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Exploring the Therapeutic Potential of Silicon and its Impact on Crude Plant Drug Production in North East India

Mayanglambam Homeshwari Devi[1], Immanuel Chongboi Haokip[2],
Seram Raghumani Singh[3], Ampee Tasung[4], Mayanglambam Neshwari Devi[5]

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ABSTRACT

Silicon (Si) exhibits a beneficial impact in mitigating both biotic and abiotic stress, yet its potential significance in the context of medicinal plant and crude plant drug production, particularly in the strongly acidic soils of North East (NE) India, remains underreported. This study aimed to assess the effects of Si application on medicinal plants, focusing on growth, physico-chemical and biological attributes under stressful conditions.The study highlighted the benefits of Si application, particularly through foliar application, on medicinal plants such as lemongrass [*Cymbopogon flexuosus* (Steud) Wats], ginseng (*Panax ginseng*), coriander (*Coriandrum Sativum* L.) and bananas. Foliar Si application demonstrated improvements in plant growth and yield, employing morphological, physiological and biological responses in lemongrass and ginseng while enhancing the growth and yield of coriander by improving relative water content, total phenolic and total flavonoid content under water stress. Si applications also resulted in increased fresh and dry weight of bananas, alongside improvements in biochemical parameters, like increased starch and total sugar content and delay in banana ripening through the reduction of cellulose and amylase activity. The study underscores the effectiveness of Si in enhancing the growth and yield of medicinal plants. Within the context of NE India, this report draws attention to the considerable challenges faced in cultivating well-suited medicinal plants and crude plant drugs, crucial for herbal healthcare and the future well-being of humanity. Consequently, Si's role in fostering therapeutic plants and enriching soil nutrient status emerges as a compelling policy to usher in a new era of medicinal plant drugs.

Key words: Acid soil, Beneficial element, Crude drug Plants, Medicinal plants, Therapeutic potential.

The northeastern region (NE) of India consisting of eight states - Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura, is a treasure trove of biodiversity, particularly known for its abundance of medicinal and aromatic plants. This region boasts remarkable cultural diversity with numerous ethnic communities coexisting for generations. The unique relationship between these communities and their natural surroundings, especially plants, has enriched modern civilization with a wealth of herbal remedies, many of which are specific to particular tribes in the area. According to Forest cover in India (FCI), 2023, around 70% of the medicinal plant species thrive in the region's forests, yet only 5% of these plants make it to the market. The geographical area and total forest cover (%) in NE India is shown in Fig 1. To unlock the entrepreneurial potential and preserve indigenous knowledge, it's crucial to adopt the scientific approach to exploring, utilizing, conserving and enhancing the value of these plants. Traditional herbal therapies, deeply rooted in the indigenous knowledge of these plants, have significantly contributed to the evolution of traditional medicine. Sadly, as time passes, this invaluable folk knowledge is fading away due to challenges such as reluctance to scale up production, limited income, improper soil management, shifting cultivation, land conversion, road development and soil erosion. Efforts to explore medicinal plants in NE India span across forests, local crude drug markets and the regions where these plants are traded. Additionally, there have been attempts to cultivate medicinal plants from one zone to another within the region. Notable high-value medicinal plants native to NE India include *Acorcus calamus, Aconitum heterophyllum, Aquilaria malaccensis, Bacopa, Bacopa monnieri, Berberis aristata and* many more (Shankar *et al*., 2013).

One of the primary challenges affecting medicinal and crude plant production in NE India is acidic soil. Out of

[1]AINP-SBB, ICAR-Indian Institute of Soil Science, Bhopal-462 038, Madhya Pradesh, India.
[2]All India Coordinated Research Project on Soil Test Crop Response, ICAR-Indian Institute of Soil Science, Bhopal-462 038, Madhya Pradesh, India.
[3]Department of Life Science, Manipur International University, Imphal-795 140, Manipur, India.
[4]Division of System Research and Engineering, ICAR-Research Complex for North Eastern Hill Region, Basar-791 101, Arunachal Pradesh Centre, India.
[5]Deptartment of Chemistry, Waikhom Mani Girls' College, Thoubal-795 138, Manipur, India.

