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Advances in zinc and silicon applications for maize yield enhancement: A review on nutrient efficiency and stress tolerance

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Keywords: *Maize, Silicon, Antioxidant, Zinc, Plant defence, Resistance, sustainable agriculture*

Abstract

Maize is a crucial crop worldwide, and various environmental stresses often threaten its yield. Recent advancements in applying zinc (Zn) and silicon (Si) have shown promising results in enhancing maize yield and stress tolerance. Silicon application in maize plants enhances resistance against Maydis Leaf Blight and increases leaf gas exchanges, chlorophyll fluorescence parameters, and antioxidant activities. Silicon alters phytophagous insects' attack by stimulating deterrent effects on oviposition site selection and affects nutrient digestion, decreasing leaf palatability and digestibility. Silicon contributes to stress mitigation in maize plants under potassium deficiency by enhancing nutrient use efficiency, photosynthetic rate, and dry matter production. Zn oxide nanoparticles have been studied for their synthesis, characterization, modification, and applications in food and agriculture. Silicon plays a crucial role in plant defence against biotic stress, acting as a barrier against insects, fungi, and bacteria, and stimulating the production of defence compounds. We discuss the effects of conventional and nano-scale Zn and Si fertilizers on maize growth, economic and metabolic profiles, and stress responses. The review highlights the potential benefits of combining Zn and Si applications for improved maize productivity under stressful conditions and summarizes the current state of knowledge on using Zn and Si in maize cultivation, focusing on nutrient efficiency and stress tolerance.

Abbreviations

ADF%: acid detergent fiber
BOZ: Bio-activated organic fertilizers
CAT: catalase
HMs: heavy metals
HIPVs: herbivore-induced plant volatiles
JA: jasmonic acid
Lsi1: Low silicon1
NPs: nanoparticles
NUE: nutrient use efficiency
PGPB: plant growth-promoting bacteria
POD: peroxidase
QPM: quality protein maize
ROS: reactive oxygen species
SAR: specific absorption rate
SOD: superoxide dismutase
TSP: total soluble proteins

Introduction

Maize is the second most popular crop in the world, farmed in temperate, subtropical, and tropical climates. Maize has several varieties, including field, sweet, and baby corn. There are several varieties of field corn, including high-oil, waxy, and quality protein maize (QPM) varieties. The agricultural sector faces significant losses due to different stresses consequently, farmers major goal is adopting appropriate genotypes and management approaches to achieve resilience against such stress (Mariani and Ferrante 2017). Maize upon getting exposed to abiotic stresses; drought, salt, or heat stresses gives leaf responses at metabolome and transcriptome levels marked by the accumulation of amino acids including proline, arginine, and γ-aminobutyrate as well as the depletion of important glycolysis and tricarboxylic acid cycle intermediates (Joshi *et al.* 2021). Regardless of the particular element deficiency, oxidative stress is indicated by decreased dry matter production, increased lipid peroxidation, and early senescence of older plant portions in maize.

Mineral nutrients play a crucial role in plant defence by serving as a first line of defence against pests and pathogens (Walters and Bingham 2007, Jakob and Marschner 2012). Essential and beneficial elements activate enzymes that enhance the defence mechanism in plants directly as it promotes the production of defence metabolites, and indirectly, by altering root exudates, rhizosphere pH, and microbial activity (Datnoff *et al.* 2007). They enhance plant protection strategies by acting as a physical barrier (shape, surface properties, hairs, color, etc.) and mechanical strengthening (fibers, silicon) (Yuksel *et al.* 2012).

Silicon (Si), the second most abundant element in Earth's crust, enhances photosynthesis efficiency, and root water absorption, regulates nutrient uptake, reduces transpiration rate, and increases the production of compatible solutes. Its uptake by root cells through the soil and further transport is aquaporin protein family based Lsi1 (Low silicon1) anion transporter that belongs to nodulin-26 like major intrinsic protein, respectively (Ranjan *et al.* 2021). It also improves soil fertility by improving microbial biomass and colonies (Rajput *et al.* 2021). The imperious role of Si in instigating plant growth and development through the regulation of overall plant physiological and metabolic characteristics (Souri *et al.* 2021). Plant cell wall gets strengthened due to Si accumulation, strengthening plant by accelerating lignin, phenolic, volatile, and non-volatile compounds, and physiological modifications like trichomes (Murali-Baskaran *et al.* 2021). Si attracts natural enemies against arthropods that attack plants, increasing biological control. Soluble Si upon interactions with jasmonic acid (JA) influences plant defence signaling by boosting herbivore-induced plant volatiles (HIPVs) which are crucial for plant defence signaling (Reynolds *et al.* 2016a). An in-depth understanding of plants physiological and biochemical responses induced by silicon revealed enhanced activities of defence (chitinase, β-1,3-glucanase, phenylalanine ammonia-lyase, polyphenol oxidase, peroxidase, and lipoxygenase) and antioxidative (ascorbate peroxidase, catalase, superoxide dismutase, and glutathione reductase enzymes) activities (Lata-Tenesaca *et al.* 2024a).

Silicon deposition in cell walls provides mechanical strength against lodging, particularly in the form of phytoliths that act as a protective barrier through stress signaling pathways (Coskun *et al.* 2016), mitigating osmotic and ionic stressors allied with drought and salinity (Malik *et al.* 2021) (Figure1). Controlling stomatal opening and closing adjusts plant water balance and induces plant defence-linked signals (Wang, Wang, *et al.* 2021), additionally mitigates water-scarce stress by regulating physiological activities in plants (photosynthesis, transpiration, root water, and nutrient uptake) (Ma 2004). Nanoparticles gaining immense popularity because of their size, flexibility, biocompatibility, large surface area, and functionality in wider sectors like agriculture, pharmaceuticals, etc. Scientific evidence revealed the significance of silicon nanoparticles (NPs) in plant growth and development (Okeke *et al.* 2023).

