PLANT SCIENCE TODAY
Vol 12(sp1): 01–13
https://doi.org/10.14719/pst.10320

eISSN 2348-1900

REVIEW ARTICLE

Utilization of nano-silica from *Equisetum* sp. - A pathway to sustainable agriculture, economic development and insights into toxicological safety

Kalyan R[1], Jeya Sundara Sharmila D[1*], Gomathi V[1], Auxcilia J[2], Sheela V[3] & Ram Kumar P[4]

[1]Centre for Agricultural Nanotechnology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Department of Horticulture, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Department of Agricultural Entomology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Department of Agricultural Entomology, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia 741 252, West Bengal, India

*Correspondence email - jeyasundarasharmila.d@tnau.ac.in

Received: 27 June 2025; Accepted: 25 July 2025; Available online: Version 1.0: 24 September 2025

Cite this article: Kalyan R, Jeya SSD, Gomathi V, Auxcilia J, Sheela V, Ram KP. Utilization of nano silica from *Equisetum* sp. - A pathway to sustainable agriculture, economic development and insights into toxicological safety. Plant Science Today. 2025;12(sp1):01–13. https:/doi.org/10.14719/pst.10320

Abstract

This review aims to assess the potential applications of nano-silica derived from *Equisetum* sp. in agriculture. It aims to implement sustainable farming practices to address environmental and economic challenges. The study investigates the effectiveness of nano-silica as a transformative tool for smart delivery systems in fertilizers, pest control and cleaning pollution. A comprehensive review of literature to synthesize and characterize nano-silica from *Equisetum* sp. through eco-friendly green synthesis methods. Techniques such as acid and alkali treatments and calcination were highlighted for their efficiency and sustainability. The review also evaluated nano-silica pathways in plants, mechanisms of action and its integration into agricultural technologies. Its application in wastewater treatment demonstrated efficacy in removing heavy metals like cadmium and lead. Additionally, nano-silica based smart delivery systems improved efficiency, minimized environmental impacts and reduced input costs. Economically, nano-silica promotes postharvest preservation and supports the circular economy through recycling agricultural waste. *Equisetum*-based nano-silica is highly economical and a resource-efficient alternative for the advancement of sustainable agriculture systems by increasing resistance to stress factors in crops, maintaining soil quality and reducing contaminants. However, there are still issues in supplying, safety testing and cost of mass production of these materials. Future research should address these gaps to fully harness nano-silica potential in precision farming and sustainable food systems.

Keywords: *Equisetum* sp.; green synthesis; nano-silica; recycling management; smart delivery systems; sustainable agriculture

Introduction

The escalating global hunger crisis and the environmental impacts of conventional agriculture have intensified the call for sustainable agricultural practices. According to the Food and Agriculture Organization (FAO), nearly 733 million people faced undernourishment in 2023, representing about one in every eleven individuals worldwide (1). Nanotechnology seems to have some attention due to its strong potential in enhancing crop yield while minimizing resource-use and environmental harms. Of the various types of silica that have been studied, nano-silica is superior because it can assist in various aspects such as vegetation, stress tolerance and even soil enhancement (2). The *Equisetum* sp. horsetail plant appears to have promise as an environmentally friendly source of nano-silica and it certainly has a high silica concentration, however, its use in agricultural has not gained popularity as it could help with farming as well as boosting the economy, advancement of technology and improvement in security forces. *Equisetum* sp. has traditionally been used in agriculture as a fertilizer because it is rich in silica (3).

Unlike other plants containing silica, the *Equisetum* founded family has the unique ability to absorb monosilicate directly from the soil and store it in their incarnations. The added silica content fortifies and strengthens the plants, aiding them in maintaining their form and providing structural support (4). In conjunction with advancements in nanotechnology, there has been the potential to derive and synthesize nano-silica from this plant specifically for agricultural purposes (5). Nano-silica increases the ability and efficiency of plants to uptake nutrients and conserve water, also improves their overall resilience to environmental stresses, pests and diseases. As some literature suggests using nano-silica could increase plant productivity, enhance photosynthesis in plants and make them more resilient to stress caused by heavy metals and diseases, more works needs to be done on plant fizzy from *Equisetum* sp. Important ones include absence of precise protocols for extraction and synthesis of nano silica, few investigations assessing its toxicity and apparent neglect of its economic use and technological advantages. These deficiencies inhibit the effective application of nano-silica obtained from *Equisetum* sp.

especially in developing nations where efficient resource use is of great importance. These issues need for a joint resolution of issues belonging to different areas (6-8).