Corresponding Author: Mayanglambam Homeshwari Devi, AINP-SBB, ICAR-Indian Institute of Soil Science, Bhopal-462 038, Madhya Pradesh, India. Email: mdevi271@gmail.com

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India's 92 million hectares of acidic soil, NE India accounts for approximately 21 million hectares (81% Total Geographical Area, TGA), with around 5.6 million hectares (22% TGA) being strongly acidic (pH<4.5) (Maji *et al*., 2012). Aluminum (Al) contamination/toxicity is a significant constraint for plant production in the region's agricultural soils (Awasthi *et al*., 2017). Al toxicity inhibits root growth and reduces water and mineral uptake and also affects the root physiology like degradation of cell integrity and lipid peroxidation (Awasthi *et al*., 2017; Silva *et al*., 2012). Additionally, it is associated with P deficiency which reduced the crop production to around 67% of the total acid soil areas (Manoj *et al*., 2012; Patiram, 1991).The beneficial role of Si nutrition in mitigating Al and Fe toxicity in cereals is well documented (Sistani*et al*., 2008). Further, its beneficial role improves crop response in rice under the strongly acidic soil of NE India (Devi, 2018; Devi *et al*., 2022). However, its specific role in promoting medicinal plant and crude plant production in this region remains to be confirmed. Therefore, this paper aims to investigate the effects of Si application on the growth of medicinal plants, physico-chemical attributes and biological responses under stress conditions.

Role of silicon in acid soil

In acid soils, particularly in NE, India, Al toxicity stands out as a significant constraint on crop production. Al^{+3} hinder the root growth and the uptake of essential nutrients (Ma *et al*., 2001). Numerous studies have underscored the beneficial impact of Si in mitigating Al toxicity in various crops like rice, sorghum, barley, maize and soybean, among others. Ma *et al*.(1997) observed that the application of silicic acid significantly reduced the inhibitory effects of Al on root elongation in maize. This ameliorative effect became more pronounced as the concentration of Si increased. The inclusion of silicic acid lowered the toxic Al^{+3}. These findings suggest that Si and Al likely interact in the solution, possibly forming non-toxic Al-Si complexes. However, alternative explanations for Si's alleviating effect have been proposed, including the co-deposition of Al and Si in the plant tissues, actions in the cytoplasm, influences on enzyme activity and indirect effects (Cocker *et al*., 1998). Additionally, Si deposition in leaves and hull alleviates water stress by reducing transpiration and keeping the leaves erect to enhance light interception (Ma, 2004). Plants pre-treated with Si exhibited higher rates of root elongation compared to those without Si pretreatment, potentially due to reduced Al uptake in Si-pretreated plants. It should be noted that this increase in root growth was not a result of decreased Al availability in bulk solution (Corrales *et al*., 1997). Si proved effective in reducing phytotoxicity caused by Al at lower concentrations (up to 50 µmol L^{-1}) in barley but had an exacerbating effect at higher Al concentrations. The extent of Si's alleviating effect on Al toxicity varies among different plant species, possibly due to variations in Al tolerance and/ or underlying mechanisms (Liang *et al*., 2001). In addition to its role in mitigating Al toxicity, Si application also resulted in a decrease in the translocation of iron (Fe) from root to shoots (Junior *et al*., 2010).

The spread of heavy metals contamination is a growing global concern, posing risks to the well-being of plants, animals and humans. Notably, heavy metals like cadmium (Cd), lead (Pb) and chromium (Cr) have no essential role in biological systems but can induce structural, physiological and biochemical changes in plants when they accumulate in excessive amounts. These metals exert adverse effects on plant growth, photosynthesis and the accumulation of essential elements. Mitigating heavy metal pollution is imperative to curtail the threat of toxic bioavailability and plant uptake. The nutrient and heavy metal content including Aluminum in NE India is shown in Table 1.

Research has demonstrated that Si can alleviate the detrimental impact of heavy metals on plants. Multiple studies have highlighted the beneficial effects of Si application on plants cultivated in contaminated soils. By mitigating the adverse consequences of toxic metals, Si contributes to enhanced plant growth, increased yields and

