Review Article

A Comprehensive Review of Nano-sized Silica's Effects on Plant Growth, Molecular Responses, and Biochemical Changes

ABSTRACT

Silicon (Si) is a tetravalent metalloid and second most abundant on earth approximately 28%. Slags were used in agriculture as a silica fertilizer (10–28% Si); which improvise degraded crop soils, as well as crop growth and disease resistance. Si improves abiotic stress in crop lodging, UV tolerance, improves water uptakes and blocking the NaCl toxicity was observed in Gramineae family. It shows tolerance to biotic stress in terms of physical strengthening of plants against microbial infestation and activation of defensive enzymes such as peroxidase, polyphenol oxidase, lipoxygenase, phenylalanine ammonia lyase. There was an enhanced vegetative growth and germination percentage in varied vegetable crops with 100 to 500ppm range of silica nanoparticle. The plants available Si (H_4SiO_4) form in soil solution ranges about 0.1 to 0.6 mM and it get absorbed from roots via xylem to shoot containing a specialized cell surface protein called as Nod26-like major intrinsic protein (NIP) of aquaporin family. The list of total genes responsible for uptake of silica form are Low silica genes (Lsi1, Lsi2, Lsi3, Lsi6) and Si efflux transporter genes (SIET3, SIET4, SIET5). The nano-sized silica have more validated impact on genes responsiveness via morpho-physiological parameter relationship. It is concluding that, use of silica in commercial crops have deep root to influence the genes and a bright future in its crop growth development aspects.

Keywords: Nano-sized Silica, fertilizer, soil solution, vegetable crops, Plant Growth, Biochemical Changes

1. INTRODUCTION

The importance of elemental silicon came into the picture in second world war, silica applications were seen an improved results in paddy fields which were destroyed previously during the war. Industrial by-product which is called as slag (calcium silicate) was also helped for commercial boost of elemental silicate. By the time 1952, Japanese Ministry of Agriculture, forestry and fisheries declared silica as fertilizer list for the first time by conducting field trials (Ma *et al.,* 2002). The element silicon has many uses from electronic device to nano sized materials in real life. It is a tetravalent metalloid and the second most abundant after oxygen in soil as comprising 28% (approx.) on earth surface (Liang *et al.,* 2015). Application of silica fertilizer in Agriculture as Potassium silicate, Calcium silicate, and Sodium silicate as seen many benefits and there response in decreasing oxidative damage under salt stress, enhancing metabolic activities in cucumber was seen by K_2SiO_3 application and reducing the damage of stem borer larva, delaying larval penetration to the sugarcane stalk in case of $CaSiO_3$ (Tayade. R *et al.,* 2022). Many reports revealed that the silica has the capacity of decreasing the toxicity of heavy metals [arsenic (As), chromium (Cr), cadmium (Cd), lead (Pd), nickel Ni, cupper (Cu), zinc (Zn)] including As toxicity through competitive transport in aquaporins cells surface of root (Syu. CH *et al.,* 2016). In case of biotic stress, it gives resistance against fungal infection by resisting the appressorial penetration on leave surface by silica application in rice blast fungi (Hayasaka *et al.,* 2008). The genes responsible for the uptake of soil's silicic acid $Si(OH)_4$ into the plants root system are done by the aquaporins on cell surface of plasma membrane, this are Low silica 1 (Lsi1) and Low silica 2 (Lsi2). The function of Lsi1 is to transport the silicon from soil solution into root cells which are present in distal part of the exodermis and endodermis, similarly the function of Lsi2 is to efflux the silicon from root cell to neighbouring root cells (Ma *et al.,* 2007). The name Lsi1(low silica rice 1) gene came from a mutant variety of rice, which is defective in accumulation of silica in the rice shoot and reported a less grain yield compared to wild type (Ma *et al.,* 2006). The plants which are belongs to family fabaceae have the capacity of symbiotic association between the plant and bacteria to increase the mutual benefits in providing shelter to bacteria and atmospheric nitrogen to plant, studies conducted in brazil showed that using calcium and magnesium silicate as fertilizer increased significantly the nodular nitrogen fixation level and plant growth in soybean (variety: BRS 1074 IPRO) (Steiner F *et al.,* 2018). In grass family, the most know for the silica deposition is the *Oryza sativa* (Rice), in an experiment conducted by Ueno O showed a differential deposition of silica in treated plant (100ppm SiO_2) and non-treated rice plant. The major finding got a conclusion of reduced stomatal and cuticular evaporation by reduce in water loss in treated rice and in case of silica deficient plants revealed an aberrant movement in stomatal cells and increase water loss as a result of low silica deposition in cell wall (Ueno O *et al.,* 2005).

