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Review article

Silica nanoparticles as novel sustainable approach for plant growth and crop protection

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ABSTRACT

Agriculture crops encounter several biotic and abiotic stresses, including pests, diseases, nutritional deficits, and climate change, which necessitate the development of new agricultural technologies. By developing nano-based fertilizers, insecticides and herbicides, and early disease diagnostics, nanotechnology may help to increase agricultural crop quality and production. The application of silica nanoparticles (SiNPs) may be the solution for increasing the yield to combat the agriculture crisis in the near future. SiNPs have unique physiological properties, such as large surface area, aggregation, reactivity, penetrating ability, size, and structure, which enable them to penetrate plants and regulate their metabolic processes. Pesticide delivery, enhanced nutrition supply, disease management, and higher photosynthetic efficiency and germination rate are all attributed to SiNPs deposition on plant tissue surfaces. SiNPs have been demonstrated to be non-toxic in nature, making them suitable for usage in agriculture. In this regard, the current work provides the most important and contemporary applications of SiNPs in agriculture as well as biogenic and non-biogenic synthetic techniques. As a result, this review summarizes the literature on SiNPs and explores the use of SiNPs in a variety of agricultural disciplines.

1. Introduction

Nanotechnology is a well-established discipline of science and technology that plays a significant role in the agricultural industry. It is a branch of research concerned with the use of nanoparticles (NPs) in order to develop new nano-based products of higher quality that may be used in a variety of fields such as health, manufacturing, electronics, wastewater treatment, and agriculture. Nanotechnology, along with biotechnology, plays a significant role in the advancement of the agricultural field (Tubana et al., 2016). The ability of nanotechnology to detect and manage plant pathogens has proven beneficial to the agricultural industry, leading to increased livestock production (Adebisi et al., 2018). NPs, which are also very potent fertilizers for agricultural productivity, can be used to control pesticides and plant diseases (Adebisi et al., 2020). SiNPs, among the several metal and non-metal NPs, have reportedly increased plant tolerance to biotic and abiotic stress, reducing the negative effects (Khan et al., 2021). Aside from that, it improves plant resistance to a variety of heavy metal elements (Jia-Wen et al., 2013). Nanotechnology increases the production rate and improves the quality of agriculture crops at a low cost and with no toxic effect on living beings or the environment. The primary premise behind SiNPs use in agriculture is to reduce hazardous environmental inputs and excessive fertilizer costs because they are made using greener concepts and will mitigate the negative effects of chemical fungicides. Due to executive characteristics such as large surface area and small dimension, SiNPs have agricultural potential, ensuring realistic dispersion in plant tissues (Bhat et al., 2021). Scientists have explored the research and utilization of NPs as soil stabilizers. A SiNP is polymerized in root tissues before being transferred and deposited in shoot sections (Debona et al., 2017). However, the confirmed mechanism still needs to be researched (Coutris et al., 2012). SiNPs were also used directly on plants as pesticides, herbicides, and fertilizers (Malik et al., 2021). SiNPs also act as carriers for the transport of materials for proteins, nucleotides, and other compounds in flora and might be successfully utilized in farming to enhance the water holding capacity of soil (Bapat et al., 2020).

SiNPs have a broad range of applications since they are often affordable to manufacture on a large scale, hydrophobic, have a high surface area and pore volume, and are biocompatible. Because of their remarkable adsorption power and non-toxic nature, SiNPs, for instance, have been employed to address issues in agriculture. SiNPs have recently been used to boost agricultural yields, improve plant development, and promote disease resistance. The research to investigate and exploit new potential applications for SiNPs is still ongoing. The improvement of agricultural

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output is thought to be the second most important application of nanotechnology. The actual and potential effects of SiNPs on flora, as well as the importance of their use in agriculture, will be the focus of the following sections of this review.

1.1. Status of nanotechnology in agriculture field

The existing world population is estimated to be 8.6 billion in the year 2030, 9.8 billion in 2050, and 11.2 billion in 2100 (Islam and Karim, 2019). As a result, it will greatly increase the demand for advanced agricultural practices for improved crop production in order to meet the growing food demand. Finally, the implementation of nanotechnology in the agriculture sector will ultimately reduce food scarcity, hardship, and hunger (Khandker and Mahmud, 2012). Several countries have now recognized the benefits of nanomaterials in the agricultural sector and have offered money for future development throughout the world (Banterle et al., 2014). Plant infection management, slow fertilizer discharge, and effective agro-nanomaterials like herbicides and pesticides have all been observed to use nanomaterials (López-Salazar et al., 2014). Therefore, it is a major requirement to implement innovative methods that assure improved crop production in a short period of time. Yet, agriculture is still in its primitive phase and requires investigation (Adinarayana et al., 2020). The most recent advancement reported for improving agricultural productivity and soil properties for farming is agronomic nanotechnology (Goswami and Mathur, 2019). The present review will focus on the application of SiNPs that have improved agriculture in multiple ways to achieve an evergreen revolution.

2. Material and methods

This investigation is a systematic review representing the novel sustainable approach of SiNPs in plant development and crop protection (Figure 1).

2.1. Data resources and search strategy

Online databases such as PubMed, Science Direct, Scopus, Web of Science, Embase, and ProQuest were used to find previous studies published up until December 2021. The keywords included "Si", "NPs", "Biogenic", "Synthesis", "Agriculture", "Agro-waste", "and Plant development", "Nanomaterials", "Biotic and Abiotic".

In addition, we combed through the references of selected papers to identify relevant works. Two independent researchers conducted the first and second screenings to further assess the publications' eligibility in accordance with the standards of the recommended reporting items for systematic reviews and meta-analyses.

2.2. Inclusion criteria

Publications that fulfilled the inclusion criteria were considered: a) published peer-reviewed publications; b) research articles published up to December 2021; c) English language papers; d) novel in-vitro studies related to the application of SiNPs to sustain agriculture; and e) articles that contain sufficient data.

2.3. Exclusive criteria

We eliminated articles with replicated records, review articles, conference proceedings, letters and editorials, non-English language papers, papers evaluating the negative consequences of nanomaterials, and papers examining the toxicological effects of SiNPs on plant growth, transpiration, and stomata opening.

2.4. Assessment and data extraction

Two researchers extracted data from the chosen publications using a data extraction form that contained the first author, year of publication, a biological source with a scientific name, the use of SiNPs as fertilizers, fungicides, pesticides, and notable outcomes. The following summarizes the search procedure for SiNPs application in agriculture.