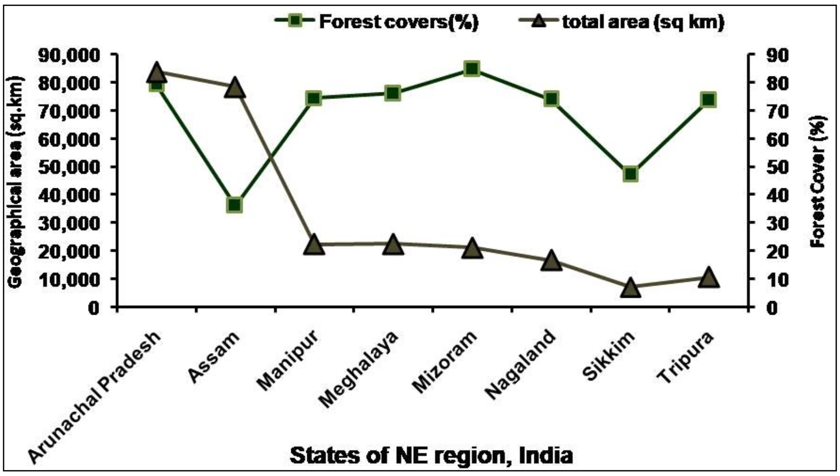

Fig 1: The geographical area and total forest cover (%) in NE India.

the promotion of safe food production (Adrees *et al*., 2015). The hypothetical mechanisms for Si-mediated alleviation of heavy metal toxicity in plants encompasses the reduction of heavy metal ions within the growth medium, diminished uptake and translocation of metals from roots to shoots, chelation and the activation of antioxidant systems within plants, complexation and co-precipitation of toxic metals with Si in various plant components, compartmentalization and structural modifications within plants and the regulation of metal transport gene expression. Nevertheless, it's important to note that the effectiveness of these mechanisms may vary depending on factors such as plant species, genotypes, specific metal elements, growth conditions and the duration of stress exposure (Adrees *et al*., 2015).

The positive effect of silicon on mitigating manganese (Mn) toxicity has been observed in various plants such as rice, barley, bean and pumpkin. This beneficial effect hinges on distinct mechanisms that vary depending on the plant type. For example, in rice, Si enhances the root's oxidation capability, thereby reducing Mn uptake (Okuda and Tkahashi, 1962). Similarly, in bean and barley, Si results in a more even distribution of Mn in the leaves without reducing uptake (Horst and Marschner, 1978; Williams and Vlamis, 1957). This uniform distribution is thought to arise from alterations in the cation-binding properties of the cell wall and the maintenance of a reduced state of apoplast. In pumpkin, Si causes a localized accumulation of Mn around the base of trichomes. Further, Che *et al*. (2016) reported that the accumulation of Mn in rice is influenced by several factors, including reduced translocation of Mn from root to shoot, potentially through the formation of Mn-Si complexes in the root cytosol and the down-regulation of the OSNramp5 gene. Moreover, under the condition of P deficiency, Si improves the internal availability of P by reducing Mn P Uptake, while under excessive P conditions, Si decreases P uptake (Ma, 2004).

Si also demonstrated its effectiveness in ameliorating the toxicities of other heavy metals including cadmium (Cd),

Table 1: Nutrient content and heavy metal levels in acidic soils of NE, India.

Location	Crop/Land uses	pH	Macro nutrient (kg ha^{-1})	Micronutrient (mg kg^{-1})	Heavy metals /Al (mg kg^{-1})	Reference
Golaghat district, Assam	Rice, Vegetable, Sugarcane, Bamboo, Tea	4.7-5.7	P: 9.5 -16.2 Ca:0.7-2.6 cmol(p^+) kg^{-1} Mg: 0.5-1.7 cmol (p^+) kg^{-1}	Fe: 10.3-80.3 Mn:2.0-29.2 Zn:0.1-0.8 Cu:0.1-1.8 B:0.3- 0.6	Al:1.3 -1.7 cmol (p^+) kg^{-1}	Barala *et al*., 2023
North-eastern Himalayan region of India	Shifting cultivation, upland, lowland, evergreen forest, grassland, scrub land, plantation and horticulture	4.1-4.94	-	Fe: 35 - 84.27 Mn:5.91-30.46 Cu: 0.59-1.74 Zn: 0.68-3.01	-	Choudhury *et al*. 2021
Kulsi River Basin, NE India		6.8-7.7	- -	Fe:2189 Zn: 22.7 Ni:7.26	Cr: 5.52 Pb:9.41 As: 0.90 Co: 2.30 Al: 22986	Jain *et al*., 2019
Ukhrul district, Manipur	-	4.9-5.5	N: 226- 302 P: 50-100 K: 90-575	Fe: 50-1005 Mn:12-112 Cu:0.23-5.60 Zn:0.72-5.64 B: 0.039-1.09	-	Jayanthi *et al*., 2015
Dibang district, Arunachal Pradesh	-	4.3-5.3	N: 119-367 P: 21-95 K:133-431 S:14-65	Fe:21-106 Mn:0.45-19.5 Cu: 0.37-4.09 Zn: 0.18-2.74 B:0.18-6.53	-	Thungon *et al.,* 2018
Ribhoi district, Meghalaya	Rice	4. 85	N: 258 P: 4.02 K: 228		Al: 4.3	Devi, 2018