2. Nanotechnology and their applications

The world of nano-scale is already well established in mother nature in the form of biological bodies like virus, bacteria, fungi and eukaryotes. On can imagine, how a nano-scale size function of having motor and gear mechanism by human invention, but in living organism like the function is already exist in form of protein in bacteria as flagella for movement, F_O-F_1 ATP synthase in cell, actin and myosin filament in muscle, RNA and DNA polymerase for cell division (Van and Dekker, 2007). Application of nanotechnology in agriculture is very useful in terms of source utilization. The widely available building blocks of living organism is carbon and using an allotrope called Carbon Nano tubes (CNT), using CNT in soil along with tomato seed sowing resultant to faster germination due to penetration of CNT into the seed coat and enhanced the faster water imbibition.

3. Application of Nano-silica against Biotic and Abiotic stress

Similarly, the nano-scale silver is most effective against rose powdery mildew compare to normal silver due to its increased surface area and change in properties. Nano-silica is also used to strength the plant physiologically and sustain in biotic and abiotic stress. The main dis-advantage of nano-silver is change in oxidizing or reducing state due to change in environment, so the efficiency get reduced. A combination of nano-silver and silica maintained the property of silver and can use only 0.3 ppm to control the powdery mildew in pumpkin (Sharon *et al.,* 2010). For efficient and precise release of pesticide, the mesoporous nano-silica is used in which the silica particles are filled with captain (fungicide) and capped with glucan and sprayed on to the plants which are get observed into the plant body, when even the plant get attacked by fungi, the plant releases the glucanase and digest the glucan cap by which the action of fungicide happened at specific area of infection (Kaziem *et al.,* 2022). In term of abiotic stress, an experiment conducted on *Triticum aestivum* in hydroponics with provided stress of UV-B showed a negative effect on photosynthesis, increased level of superoxide radicals and decreased level of antioxidant protein was observed. On application of SiNPs showed an improved UV-B tolerance by NO-mediated triggered antioxidant defence mechanism (Tripathi et al., 2017). Liang et al. 2013 reported that Si demonstrated a counteractive role against NaCl toxicity by blocking and precipitation in exodermis and endodermis in *Oryza sativa*.

4. In-organic and organic sources of silica

The nature's chemical weathering process of primary silicate minerals are leads to desilication and some of them are listed in table 1. Immediately after weathering, silica comes under moderately mobile element between highly mobile elements like Ca+2, Mg+2, K+, Na+ and immobile Al and Fe. Silica in soil are in three phases which are Liquid, Adsorbed and solid phase (fig 1). The adsorption of silica is only a little bit after weathering is happened along with Al, Fe, Mg and most of the Si are lost through leaching into the deeper layers. There is a positive relationship between the pH and silica availability, the increase of $H_3SiO_4^-$ available form in soil solution with increase in pH of optimum 9.8. Plant absorb silica in mono-silicic acid (Haynes RJ *et al.,* 2014). Most of silica fertilizers are from plant-based byproducts like rice hull, sugarcane bagasse, but the demand raised rapidly and the supply needs were now rely on inorganic sources like industrial waste processing methods. The increase in temperature makes the Si release from bounded row mineral using electric arc furnace in case of phosphate rock and coke reaction for phosphate element and processing of byproduct to calcium silicate slag which is used as fertilizer in agriculture (Gascho GJ, 2001). One of the naturally available sources of silica is Diatomaceous Earth (DE) which consist of biogenic silica, smectite, kaolinite and quartz. Studies conducted in south Indian on application of DE and the rice growth in two types of water level in pot experiment (full capacity and submergence) showed a positive co-relation of grain yield in alkaline and acidic soils (Sandhya K *et al.,* 2018). Many researchers revealed the beneficial properties of silica fertilizer on crop growth and yield is listed in the table 2