Also, there are economic studies that are important in demonstrating the efficiency of using nano-silica from *Equisetum* sp. This involves agricultural development on less productive lands and even rural employment creation. Why not revolutionize agriculture by applying smart delivery modes, such as nano silica-based fertilizers and pesticides, to enhance efficiency and protect the environment? The purpose of this review is to provide an overview of the state of research, outline the key problems and propose potential applications of nano silica from *Equisetum* sp. in modern agriculture (Fig. 1).

Natural source of silica

Silica is undoubtedly one of the most abundant minerals present on Earth, commonly found in various forms across soils, rocks and biological systems. Among the wide array of naturally occurring minerals, silica stands alongside others such as alumina, iron oxides, calcium carbonate and magnesium oxides in terms of global abundance and industrial relevance. Interestingly, silica is now increasingly sourced from agricultural waste, offering a sustainable and eco-friendly alternative to conventional mining. Agricultural residues from crops such as rice husk, wheat straw, sugarcane bagasse and corn cob are rich in silica content, making them valuable raw materials for nano-silica production. This green approach not only aids in waste but also aligns with circular economy principles by transforming agro-waste into functional nanomaterials (9). It is interesting to note that silica is mostly sourced out of agricultural waste in several crops is listed in Table 1. Such waste is primarily either dumped or even burnt, thereby causing pollution to the environment (10). This is particularly concerning for countries such as India where agriculture is heavily depended on, there's a lot of "waste" created. This agricultural waste on the other extends is being worked on by researchers in order to transform it into useful products and therefore contributes towards sustainable development altogether (11,12). It is understandable therefore that silica is seen as abundant and useful given the number of applications it serves for multiple fields and industries. Several studies have unfortunately found that agricultural waste has a much higher silica recovery rate than any other sources. Combined with agriculture processes, ash formed as a by-product is encompassed with silica therefore multiple studies have sought to extract and utilize it further in a more economically sustainable manner. The strength of plants is increased overall when their leaves, shoots, roots are fortified with silica as well which in turn allows them to withstand harsh environments.

Additionally, silica decreases the effects of adverse toxicogenic constituents in the soil, such as heavy metals, aluminium toxicity and salinity stress, by immobilizing harmful ions and reducing their bioavailability to plants. In the formation of plantlets, silica exhibits osmoregulatory properties, such as suppressing excessive osmotic stress caused by unfavourable soil conditions. This action stabilizes cellular functions and improves water retention within plant tissues, thereby augmenting the total percentage of seed germination and promoting healthy seedling establishment. Particular interest is nano-silica, a low-cost alternative that comes in small nano-sized particles (1-100 nm) and has a high surface area, thus allowing for easy cell membrane permeability. Thus, such nanosized plants such as nanosized silica are set to play a critical role in the improvement of agricultural and food security in a sustainable manner (13,14).

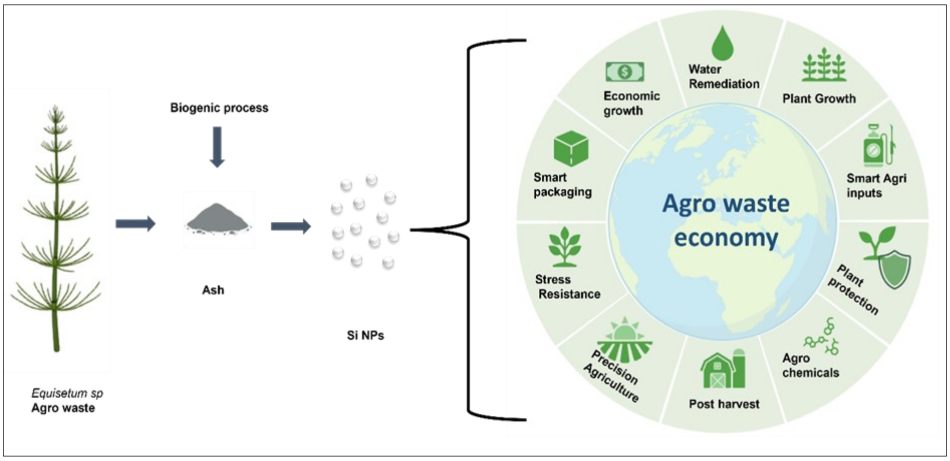

Fig. 1. Nano silica from *Equisetum* sp. - a sustainable innovation for agro-waste utilization and agricultural advancement.