arsenic (As), chromium (Cr), copper (Cu), lead (Pb) and even zinc (Zn). Notably, in the heavy metal-tolerant plant *Cardaminopsis halleri*, the coexistence of Zn and Si in the cytoplasm was observed (Neumann and zur Nieden, 2001) leading to the suggestion that the formation of Zn-silicate may play a role in heavy metal tolerance and reducing Zn toxicity. Si's ability to reduce Cd toxicity in maize plants was attributed to the development of apoplastic barriers and the maturation of vascular tissue in the roots, which enhanced the binding of Cd to the apoplastic fraction in maize shoots (Vaculik *et al*., 2012). Foliar application of potassium silicate @ 8 ml L^{-1} in acidic soil of Karnataka has been found to enhance macronutrient utilization in Sapota plants, leading to improved yield and quality (Lalithya *et al*., 2014). The application of calcium-silicates also reduced the content of heavy metals like Fe, Cu, Zn and Mn in sugarcane leaf tissue and soil, while simultaneously improving the nutrient status of macronutrients as well as the cation exchange capacity of the soil (Bokhtiar *et al*., 2012).

Medicinal plants in northeast india

The Northeast region is not only a confluence of various ethnicities and languages but also a reservoir of a vast range of medicinal plants, which play a significant role in traditional healthcare systems. Such systems are crucial, especially for rural communities that rely heavily on natural remedies for primary healthcare (Devi *et al*., 2021). These states, draped over varied topographies of plains, plateaus and mountains crisscrossed with valleys, experience a range of climatic conditions (Mao *et al*., 2009). Temperatures average around 30°C in the summer and drop to between 16 to 20°C during the winter months. The entire region benefits from a tropical monsoon humid climate, receiving copious amounts of rainfall during the Southwest monsoon from June to September, with rainfall peaking in June (De *et al*., 2010). Such favorable environmental conditions contribute to the lush vegetation and rich biodiversity that characterize the area.

Northeast India is recognized globally for its ecological significance. It is one of the world's biodiversity hotspots (Shankar and Rawat, 2006), home to myriad ecosystems including marshes, swamps, prairies and forests-both evergreen and deciduous-as well as alpine and temperate vegetation (Hore, 1998). This rich biodiversity is not only crucial for environmental balance but also offers a treasure trove of medicinal plants, which are integral to the traditional medicinal practices prevalent across the region (Chatterjee *et al*., 2006). According to the World Health Organization (WHO), 80% of the rural population in Asia and Africa, including those in Northeast India, depend on medicinal plants for their basic health care needs. These plants are primarily harvested from forests, with a small percentage growing in open fields, agricultural lands and other landscapes (Mazid *et al*., 2012). However, modernization poses challenges to these age-old practices, necessitating efforts to preserve and integrate traditional knowledge into contemporary healthcare systems (Kala, 2004). The indigenous tribes of the Northeast, numbering over 200 distinct groups, have honed their knowledge of medicinal plants over centuries. Each tribe, with its unique language and cultural practices, contributes to a rich repository of traditional knowledge. This knowledge encompasses the use of plants not only for medicinal purposes but also for nutritional needs (Mao *et al*., 2009; Chakraborty *et al*., 2012). The tribal communities possess a profound understanding of the flora in their region, often using leaves, roots and other plant parts to treat a myriad of ailments from common colds to more complex health issues (Ali and Das, 2003; Chandra, 2005).