5. Silica characterization

5.1 Transmission electron microscopy (TEM)

TEM is an effective microscopy for sample visualizing with in the internal composition of sample by electron beam. There are three systems which we use to make magnified image. First one is illumination system, which produce electron beam and can adjust the intensity, diameter by lenses based on the sample. Second the specimen stage, where we keep our sample for a stable image. Third the imaging system, here the specimen is magnified (10^3 to 10^6) by lenses and image visualization based on transmitted electron on photographic films (Egerton, 2005).

5.2 Field Emission Scanning electron microscope (FESEM)

SEM determines the specimen topographic, crystallographic properties, morphological and surface composition. The source here is electron and the beam hits the sample, which the sample produce electron or X-rays which are used to detect the sample surface and structure in detail. The size of specimen can be as minimum as 1nm and magnification capacity of 300,000 X (Akhtar *et al.,* 2018).

5.3 Fourier transform infrared (FTIR) spectroscopy

The advancement of old infrared (IR) spectroscopy to new FTIR spectroscopy based on computational development. The infrared rays hit the sample and the calculated rotational and vibrational changes in energy of dipole movement within the range can predict the molecules present in the given sample by using 780 nm (Eid, 2022).

5.4 UV-spectroscopy

The sample quantification is done by using UV spectroscopy by exiting the electrons of sample which are placed in transparent silica or quartz cuvette. The electrons which exit from ground state to higher orbit of atom by using source of 200-800nm and the emitting wavelength is detected by photomultiplier tube detector or photo diode detector (Mandru *et al.,* 2023).

5.5 Dynamic light scattering (DLS)

The main principle used in DLS is Brownian motion to determine the particle size. It is basically the laser which hits the sample in cuvette and the detector detect the particle size based on fluctuation made by particles. Every dot and there shift in position frequently made by suspension molecules present in the sample will co-related the size. The particle diffusion co-efficient is reverse the calculation to particle size (Babick, 2020).

6. Methods involved in Plant application

There are three methods involved in effective application of nanoparticles. Seed coating includes an agent which provide proper attachment of silica nanoparticles (SiNPs) to seed i.e., carboxy methyl cellulase (CMC) (Nguyen *et al.,* 2019). With every one gram of SiNPs of 0.30 g CMC was mix with appropriate solvent. If the application is foliar then, a 0.05% v/v tween 20 will act as surfactant for efficient shoot spray (Asadpour *et al.,* 2020). Direct soil application was also seen with a range of 100 to 400 mg per kg soil for effective growth in maize crop (Yuvakkumar *et al.,* 2011).