3. Results and discussion

3.1. Synthesis of SiNPs

3.1.1. Chemical synthesis of SiNPs

Previously, SiNPs were formed using traditional methods such as the sol-gel method, Stober's method, flame synthesis, and micro emulsion (Liou and Yang, 2011). Although these chemical pathways are simple to follow and adjust in terms of parameters and can be expensive and hard to manage. This method of synthesis yielded NPs that were successfully used as functional group coatings (Liberman et al., 2014; S. Liu and Han, 2010). Chemical vapour condensation (CVC) is another prominent method for producing SiNPs. This process involves the reaction of silicon tetrachloride with oxygen and hydrogen. In this method, the physical features of the NPs, such as shape and particle size, can be adjusted to achieve the desired results. Similarly, the sol-gel technique is a well-known approach for producing Si and Si gel (Du et al., 2020; Sriwuryandari et al., 2020). In the presence of a catalyst, it mainly includes the hydrolysis and condensation of metal alkoxides such as TEOS (Tetraethyl orthosilicate) or inorganic salts such as sodium silicate. Despite their advantages, chemical synthesis procedures are costly, contain dangerous ingredients, and demand a lot of energy.

3.1.2. Biogenic synthesis of SiNPs

Among all the other reported processes, the green synthesis route was considered the most advantageous route for NPs synthesis. Generally, the physical and chemical methods that have been used for the production of NPs have the dispute of being hazardous (Karande et al., 2021). A biological approach to NP synthesis is defined as the use of natural resources as nontoxic and environmentally friendly lowering and stabilizing agents for the production of NPs of various sizes and morphologies. Biogenic SiNPs were discovered to have high efficacy in agriculture and farming, according to studies (Snehal and Lohani, 2018). Furthermore, a number of research studies have been conducted to investigate the practicality of biogenic SiNPs in a range of domains, including healthcare and industrial, with varied levels of effectiveness. Plants and plant wastes were the most commonly used biological resources in the production of SiNPs. In order to reduce the toxicity, green approaches have been practiced to manufacture the NPs of our interest, which are measured to be less toxic and eco-friendly (Jeelani et al., 2020).

Therefore, the NPs are less lethal and practically cleaner than those synthesized through chemical processes (Kumar et al., 2020). Among the various metal NPs synthesized using the green method, SiNPs have been extensively studied (Adinarayana et al., 2020). Several agricultural residues, including rice husk, hull, and straw, as well as industrial residues, such as sugarcane bagasse, were used as excellent sources of Si (Karande et al., 2021). Taking into consideration the vast significance of SiNPs in cultivation, it is necessary to develop and implement biogenic SiNPs in the agriculture field. Generally, the regular crystalline SiNPs are synthesised in the nano-meter range through green routes utilizing agricultural waste (Jansomboon et al., 2017). Agricultural and plants wastes are utilized as precursors for the preparation of SiNPs (Figure 2). The major benefit of utilizing the waste is its accessibility, which is cost-effective, biodegradable, and less toxic as compared to other reported chemically synthesized NPs. Several reports were obtained for SiNPs production through rice husk (Jansomboon et al., 2017). Besides this, sugarcane bagasse is considered a common waste material obtained through the sugar manufacturing industry (Lu and Hsieh, 2012; Mohd et al., 2017). Falk with his colleagues utilized sugarcane bagasse ash to manufacture SiNPs through isothermal reactions (Falk et al., 2019). Sankar and his colleagues utilized gummy, red, and brown rice husk ash and prepared eco-friendly silica nanoparticles (Sankar et al., 2016).

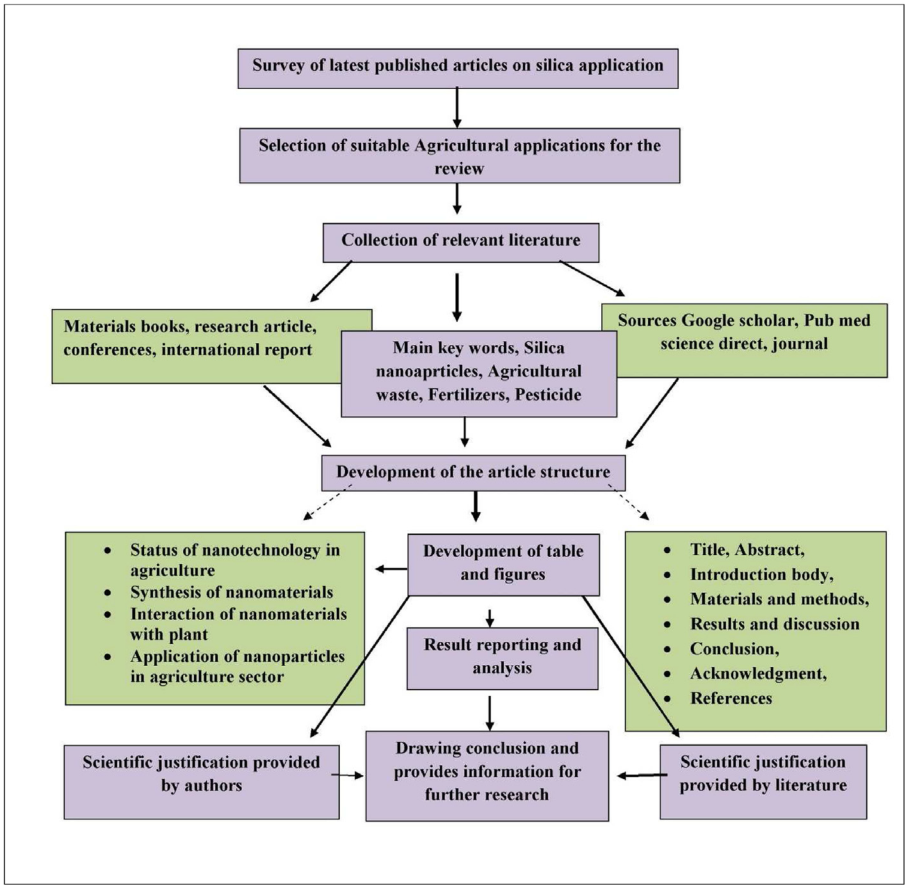

Figure 1. The methodology of the pertinent research covered in the review, as well as the stages involved in processing the information and data contained in the publications, are represented schematically.

SiNPs are also prepared from the farm waste such as rice husks, bamboo leaves, sugarcane bagasse, and peanut shells and obtained 52–78 percent SiNPs from individual wastes (Table 1) (Vaibhav et al., 2015). Farming wastes were applied to annelid treatment, utilizing *Lumbricus terrestris* variety to create humus, and then SiNPs were developed through calcinations and acid application (Espíndola-Gonzalez et al., 2010).