The significance of these traditional practices and the role of medicinal plants have gained attention not only for their health benefits but also for their potential for sustainable economic development. In recent years, scientific interest has surged in exploring the medicinal potential of Northeastern flora, paving the way for innovative drug development (FCI, 2023). Ethnobotanical studies have uncovered a plethora of therapeutic plants, offer sustainable alternatives to synthetic medications (Baidya *et al*., 2020; Nath *et al*., 2021). To harness this wealth ethically and sustainably, concerted efforts are required to document, preserve and utilize traditional knowledge (Baidya *et al*., 2020). The Northeast thus emerges not only as a biodiversity hotspot but also as a cradle of traditional wisdom, beckoning humanity to rediscover the healing power of nature. As we navigate the complexities of modern healthcare, the Northeast serves as a beacon, reminding us of the timeless synergy between humanity and the natural world. Some of the common medicinal plants found and used as medicine by indigenous people of northeast India are shown in Table 2.

Role of silicon in medicinal plants

Silicon has been found to play a crucial role in the growth and development of many plants, including medicinal ones. The roles of Si in enhancing plant growth and its effect on plant metabolism have been extensively studied in agriculture. However, the effect of Si on medicinal plants and their therapeutic properties has gained increasing in recent years. The use of medicinal plants in traditional medicine is well established and the demand for plant-based medicine is growing rapidly. Silicon has been shown to enhance the production of secondary metabolites, including the bioactive compounds found in medicinal plants. These compounds are responsible for the medicinal properties of the plant and are used to treat various ailments.

The application of Si as both Si and Si- nanoparticles (Si-NPs) improved the plant growth and yield through improved relative water content (RWC), total soluble sugar (TSS), total phenolic content (TPC) and total flavonoid content (TFC). However, Si-NPs were found to be highly effective in enhancing the antioxidant capacity and essential oil (EO) yield of coriander plants under moderate drought stress (Afshari *et al*., 2021) and also EO yield in lemon

Table 2: Some of the commonly used medicinal plants discovered and utilized in North East India.

Location	Medicinal activities	Medicinal plant	Parts used	Treated ailments	Reference
Dibrugarh, Assam	Antibacterial	*Garcinia lanceifolia* Roxb.	Bark	Dysentery, dyspepsia and biliousness	Bora *et al.* (2014)
Jorhat, Assam	Antioxidants, anti-inflammatory antimicrobial agents	*Curcuma caesia* Roxb.	Leaf oil		Borah *et al.* (2019)
Karbi Anglong, Assam,	Antimicrobial and antioxidant	*Brucea mollis* Wall	Leaf, Stem, Roots	Cancer, Tumor, Leukemic, Plasmodial, antibacterial and pesticidal effect	Das *et al.* (2020)
NE India	Anticancer , diuretic activity and cardiovascular effect	*Brucea mollis* Wall	Leaf, Stem, Roots	Malaria	Bharati and Singh (2012)
Mizoram	Antiviral Anti-inflammatory	*Aeginetia indica* *Andrographis paniculata*	root leaf	Viral disease Dry cough and inflammation	Lalbiaknii *et.al.* (2023)
CSIR NEIST, Jorhat, Assam	Antibacterial Antifungal	*Ocimum sanctum Cymbopogon flexuosus*	Fresh leaf oil	-	Munda *et al.* (2019)
NE, India	Respiratory disorders	Many plants sps belong to family *Acanthaceae, Acoraceae, Asteraceae, Solanaceae, Zingiberaceae, Rutaceae, Liliaceae, Musaceae, Euphorbiaceaeetc.*	-	Asthama, Bronchitis, common cold, cough, Pneumonia, sore throat, Tonsillitis, tuberculosis	Nath *et al.* (2021)
Manipur, NE India	Herbal vapor therapy	*Justicia adhatoda* L.	Leaf	Asthma, chronic, Nasal catarrh, acute	Ningthoujam *et al.* (2013)
		Acorus calamus L.	Root and Leaf	Haemorrhoids, chronic	
		Allium sativum L	Bulb	Epilepsy, chronic	
		Centella asiatica (L.) Urb.	Leaf	Constipation, chronic	
		Blumeopsis flava (DC.) Gagnep.	Leaf	Cold, acute	
		Leucas aspera (Wild.) Link	Leaf	Sinusitis, chronic	
		Azadirachtaindica A.Juss	leaf	Pneumonia, acute, Skin disease, acute, acidity, acute	
		Cinnamomum camphora (L.)J.Presl	leaf	Epilepsy, chronic, influenza, acute	

Table 3: Effects of Si application against different stresses in some medicinal plants.