7. Morphological, Physiological and Biochemical changes

Dose development and their application is an important step to treat the plant with nanoparticle. There was a study conducted on garden pea (*Pisum sativum L.*) applying nano CuO, Mo, B and SiO_2. SiNP with 12.5, 25, 50, 100 ppm treated on pea and shown a positive relation of growth, antioxidant content and mineral uptake by 50 and 100 ppm of SiO_2 NP (Sutuliene *et al.,* 2022). A comparative study of silica fertilizer and nano silica is conducted on strawberry to see the efficiency of both fertilizer types. Out of 0, 500, 1000, 1500 ppm of both nano SiO_2 and K_2SiO_3 gave an increased fresh and dry weight of strawberry in 500 ppm SiNP against 1500 ppm of silica fertilizer (K_2SiO_3) (Dehghanipoodeh *et al.,* 2016). In case common bean (*Phaseolus vulgaris*), a experiment done on petri dish for 10 day of duration, initially the seeds are soaked in dose of nano-SiO_2 (100, 200, 300, 400 mg L^{-1}) for four hours and the treated 15 seeds from each is placed in 15 cm petri plate and provided 15 ml of each dose solution. 300 ppm of Nano SiO_2 shown the optimum germination and vegetative growth among all the treatment on common bean (Alsaeedi *et al.,* 2017). Under greenhouse condition an experiment is conducted on cucumber, a total of 4 treatment (100, 200, 300, 400 mg kg^{-1}) are done on the plant by drip irrigation supplement, 200 ppm (SiNP) given an improved in plant height, chlorophyll content, yield and increase in nitrogen, potassium, silicon in plant body (Alsaeedi *et al.,* 2019). Foliar spray SiNPs (0, 30, 60, 90 ppm) on rice seedlings improved the leaf area index and dry matter for sustainable approach (Goswami *et al.,* 2022). Soil application of synthesized nanoparticle is seen in maize experiment conducted in Egypt. Application of SiNP (0, 2.5, 5, 10 g/kg of soil) on 25 and 50 days after sowing of maize seeds in field. The soil dose of 10 g/kg SiO_2-NPs with 50% of recommended dose of N: P: K increased the plant photosynthesis, chlorophyll content, yield (El *et al.,* 2020). The soil microbial count was also found to be increased positively by SiNPs application in terms of enhanced microbial surface area for cell proliferation and improved maize germination as reported in Karunakaran *et al.,* 2013.

8. Genes responsive to silica

As we know the uses of silicon as beneficial element to plants on both biotic and abiotic stress tolerance, but the gene responsible for silica uptake and their deposition is still unknow, until the research conducted on rice cultivar which is mutant on deficient to uptake the silica into plant body and named as Low silicon rice 1 (*Lsi1*). For fine mapping of that gene, they used 1000 homozygote rice plant which was crossed between F2 plants of Lsi1 with indica cultivar Kasalath. By using new markers, gene prediction software, sequencing and comparing the specific kb region with wild and mutant Lsi1, they come to a conclusion that the mutation in DNA sequence and protein structure given a membrane channel. The difference in adenine instead of guanine and threonine instead of alanine with wild type discovered the sequence of 1,409 bp and protein with 298 amino acids as family member of Nod26-like major intrinsic protein (NIP) (Ma *et al.,* 2006). The gene Lsi1 is responsible for silicon uptake from soil solution to plant root system, but for further transportation into plant shoot system there should be another protein responsible for it, with due curiosity of the same scientists conducted an experiment to know about second protein as Low silicon 2 (Lsi2) for. For finding the gene, a mutant low silicon rice 2 (Lsi2) which developed by N-methyl-N-nitrosourea mutation and compared with wild type by mapping and using software as similar as in case of lsi1 procedure (Ma *et al.,* 2007). Finds showed that the Lsi1 is responsible for influx of silicon by a symplastic pathway and Lsi2 as efflux of silicon by apoplastic connections in exodermis and endodermis of root region. Another gene homologue to Lsi2 is Lsi3 found in pericycle of root system (Mitani *et al.,* 2023) and Lsi6 is homologue of Lsi1 found in shoot region for unloading of monosilicic acid from xylem stream to panicle of the plant (Ma *et al.,* 2011). Apart from this, the cell specific deposition of Si (amorphous) in shoot region as phytolith bodies is also been reported and named it as SIET4 (Silicon Efflux Transporter 4) gene for healthy growth of rice (Mitani *et al.,* 2023). Not only rice, there is a lot findings and discoveries are done in relationship with silica and gene responsiveness, one of them is in mangrove plant, which is the amount of Si accumulation with increased serine-rich protein gene expression (Sahebi M *et al.,* 2015) and such are listed in table 3.