Ghorbani along with his colleagues developed an original technique to prepare SiNPs through sedge (Ghorbani et al., 2013). The sedge, *Carex riparia* Curtis. is a wild plant that generates a huge quantity of waste. *Sorghum bicolor* (L.) Moench also generates farming remains, but these farming wastes are not disposed of accurately, so they cause pollution. Its wastes have the highest concentration of Si, so they can be used as a prerequisite for the production of SiNPs (Athinarayanan et al., 2020). SiNPs were also prepared through the application of *Sorghum vulgare* Pers. seed by (Balamurugan and Saravanan, 2012). As a consequence, all of the preceding evidence from diverse research shows that agro-based residue is a valuable choice for the manufacture of SiNPs due to its accessibility. (Babu et al., 2018) used a *Cynodon dactylon* (L.) Pers. plant as source for Si. (Sethy et al., 2019) used bamboo leaf ash to prepare SiNPs and integrated them into a poly di-methyl siloxane (PDMS) membrane to increase their separation characteristics. The majority of the literature has utilized extracts of plant tissues as a support for the preparation of SiNPs in the alkaline hydrolysis step. (Durairaj et al., 2019) prepared SiNPs through a sol–gel process utilizing *Bambusa vulgaris* Schrad. ex J.C. Wendl. leaf ash and applied them for ecological benefits. (Jabeen et al., 2017) observed the development of SiNPs utilizing *Azadirachta indica* A. Juss. leaf extract that behaves as a successful chelating material. (Al-Azawi et al., 2019) developed SiNPs through hot aqueous extract of *Thuja orientalis* Linn. leaf and observed its outcome on bio-film development.

Numerous chemical compounds found in plant extracts have been shown to behave as both reducing and stabilizing agents during the NPs formation process (Dumur et al., 2011). Plant tissues such as leaves, roots, latex, seeds, and stem are extensively utilized for different NPs preparations (Rahman et al., 2019). Extracts such as bioactive polyphenols, proteins, phenolic acids, alkaloids, sugars, terpenoids etc., are responsible for reduction during NPs development (Figure 2). The major sustaining aspect for physical properties of the synthesized NPs is the difference in quantity and conformation of these reducing bio agents with aqueous metal ions (Aslam et al., 2021). During the process, the plant and waste extract and the metal salt suspension are mixed perfectly at room temperature (Siddiqi et al., 2018).

The several instrumental approaches such as Field Emission scanning electron microscope (FESEM) Energy-dispersive X-ray spectroscopy (EDX), Fourier-transform infrared spectroscopy (FTIR), X-ray crystallography (XRD), and Transmission electron microscope (TEM) are used to characterize NPs. Finally, the utilization of SiNPs in the agricultural area is highlighted in this review. Other than biocompatibility and stability, these materials' unique characteristics include variable pore size, high surface area, and surface reaction. The simplicity with which SiNPs may be surface functionalized expands their agricultural applicability.

3.2. SiNPs interaction with plants

NPs having a diameter of 5–20 nm might penetrate through the cell wall and reach the plasma membrane with ease. They can pass through stomata openings or the base of trichomes, then foliar spray them into different tissues. After accumulation and translocation of NPs, produces changes in different cellular and physiological functions of the plant. Plants uptake SiNPs through their roots and get polymerized in their

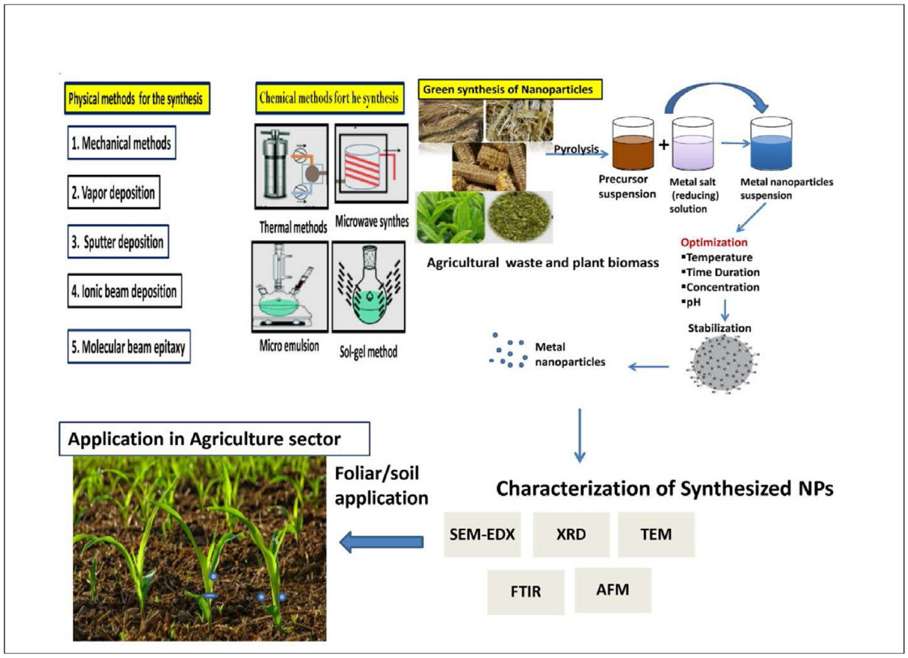

Figure 2. An illustration of the process of synthesizing and characterizing SiNPs in general.

Table 1. Utilization of waste materials in the manufacture of SiNPs.

Sr. No.	Synthesized NPs	Waste material	References
1.	SiNPs	Corn cob	(Okoronkwo et al., 2013)
2.	SiNPs	Sugarcane bagasse	(Falk et al., 2019; Mohd et al., 2017)
3.	SiNPs	Rice husk, rice straw Rice hull	(Chen et al., 2013; Sankar et al., 2016)
4.	SiNPs	Bamboo leaves	(Vaibhav et al., 2015)
5.	SiNPs	*Citrus limon*	(Tiwari et al., 2019)
6.	SiNPs	*Thuja orientalis* leaf	(Al-Azawi et al., 2019)
7.	SiNPs	Wheat husk	(Patel et al., 2018)
8.	SiNPs	*Casava Periderm*	(Adebisi et al., 2018)
9.	SiNPs	Maize Stalk	(Adebisi et al., 2020)
10.	SiNPs	*Cynadon dactylon*	(Babu et al., 2018)
11.	SiNPs	Groundnut shell	(Yaro et al., 2017)
12.	SiNPs	*Sorghum bipolar*	(Athinarayanan et al., 2020)
13.	SiNPs	Teff straw	(Wassie and Srivastava, 2017)
14.	SiNPs	Palm kernel shell Ashes	