Table 1. Nano silica production from agro waste

Agricultural waste	Silica content (% by weight)	Applications	Advantages	Processing methods	Nano-silica Size (nm)	References
Rice Husk	15-20 %	Fertilizer, soil amendments	Abundant, cost-effective, renewable	Calcination, acid leaching	10-22	(15,16)
Wheat Straw	8-12 %	Composite materials, biochar	Easily accessible, sustainable	Pyrolysis, thermal treatment	20-80	(17,18)
Sugarcane Bagasse Ash	10-15 %	Construction, silica gels	Byproduct of sugar production, versatile use	Combustion, washing	30-90	(19-21)
Corn Cob	6-10 %	Adsorbents, catalysts	Lightweight, biodegradable	Milling, alkali extraction	15-50	(22,23)
Bamboo Leaves	20-25 %	Nanomaterials, structural additives	High silica yield, rapid growth source, development of Li-ion battery anode	Chemical extraction, heating	5-40	(24-26)
Coconut Shell Ash	5-8 %	Activated carbon, silica compounds	Durable, widely available in tropical regions	Carbonization, acid washing	10-70	(27,28)

Green synthesis of nano silica from *Equisetum* sp.

Plant sources can produce nanoparticles by a method called green synthesis which has attracted the notice of a great number of scientists as it is environment friendly. This approach is also noted to be cheap, require less time and rather uncomplicated procedures in comparison to other of the synthesis techniques making it an effective biological means for producing nanoparticles (29). Silica Nanoparticles (SiNPs) can be synthesized by a variety of techniques, including chemical and mechanical techniques.

But in view of environmental problems, the most appropriate would be through the synthesis using natural products. So, in this aspect we can look at the biogenic route for silica synthesis from *Equisetum* (3,30).

Method 1 (chemical and thermal treatment)

The first step involves the harvesting of *Equisetum*, which should be done precisely once the plant has been thoroughly washed with distilled water to remove any residual parts. Furthermore, the plant has to be preserved in a cuprammonium solution for a duration of a week in order to get rid of any cellulose smearing its surface (30). After the wash is done, the plant is required to rest under room temperature for a period of 1 day so that it can dry up. Once the plant material is dry, it is roughly ground and even sieved so that it may undergo yet another distilled water wash. Following the wash, the plant material would be required to dry once more, this time around for 5 hr but the temperature must be set to 110 °C. At this point, the dry material would need to be revisited as 8 g of the dry *Equisetum* powder would be required alongside 400 mL of 4 M hydrochloric acid (HCl).

The solution in this case would require heating till its boiling point which will persist for 2 long hours. Cool the container after the given time and take the supernatant liquid out. After which the HCl infused *Equisetum* would need to be centrifuged and rinsed in deionized water until the pH level reaches its neutral state which equals 7, Once achieved, the material is finally set to air dry until it reaches the 50 °C mark and then it would be calcined instead so the organic residue can be cleared (31).

Method 2 (hydroalcoholic extraction, acid hydrolysis and calcination)

The extraction of silica from horsetail plants involves a multi-step process starting with harvesting and preparation. The harvested plants are chopped into small fragments sized between 10 and 40 mesh, then thoroughly washed to remove impurities. The cleaned plant material is oven-dried at 60 °C to reduce moisture content. Silica extraction is carried out through three primary steps: hydroalcoholic extraction, acid hydrolysis and calcination. Initially, the dried horsetail biomass is subjected to hydroalcoholic extraction using a 1:1 ethanol-water mixture at a solid-to-liquid ratio of 1:10. This mixture is left under heating conditions for 24 hr to facilitate compound extraction. Afterward, the solids are separated through filtration and further dried at 103 °C. Subsequently, 2 g of this dried material are mixed with 20 mL of diluted sulfuric acid, maintaining the same solid-to-liquid ratio and the mixture is heated at temperatures between 120 °C and 160 °C for 1 to 4 hr. The residue is washed with distilled water until reaching a neutral pH. Finally, 1 g of the dried sample is calcined in a muffle furnace for 1 hr to remove organic components (32).

Method 3 (acid treatment and calcination)

Horsetail stems and leaves need to be purified with deionized water to filter out unwanted substances. The water-washed samples are subsequently dried in an oven at 60 °C for about 3 hr. Then the sample is refluxed in a solution of 10 % HCl for 2 hr. The purpose of this procedure is to free the sample of unnecessary ions. The caustic sample is later neutralized with deionized water so that the pH is equal to that of 7. The sample is also calcinated to get rid of the organic matter. In this process the temperature is raised to 580 to 700 °C for 3 hr. In the end, SiNPs are produced (33).