Silica enhances the gene expression of S-adenosylmethionine decarboxylase (s-AMD) which increase the polyamine and inhibiting ethylene synthesis was studied earlier by Yin *et al.,* 2016 in Sorghum bicolor, Lignin biosynthesis was enhanced by increase deposition of silica in root tissue, thereby increase in lignin content which binds with silica in the interspace of cell responsible by protein Phenylalanine ammonia-lyase 2 (PAL-2) as reported by Jadhao *et al.,* 2020 in finger millet. Studies revealed that, silica defend the ROS by increase the scavenger enzymes. Catalase breaks the H2O2 into H2O and O2. The Superoxide dismutase (SOD) and peroxidase-1 (Px 1) increase the superoxide anion (O2-), Silica enhance MAPK (mitogen-activated protein kinase) and WRKY transcription factor which increase MAPs, this is inert signalling molecule and express when it hit stress and thereby increase the defence hormone (jasmonic acid) with the help of protein Allene oxidase synthesis (AOS) as reported by Ye *et al.,* 2013 in rice and silica upregulates the Arginine decarboxylase (ADC) which enhance the polyamines. Polyamines are involved in cell division, elongation, and differentiation. Upregulation of arginine decarboxylase promotes various processes leading to enhanced growth and development of plant tissues which was reported by Yin *et al.,* 2016 in Sorghum bicolor.

9. Deposition of silica

The criteria of essential element required to complete the life cycle without any deficiency symptoms as listed 16 (Arnon D, Stout P, 1939) and later studies conducted by Brown on barley as there is large reduce in germination percentage (50%), plant vigour and embryo maturation to fill up the grain is shown in nickel deficient media and resumes the normal plant life cycle on addition of Ni, as nickel is included the 17th essential element category (Brown *et al.,* 1987). But in case of silicon, which is categorized as beneficial element because of its positive benefits to only some extant of plant which includes rice, wheat, barley etc (Ma *et al.,* 2001).

9.1 Rice

Rice is one of the most accumulator of silica in the plant body. Approximately 230-470 kgs/ha of silica is accumulated in the form of silica gel as a beneficial element, it improves crop growth and productivity and also seem to be a positive corelation with nutrient availability (N, P, K, Ca, Mg etc.) and reduced toxicity (Fe, Mn, P, Al). Available form of silica is mono-silicic acid (Si(OH4)), it is absorbed from soil solution and transported by xylem via symplastic, apoplastic pathway and finally reaches to shoot. Mono silicic acid is carried by water and stayed in plant tissue but the water is lost by transpiration and over the time it's accumulates and polymerized to silica gel in various part of plant body by non-enzymatical process. Silica tends to deposit beneath the cuticle as a 2.5 micron thin layer called Si double layer. The only form of silica is amorphous which is present in plants and their precipitation in cells is called as phytoliths or plant opal. Phytoliths are found in specific cell as silica cells in vascular bundles. (Rao GB *et al.,* 2017).

9.2 Sorghum

Studies conducted on sorghum suggest that the silica deposition in plant tissue is reduced to half (50%) when the surrounding humidity is increased to 100% their by reduce in the transpiration rate. It conforms that the silica deposition is occurs through xylem vessels by transpiration (Kumar S *et al.,* 2017). The deposition of Si begins after the programmed cell death of parenchyma cells and dissolution of their organelles to a specialized cell called silica cells (Kistler L *et al.,* 2013). Most of the silica cell formation in shoot happens during active stage of leave formation. The process of silicification occurs in dead cells and the organic material which are present in apoplastic space of silica cells enhance the conversion of soluble silicic acid to solid silica by protein, peptides and sugars etc., (Kumar S *et al.,* 2017).