tissues, then translocated and stored in shoot tissues (Mittal et al., 2020). Phytoavailability of Si depends on numerous parameters such as Si quantity in soil, organic material, soil pH, and soil humidity. Plants uptake Si through two expected systems, such as active and passive transportation, based on plant varieties (Klotzbücher et al., 2020). Quite a few plant varieties are identified for their passive uptake of Si as grasses (Attia and Elhawat, 2021; Ryalls et al., 2018). Besides this, SiNPs enter the plant xylem through active route transportation, as formerly shown in rice (Etesami and Jeong, 2018). The mechanism of interaction of SiNPs in plants is not completely understood yet. SiNPs accumulate and may form a second layer of cuticle-Si behind the cuticle, blocking pathogen penetration and decreasing illness incidence. The majority of the Si in cell walls is crosslinked with hemicellulose, which improves mechanical properties and regeneration. A lot of investigations are being done on translocation mechanism of SiNPs into the plant. The route of SiNPs treatment for plants will promote understanding regarding the effectiveness of Si uptake (Figure 3) (Alsaeedi et al., 2019). In a study, green synthesized SiNPs effects were observed after foliar application on maize plants. The foliar-treated maize leaves reduced the stress that enhanced its Si concentration. Observations from the study confirmed that soil amendment with NPs was much more effective than foliar treatment for maize plants (Suriyaprabha et al., 2014). Thus, it can assist in improving sustainable agriculture as a Si fertilizer. A study was conducted to evaluate the outcome of dissimilar concentrations of SiNPs (0, 30, 60, and 90 ppm) as foliar treatments on rice seedlings. According to the findings, there was a significant improvement in leaf area index as well as in the dry matter content of grains, biological yield, and chlorophyll content. The foliar treatment of SiNPs increased all the above mentioned factors up to a particular amount (El-Samahy et al., 2015).

3.3. Application of SiNPs in agriculture sector

Agriculture is facing major problems such as shrinking farm land, minimum water availability, low organic soil, and diminishing resources with an increasing population. To address all these challenges, researchers are looking for an alternate technology like "nanotechnology" that is required by agricultural crops that improve productivity and variety (Figure 4) (Goswami and Mathur, 2019). SiNPs have physiological features that permit them to penetrate plants and manipulate plant metabolic actions (Rea et al., 2022). Thus, this review includes studies on biogenic SiNPs and discusses their effects on numerous factors of farming. There are two major processes related to biotic and abiotic stress resistance: (i) a physico-mechanical mechanism produced by SiNPs, and (ii) a biochemical mechanism controlling metabolic activity. The interaction between plants and NPs is determined by various parameters such as dimension, morphology, mode of treatment, physico-chemical characteristics of the NPs (Rastogi et al., 2017). Latest research has depicted that SiNPs might directly react with flora and manipulate their morphology and physiology, thus assisting in enhancing plant growth and yield (Table 2) (Rastogi et al., 2019). SiNPs were illustrated to form dual layers on the epidermal cell wall after accumulation. It is also considered as a strengthening substance that might work as a mediator to avoid fungal, bacterial, and nematode contamination. Researchers also illustrated that a SiNPs layer might decrease plant transpiration and,

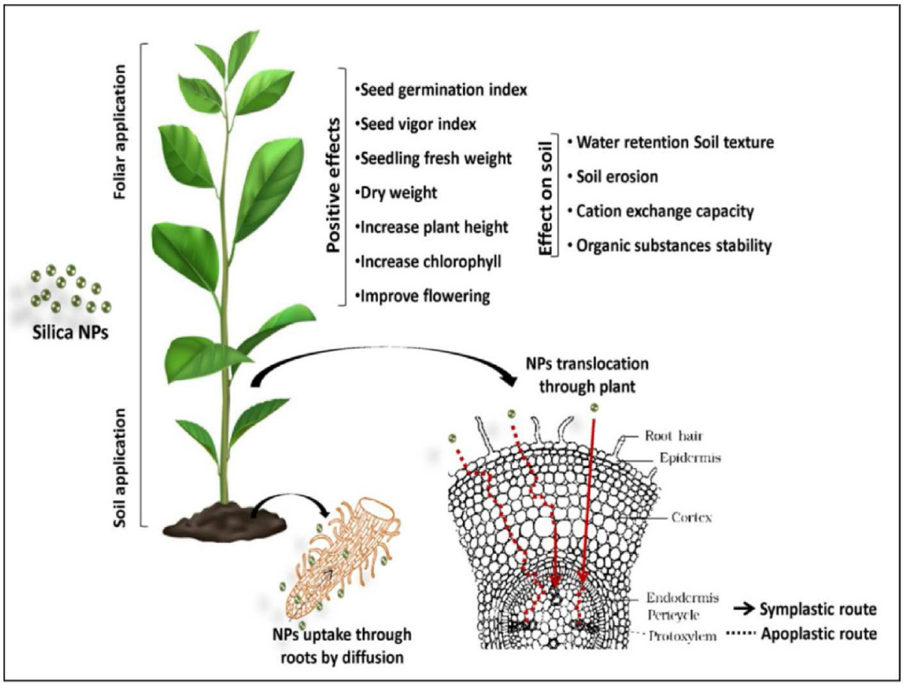

Figure 3. Different routes for the interaction and transport of SiNPs into the plant system are depicted in a schematic diagram.

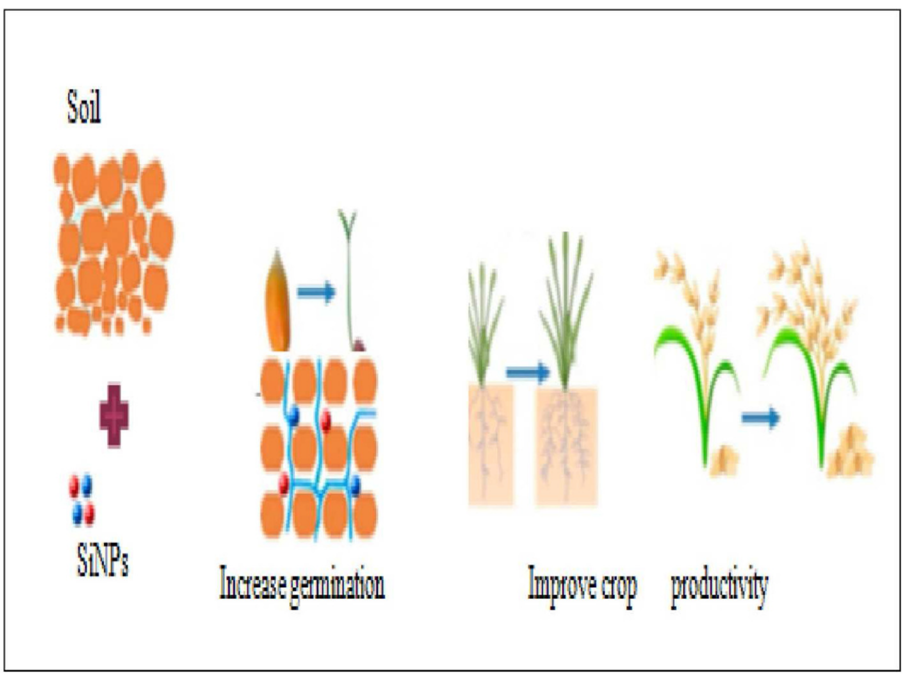

Figure 4. SiNPs enhance the mechanical and physiological properties of plant tissue.

therefore, create flora that is extra resistant to drought stress (Strout et al., 2013).

