y, Pessarakli M (2016) Effect of Silicon on photosynthetic gas exchange, photosynthetic pigments, cell membrane stability and relative water content of different wheat cultivars under drought stress conditions. *Journal of Plant Nutrition* 39 (7) : 1001—1015.

Mahajan G, Chauhan BS, Timsina J, Singh PP, Singh K (2012) Crop performance and water-and nitrogen-use efficiencies in dry-seeded rice in response to irrigation and fertilizer amounts in Northwest India. *Field Crops Research* 134 : 59—70.

Mahapatra P, Panda D, Mohanty S K (1990) Efficiency of urea based fertilizers for wetland rice (*Oryza sativa*). *The Journal of Agricultural Science* 114 (2) : 187—191.

Mahmood S, Daur I, Al-Solaimani SG, Ahmad S, Madkour MH, Yasir M, Hirt H, Ali S, Ali Z (2016) Plant growth promoting rhizobacteria and silicon synergistically enhance salinity tolerance of mung bean. *Frontiers in Plant Science* 7, 876.

Maiti D, Das DK, Karak T, Banerjee M (2004) Management of nitrogen through the use of leaf color chart (LCC) and soil plant analysis development (SPAD) or chlorophyll meter in rice under irrigated ecosystem. *The Scientific World Journal* 4 : 838—846.

Ma JF, Takahashi E (2002) Soil, fertilizer and plant silicon research in Japan. *Elsevier*. https://doi.org/10.1016/b978-0-444-51166-9.x5000-3

Majumdar B, Venkatesh MS, Kumar K, Patiram P (2005) Nitrogen requirement for lowland rice (*Oryza sativa*) in valley lands of Meghalaya. *The Indian Journal of Agricultural Sciences* 75 (8) : In press.

Majumder S, Shankar T, Maitra S, Adhikary R, Sairam M (2023) Effect of nutrient omission on growth and productivity of *rabi* rice. *Crop Research* 58 (3-4) : 129—135.

MalavJugal K, Ramani V (2017) Effect of silicon on nitrogen use efficiency, yield and nitrogen and silicon contents in rice under loamy sand soil. *Research Journal of Chemistry and Environment* 21 (4) : 58—63.

Manaf A, Shoukat M, Sher A, Qayyum A, Nawaz A (2020) Seed yield and fatty acid composition in sesame (*Sesamum indicum* L.) as affected by silicon application under a semi-arid climate. *Agrociencia* 54 (3) : 367—376.

Manoj Kumar S, Karthikeyan R, Maragatham N (2018) Effect of silicon fertilization on growth and yield of hybrid maize under irrigated and rainfed conditions. *Madras Agricultural Journal*, 105 (10–12) : In press. https://doi.org/10.29321/maj.2018.000198

Mikhina M, Rani PS, Latha P, Chandrika V (2019) Role of silicon and salicylic acid in growth and yield of groundnut under moisture stress conditions. *Andhra Pradesh Journal of Agricultural Science* 5 (4) : 229—236.

Moghadam MSK, Rad AHS, Khodabin G, Jalilian A, Bakhshandeh E (2022) Application of silicon for improving some physiological characteristics, seed yield, and oil quality of rapeseed genotypes under late-season drought stress. *Journal of Soil Science and Plant Nutrition* 22 (3) : 2872—2890.

Naik BSS, Sharma SK, Pramanick B, Chaudhary R, Yadav SK, Tirunagari R, Gaber A, Hossain A (2022) Silicon in combination with farmyard manure improves the productivity, quality and nitrogen use efficiency of sweet corn in an organic farming system. *Silicon* 14 (10) : 5733—5743.

Nasseri A, Ali Fallahi H, Siadat A, Eslami-Gumush Tappeh K (2009) Protein and N-use efficiency of rainfed wheat responses to supplemental irrigation and nitrogen fertilization. *Archives of Agronomy and Soil Science* 55 (3) : 315—325.

Neu S, Schaller J, Dudel EG (2017) Silicon availability modifies nutrient use efficiency and content, C:N:P stoichiometry and productivity of winter wheat (*Triticum aestivum* L.). *Scientific Reports,* pp 7. https://doi.org/10.1038/srep40829

Othmani A, Ayed S, Bezzin O, Farooq M, Ayed-Slama O, Slim-Amara H, Ben Younes M (2021) Effect of silicon supply methods on durum wheat (*Triticum durum* Desf.) response to drought stress. *Silicon* 13 : 3047—3057.

Pandu U, Bhairappanavar ST, Jayadeva HM, Raddy G, Harisha S (2022) Influence of STCR based fertilizer recommendations on growth and yield of paddy in command area of Hosahalli village tank. *The Pharma Innovation Journal* 11 (9) : 1986—1990.

Pati S, Pal B, Badole S, Hazra GC, Mandal B (2016) Effect of silicon fertilization on growth, yield and nutrient uptake of rice. *Communications in Soil Science and Plant Analysis* 47 (3) : 284—290.