9.3 Cucurbits

In Cucumis sativus Linn., their was an observation and analysis of warts of exodermis which are appears in anthesis and disappear after fruit maturation (Zhang H *et al.,* 2016). But the analysis by using Scanning electron microscopy (SEM) and electron probe micro-analyzer (EPMA) shown that the warts are accumulating major silica and minor other minerals, mostly highest silica and second highest Nickel deposition was seen in warts and which we use cucumber for salad along with exodermis have beneficial effects on health (Tripathi D *et al.,* 2017)

9.4 Horsetail

The highest silica deposition till date is recorded in plant horsetail (Equisetum) (Bauer P *et al.,* 2011). Experimental studies conducted on horsetail by hydroponics revealed numerous silicified structures including cell wall, cell plates, plasmodesmata, guard cells and stomata. An interesting co-relation between the macromolecules and the silica deposition shows that the polysaccharide callose in between the cell wall makes a template provider for bio-silicification (Law C and Exley C, 2011).

10. Silicification and polymerization process

The absorbed form of silica is mono-silicic acid from soil solution into the plant system. When the acid concentration reaches more then 100-200 mg/kg, the polymerization among the Si molecules starts and proceed to increase the surface area. Initially the monomeric forms get condensed to oligomeric molecules which are cyclic in nature and size is nearly 1-3nm and are called as nano-colloids. This nano-molecules have negative surface charge and the interaction with cell wall polymers begins, there are many factors which effects further polymerization in cell wall depending on the type of biomolecule present in it. Experimental proofs suggested that polysaccharides, pectin and lignin will negatively effect's the polymerization and amines have a positive relationship of increasing in biological system called as bio-silicification for silica gel formation and the entire process is depicted in fig 2 (Zexer N *et al.,* 2023). Polymerization begins with neutral molecule $Si(OH)_4$ and a negatively charged $[SiO(OH)_3]^-$ via oxolation reaction of SN2 nucleophilic substitution. Studies suggested that for silicification, the two precursor molecules should come close enough to make bond and further polymerization. There are two possibilities of polymeric reaction to start, either there is a spontaneous collision between molecule via Brownian motion or there should be a bio-molecule which favours the reaction, most studies revealed that peptides and amino acids are the molecules which favours bio-silicification (Coradin T *et al.,* 2001). Researchers studying on kinetics of silica nucleation revealed that amine-terminal of amino acid surface do not promote silica nucleation, it is the carboxyl and hybrid (NH3+/COO-) substrates which actively supports the silica deposition (Wallace *et al.,* 2009). ~~Another study got results, that hydroxyl and hydrophobic group containing amino acid are producing small size particle (Si) and amino acids which having nitrogen are making larger particles. Specially the lysine oligomer accelerated the silica aggregation exponentially (Belton D *et al.,* 2004).~~

11. Conclusion

The nano-sized particles particularly silica have a strong impact on morphological, physiological and biochemical aspects. The SiNPs as revealed more responsive over traditional fertilizers and the penetration into the biological system. The experiments on SiNPs synthesis, plant application, morpho-physiological parameters, process of silicification and detail study of gene responsiveness concludes a sustainable approach for agricultural practices over traditional method with minimum utilization of resources.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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Table 1: Silicate classification based on class and examples listed (Duffin and Christopher, 2006)

Class	**Common name**	**General formula**	**Example**
Nesosilicates	Island silicates	SiO4	Olivine, Granets
Sorosilicates	Couplet silicates	Si2O7	Epidote group
Inosilicates	Chain silicates	SiO3 or Si8O22	Pyroxenes, amphiboles
Cyclosilicates	Ring silicates	Si6O18	Beryl, tourmalines
Phyllosilicates	Sheet silicates	Complex and variable	Micas, Clay minerals
Tectosilicates	Framework silicates	Complex and variable	Feldspars, feldspathoids, zeolites, quatz