Stress env.	Medicinal plant	Si source	Form of Si applied	Observed effect of Si	References
Acidity	Ginseng	$Na_2SiO_3.9H_2O$	Foliar Application	200 mg L^{-1}Si is the most effective Si dose. Si addition increase growth and promotes physiological and morphological traits and increased yield.	Jang *et al.* (2020)
	Tomato	Silicates of calcium and magnesium	Soil application	20 g of silicon/plant recorded the highest yield but higher doses of Si decreased yield.	Perez and Herrera (2020)
Nearly neutral soil	Lemon grass	Si nano particles	Foliar application	150 mg L^{-1} Increased plant growth and yield by improving physiological and biochemical responses.	Mukarram *et al.* (2021)
	Banana	Potassium silicate	Fertigation	Increase biomass, starch and total sugar content and decrease cellulose and amylase activity.	Rangwala *et al.* (2021)
Salinity	Sweet pepper	Sodium and Potassium silicate @ 2.7 mmol L^{-1}	Foliar application	Increased the concentration of chl. and nutrient content (N, P, K), water status and yield. Decreased lipid peroxidation, electrolyte leakage, levels of superoxide and hydrogen peroxide.	Abdelaal *et al.* (2020)
	Honeysuckle (*Lonicera japonica* L.)	$K_2SiO_3{\cdot}nH_2O$	Added to in haogland solution in sand culture	Improved plant growth and Chlorogenic acid production	Gengmao *et al.* (2015)
	Borage (*Borago officinalis* L.)	Sodium slicate	Hydroponic	1.5 mM Si in nutrient solution improves the growth under salt stress.	Torabi *et al.* (2015)
Draught	Coriander	Na_2SiO_3 and Si nano particles	Foliar application	Improved relative water content, total soluble sugar, total phenolic content, total flavonoid content and increased essential oil yield.	Afshari *et al.* (2021)
Metal Toxicity	Wheat	Na_2SiO_3	Foliar application	Under Cd stress, the application of Si increased growth related-attributes, improved photosynthetic machinery and nutrient uptake and decreased MDA and H_2O_2 content.	Thind *et al.* (2021)
Biotic stress	Lavender (*Lavandula of cinalis*)	Si nano particle (10-20 nm)		50 mg L^{-1} Si-NP enhanced the multiplication of explants and increased the antimicrobial activity (*E coli* and *S aureus*) at 100 mg L^{-1} Si-NP.	Khattab *et al.*(2022)

Table 3: Continue..

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Bioreactor stress	Ornithogalum dubium	Sodium silicate		Increases plant biomass and *ex vitro* survival by improving plants protein, wax and chlorophyll levels and reducing the redox activity.	Ziv (2010)
Others	Basil (*Ocimum basilicum* L.)	Sodium silicate	Foliar application	Resistance to wilting and increase shelf-life	Tebow (2021)

grass particularly, citral and geranial content in oil (Mukarram *et al*., 2021). In addition to that, the role of Si in mitigating the negative effects of salinity on sweet pepper plants in two seasons by subjecting them to two concentrations of sodium chloride. Foliar application of Si on sweet pepper resulted in improved water status, nutrient concentration and fruit yield and reduced levels of lipid peroxidation, electrolyte leakage and reactive oxygen species (Abdelaal *et al.,* 2020). Foliar application of Si (200 mg/L) increased the Si content in ginseng leaves, hereby thickening cuticle and increasing root production while foliar Si at 100mg/L increased the stem hardiness, photosynthesis rate and, chlorophyll content. The addition of Si also increased the ginesocide contents per gram in ginseng roots (Jang *et al*., 2020). The beneficial effects of Si in medicinal plants under different stresses are shown in Table 3.

Silicon enhances medicinal plants' therapeutic potential and crude drug production

Nitrogen containing metabolites

Alkaloids are a group of organic compounds naturally containing primarily nitrogenous bases. This category also encompasses various compounds with neutral or mildly acidic characteristics. Additionally, similar synthetic structures may be classified as alkaloids (Awuchi, 2019; Robert, 1998). Alkaloids exhibit a wide array of pharmacological effects, including anti-asthma properties (such as ephedrine), anti-cancer (like hemoharringtonine) and anti-malarial effects (such as quinine). They also have stimulating effects (seen in substances like cocaine and caffeine) and psychoactive properties (such as psilocin), which make them popular for recreational and ritualistic use. Some alkaloids are known for their toxicity (for example, tubocurarine and atropine) (Awuchi, 2019a; Robbers *et al*., 1996). Typically, alkaloids induce a bitter taste and impact various metabolic systems in humans and animals (Awuchi, 2019). Another, nitrogen-based defensive compounds such as cyanogenic glycosides and glucosinolates are also crucial; they release harmful agents to ward off herbivorous insects. These substances typically consist of an á-hydroxynitrile-type aglycone linked to a sugar, usually d-glucose (MacFarlane *et al*., 1975; Vetter, 2000).