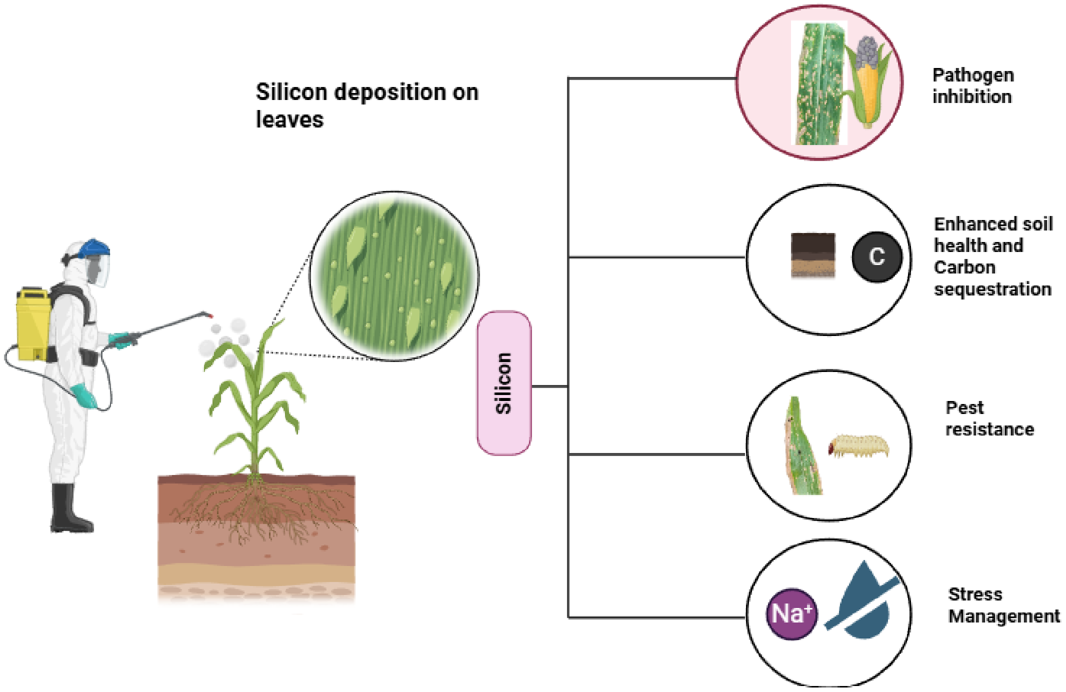

Fig. 1 - Silicon: A Multi-Functional Shield for Crop Protection and Soil Health

Zinc (Zn) regulates various physiological and biochemical processes in plants, plant growth-promoting bacteria (PGPB) help in increasing Zn absorption and nutrient utilization efficiency (Jalal *et al.* 2024). Plants lacking Zn cause growth stunting, a reduction in the crop's maturity time, sterile spikelet, and lower harvest product quality (Suganya *et al.* 2020), impacting various physiological and anatomical parameters including lower vascular bundle proportion coupled with a higher stomata density which negatively impacted plant growth (Mattiello *et al.* 2015). Zn uptake in corn enhances in highly calcareous soils upon N application, followed by decrease in phosphorus (P) concentration and a lowered P: Zn ratio of plant tops to a more optimum range for plant growth (Karimian 1995). Zn oxide NPs huge potent antibacterial properties, making them highly utilized in the food and agriculture industry (Zhou *et al.* 2023). Utilization of Zn in the fortification of crops substantially increase Zn availability and increases human Zn uptake (Wessells *et al.* 2024). Foliar fortification of biologically synthesized Zn NPs on crop plants enhanced nutrient use efficiency (NUE), Zn content in plant biomass, and better crop yields which its best alternative over conventional method of fertilizer application (Sabir *et al.* 2014, Reshma and Meenal 2022). They play a diverse role in plant growth and development. In recent years, there has been heightened interest in exploring more nutrient nutrient use efficency and stress management in plants in modern agriculture and environment management.

Therefore, the review focused on carbon-silicon (C-Si) coupling in Si char and summarized the advanced studies on Si in Sachar regarding characterization, soil improvement, pollution remediation, and C–Si coupling interactions. After examining of Si content, morphology, species, and releasing behaviours, the environmental effects on soil Si balance, the plant uptake of Si, and remediation potentials of inorganic pollutants (aluminum (Al), arsenic (As), cadmium (Cd) and chromium (Cr)) were summarized. It also focuses on the significant role played by Zn and discusses Si and Zn-based studies in plants associated with its transport, uptake, and accumulation. Apart from this, we have also discussed their role in ameliorating stresses from plants by activating their defence. Moreover, their roles in plant hormonal crosstalk have also been elucidated. Above all, we have also revealed the application technologies evolved recently in enhancing plant productivity.

Silicon's significance in agriculture

Soil is the primary key reservoir of Si and its biological cycling regulates its mineral form and dissolved form (Cornelis and Delvaux 2016). The silicon availability influence plants absorption of Si, application of soluble fertilizer indorses its uptake even in water scarcity conditions. This movement is vital for stress mitigation in plants as Si deposition in various plant tissues acts in increasing relative leaf water content, decreases the cell leakage index, and preserves the content of photosynthetic pigments, which amplifies the quantum efficiency of photosystem II, content and use efficiency of macronutrients, thus leading to greater growth and biomass (Teixeira *et al.* 2022). At different soil pH, Sipools dissolution gets impacted influencing its feasibility and uptake by plant (Sirisuntornlak *et al.* 2021). Following root adsorption, it moves within root cells via diffusion and translocated rapidly into the leaves of the plant via transpiration stream, further getting concentrated in epidermal tissue acts a means of providing protection (Figure 2) and mechanically strengthen plant structures (Ma 2003). Plants deposits absorb Si inside the plant's cell wall and lumens as amorphous silica or intercellular sites like phytoliths (Piperno 2006), which escalates growth and stress resistance (Puppe and Sommer 2018a), more enhanced mechanism of silica on maize growth and productivity (Table 1).

Response to abiotic stress

Maize crop yield has a detrimental impact due to drought, salt and temperature stress, and a lack of nutrients. Recently intensification of eruptive climatic events droughts, waterlogging, and extreme temperatures have severely affected maize growth and yield ranging from 51-82% globally, highest loss due to drought reported in China (60%) followed by India (25-30%) (Ahuja *et al.* 2010, Zaidi *et al.* 2010, Oshunsanya *et al.* 2019). The global average yield in maize is 5 tons per hectare (t/ha), but due to abiotic and biotic stress national average yield of Sub-Saharan Africa and South Asia to 1–3 t/ha (Prasanna 2016). Due to increasing demand of sustainable approach for mitigation and adaptation against high salinity conventionally used chemicals are not applicable (Wang *et al.* 2019), this being very challenging due to its multigenic and quantitative nature (Ahmad and Rasool 2014).

Alleviation of salinity and drought stress

Drought stress management is a very apprehension factor for reduces agricultural yields, particularly limiting maize yield, affecting worldwide economics of people's livelihood (Ali *et al.* 2011, Sheoran *et al.* 2022). During periods of water stress, Si fertilization help maintain cell turgor by enhancing development of root system, decreasing evaporation loss, and enhancing water uptake (Zaidi *et al.* 2010). Si induces maintenance of plant water relation by enhancing crop root water uptake and stomatal conductance associated with aquaporins

Table 1 - Mechanism of silica on maize growth and productivity

Parameters	Si mediated response	Reference
Growth	enhanced leaf area, chlorophyll content, photosynthetic rate, osmolyte content, and enzymatic antioxidant activities	(Ning *et al.* 2020a)
	developed plant growth, photosynthetic pigment contents, and increased stomatal size and aperture	(Xu *et al.* 2022)
	improved plant height and leaf area, soil electrical conductivity and specific absorption rate (SAR)	(Pitann *et al.* 2021)
	amplified midrib area, stomatal area	(Bijanzadeh *et al.* 2022)
Physiological attributes	elevates the antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT) of maize plant alleviating salinity stress	(Younas *et al.* 2021)
	upon deposition on stomatal guard cells, lessens stomatal conductance (28%) and cuticular conductance (23%)	(Vandegeer *et al.* 2021)
	casparian bands, suberin lamella as well as vascular tissues development in the root.	(Vaculík *et al.* 2012)
	elevates plant root hydraulic conductance through enhancing aquaporin transcript levels and inhibits H_2O_2 level	(Liu *et al.* 2015)
	enhanced stomatal density, and bulliform cell diameter, increasing grain production	(Marques *et al.* 2022)
	maintain membrane stability by regulating osmolytes to improve water status and antioxidants	(Zhang *et al.* 2018)
	phytolith deposition in vascular bundles strengthens them and enhances stem water transport efficiency	(Wang, *et al.* 2021)
Yield parameters	uplifts net photosynthetic rate, maize grain yield, biomass, and quality followed by nutrient absorption	(Liang et al. 2015, Xu *et al.* 2016)
	elevates plant height, spike insertion height, spike and corncob diameter, and grain productivity	(Rodrigues *et al.* 2020)
Enzyme activity	induces high antioxidant enzyme activities to guard plant tissue from membrane oxidative damage in salt stress	(Zhu *et al.* 2004)
	bio protection agent against the root parasite *F. verticillioides.*	(Kumar *et al.* 2009)
	higher in enzymatic activities (ascorbate-glutathione, catalase, superoxide dismutase, and cytosolic and wall peroxidase) and gene expression for inhibiting pathogen attack	(Maschietto *et al.* 2016)
Abiotic stress	induce resistance against water-stressed condition	(Atta *et al.* 2022)
	significant repression in accumulation of Na^+ at all Na_2CO_3 concentrations further increases K^+ content and K^+/Na^+ ratio in maize under stress	(Abdel Latef and Tran 2016a)
	reduces the accumulation of reactive oxygen species (ROS) and membrane lipid peroxidation which helps plants in overcoming Na^+ and other heavy metal toxicity	(Mathur and Roy 2020)
	in leaves concentrations of silicon, potassium, phenols and tannins are negatively correlated	(Wang, *et al.* 2021, Nagaratna *et al.* 2022)
Biotic stress	enhances resistance against fungal diseases by activation of damping-off mechanism	(Suriyaprabha et al. 2014)
	act as a physical barrier and initiate silicon-mediated biochemical defence mechanism in plant	(Reynolds *et al.* 2016b)