SiNPs were also reported to be either advantageous or useless for plants, either through supporting flora development or having no effects, in part from a small number of studies where SiNPs were reported to have a harmful effect on flora. The comprehensive features of SiNPs permit them to give plants more resistance against abiotic and biotic stresses. Silica nanoparticles have been reported to be utilized as fertilizers, insecticides, and herbicides, as well as a new agent towards heavy metal impacts, salt stress, and drought stress. As a result, SiNPs have the potential to enhance crops for long-term farming (Rastogi et al., 2019). Also, the SiNPs decreased the harmful impacts of the UV rays, such as low fresh weight, decrease in chlorophyll, and tissue injury (Tripathi et al., 2017). In pea plants treated with Cr (chromium), SiNPs provided defense by removing oxidative stress; the activities of enzymes such as SOD (Superoxide dismutase) and APXs (Ascorbate peroxidase) was improved extensively due to the presence of SiNPs, whereas CAT (Catalase), GSR (Glutathione reductase), and DHAR (Dehydroascorbate reductase) were less repressed by Cr in the presence of SiNPs (Tripathi et al., 2015). SiNPs were confirmed to enhance germination, fresh and dry weight in the tomato

Table 2. Biological activity of biosynthesized SiNPs.

Application	Plant species	Biological activity	References
Plant growth and crop productivity	Tomato Oat *Astragalus fridae* Rech. F. Potato Wheat and Lupin *Fenugreek Foenum graecum L.* *Larix olegensis* Maize	Improved seed germination, fresh and dry weight Increase plant growth Enhance expression of PAL and lignification in leaf & roots Reinforced in vascular system and leaf thickness Increase mass of potato Increase plant growth and biomass, chlorophyll content and seed germination Increase cell wall lignification, activity of PAL and protein content Increase root and chlorophyll content Increase seed germination and root elongation Increase flowering Increase PAL activity & Phenolic compound	(Siddiqui and Al-Whaibi, 2014) (Asgari et al., 2018) (Moghanloo et al., 2019) (Mushinskiy et al., 2018) (Sun et al., 2016) (Nazaralian et al., 2017) (Esmaili et al., 2022) (Karunakaran et al., 2016) (Roohizadeh et al., 2015)
Environmental stress Salt stress Water deficient and salt stress UV-B stress Metal toxicity Lead (Pb) and Cadmium (Cd) Cromium (Cr)	Cucumber Soybean Tomato Cucumber Bean *Phaseolous vulgaris* L. Wheat Pea	Increase growth and yield N & P nutrient content Increase K concentration, antioxidant activity and decrease in Na concentration, lipid peroxidation and ROS production Improves several physiological attributes Increase productivity and chlorophyll Highly increase germination percentage Provide resistance Reduce metal concentration, increase plant growth and biomass Reduce Cr accumulation and increase nutrient content	(Alsaeedi et al., 2018) (Farhangi-Abriz and Torabian, 2018) (Haghighi et al., 2012) (Haghighi and Pessarakli, 2013) (Alsaeedi et al., 2018) (Alsaeedi et al., 2017) (Tripathi et al., 2017 (Ali et al., 2019; Z. S. Khan et al., 2020) (Tripathi et al., 2015)
(Fungicidal effects against some fungal pathogen)	Rice Maize Tomato *Panax ginseng* Grapes	*Fusarium oxysporum* *Aspergillus niger* *Candida albicans* *Ilyonctrial mosspanacis* *Botrytis cinea*	(Suriyaprabha et al., 2014) (Abbai et al., 2019; Derbalah et al., 2018) (Youssef et al., 2019)
Entomotoxic effect against		*Sitophilus oryzae* *S. Tutaabsoluta* *C. maculates*	(Debnath et al., 2011) (Debnath et al., 2012) (Magda and Hussein, 2016; Rouhani et al., 2013)

plants at 8 g/L concentration (Siddiqui and Al-Whaibi, 2014). The advantageous effect of SiNPs and their function are well recognized, but the benefits of SiNPs over their mass matter are not as well investigated.

3.4. SiNPs as nanocarriers

Among all the Si nanomaterials forms, mesoporous SiNPs (MS SiNPs) has achieved the latest consideration. Currently, gold-coated SiNPs has been confirmed to transport DNA, protein, and chemicals through the gene gun technique (Singh et al., 2021). The mesoporous character of SiNPs also considers them excellent applicants as appropriate nanocarriers for diverse molecules that might facilitate farming. Numerous reports have revealed the significance of SiNPs in farming. Some research has shown that the MS SiNPs can enter the cell wall barrier and work as an instrument for transient gene expression in Arabidopsis (Chang et al., 2013). Utilization of MS SiNPs as nanocarriers would be a great step because of these physiological properties: (1) no enzymatic action is necessary for breaking the plant cell walls; (2) MS SiNPs transport DNA to inner tissues, like the cortex and endodermis; (3) a low quantity of DNA is needed to acquire a rational effectiveness for momentary gene expression; (4) the contribution of an energy-independent course for MS SiNP uptake offers a capable way for biomolecule transport; (5) mesoporous SiNPs could travel to numerous organelles like plastids and nuclei that could work in targeted transport, for example, for plastid alteration (Chang et al., 2013). SiNPs might be used as an operating agent for the targeted release of herbicides and fertilizers in situations where the goal is to improve agricultural output or remove wild plants. Si nanocarriers have also been reported to bring herbicides implanted in a diatom fistula to the surface and distribute the herbicide to the ground (Figure 5) (Shang et al., 2019). Another study analyzed the action of SiNPs for transporting proteins in tomato plants via the vascular system and the outcome of the studies. Researchers suggested the application of SiNPs as a plant transport medium in the upcoming time (Bapat et al., 2020).

3.5. SiNPs for plant disease management

SiNPs approaches can be uses to protect the crops from pathogen by effective monitoring. Surface-modified hydrophobic SiNPs have been effectively used to control pest in agriculture.