Table 2: Organic waste source for silica and major findings

crop	Source	Major findings	Reference
Rice	Rice husk	Increase in grain yield and dry matter using of plant based silica fertilizer instead of chemical fertilizer	Moghadam and Heidarzadeh, 2014
Rice	Mineral ash	Increase in effective tiller no., yield	Yasari E *et al.,* 2012
Timothy grass	Optysil	Positive effect on plant height, seed yield and quality	Radkowski A&I, 2018
maize	Active silica	Raise in uptake of N, P, K and yield of plant	Prajapat BS *et al.,* 2021
Lettuce	Liquid fertilizer (Si 7% & K 1%)	Increase in productivity of red leaved lettuce	Semenova NA *et al.,* 2021

soybean	Commercial fertilizer (25% SiO_2) & sodium metasilicate	Increase in root nodule no. and size	Tripathi P *et al.,* 2021
rice	Silica '(5 L/ha)	Plant growth	Syamsiyah J *et al.,* 2023
Oil palm	Calcium silicate	Increase Si content, growth, fresh & dry weight, chlorophyll a content, net photosynthetic rate.	Duangpan S *et al.,* 2022
soybean	Sulfur-silica fertilizer (2.3% S & 10% Si)	Increase in no. branches, leaves, pod and pod weight	Hariyono K *et al.,* 2024

Table 3: List of Genes responsive to silica

Gene name	Major findings	Reference
Lsi1(Low silicon rice 1)	Influx of silicic acid in root	Ma *et al.,* 2006
Lsi2**(**Low silicon rice 2)	Efflux of silicic acid in root	Ma *et al.,* 2007
Lsi3(Low silicon rice 3)	Efflux of silicic acid in root	Mitani *et al.,* 2023
Lsi6(Low silicon rice 6)	Influx of silicic acid in panicle	Ma *et al.,* 2011
SIET4(Silicon Efflux Transporter4)	Efflux of silicic acid in shoot	Mitani *et al.,* 2023
Rhizophora apiculata serine-rich protein gene	Expression level of serine-rich protein genes with the Si accumulation in mangrove (*Rhizophora apiculate*)	Sahebi M *et al.,* 2015
PR1 pathogenesis-related protein 1	SA(salicylic acid)-dependent defence signalling is essential for $Si(OH)_4$- and SiO_2 NP-induced disease resistance	El-Shetehy *et al.,* 2021
PR5 pathogenesis-related protein 5	SA(salicylic acid)-dependent defence signalling is essential for $Si(OH)_4$- and SiO_2 NP-induced disease resistance	El-Shetehy *et al.,* 2021
Auxin-responsive protein IAA6-like, GH3	Upregulation of IAA6-like, GH3 genes expression on F-SiO_2 exposure	Cheng B *et al.,* 2021

Cell wall (A2WZ30), programmed cell death (B8BCT6), glutathionine (A2YX67), wax related genes (B8AP99)	Upregulation of this genes on application of 5mglL-1 of F-SiO2	Cheng B *et al.,* 2021
Protochlorophyllide oxidoreductase	Root application of Si in cucumber increased the upregulation of POR gene, which is protochlorophyllide to chlorophyllide conversion is a critical step in synthesis of chlorophyll	Gou T *et al.,* 2020
dehydration-responsive element genes	Triggered up-regulation of **dehydration-responsive element-binding protein** in drought and increase temperature	Manivannan A & Ahn YK *et al.,* 2017
S-adenosylmethionine decarboxylase (SAMDC)	Si elevated the expression of SAMDC, which is used in processing SAM in shikimate pathway and it produce aromatic amino acids	Manivannan A & Ahn YK *et al.,* 2017
EcPAL (Salicyclic acid), EcLOX	Significant increase in transcript level of EcPAL, EcLOX on silica treatment on stem borer infestation in finger millet	Jadhao KR *et al.,* 2020
linoleate 9S-lipoxygenase-3	Downregulation of all expressed lipoxygenase genes was observed in leaves, decreased level of hydrogen peroxide and lipid peroxidation indicated lower oxidative stress level in silicated shoot tissues	Bat-Erdene O *et al.,* 2021

Fig 1: Silica phases and form available in soil (Tubana and Heckman, 2015)