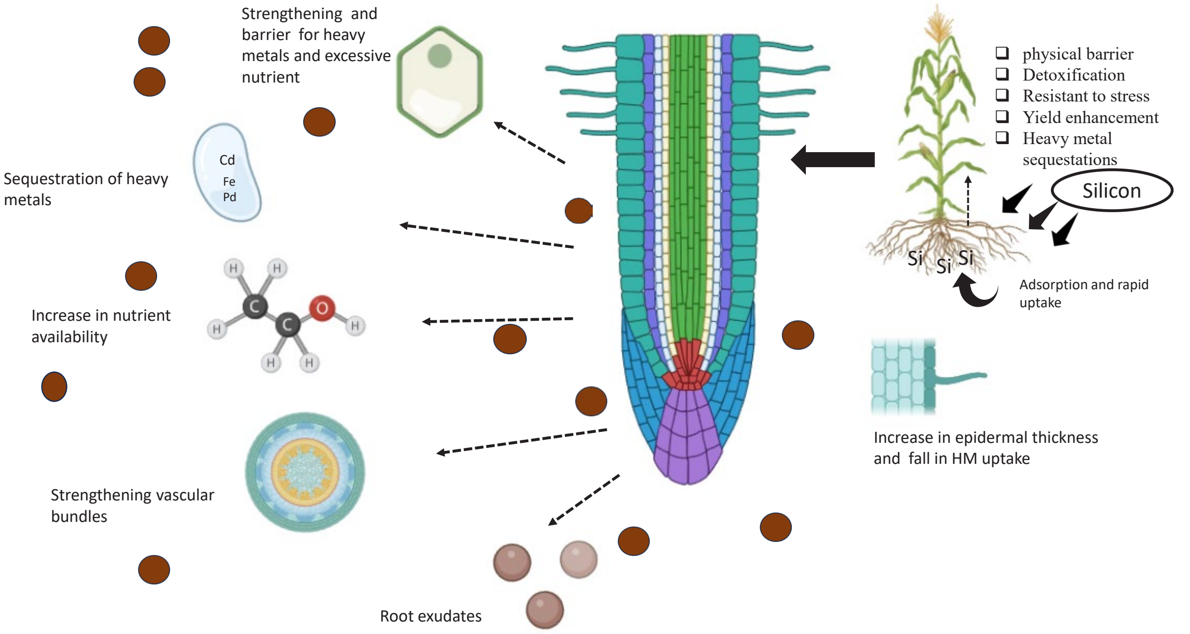

Fig. 2 - The schematic diagram shows the Silicon mediated response in maize plant

up-regulations to cope with famine-like conditions (Farooq *et al.* 2009, Gong and Chen 2012, Liu *et al.* 2014). Si contributes to the Additionally, they contribute in accumulation of phytoliths in leaf veins and elevate polyamine levels beneficial for strengthening the leaf and delaying senescence followed by physiological and agronomic responses by boosting leaf area, osmolyte content, and the activity of enzymatic antioxidants CAT, SOD and POD. Physiological and agronomic responses that mitigate yield decline during the water stress phase by boosting leaf area, osmolyte content, and the activity of enzymatic antioxidants (Yin *et al.* 2014, Ning *et al.* 2020b).

In maize, Si deposition in the cells surrounding the base of trichome hairs effect morphological and physiological properties associated with enhanced drought resistance (Mandlik *et al.* 2020). Si foliar application of 2kg/ha, enhancement for alleviating the adverse impacts of irrigation water salinity on the growth, physiological, and yield parameters of maize (Alayafi *et al.* 2022). It has been to develop a cost-effective, rapid, and sustainable method to alleviate salinity which impact 20% of arable land. It has been reported effective mechanism for defends through antioxidants, apoplast based physical barrier, and mechanical strength. (Liu *et al.* 2014, Luyckx *et al.* 2017, Thorne *et al.* 2020). Under salt conditions Si enhances leaf roughness by leaf rigidity, which has positive impact on mineral nutrition and mechanical strength (Hamayun *et al.* 2010, Ouzounidou *et al.* 2016).

Role in heavy metal detoxification

The application of Si as soil amendment has been demonstrated to increase in soil pH, decrease the organic matter and electrical conductivity, which has led to reduction of cation (including copper (Cu), Cd, Cr, lead (Pb), iron (Fe) and manganese (Mn)) and Zn) availability (Guo *et al.* 2018, Wan *et al.* 2019, Ma *et al.* 2021). Furthermore, the Si plays vital role in detoxifying heavy metals through various mechanisms: coprecipitation of toxic metals, lessening of metal ion in soil substrate, transport related gene regulation, chelation, stimulation of antioxidants, compartmentalizing metal ions, and structural changes in plants. Additionally, the application of exogenous Si can increase heavy metal tolerance in numerous plant species (Bhat *et al.* 2019). Si relatively high surface area and contain reactive sites that are highly compatible with metal ions, facilitating strong adsorption and formation of complexes that demonstrated their effectiveness in absorbing heavy metals such as Pb, Cd, and As, thereby metals inclusion within colloidal Si and mineral layer (Selim *et al.* 2021). By immobilizing metal ions and reducing their bioavailability, Si condenses these ions mitigating stress. Metals ions get trapped within more stable fractions such as organic matter and crystalline iron oxides (Emamverdian *et al.* 2018).

Beyond detoxifications, Si acts as a physical barrier within plant tissues, reducing oxidative damage induced due to higher concentrations of MDA and H_2O_2. Moreover, offers mechanical reinforcement and shields against Cd stress in *Z. mays* cultivars (Saleem *et al.* 2022). This antioxidant enzymatic defence is mainly evident in maize plants, where Si inhibits As and Ni uptake, which can trigger deterioration of cell membrane and antioxidant system. This supports root lignification and suberization, enhancing chlorophyll pigments and organic osmolytes (Vaculík *et al.* 2021, Sattar *et al.* 2022).

Thus, Silicon holds ecological significance in plant metal interactions. In addition to their role in heavy metal detoxification, subsidizes in refining plant health, soil heath and sustainable agriculture practices (Sharma *et al.* 2023).