Porpavai S, Babu M, Nadanassababady T, Jayapaul P, Bala Subramanian V (2000) Standardizing critical leaf color chart (LCC) values for direct seeded rice establishment systems. In: *Abstracts of the 3rd CREMNET India Workshop Cum-meeting on Direct Seeding and Seeders in Rice, Mysore, India, August* 11 : 18—19.

Prakash NB (2002) Status and utilization of Si in Indian rice farming. *Second Si in Agriculture Conference* 1 : 266—273.

Prakash NB, Anitha MS, Sandhya K (2019) Behavior of different levels and grades of diatomite as Si source in acidic and alkaline soils. *Silicon* 11 : 2393—2401.

Premalatha BR (2001) Integrated nitrogen management in direct seeded rainfed lowland rice through leaf color chart (LCC). MSc (Agric) thesis. University of Agriculture Science, Dharwad, India.

Premalatha PR, Angadi VV (2005) Crop-need-based N management through leaf color chart (LCC) in direct dry-seeded rainfed lowland rice. *Mysore Journal of Agricultural Sciences* 39 (1) : 140—143.

Ramu N (2008) Nitrogen management in wheat under irrigated conditions. MSc (Agric) *thesis*. University of Agricultural Science, Dharwad, Karnataka (India).

Rao GB, PI PY, Syriac EK (2018) Effect of silicon fertilization on yield attributing factors, yield and economics of rice cultivation. *Journal of Pharmacognosy and Phytochemistry* 7 (2) : 1381—1383.

Reddy BGM, Pattar PS (2006) Leaf color chart-a simple and inexpensive tool for nitrogen management in transplanted rice (*Oryza sativa*). *The Indian Journal of Agricultural Sciences* 76 (5) : 289—292. http://epubs.icar.org.in/ejournal/index.php/IJAgS/article/download/2871/964

Sahrawat KL (2005) Fertility and organic matter in submerged rice soils. *Current Science,* pp 735—739.

Sandhya TS, Prakash NB, Nagaraja A, Reddy NYA (2020) Effect of foliar silicic acid on growth, nutrient uptake and blast disease resistance of finger millet *(Eleusine coracana* (L.) Gaertn.). *International Journal of Current Microbiology & Applied Science* 9 (4) : 2111—2121.

Sapkota TB, Singh LK, Yadav AK, Khatri-Chhetri A, Jat HS, Sharma PC, Jat ML, Stirling CM (2020) Identifying optimum rates of fertilizer nitrogen application to maximize economic return and minimize nitrous oxide emission from rice–wheat systems in the Indo-Gangetic Plains of India. *Archives of Agronomy and Soil Science* 66 (14) : 2039—2054.

Sarnaik PH (2010) Nitrogen management in hybrid maize (*Zea mays* L.) through leaf color chart. MSc (Agric) thesis. University of Agricultural Science, Dharwad, Karnataka (India).

Savant NK, Datnoff LE, Snyder GH (1997) Depletion of plant-available silicon in soils : A possible cause of declining rice yields. *Communications in Soil Science and Plant Analysis* 28 (13-14) : 1245—1252.

Savant NK, Snyder GH, Datnoff LE (1996) Silicon management and sustainable rice production. *Advances of Agronomy* 58 : 151—199. doi:10.1016/S0065-2113(08)60255-2

Shahzad S, Ali S, Ahmad R, Ercisli S, Anjum MA (2021) Foliar application of silicon enhances growth, flower yield, quality and postharvest life of tuberose (*Polianthes tuberosa* L.) under saline conditions by improving antioxidant defense mechanism. *Silicon* 14 (4) : 1511—1518.

https://doi.org/10.1007/s12633-021-00974-z

Sharma PP, Jawahar S, Kalaiyarasan C, Sriramachandrasekharan MV (2021) Effect of different silicon sources on yield, nutrient uptake and silicon use efficiency of rice under different establishment methods. *Annals of the Romanian Society for Cell Biology*, pp 7478 —7486.

Shirani Rad AH, Eyni-Nargeseh H, Shiranirad S, Heidarza deh A (2022) Effect of potassium silicate on seed yield and fatty acid composition of rapeseed (*Brassica napus* L.) genotypes under different irrigation regimes. *Silicon* 14 (17): 11927—11938.

Shwetha Kumari U, Prakash NB (2018) Effect of foliar application of silicic acid on soybean yield and seed quality under field conditions. *Journal of the Indian Society of Soil Science* 66 (4) : 406—414.
https://doi.org/10.5958/0974-0228.2018.00051.8

Singh AK, Singh R, Singh K (2005a) Growth, yield and economics of rice (*Oryza sativa*) as influenced by level and time of silicon application. *Indian Journal of Agronomy* 50 (3) : 190—193.