Relatively few studies have directly linked the regulation of plant stress tolerance to silicon (Si) through nitrogen-containing secondary metabolites. For instance, Khan *et al*. (2019b) demonstrated that Si supplementation boosts alkaloid levels, which in turn helps neutralize reactive oxygen species (ROS) during salinity stress. Key polyamine alkaloids such as putrescine (Put), spermidine (Spd) and spermine (Spm) are known to be crucial in plants' responses to both biotic and abiotic stressors, as discussed in several studies (de Oliveira *et al*., 2017; Mustafavi *et al*., 2018). While the roles of polyamines in enhancing plant stress tolerance are well-established, Yin *et al*. (2016) were among the first to explore how Si influences polyamine levels at the molecular level in Sorghum bicolor. Their research revealed that Si triggers the up-regulation of the gene for S-adenosyl-L-methionine decarboxylase (SAMDC), a pivotal enzyme in the synthesis of Put, Spm and Spd. They suggested that this effect of Si on polyamine-alkaloids and ethylene synthesis contributes to salinity tolerance in sorghum. Interestingly, while SAMDC was up-regulated, ethylene production decreased in sorghum exposed to salinity stress when treated with Si, likely due to the shared precursor between ethylene and Spd/Spm, creating a competitive scenario (Gill and Tuteja, 2010; Pandey *et al*., 2000). This indicates that Si may preferentially support polyamine synthesis over ethylene, thereby helping to balance these metabolic pathways and alleviate abiotic stress (Yin *et al*., 2016). Beyond stress response, polyamines are also involved in regulating vital molecular functions such as DNA replication, transcription, translation, membrane stabilization and enzyme activities (Gill and Tuteja, 2010; Chen *et al*., 2019), suggesting that Si's influence on polyamine biosynthesis not only aids in stress mitigation but also supports broader physiological processes, thus promoting growth and development in stressed plants (Yin *et al*., 2016).

Phenolic

Phenolic compounds are critical secondary metabolites in plants, playing essential roles in their defense mechanisms Typically, these compounds, including tannins, flavonoids and lignins, are present in low concentrations but increase significantly when plants face various environmental stressors (Ahanger *et al.,* 2019b). Studies have identified that phenolic substances like flavonoids and hydroxycinnamates can remove ROS (H_2O_2) and prevent their build-up by activating antioxidant enzymes, including guaiacol peroxidases (Sroka and Cisowski, 2003). Phenoxyl radicals, produced during these antioxidant processes and in lignin formation, can serve as pro-oxidants (Reyes and Cisneros-Zevallos, 2003). Phenol production is also known to escalate following wounding stress, leading to the oxidation of phenolics that generate free hydroxyl radicals, causing DNA damage (Kumar and Arora, 2015).

The role of silicon in modulating phenolic compounds has been extensively researched, with numerous studies showing how silicon can mitigate plant stress by influencing the synthesis and accumulation of these compounds. The absorption of silicon by plants has been found to boost the production of phenolics that perform antioxidant or structural roles under stress (Song *et al.,* 2016). Research also indicates that silicon's enhancement of plant disease resistance is linked to the stimulation of phenolic compounds (Chain *et al*., 2009). For instance, Shetty *et al*. (2011) have shown that the application of silicon increased the accumulation of fungi toxic phenolics such as chlorogenic acid and rutin in rose plants (Rosa hybrida), enhancing their resistance to powdery mildew (Shetty *et al*., 2011). In chestnut plants, silicon also bolsters defense against pathogens like *Phytophthora cinnamomi* and *Cryphonectria parasitica* by promoting the production of phenolics including castalagin, gallic acid and its derivatives in leaf tissues (Carneiro-Carvalho *et al*., 2019). Yang *et al*. (2017) noted that silicon supplementation in rice significantly raises the levels of phenols and lignins, improving defenses against brown plant-hopper attacks. Vega *et al*. (2019) suggested that silicon may reduce aluminum (Al) toxicity in barley by inducing phenol and lignin accumulation in the roots. Similarly, silicon helps mitigate Al-induced oxidative stress in ryegrass by increasing phenolic concentrations and influencing the activity of antioxidant enzymes (Pontigo *et al*., 2017). Silicon is also thought to boost Al tolerance by elevating the production of phenolics with Al-chelating properties (Shahnaz *et al.,* 2011). Maksimovic *et al.* (2007) demonstrated that silicon alters the metabolism and utilization of phenolics in cucumbers grown under excess manganese conditions.