Response to biotic factors

Si act as barrier against biotic stress by providing mechanical and chemical barriers against biotic agents. It gets accumulated in aerial parts gets polymerized in intercellular spaces and underneath cuticle acts as a barrier against biotic stresses (insects, fungus and bacteria), followed by attracting natural predators and parasitoids against pests (Bakhat *et al.* 2018).

Physiological and biochemical aspects of defence against pathogen and pest

It has been demonstrated that due to higher silicon application in maize plant, resistance is developed against Maydis Leaf Blight by less production of malondialdehyde, and hydrogen peroxide. Studies have depicted there is Si stimulated increase in leaf gas exchanges, chlorophyl a fluorescence parameters preservation of their photosynthetic apparatus along with enhanced activities of defence and antioxidant activities compared Si deficient plant (Lata-Tenesaca *et al.* 2024b). During plant-pathogen interactions, Si activates defence related enzyme's invigorating antimicrobial compounds production regulating signal pathway network and defence-related genes expression (Wang *et al.* 2017). Besides, formation of barrier of Si polymerized under cuticle and its cell walls, rapid production of defence compounds via secondary metabolic pathway its defensive mechanism beyond physical barrier against fungal pathogens. Moreover, enhanced plant nutrition and plant health (Ahammed and Yang 2021). Direct defence traits (physical and chemical barriers) and indirect defence approaches (releasing volatile compounds) work together against insect herbivores (Belete 2018).

Arthropod herbivory poses a substantial stress under natural conditions. Consequently, plants have evolved diverse defences to act as a barrier for arthropod attacks (Bonnet *et al.* 2017). There have been significantly higher levels of total phenols and antioxidant activity followed by increased enzymatic activities (e.g., AO, CAT, APX) increased in response to damage by *C. partellus* compared to susceptible ones (Bhoi *et al.* 2020). Silicon alters phytophagous insects attack by stimulating JA and HIVs which cascade deterrent effects on oviposition site selection by *Spodoptera exigua* Hübner (Leroy *et al.* 2022).

Defence Signalling Modulation and primed defence response

Si directly inhibits infection of plant pathogen by creating physical blockade that prevents penetration of pathogens. Silicon has notable effect on fungus *Stenocarpella macrospora* where Si polymerization act as a barrier by and potentiating the phenylpropanoid pathway (Hawerroth *et al.* 2019). Research indicates that plants containing Si have stronger defences against insect herbivores because it affects nutrient digestion and decreases leaf palatability and digestibility. Studies show that while Si by itself causes more larval deaths because early instars cannot feed the larvae effectively, silicon combined with nitrogen (N) boosts larval survival. Si supplementation improved armyworm digestibility and nitrogen absorption efficiency but decreased maize intake. This shows that rather than compensatory feeding behaviour, improved physiological responses after ingestion may lessen the negative effects of Si on pupal weight (Moise *et al.* 2019).

Contribution to nutrient uptake

Research findings, have indicated that Si application in maize plant under K deficiency leads to stress mitigation by enhancing NUE of C, N and phosphorus (P); photosynthetic rate; and dry matter production of maize plants (David *et al.* 2019, Campos *et al.* 2021, de Mello Prado 2021, Teixeira *et al.* 2021, Costa *et al.* 2023).

The application of calcium and magnesium silicate significantly enhanced nutrient content in corn, resulting in increased shoot uptake of phosphorus (P) B as well as grain uptake of calcium. Inoculation with *Azospirillum brasilense* boosted nutrient absorption, showing higher shoot uptake of nitrogen N, K, Ca boron (B), Si and grain uptake of Cu. When plants were inoculated and 200 kg N/ha was applied, grain nitrogen and sulfur levels surged by 22.5% and 26.8%, respectively. Additionally, grain Zn levels rose by 88.6%, 65.7%, and 99% with inoculation. This underscores the impactful role of silicon, coupled with PGPB inoculation, in optimizing plant nutrition and enhancing cereal development for improved nutrient replenishment (Galindo Pagliari, *et al.* 2021). Greenhouse experiment-based silicon application on maize enhanced shoot dry matter production and root dry matter production, by high nutrient use efficiency (Buchelt *et al.* 2020).

Role of Zn fertilizers in maize plant

Zn arrives in the environment from various sources, with the most common being the erosion of Zn containing soil particles. In plants, Zn plays a crucial role in several essential physiological processes, defence against drought and disease although required in small quantities (Noulas *et al.* 2018). Plant roots absorb Zn in two forms: bivalent form (Zn^{2+}) and ligand-Zn complexes. The secretion of organic acids and hydrogen ions (H^+) allows Zn^{2+} ions uptake by epidermal roots. Another way is the release of chemicals, enabling the easy absorption of Zn^{2+} ions by cereal crop roots through the formation of stable complexes (Gupta *et al.* 2016a). Zn important structural constituent of enzymes and proteins involved in biochemical pathways (Alloway 2009), more than 300 enzymes found in plants (Shabaz *et al.* 2015), its bioavailability enhances crop quality (Ehsanullah *et al.* 2015). Zn belongs to the group of essential trace elements playing dual role, dynamic in small amounts to living organisms for normal metabolic functions and become toxic at higher concentration in plant physiology and biochemistry (Natasha *et al.* 2022).

Maize nutritional quality (include Zn concentration) gaining more and more attention (Chaudhary *et al.* 2014, Manzeke *et al.* 2014). Recent study depicted the response of maize plant to Zn foliar application. Zn regulated transporter responsible for the uptake and transport of divalent metal ions in plant, root-to-shoot translocation (Li *et al.* 2019). AMF inoculation in plant led to Zn balance uptake and enhances the growth and yield of crops (Saboor *et al.* 2021), extension of fungal hyphae in the rhizosphere contributing up to 50% of total Zn uptake in crops. The application of phosphorus (P) significantly lessens the hyphae-mediated advantages. Thus, identifying resilient cultivars and comprehending the genetic and microbial aspects of the P-Zn relationship is vital for addressing Zn deficiencies in intensive agriculture (Cavagnaro 2008). Zn fertilizer application significantly increases rot dry matter, root length, and root surface area but decreases shoot/root (Zhang *et al.* 2013). P and Cu negatively regulate the Zn uptake and transmission in plant.

Zn deficiency stunts plant growth by elevating boron concentration in young leaves and branch tips (Mousavi *et al.* 2012). Zn deficiency in maize particularly at male reproductive phase (tasselling stage) show case symptoms like chlorosis, stunted growth, delayed tassel formation and impaired pollen development, with a significant percentage of anther failing to of mature and instead forming vascular tissues (Sharma *et al.* 1987). While Zn level below or equal to 5 mg/kg at early stages (4–5 leaf stage) showcased symptoms like white stripes between the midrib and the margin of leaves (Drissi *et al.* 2017), hinderance in development, reduced tillering, spikelet sterility, leaf chlorosis and shrinkage (Yadavi *et al.* 2014).

Zn availability in soil either already present or applied externally undergoes inorganic and organic phases regulating its availability (Shambhavi *et al.* 2020), and its sorption-desorption into soil solution (De Vasconcelos *et al.* 2011). Micronutrient (like Mn, and Zn) uptake is significantly affected by different N forms like urea and ammonium. Ammonium and urea-fed plants have higher concentrations of Zn, Mn, Cu, maximum shoot, and root dry matter (Sabir *et al.* 2013). It has been documented that high phosphate fertilization led to the formation of insoluble Zn-phosphate, such as $Zn_3(PO_4)_2$ as a result of antagonistic interaction between Zn and P, which is the primary cause of Zn deficiency in soils, leading to plant deficiency and impaired growth (Jurinak and Inouye 1962, He *et al.* 2021).