3.5.1. SiNPs mediated possible mechanism involved in disease resistance

Physiological, biochemical, and molecular factors have all been investigated in relation to how SiNPs affect plant-pathogen interactions. SiNPs increase resistance during plant-pathogen interactions, namely by activating defense-related enzymes, promoting the synthesis of antimicrobial compounds, controlling signaling pathways, and also triggering the expression of defense-related genes. SiNPs interact with plant cell walls physically to create a second layer of cuticle that prevents pathogen penetration and lowers the frequency of diseases in plants, including *Pyricularia oryzae* Cavara, *Bipolaris sorokiniana* Shoemaker, *Pyricularia grisea* Sacc., and *Rhizocotnia solani* Kühn, among others (Asgari et al., 2018). SiNPs improved plant biochemical resistance by activating defensive enzymes such as peroxidase, polyphenol peroxidase, and phenylammonia lyase, as well as antimicrobial substances such as phenolics, flavonoids, and some pathogen-related proteins. Expanding the function of defensive enzymes responsible for the synthesis of biologically active antimicrobial compounds, such as polyphenoloxidase, β-1,3glucanase, peroxidase, and phenylalanine ammonia-lyase (PAL), superoxide dismutase, ascorbate peroxidase, glutathione reductase, catalase, lipoxygenase, and chitin (Waewthongrak et al., 2015). 2) modulating systemic signals in plants such as salicylic acid (SA), jasmonic acid (JA), and ethylene; and (3) producing antimicrobial substances in plants such as phenolics, flavonoids, phytoalexins, and pathogenesis-related (PR) proteins (ET).

SiNPs also regulate signal pathways such as salicylic acid, jasmonic acid, and ethylene. Such nanobio-pesticides are more acceptable due to their less toxic environmental impacts in comparison to conventional pesticides.

3.5.2. SiNPs as fungicide

Si formulation from agro-waste may overcome the problems of fungal infection, viz., and fungal spore degradation. The development and implementation of SiNPs could lead to new applications in plant pathogen interaction and management (Goswami and Mathur, 2022). Many

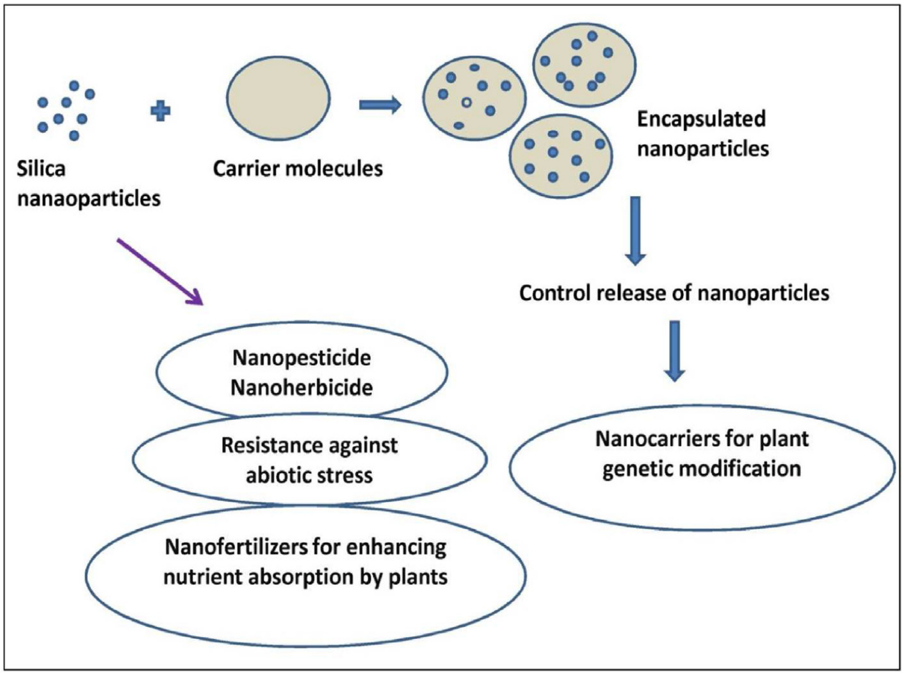

Figure 5. Development of stable SiNPs for delivery system (encapsulated with carriers molecule) and their direct application.

organic and inorganic NPs are used for plant disease management. Among all the NPs, silver, zinc, magnesium, and silica possess antimicrobial property. SiNPs with a broad spectrum of antifungal activity reduce various plant diseases caused by fungal pathogens. SiNPs were also reported to reduce levels of several important diseases such as sheath blight, brown spot, and grain discoloration in rice. The inhibitory effect of SiNPs has also been reported on early blight of tomatoes caused by *Alternaria solani* and black root rot (Debona et al., 2017). In addition to rice blast disease, powdery mildew, leaf spot of cucumber, and *Fusarium* wilt were also suppressed by SiNPs application. Allyl isothiocyanate, carvacrol, and cinnamaldehyde volatile compounds encapsulated with MS SiNP and then the impacts of these substances were compared with the impacts of pure compounds. The encapsulated selected volatile compounds were shown to have long-term activity against *Aspergillus niger* (Janatova et al., 2015). SiNPs were found to be effective in controlling rice blast and brown spot, like fungal diseases. Mesoporous Si acts as a podium for the delivery of antifungal compounds 1.5 g/1kg, which was the most effective treatment to reduce blast disease severity. Similarly, due to the high porosity of Si, antifungal activity is enhanced against *Candida albicans* (Tang and Cheng, 2013). MS SiNP is very useful and non-toxic substitute for fungicides to control early blight of tomatoes caused by *A. solani* (Derbalah et al., 2018).

3.5.3. SiNPs as an insecticide

Studies have clearly shown that SiNPs are effective pesticides that may be used alone or in conjunction with other commercial pesticides to go where they need to go. When SiNPs are placed on the surface of leaves and stems, Si is physisorptionally assimilated into the cuticular lipids, causing insects to die by physical methods. Animal SiO_2NPs with garlic essential oil were infused into the plant, and surface charged altered hydrophobic nano-silica (3–5 nm) may be successfully employed to manage a range of agricultural insect pests. Several studies have shown that SiNPs might be employed as nanopesticides (Rouhani et al., 2013). SiNPs have been documented to be utilized in two ways: as field pesticides, controlling pests and larva, or as nanocarriers, releasing commercial pesticides to boost their efficiency. SiO_2 nanoparticles were reported to be lethal to *Callosobruchus maculates* (Rouhani et al., 2013). SiNPs lethal effect on pests can also be linked to spiracle and tracheal constriction, as well as adsorption and abrasive damage to the cuticle's protective wax layer. Nanosilica is hypothesized to kill pests by physical adsorption, which breaches the protective lipid hydrophilic membrane, leading to the death of the targeted organisms. SiNPs are absorbed and destroyed, resulting in the death of insects due to desiccation (Ayoub et al., 2017; Elnahal et al., 2022). These NPs might also damage the digestive system of pest herbivores that consume the SiNPs treated plants (Thabet et al., 2021). The direct consequence of SiNPs on a range of pests has been studied at the laboratory scale (Mousa et al., 2014). The in-field outcome of SiNPs has estimated for an inadequate number of pests and they are harmful and quantity-based; calculated varieties comprise a chewing insect (moth: *Spodoptera littoralis*), a piercing-sucking insect (aphid: *Aphis craccivora*), and an internal feeder (leaf mining fly: *Liriomyza trifolii*) (El-Samahy et al., 2015; Thabet et al., 2021). Hormonal signalling has been identified in SiNPs like rice (against the leaf folder *Cnaphalocris medinalis* through attracting the parasitoids *Trathalaflavor orbitalis* and *Microplitis mediator*) (J. Liu et al., 2017).