Method 4 (acid and alkali treatments)

The washing procedure for this type of stem is aimed at achieving a clean stems sample. This is followed by over-drying the uncluttered sample at a temperature of up to 110 °C for a number of hours, specifically twenty four. The stems sample is then soaked in 0.1 M HCl for 1.5 hr. The acidified stems are swollen with water and aims at room temperature for overnight before being heated enough to evaporate liquid completely off it, leaving behind a dry substance quite rich in alfalfa sprouts. Thereafter, a mixture of 20 g of the previously dried stems sample are mixed with 200 mL of 2.5 M solution of sodium simultaneously with a 30 °C temperature for 3 hr. Following cleaning, the mixture now contains only a small amount of ammonia hydroxide to stabilize pH at 8.5 after which its acidity was adjusted with sulfuric acid solution. This was left to cool down for 3 hr where after it was washed using deionized water and last exposed to a wet environment for two days at an average temperature of 50 °C (34).

The treatment of acid and alkali techniques appears to be the most efficient of the four methods for the synthesis of nano-silica. This method displays remarkable ecological acceptability by avoiding the use of very high temperatures and hence it is reasonably energy conservative. The two-stage acid and alkali treatment offer a better control of the pH of the silica and its quality, which further results in the formation of nano-silica with predictable properties. In addition, the process, though less intensive, but relatively simple, increases its potential for mass production, thus making it more efficient. Also, the neutralization of the residual acids enhances safety and sustainability by reducing the hazards that are related to residual acids (35).

Pathway of silica in higher plants

The factors that affect the absorption of Nanoparticles (NPs) by a plant include the plant's age, environmental factors, as well as species. In the same way, the physicochemical characteristics of the NPs do matter as well, where aspects such as shape, size, chemical composition, crystalline structure and the stability of the NPs are of concern. With an estimated size of 20 nm, mesoporous silica is deemed as an appropriate carry material. Different modes, including foliar and soil application, can be used for applying this silica to plants (36). In the case of foliar application, required quantities of liquid SiNPs are added to water. The SiNPs are introduced to the stomatal openings when the spray is applied to leaves of the plants in order to reach SiNPs into the biological systems of the plants. In soil application, SiNPs are put to the soil without any intermediaries and their absorption is influenced by some factors like pH, texture, fertility and the presence of salt of the soil. In hydroponic farming, SiNPs, in either powder or liquid form, are incorporated into the nutrient solution and made available to the plants. The roots absorb the Si amount contained in the NPs and it is transferred to the tissues of the interior plant. Soil application is relatively more efficient for plants than the foliar spray application (37).

Colloidal metals or NPs are initially absorbed at the root zone and subsequently transported through ion channels into plant tissues via endocytosis, with carrier proteins such as aquaporins facilitating this process. Penetration is inhibited when nanoparticle diameter exceeds 20 nm. Subsequently, the NPs move to the roots and reach the other aerial parts through xylem via apoplast pathway. In contrast, protein structures for the passive transport through the cell membranes are necessary, for example, Nodulin Intrinsic Protein 2 (NIP2) for the symplastic route, which is in part controlled by LSi1 influx and tilted towards LSi2 efflux. Furthermore, it was revealed that LSi6 is responsible for the transportation of silicon into the leaf tissue. Silicon from the soil is initially absorbed by root hairs and transported to cortex cells. Mean density of these transporters is however species dependent. It was found that the density of this transporter is higher among rice than that of sugarcane (38).

Such a transport process requires energy and is, accordingly, influenced by metabolic inhibitors and chilling temperatures. From the cortical cells, SiNPs are then moved into the xylem and translocated to the shoot. It is known that when the biological system of the plant assimilates silicic acid from the soil, it gets converted into silica gel (39). Most vascular flowering plants, total silica concentration is probably higher in the part of xylem sap. In the shoot, loss of water (transpiration) gives rise to polymerization of silicic acid which is transformed colloidal silicic acid and ultimately as silica gel. The spatial distribution of silicon in the plant tissues is largely governed by transpiration of water movement which causes an increasing accumulation of silicon in older tissues which are more easily accessible. The movement of NPs from one cell to another is through the plasmodesmata (40,41). In plants, a huge amount of nanosilica is transported via the apoplastic pathway is illustrated in Fig. 2.

Smart delivery system of nano-silica

The present circumstance is characterized by an ever-increasing global population, which has naturally resulted in an increase in food requirements. However, current food production systems are struggling to meet this growing demand. Technological advancements in agriculture present a viable solution to this challenge. Presently, the world population stands at 8.2 billion and it is estimated that there will be a total of 9.6 billion by the year 2050. Approximately 700 million people are predicted to be displaced by water shortages by the year 2030. By 2040, 1 out of every 4 children is likely to be residing in areas with extremely high levels of water stress (42). The issues of food security and water scarcity can be addressed by applying technology in the field of agriculture. In recent times, the agriculture sector has had to grapple with major challenges like land constraints, water limitations and organic matter decline in soil. Such challenges can be attempted to overcome by carrying out nanotechnology (43).