Role in enzymatic activities, hormone regulation

In plants Zn up taken and transferred the form of Zn^{2+} in plants and is an essential nutrient that plays important function in plant physiology, also has a positive impact on crops yield (Mousavi *et al.* 2013), Zn-regulated transporters and the iron-regulated transporter-like proteins regulates its influx (Eide 2006). It plays vital role in various biochemical and enzymatic processes. It serves as a functional, structural, or regulatory component in numerous enzymes essential for physiological functions. Its deficiency can disrupt enzyme activity, negatively impacting photosynthesis by diminishing the effectiveness of key photosynthetic enzymes and increases membrane permeability due to the impaired detoxification of harmful oxygen radicals (Mousavi *et al.* 2013). Zn doped urea enhanced growth rate of *Zea mays* seeds (69%) and the germination rate (19%), potentially delivering nitrogen, phosphorus, and Zn at the seedling stage (Abeywardana *et al.* 2021). Additionally, it acts precursor for IAA formation (Bennett and Skoog 1938, Waraich *et al.* 2011), which alleviates drought stress by reducing the oxidative damages and regulating the osmotic balance (Jamil *et al.* 2018), along with detoxifying ROS generation and increasing antioxidant enzymes. Moreover, Zn emphasised that Zn involves in physiological functions and constituent of regulatory cofactor of many enzymes, carbohydrate and chlorophyll production, pollen development, fertilization, RNA and DNA metabolism, and protein synthesis (Khan *et al.* 2004, Nasiri and Najafi 2015). Moreover, plays key role in photosynthesis related enzymatic process (Bashir *et al.* 2019, Hussain *et al.* 2021, Saleem *et al.* 2022).

Influence on Photosynthetic Efficiency

$ZnSO_4$ application on maize either by seed priming, foliar and basal application has better effect on leaf chlorophyll content, photosynthesis rate followed by increase in grain yield (47%) (Liu *et al.* 2016b, Choukri *et al.* 2022). Followed by significantly altering shoot sodium (Na) concentration followed by increasing the shoot K/Na, Ca/Na, and Mg/Na concentration ratios increasing plant adaptability in saline soils (Basit *et al.* 2020). Zn has an influence on photosynthesis and sugar metabolism which plays vital role in carbohydrate metabolism (Rudani *et al.* 2018). Plants agronomic Zn use efficiency gets enhanced upon Inoculation with plant growth-promoting bacteria, such as *Azospirillum brasilense* increases yield by 6% (Galindo *et al.* 2021).

Zn's involvement in protein and carbohydrate metabolism

Zn is a vital micronutrient for plants, essential for many metabolic activities in plants such as integrity of membrane, gene expression, carbohydrate, enzyme activation, photosynthesis, gene expression, phytohormone activity and everyday activities of many enzymes, and lessens the toxicity of P (Cakmak 2000, Prasad 2006). The Zn plays very important role in plant metabolism by influencing the activities of hydrogenase and carbonic anhydrase, stabilization of ribosomal fractions and synthesis of cytochrome (Hafeez 2013).

Response to abiotic stress

Abiotic stress is become one of major threat to crop growth and development, to effectively mitigate abiotic stress, Zn plays a significant role in alleviate all adverse effects of drought, salinity, and heavy metals (HMs). During period of stress silicon helps enhancing the chlorophyll level to improve photosynthesis, reducing oxidative stress by limiting ROS production, controlling heavy metals absorption and maintains homeostasis (Ganguly *et al.* 2022). ZnO NPs have a prospective role in preventing abiotic stress by promoting the production of phytohormones, osmolytes, antioxidant enzymes, and metabolites in plants (Thounaojam *et al.* 2021).

The research finding of (Saeed *et al.* 2024), revealed that upon combined application of glutathione and Zn enhance maize resistance to water stress by escalating biosynthesis of enzymatic and non-enzymatic antioxidants, photosynthetic pigments, accumulation of total soluble proteins (TSP), total soluble, reducing, and non-reducing sugars.

Improving key physiological and biochemical attributes for alleviation of salinity and drought stress

Salinity stress adversely affects plant growth by disrupting water relations, photosynthesis, and nutrient upta-

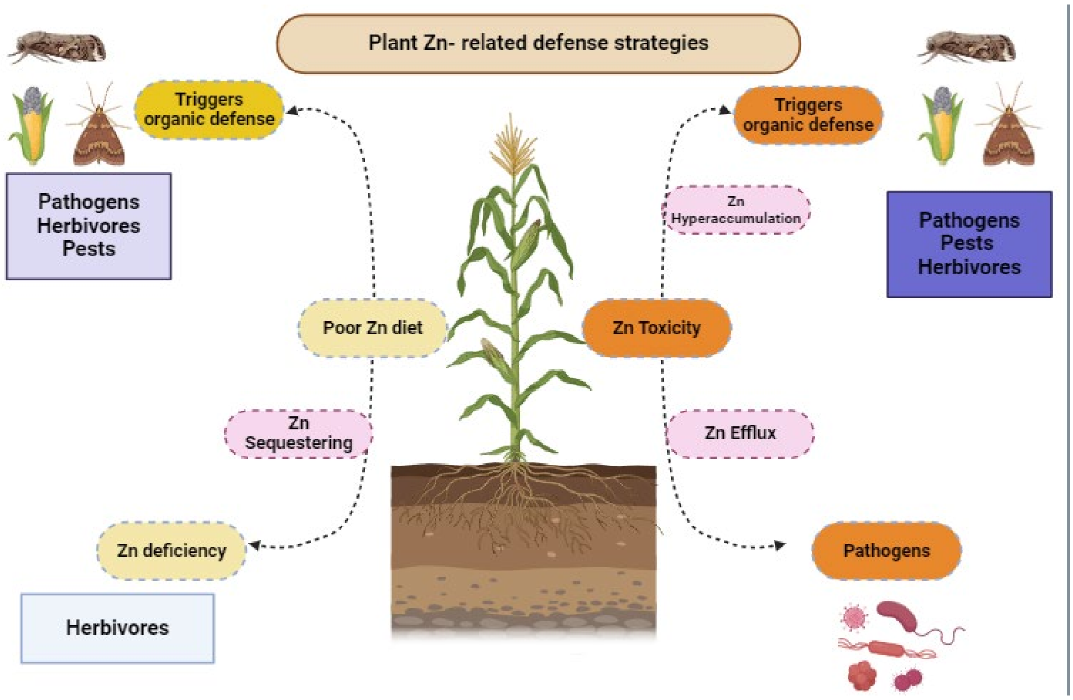

Fig. 3 - Response towards developing resilience against biotic and abiotic stress in maize under zinc.

ke. Applying Zn and copper to the leaves helps counter these impacts by boosting antioxidant activity and promoting the accumulation of protective molecules (Iqbal *et al.* 2018). Drought stress limits nutrient uptake, resulting in stunted growth and reduced yield. Foliar application of Zn chelates or nanochelates can improve drought tolerance by enhancing nutrient uptake and overall plant health, leading to increased yield (Weisany *et al.* 2021). Under moisture stress, Zn led to enhancing roots hydraulic conductivity (51%) and decreased roots antioxidant enzymes activity (Zhang *et al.* 2021).