3.5.4. SiNPs as herbicides

Herbicides that are available on the market; inhibit the growing parts of the weeds but not the underground plant parts like rhizomes and tubers, which are a major source of new plants. Weeds interfere with crop growth and cause a yield loss to the tune of 10% of crop production. A nano-herbicide formulation is available on the market to combat weed plants. Si accumulation increases in plant tissue, thus reducing palatability and digestibility for herbivores. Due to NPs size, they can be properly functionalized, providing better penetration through the cuticle and allowing release of active ingredients onto the target site. A decrease in herbivore populations in Si-accumulators and non-accumulators has also been observed, specifically in soybean (against the cotton bollworm *Helicoverpa armigera* by attracting the predatory beetle *Dicranolaius bellulus*) and grapevine (against *Helicoverpa punctigera* by attracting the predatory beetle *Dicranolaius bellulus*) (against the light brown apple moth *Epiphyas postvittana* by attracting *D. bellulus*) (Johnson et al., 2020; Kvedaras et al., 2010).

3.5.5. SiNPs in the soil as fertilizers

The nanofertilizers are nutrient carriers of NPs ranging from 30-40 nm, which are capable of holding the nutrients ions due to their specific properties like high surface area, high absorption quality, increased

20–200% production rate, rise in chlorophyll content, and expansion of leaf surface area. Maintaining the quality of soil is very important for the agriculture sector. In terms of soil contamination, conventional remedies and treatment technologies have shown only limited efficacy in reducing pollutant levels in soil. 5–40% of Si complexes are generally present in soil in the form of silicon dioxide and different silicates (Matichenkov and Bocharnikova, 2001). The competence of SiNPs was estimated in terms of its impacts on advantageous microbial colonies like phosphate solubilizers, nitrogen fixers, silicate solubilizers, microbial biomass carbon and nitrogen concentrations, and Si amount in contrast with other Si sources like micro Si, sodium silicate, and silicic acid. SiNPs are reported to considerably improve microbial communities, overall biomass concentration, and Si concentration. Although micro Si sources improved parameters connected with soil productiveness, their application through maize roots was observed to be low.

3.6. SiNPs increase the resistance to abiotic stresses

Abiotic stresses such as nutrient deficiency, heavy metal toxicity, water stress, climatic changes, heat and light stress, etc. are the major problems that affect the growth and productivity of crops. The destructive effects of accumulated ROS (reactive oxygen species) on plant cells indicate that the plant has been subjected to abiotic stress. Generally, plants are well equipped with defense mechanisms to deal with stress, but SiNPs have been recognized as a regulator for plant protection against abiotic stress. Furthermore, SiNPs can provide resistance to plants viz., SiNPs form a dual layer on the epidermal cell wall and help to reduce the detorious impact of stress by modulating the antioxidant defense system.

3.6.1. Physical stress

3.6.1.1. Radiation stress. SiNPs seem to protect plants from radiation damage. When rice seedlings are irradiated with gamma rays, their growth rate has been reduced. Furthermore, when the plant was treated with SiNPs, the growth was faster compared to when it was not supplied with the SiNPs. SiNPs also enhance UV resistance due to the defensive deposition bodies of SiNPs on the plant cell wall (Goto et al., 2003). Similar results were studied in wheat seedlings against UV stress through modulating the antioxidant defense system (Tripathi et al., 2015).

3.6.1.2. Drought stress. Cuticular transpiration is reduced by the arrangement of a Si cuticle double layer beneath the leaf epidermis (Malik et al., 2021). SiNPs induce resistance in plants against drought conditions by reducing stomata conductance and also modifying the cell wall properties. SiNPs enclosing absorbent have been reported to be capable of slowly discharging nutrients and storing large amounts of water, which can help flora manage salinity and resist in drought and saline conditions without harming the environment (Rajput et al., 2021).

3.6.2. Chemical stress

3.6.2.1. Salt stress. The studies demonstrated that SiNPs play an essential function in manipulating soil nutrient concentration and microbial biota and thus might support the development of maize plants (Rangaraj et al., 2014). SiNPs provide resistance to NaCl stress alleviation by preventing NaCl uptake. The uptake and transcription of accession of ions or toxic ions from soil is also reduced by SiNP treatment. Si application was observed to amplify salinity resistance in flora; as a result SiNPs were also utilized as an experiment to develop salinity resistance in flora. In this research, SiNPs have been prepared and impregnated with NPK in chitosan as the first semi-permeable layer and sodium alginate and kaolin as the external layers.

3.6.2.2. Heavy metal stress. An alleviative function of SiNPs on metal toxicity such as zinc (Zn), cadmium (Cd), iron (Fe), aluminium (Al), and manganese (Mn) has been studied. Different mechanisms seem to be involved depending on the plant variety. Si-containing minerals, such as sodium silicates and alkaline silica, may affect rhizospheric pH, resulting in a reduction in heavy metal concentration in the soil (Jia-Wen et al., 2013). Si accumulation in the endodermis improves manganese (Mn) accumulation in the leaf, as well as the behavior of heavy metal-treated plants in terms of antioxidant enzyme control (Adrees et al., 2015). SiNPs also control and sustain photosynthetic rates by stabilizing chloroplasts (stomata), maintaining photosystem integrity, and increasing pigment content (Figure 6). SiNPs were also effective in alleviating the Fe excess toxicity in rice (Okuda, 1962) and enhancing the oxidative powder of Fe from ferrous ions in rice roots. In Zn and Cd polluted soil, Zn was found to coexist with silica in the form of a Zn-silicate complex. The concentration of toxic Al was found to decrease by the addition of silicic acid. The defensive effect of silica on Al toxicity varies with plant species.

3.7. Factor influencing the biological activity of SiNPs

The NPs size, composition, shape, surface charge, surface chemistry and surface functionalization, pH, temperature concentration of the NPs are the major characteristics that determine the physicochemical properties and, as a result, the activity of nanomaterials (Barabadi et al., 2020a, 2020b, 2020c).