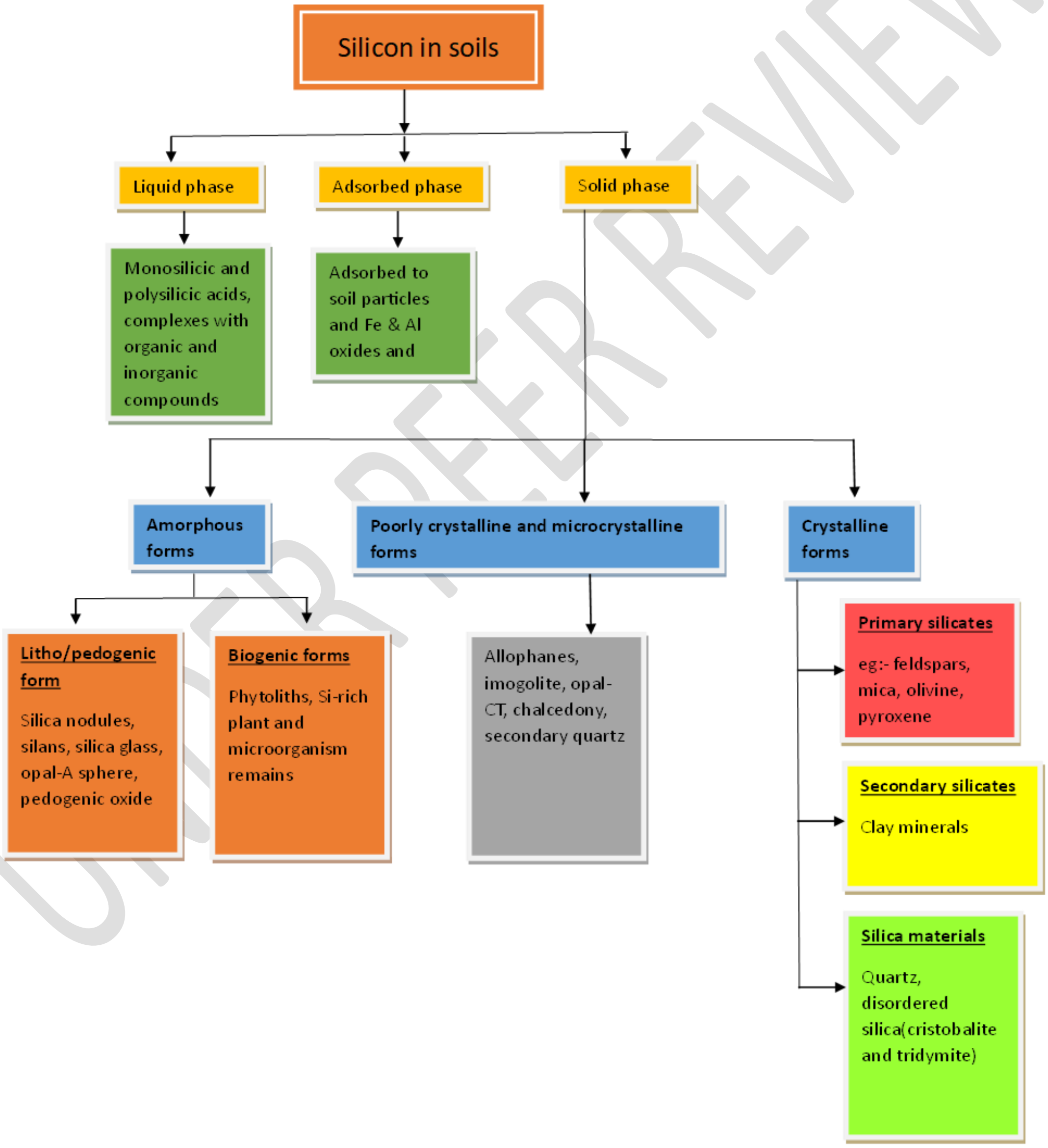

Fig 2: Process of Silicification a) mono-silicic acid reaction b) Dimeric form c) polymerization d) Nano-colloid formation e) silica gel formation.