Role against biotic stress

Nutrient deficiencies often make plants more susceptible to pests and pathogens. Nonetheless, certain signaling pathways activated by nutrient scarcity boost the plant immune system. Zn serves catalytic and structural protein cofactor in hundreds of enzymes (Hambidge *et al.* 2000), and has key structural functions in the protein domains that interact with other molecules to enhanced defencerelated mechanism against pest and pathogen depicted in Figure 3.

Agronomic response of Zn

Zn is dynamic for maize growth and productivity, positively impacting cob yield, nutrient uptake and agronomic efficiency (Ruffo *et al.* 2016). It enhances carbohydrate synthesis followed by positively influencing the seed set and seed weight, synthesising growth regulators (e.g., indole-acetic acid), pollen formation, carbohydrate metabolism and maintaining the integrity plant bio-membrane (Peda Babu *et al.* 2007, Hossain *et al.* 2011). Its role in concomitantly increase with the increase in grain yield and Fe, protein and P concentrations in the grain (Kihara *et al.* 2024).

Synergistic Interactions among Zn and Silicon on Maize

Zn-Si interaction on Cd toxicity alleviation, singularly and in combination are highly effective in reducing tissue Cd content in both genotypes, the mechanism behind which could be the dilution effect of Cd due to improved biomass and competitive nature of Zn and Si, culminating in Cd toxicity alleviation (Mapodzeke *et al.* 2021). Apart from this, upon combined application with Si, Zn, B, and zeolite nano-particles, led to alleviation of salinity and remarkable synergistic effect was observed significantly boosted retention of water and nutrients (Figure 4), induced enzymatic antioxidant activities in salt-stressed potato plants and enhanced potato tuber yield enhancing nutrient use efficiency and photosynthetic activity (Mahmoud *et al.* 2019)

Apart from their role in mineral nutrition, study revealed Zn and Si combined application on amplification for plant height, leaf area, chlorophyll content, grains per ear, kernel weight, ear size, and yield compared to other foliar treatments. For instances, their applications maintained superiority in mitigating yield losses under varying water availability (Lamlom, *et al.* 2024). Plants

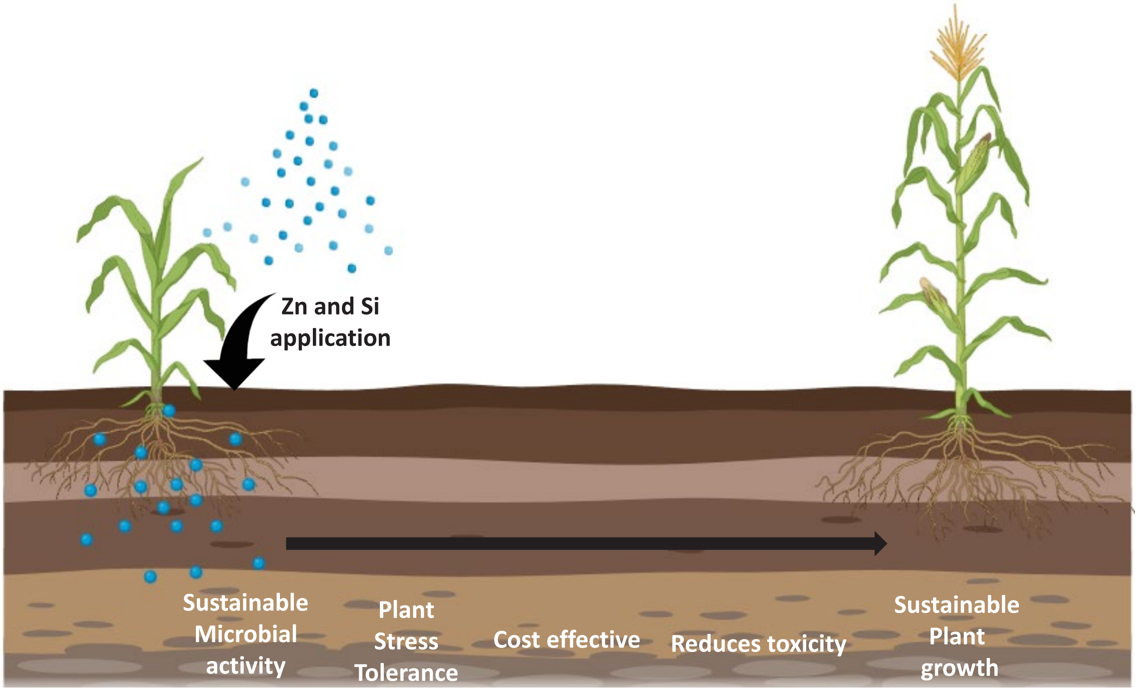

Fig. 4 - Effect of Zn and Si Application on Maize Growth and Soil Health

grown under well watered (75% water holding capacity) conditions supplemented with Zn (10 mg/kg) and Si (100 mg/kg) demonstrated enhanced physiological characters and plant yield (Idrees *et al.* 2024). Impact of their application as nano-fertilizers, particularly nano-Zn, may be exacerbated by their enhanced K/Na ratio and improved nutrient availability and uptake of the plant. There is also significant influence of Si nanoparticles (NP's) are on better osmotic adjustment and facilitating water movement. Hence, improving overall agricultural productivity and related environmental issues (Shoukat *et al.* 2024b).

Recent studies found that, upon high dosage of Zn led to increase in Zn concentration in plant root and leaf, but negative impact on leaf P and Fe. Upon introduction of Si led to modification of membrane permeability thus involvement in physiological and nutritional changes to mitigate high Zn toxicity and enhanced Fe uptake (Kaya *et al.* 2009). There was reported increased linoleic acid content led to decrease in quality of maize, it suggested that Zn or NSP + Zn can be recommended for on-time planting to increase the grain yield of maize plants by 33% and 37% (Asadpour *et al.* 2022).

Role of biofortification technique

Biofortification of cereal crops with Zn and diazotrophic bacteria provides a long-term solution to nutritional shortage and hidden hunger. Inoculation of staple grain crops such as maize helps to reduce production losses while enhancing nutrition and use efficiency in tropical savannah soils subjected to climate extremes and weathering. The use of Zn-solubilizing bacteria (ZSBs) as biofertilizers has gained popularity, and bacteria play an important role in enhancing soil nutrient content and supporting crop productivity. ZSBs have been shown to have a high potential to promote Zn availability in the rhizosphere and improve Zn delivery to crops. The use of ZSBs as biofertilizers has gained popularity, and bacteria play an important role in enhancing soil nutrient content and supporting crop productivity. ZSBs have been proven to have great ability to enhance Zn availability in the rhizosphere and to improve Zn supply to crop plants (Kumawat *et al.* 2019a)

Biofortification of Zn to a high-yielding maize variety enhances Zn content in maize grain is of great importance to the health of those feeding on these staples. The agronomic approach is a feasible method in combatting Zn deficiency in soil (Obaid *et al.* 2022). Research findings revealed that biofortification technique emerged out as most effective and sustainable approach to enhance micronutrient availability to plant (Hossain *et al.* 2019). Investigation done for evaluating best biofortification of maize crop under different irrigation intervals, using foliar application treatments of silicon Si, Zn, AgNPs. This revealed that an irrigation interval of 15 days combined with application of Si, Zn and AgNPs has the potential to improve yield and quality of maize under water deficit stress (Kandil *et al.* 2023).