3.7.1. Surface charge

Furthermore, the surface charge of NPs influences their initialization and circulation time. Because of the negative charge on the cell membrane surfaces, positively charged NPs can bind readily to them, but electrostatic repulsion between negatively charged NPs and negatively charged surface membranes prevents NPs internalization (Hotze et al., 2010).

3.7.2. Shape and size

Additionally, spherical NPs with a size of particles of 6nm demonstrated improved renal clearance than spherical NPs with a particle size greater than 8nm (Ajitha et al., 2016). Surprisingly, the size and surface charge of NPs have an effect on their CNS penetration. The particle size range of 20–70 nm was found to be optimal for CNS transport. According to (Nair et al., 2011), SiNPs (less than 20 nm) hindered seed germination and growth of rice seedlings due to their large surface area and small size. However, SiO_2 NPs larger than 20 nm had a positive impact on a number of plant characteristics. Similarly, studies discovered that tomato seedlings treated with SiO_2 NPs had improved seed germination (Siddiqui and Al-Whaibi, 2014).

3.7.3. Concentration

Because every plant reacts differently to a variety of nanomaterials, the effects of nanomaterials on plants are dependent on plant variety and nanoparticle dose mode (Hou et al., 2018; Sperdouli et al., 2021; Zulfiqar et al., 2019).

3.7.4. pH

The majority of the literature lists the steps involved in creating SiNPs, as well as the active ingredients found in plant extracts and trash. (Peralta-Videa et al., 2016) have stated that characterization of plant extracts is critical in this respect in order to fully comprehend the method of creation, but there are only a few works of literature that have undertaken experimental investigation on the subject. Different literatures have documented the precise experimental and optimization parameters suitable for green synthesis of NPs. After biosynthesizing zinc oxide NPs from *Citrus aurantifolia* at various pH levels, (Rafaie et al., 2014) was found that acidic synthesis reduces the formation of NPs compared to neutral and alkaline solutions, with NPs generated at pH 5 being smaller than those formed at pH 7 and 9, while (Nagarajan and Arumugam Kuppusamy, 2013) discovered that zinc oxide NPs made from

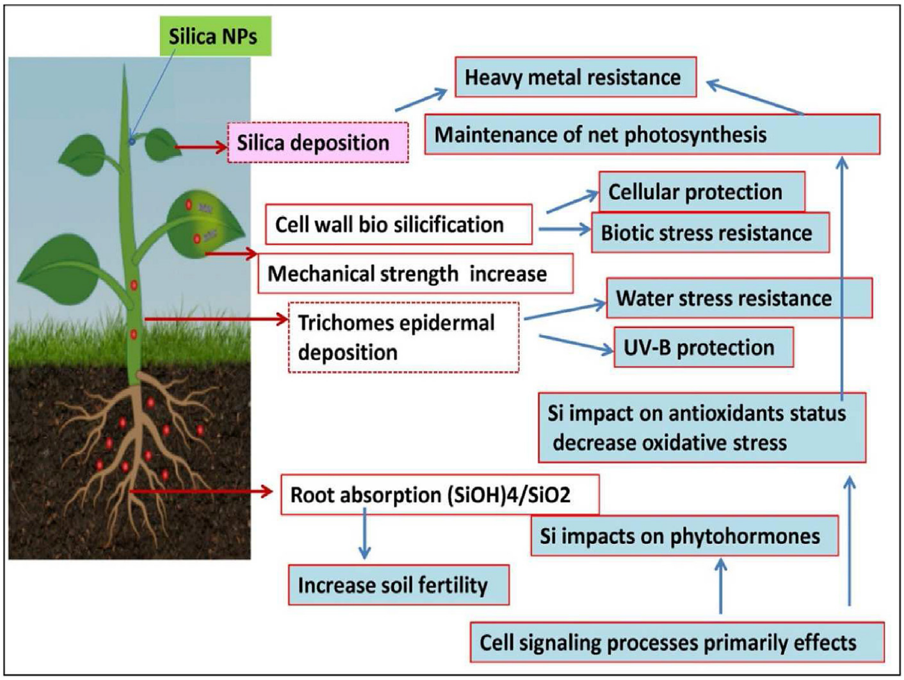

Figure 6. General overview of SiNPs impacts on plants after foliar and soil application for plant growth and protection.

S. myriocystum extract performed better at pH 8 than at other pH values like 5, 6, 7, 9, and 10.

3.7.5. Temprature and time

Another two essential criteria that have differed from literature to literature are reaction temperatures and time. While some studies suggest that 80 °C is the ideal temperature, others claim temperatures as low as 50 °C and as high as 300, 400, and 450 °C (Ambika and Sundrarajan, 2015; Azizi et al., 2015; Nagarajan and Arumugam Kuppusamy, 2013). A crucial determinant of green synthesis is the quantity of metal precursors, reducers, and stabilizing agents (plant extracts and microbial enzymes). According to certain studies, smaller NPs are produced at higher concentrations of the reducer or plant extract. For example, Ag NPs synthesized with 1–5 mL of corn husk extract were discovered by (Villanueva-Ibáñez et al., 2015) to be more compact than those prepared with greater volumes of extract (8 mL). Green synthesis research has mostly focused on NPs, but capping might disclose the fundamental process of green synthesis.

4. Conclusion

Nanotechnology uses novel ways to create NPs that can be used to solve agricultural concerns. With the increasing development of the population, the need for agricultural crops continues to rise. Extreme weather, pests, and illnesses, on the other hand, represent a significant danger to agricultural food production. The SiNPs wide surface area makes them ideal candidates to act as unique carriers for pesticides and fertilizers, giving rise to concepts like nanopesticides or nanofertilizers that may help adequately in improving the quality of the agricultural system. SiNPs also facilitate the site targeted, controlled delivery of nucleic acids and nutrients with increased crop protection. We presented several potential applications based on the aforementioned findings that could explain how SiNPs cause resistance in plants to abiotic and biotic stresses. First, SiNPs may promote plant growth and development. Second, SiNPs deposited onto the plant surface by silicification and increases the protection barrier against environmental stress. Third one is SiNPs promote the plant defense stress enzymes to bear the adverse effects of biotic and abiotic stress. Thus, future research on SiNPs must focus on the following issues in order to increase plant resilience during stress conditions. Previous research has largely concentrated on improving the physical barrier against stress, promoting plant resilience, and activating stress enzymes, but very few studies have examined the effects of SiNPs on the soil microbial population under stress. The "SiNPs-soil-microorganism'' system should be considered and research in-depth should be conducted. The combination of SiNPs with loaded with pesticide and other beneficial microorganism by surface modification, could increase the impacts of SiNPs application. Thus, SiNPs have the potential to solve the agriculture problems without harming the environment and revolutionize the agriculture sector.

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Author contribution statement

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