Singh B, Gupta RK, Singh Y, Gupta SK, Singh J, Bains JS, Vashishta M (2006a) Need-based nitrogen management using leaf color chart in wet direct-seeded rice in northwestern India. *Journal of New Seeds* 8 (1) : 35—47.

Singh F, Kang JS, Singh A, Singh T (2015) Nutrient uptake, nutrient availability and quality parameters of mechanically transplanted rice (*Oryza sativa* L.) under split doses of nitrogen. *Agricultural Science Digest-A Research Journal* 35 (2) : 95—100.

Singh KK, Singh K, Singh R, Singh Y, Singh C S (2006b) Response of nitrogen and Si levels on growth, yield and nutrient uptake of rice (*Oryza sativa* L.). *Oryza* 43 : 220—223.

Singh RP, Singh CM, Singh AK (2005b) Effect of crop-establishment methods, weed management and split nitrogen application on weeds and yield of rice (*Oryza sativa*). *The Indian Journal of Agricultural Sciences* 75 (5) : In press.

Sirisuntornlak N, Ullah H, Sonjaroon W, Anusontpornperm S, Arirob W, Datta A (2021) Interactive effects of silicon and soil pH on growth, yield and nutrient uptake of maize. *Silicon* 13 : 289—299.

Sreenivasan ST, Prakash NB (2017) Evaluation of calcium silicate, rice hull and rice hull ash as silicon sources in wetland rice on acidic and alkaline soils. *Journal of the Indian Society of Soil Science* 65 (4) : 428—434.

Srinivasagam K, Stephan H (2013) Integrated nutrient management and LCC based nitrogen management on soil fertility and yield of rice (*Oryza sativa* L.). *Scientific Research and Essays* 8(41) : 2059—2067.
https://doi.org/10.5897/sre2013.5643

Sun J, Li W, Li C, Chang W, Zhang S, Zeng Y, Zeng C, Peng M (2020) Effect of different rates of nitrogen fertilization on crop yield, soil properties and leaf physiological attributes in banana under subtropical regions of China. *Frontiers in Plant Science* 11 : 613—760.

Thind HS, Buttar GS, Kaur S, Kaur S, Bhowmik A (2017) Site-specific fertilizer nitrogen management for timely sown irrigated wheat (*Triticum aestivum* L. and *Triticum turgidum* L. ssp. durum) genotypes. *Nutrient Cycling in Agroecosystems* 109 : 1—16.

Thind HS, Gupta RK (2010) Need based nitrogen management using the chlorophyll meter and leaf color chart in rice and wheat in South Asia: A review. *Nutrient Cycling in Agroecosystems* 88 (3) : 361—380.

Ullah H, Luc PD, Gautam A, Datta A (2018) Growth, yield and silicon uptake of rice (*Oryza sativa*) as influenced by dose and timing of silicon application under water-deficit stress. *Archives of Agronomy and Soil Science* 64 (3) : 318—330.

Vasudevan V, Thiyagarajan C (2022) Screening maize hybrids for silicon efficiency to improve the growth and yield on silicon deficient soils. *Silicon* 14 (15) : 9711—9720.

Wang H, Hu R, Chen X, Zhong X, Zheng Z, Huang N, Xue C (2017) Reduction in nitrogen fertilizer use results in increased rice yields and improved environmental protection. *International Journal of Agricultural Sustainability* 15 : 681—692.

Wasaya A, Hassan J, Yasir TA, Ateeq M, Raza MA (2022) Foliar application of silicon improved physiological indicators, yield attributes, and yield of pearl millet (*Pennisetum glaucum* L.) under terminal drought stress. *Journal of Soil Science and Plant Nutrition* 22 (4) : 4458—4472.

West PC, Gerber JS, Engstrom PM, Mueller ND, Brauman KA, Carlson KM, Cassidy ES, Johnston M, MacDonald GK, Ray DK, Siebert S (2014) Leverage points for improving global food security and the environment. *Science* 345 (6194) : 325—328.
https://doi.org/10.1126/science.1246067

Wuepper D, Clech SL, Zilberman D, Mueller N, Finger R (2020) with minor processing by Our World in Data. "Which countries overapplied nitrogen without gains in crop yields?" Retrieved June 6, 2024 from https://ourworldindata.org/grapher/yield-gap-vs-nitrogen-pollution

Yadav PI, Manu CR, Abraham N (2017) Silicon nutrition for sustainable rice production in iron toxic laterite soils of Kollam District in Kerala. *Journal of Krishi Vigyan* 5 (2) : 150—153.

Yogendra ND, Kumara BH, Chandrashekar N, Prakash NB, Anantha MS, Jeyadeva HM (2014) Effect of silicon on real-time nitrogen management in a rice ecosystem. *African Journal of Agricultural Research* 9 (9) : 831—840.

Zamani GR, Shaabani J, Izanloo A (2017) Silicon effects on the growth and yield of chickpea under salinity stress. *International Journal of Agriculture & Biology* 19 : 1475—1482.
10.17957/IJAB/15.0446