Bio-activated organic fertilizers (BOZ) were produced by enriching the Zn Oorange peel waste composite with Zn solubilizing bacteria (ZSB: *Bacillus* sp. AZ6) in various formulations (BOZ1 (9:1), BOZ2 (8:2), BOZ3 (7:3) and BOZ4 (6:4)) . Thus, bio-activation of ZnO with ZSB could serve as an efficient and economical strategy for boosting up the growth, yield, physiological, and quality parameters of maize under field conditions (Hussain *et al.* 2019). The use of PGPR offers an attractive approach for the improvement of the Zn contents of food crops like chemical fertilization, agronomic practices, and transgenic plants (Hafeez *et al.* 2013).

Agronomic biofortification is the easiest and fastest way for biofortification of cereal grains with Zn (Meena *et al.* 2017). It is feasible and has the potential to contribute significantly towards increasing dietary Zn intake by humans. A greater increase in grain Zn of cowpea grown on sandy than red clay soils under Zn fertilization illustrates the influence on Zn uptake (Manzeke *et al.* 2017).

Methods of application of Si and Zn

Foliar application vs. soil application

Si fertilizers upon soil application leads to mitigation of negative effect of Zn on plants and led to enhancement of plant biomass (Zajaczkowska *et al.* 2020). Foliar application of the fertilizers often leads to a eco-friendly form of fertilization leading to reduction of amount of fertilizers. Additionally, different pathways (*i.e.*, cuticular pathways, stomata, and trichomes) of foliar uptake and functioning of Si foliar fertilizers leading to development of resistance against biotic and abiotic stress (Puppe and Sommer 2018b), enhancement of bioavailability of nutrient led to biofortification of nutrients (Xia *et al.* 2019). According to (Naeem 2015), studies revealed that ZnSO4 application on maize field as soil application and foliar application enhances yield by 23.7% and 38%, which was highly influenced by type of maize cultivars, method and time of Zn fertilization. Despite previous research demonstrating upon foliar application in maize on two growing season enhanced grain Zn content by 27% and 37%, Zn recoveries of 35.2‰ and 42.9% during the first and second growing seasons, amplification of Fe concentration where as on otherside soil application shows only 1.7% recovery (Wang *et al.* 2012). Biofortification through agronomic approach like, seed priming, foliar and soil applications are agronomic tools for biofortification, but solo and combined applications of these treatments have different effects on Zn enrichment (Maqbool and Beshir 2019).

Manure come up with suitable solution for decreasing soil fertility in sandy soils, as results revealed application of manure for three seasons increased soil organic matter, available P, pH, bases, and improved Ca and Zn concentrations in maize shoots in the greenhouse (Zingore *et al.* 2008). Indeed Si treatments increases root water uptake and enlarges root system by 34% (Besharat *et al.* 2020). Si combined with biofertilizers application on maize crop rhizosphere resulted in 20% reduction in NPK fertilization, higher water uses efficiency (2.64 kg /m^3) potential saving of 206 m^3/ha water and 157 kg NPK/ha fertilization (Besharat *et al.* 2024). Si combine straw application to maize crops has shown stimulation of plants to take up more N from the soil, the effect of Si fertilizer last short duration due to its fixation, which can be overcome by applying straw as it improves Si availability and magnify crop growth.

Seed treatment

Seed priming is typically defined as pre-sowing treatments involving water or an osmotic solution that allow seeds to absorb moisture and initiate the first stage of germination, while preventing the emergence of the radicle through the seed coat (Ashraf and Foolad 2005, Sirisuntornlak *et al.* 2019). Nano formulations of Si fertilizers due to their unique physiochemical and biological properties boost the germination percentage which act as budding step towards high crop yield but exceeding permissible limit causes toxicity to ecosystem (Singh, *et al.* 2021).

Seeds coated with Si shows escalation of crop growth under salinity conditions. There was intensified improvement of maize physiological growth due to improvement of photosynthetic contents, osmoprotectants and antioxidant, followed by lowering proline content mitigation salinity effect (Ur Rehman *et al.* 2021). The recent findings revealed its pivotal role in mitigating alkaline stress by enhancing leaf relative water content photosynthetic pigments, accumulating osmoprotectants rather than proline, activating the antioxidant machinery, and maintaining the balance of K+/Na+ ratio and emerged as an efficient strategy that can be used to boost tolerance of maize plants to alkaline stress (Abdel Latef and Tran 2016b). Study conducted to evaluate the toxicity of different Si formulation revealed that on comparison to all nanosilica emerged as non toxic towards soil bacterial populations, enhanced PGPR and nutrient level (Karunakaran *et al.* 2013).

Si based autotrophy been reported as source of energy for supporting bacterial CO2 fixation (Das *et al.* 1992). Silicic acid encourages the growth of both aerobic and facultative anaerobic soil microorganisms in ultrapure water, even under extreme oligotrophic conditions. Additionally, there is a hypothesis suggesting that silicon may have played a role in the origin of the earliest bacteria on Earth (Wainwright *et al.* 2003)

Seed priming techniques of Zn assists in getting higher physiological and yield parameters. The maximum grain yield (5.35 t/ha), biological yield (16.69 t/ha) were found in priming with ZnSO @1.5 % in 1 1 4 maize hybrid (Afzal *et al.* 2013). Seed priming with nutrients stimulates epigenetic changes, signaling proteins accumulation leading to repairing membrane and increased activities of antioxidant enzymes under environmental stress conditions (Cartes *et al.* 2010, Paparella *et al.* 2015). ZnONPs seed coating can also be considered an effective tool for the delivery of Zn micronutrient to fodder maize crop. An increase in vegetative and yield parameters (number of plants, plant height, stover yield, plant biomass), acid detergent fiber (ADF%), and hemicellulose contents and shoot Zn content on treatment of seeds with ZnONPs (20 mg/L) concentration as compared to bulk $ZnSO_4$ and control treatments was observed (Tondey *et al.* 2021). The Zn application as seed treatment found equally efficient to Zn supplementation through soil application in increasing growth and dry matter yield of maize, was economical besides reduction in chemical load (Mehta *et al.* 2011).

Foliar application technologies

Foliar fertilizer application of trace elements elevates their content in crop and soil environments. The application of chelating agents such as humic acid, amino acid, and sugar alcohol, plays vital role in improving element-utilizing efficiency and crop yield (Niu *et al.* 2021). Among all Zn chelates (Zn Ch: EDTA, Zn Ch: HEDTA) and non-chelated (ZnSO4.7H2O), Zn Ch: EDTA spray exhibits higher values for physiological and agronomic characters (Khalid *et al.* 2013), followed by enhancement of crop growth and productivity by 11% and 8% (Krishnaraj *et al.* 2020). Zn-amino acid chelates, particularly [Zn(His)2], significantly boosted grain yield compared to traditional $ZnSO_4$ (Tabesh *et al.* 2020), followed by significant improvement in qualitative and quantitative characters (Mosanna and Behrozyar 2015, Khalafi *et al.* 2022). Under water deficit condition chelated Zn enhances water use efficiency and maize yield (Elshamly and Abaza 2024). Similar results were observed by foliar application recorded higher grain and stover yield as well as Zn content and Zn uptake over all other treatments (Malathi 2021).

Nano silicon particles and Zn foliar application enhances light interception properties, decreased transpiration rates and maintain nutrient balance by keeping leaf erect followed by improving chlorophyll content (Ramírez-Olvera *et al.* 2019). Nanoparticles form of silicon and Zn improves agricultural productivity by facilitating better nutrient availability and water movement. Nano Si application has more effectiveness in maintaining ion balance, reducing salt toxicity than Zn-NPs (Shoukat *et al.* 2024a). Nano Zn contributes in enhances maize agronomical and physiological attributes such as plant height, NDVI, lead area index, dry matter accumulation, SPAD (Rajesh *et al.* 2021).