Terpenes

Terpenes constitute a broad and varied group of organic compounds produced by many plants, particularly conifers and some insects (Eberhard, 2006). As hydrocarbons, terpenes frequently emit a strong odor which can help protect the plants by either attracting natural predators of herbivores or repelling herbivores themselves (Pichersky, 2006). Terpenoids, also known as isoprenoids, are closely related to terpenes but include additional functional groups, often containing oxygen and are sometimes used synonymously with terpenes. Essential oils, which primarily consist of terpenoids and terpenes, are commonly extracted from a variety of floral plants and are extensively utilized in perfumery and traditional practices like aromatherapy (Awuchi, 2019a). In flowering plants, terpenoids contribute to growth and development through roles in hormone production, components of electron transfer systems, protein modification, membrane fluidity regulation and acting as antioxidants (Pichersky and Raguso, 2018). Additionally, terpenoid metabolites are crucial for adapting to challenging environments and managing both biotic and abiotic stresses (Zhang *et al*., 2019). Plants emit volatile terpenoids when attacked by herbivores or pathogens, serving both as direct defensive agents and as indirect means to attract the natural enemies of these threats (Pare and Tumlinson, 1999). Terpenoids also play significant roles in plant growth, development (Mazid *et al*., 2011) and interactions with insects and herbivores. Rodrigues *et al*. (2004) found that silicon might boost the accumulation of diterpenoid phytoalexins in rice, contributing to resistance against blast disease. Sterols, derived from terpenes, are vital for membrane structure, interacting with phospholipids to stabilize them under stress conditions (Rogowska and Szakiel, 2020). Hemiterpenes can enhance photosynthesis and temperature tolerance in certain species (Singsaas, 2000). Furthermore, increasing endogenous levels of monoterpenes through fumigation in Quercus suber has been shown to improve photosynthesis at high temperatures (Delfine *et al*., 2000).

Tetraterpene carotenoids protect the photosynthetic machinery from photo-oxidation by acting as accessory pigments that enhance light absorption (Pattanaik and Lindberg, 2015) and by quenching the triplet state of chlorophyll molecules to prevent singlet oxygen formation (Latowski *et al*., 2014). Abscisic acid (ABA), a terpene-derived phytohormone, is integral to metabolic pathways that enhance stress tolerance, helping crops withstand conditions like drought, extreme temperatures and high salinity (Sah *et al*., 2016). Terpenoids in Commelina benghalensis have also been found to neutralize harmful radicals such as 2,2-diphenyl-1-picrylhydrazyl (Khatun *et al*., 2019).

While the role of silicon in enhancing the therapeutic potential and production of medicinal plants is promising, it is a relatively new area of study. Practical applications in agriculture, particularly in the cultivation of medicinal plants, require more detailed research. Understanding the specific mechanisms by which silicon influences phytochemical pathways and determining optimal silicon application rates are key areas for future research. Therefore, silicon supplementation could be a valuable strategy in the cultivation of medicinal plants, enhancing both the quantity and quality of the plants and their phytochemicals. This could lead to more effective and consistent crude drug formulations from these plants, potentially improving their therapeutic efficacy

CONCLUSION

Numerous researchers have emphasized the positive impact of Si on the growth and yield of medicinal plants. However, in the highly acidic soil of NE India, despite being a rich source of biodiversity and ethnic knowledge of medicinal plants, there are no reports about the beneficial effects of Si application especially for medicinal plants. As a result, it is crucial to draw attention to the enormous challenges involved in producing well-adapted medicinal plants and crude plant drugs that can be used for herbal healthcare treatment and the better health of future generations. Consequently, the application of Si to therapeutic plants and its soil nutrient status for bioactive compounds becomes an imperative policy to explore new opportunities for medicinal plant drugs. This will help to promote the development of new medicinal plant drugs, which are necessary for the health of future generations.

Conflict of interest

The authors declare no conflict of interest regarding the publication of the review article.

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