Integrated foliar application of Si and Zn plays significant role in boosting key growth parameters specifically under water stress conditions, ensuring better crop performance led to sustainable agriculture (Lamlom, *et al.* 2024), silica deposits in plant tissues strengthens them and modifies nutrient and water mobility inside plants (Savvas and Ntatsi 2015).

Soil and rhizosphere engineering

Soil microbial populations particularly those near the rhizosphere possess huge potential in harnessing Zn biofertilization and biofortification. Zn solubilizing and mobilizing bacteria supported with organic material increases crop assimilation and Zn availability (Yadav *et al.* 2020). ZSB are possible potential alternates for Zn supplements that enhance the bioavailability of local Zn concentration within the soil to the plants through various mechanism (Chakraborty *et al.* 2022), paved the way for maintaining an environment-friendly and sustainable agriculture production system.

Nano silica affects plant rhizosphere by significantly alleviating microbial population, total biomass content, and silica content (Rangaraj *et al.* 2014). Exogenous silicon alters physiochemical soil properties and enriches the rhizosphere with enormous microbial populations contributing to soil enzyme and chemical activities (Deng *et al.* 2021). The findings of many researchers indicated the involvement of Si transporter (Ls1) localized on the root mature zone in an influx of Si inside the plant from outside and Si efflux by Lsi2 transporters localized at endodermis (Ma *et al.* 2007, Ma and Yamaji 2008, Mitani *et al.* 2009, Yamaji *et al.* 2015, Jadhao *et al.* 2020).

Precision agriculture

To minimize agricultural input losses, the involvement of precision agriculture based technologies to suit for optimization of agricultural inputs. Utilization of remote sensing has been enhanced unprecedentedly due to high-resolution (spatial, spectral, and temporal) satellite images for crop monitoring, irrigation management, nutrient application, disease and pest management, and yield prediction (Sishodia *et al.* 2020). In the agriculture domain, the Internet of Things implementation optimizes cloud computing with more efficient data offloading (Akhtar *et al.* 2021). This geoinformatics approach enables the detection of soil type, structure, and mapping of fertility (Singh *et al.* 2022). Recent focus increased on several geospatial techniques *viz.* remote sensing techniques, geographic information systems, and information and communication technologies (ICTs) help in detecting nutrient status and stress conditions in both plants and soil via various indices like normalized difference vegetation index (NDVI), further optimization in nutrients efficiency can be achieved by inculcating sensors *viz.* chlorophyll meter and Green Seeker (Gorai *et al.* 2021).

Conclusion and future perspectives

A meticulous literature review elucidates that Si and Zn fertilizers have significant implications for sustainable agriculture and mitigating diverse biotic and abiotic stress. Nonetheless, there exists ample opportunity for further exploration in the formulation of novel Si-based fertilizers utilizing cutting-edge nanotechnology. Enhancing plant resilience to stress led to a decrease in chemical usage and improved crop and soil health.

Fertilizers are indispensable for global food production, with an anticipated rise in Si-based fertilizer utilization due to the depletion of Si and essential soil nutrients from extensive cultivation practices. Additionally, the escalating application of chemical fertilizers and pesticides engenders environmental degradation, biodiversity diminishment, and public health hazards, culminating in substantial economic losses and sustainability challenges. Notably, Si-accumulating plants constitute seven of the ten most pivotal crops globally, suggesting that non-accumulator crops will likely necessitate Si applications to sustain optimal yields. The eco-friendliness and prophylactic properties of Si, along with its critical role in enhancing soil health and plant resilience against various stresses, are well-documented.

The synergic application of Si and Zn significantly boost maize (*Zea mays* L.) performance and stress resistance abilities under abnormal environmental conditions such as drought and salt exposure as well as mineral deficiencies. Plants that consume Si develop strengthened cell walls and gain better resistance to oxidative damage and improved intake of nutrients thereby becoming more resistant to environmental stress. When included as an essential micronutrient Zn supports enzymatic functions and protein synthesis and chlorophyll synthesis which directly determines plant vigour and grain composition. Their combined application produces positive effects on maize plant development especially when

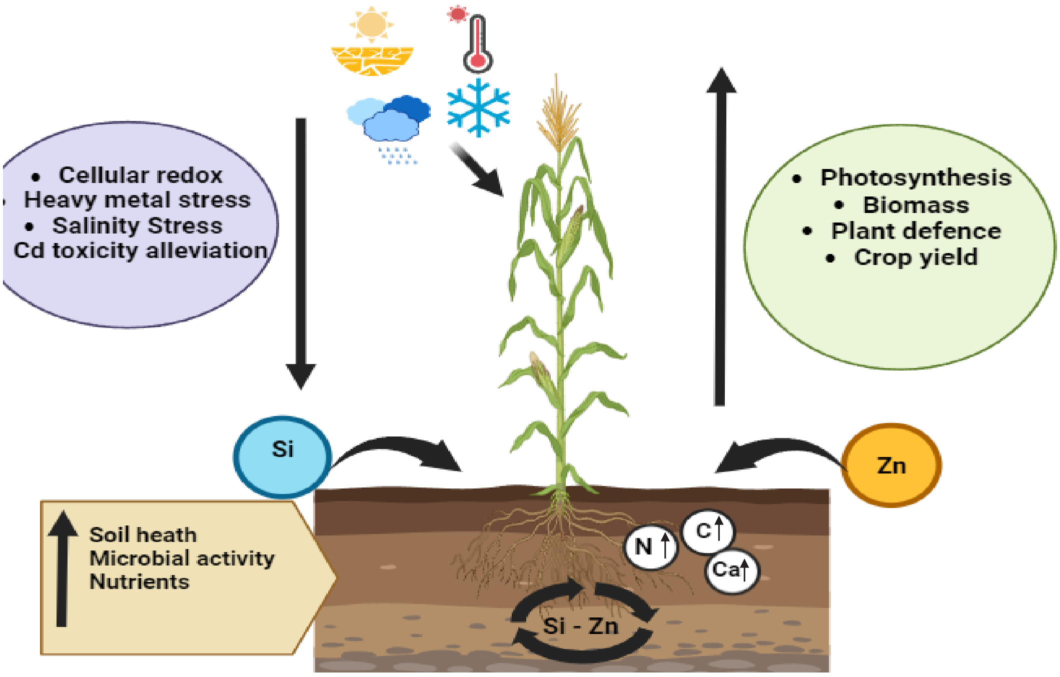

Fig. 5 - Potential benefits of combining zinc and silicon application

soils contain insufficient nutrients. Scientists should spend their next working period on identifying the molecular mechanisms that happen when nanofertilizers introduce nutrients and on implementing precise application dosages matching specific soil properties and developing improved nutrient-delivery nanofertilizers and extensive field-based testing of the system. Nanofertilizers revolutionize biofortification by ensuring precise nutrient absorption, minimizing environmental impact, and advancing sustainable agriculture.

Authorship Contribution Statement

G.S. wrote entire manuscript text of review, utilization of software for preparing figures; K.V conceptualization the idea and edited the review paper; S.S, M.R, And R.J reviewed the paper and shared their inputs for further upscaling, R.J. and P.P. supervision, formal analysis, guidance for using the software.

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