Applications of silica nanostructures in catalysis, biosensing and food safety:

Silica is a strong porous framework that displays multiple core features, such as chemical stability and thermal stability. Metal NPs embedded in silicates serve as efficient catalysts with applications across diverse fields such as environmental remediation (for pollutant degradation), chemical synthesis (in green chemistry and fine chemical production), energy conversion (in fuel cells and hydrogen production), pharmaceutical manufacturing (for selective reactions) and agriculture (for pesticide degradation and controlled release systems). Their high surface area and stability make them ideal for enhancing catalytic efficiency in these sectors (44). Nanostructures of silicon can be degraded into kidney clearance molecules as silica can be removed from the body without any toxic effects (45,46). There may also be the use of nanostructures of silicon which range between 3 to 10 nm in clinical and food applications (47). When polyacrylic acid is used in conjunction with SiNPs, those become high enzyme loading carriers. Such enzyme loaded particles are used to trace high antimicrobial materials in ELISA assays (48). For detection of pathogens *E. coli* which can originate colonies, sensors that consist of porous silica are used for chemiluminescence assay (49). In silicate NPs, airtight food packaging is developed which also prevent food contamination (50).

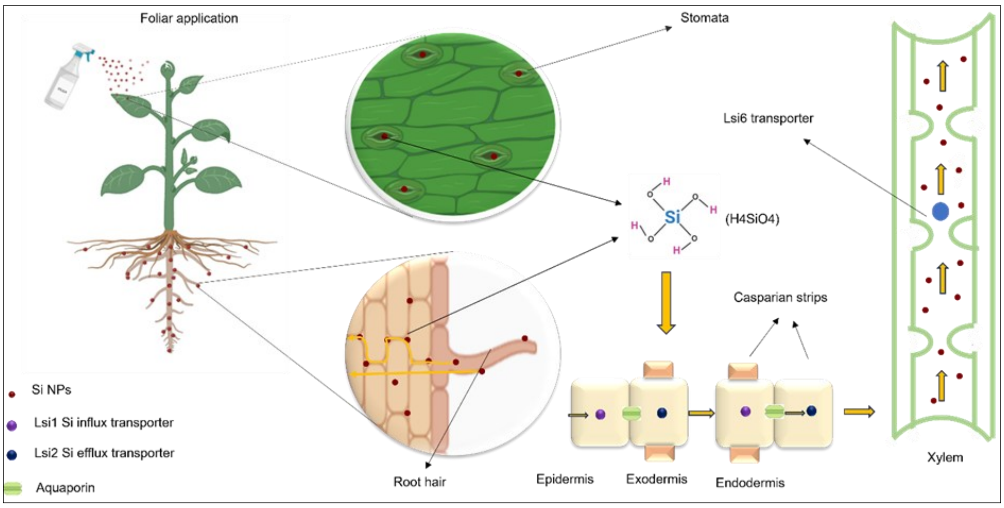

Fig. 2. Uptake of silica NPs into higher plants.

Nano-silica in wastewater treatment

For this past decade rather, much attention has been paid to the demand for water. In the arid countries, the supply of water is grossly insufficient. Water pollution is the major factor of this situation. As a consequence, both human and animal's health are at grave risk (51,52). A large quantity of water is being used up by the industrial sector. The heavy metals like cadmium, nickel, lead and arsenic for instance that contaminate the water make it unfit for reuse which is released by these industries. This cadmium has been found to be a key driver of the adverse effects on both humans and animal life (53). In particular, the role of nano-silica in wastewater treatment procedure is being studied in the dairy industry. Nano-silica is used to modify the pH control, increase the level of dissolved oxygen and lower biochemical oxygen and chemical oxygen demand (54). This maximizes the pollutants removal efficiency of the wastewater treatment so that the treated wastewater can be easily discharged or reused listed in Table 2.

Nano-silica as a sustainable nano-biopesticide

The growing threats posed by environmental issues, increased tolerance towards insecticides, bans on several chemical pesticides and a slow rate of new compound inventions has sparked further interest in biological control methods. Additionally, the biodiversity continues to support the development and citation of new drugs for both human and veterinarian purposes, as well as new biopesticides for both agricultural and household use. Nano-silica has been recognized as a revolutionary possibility. In order to ensure their survival and prevent dehydration, insect pests coat their bodies with a layer of waterproof film, which consists of a variety of cuticular lipids. Physical means are the only method of insect extermination through the consumption of these lipids that nano-silica within which cuticular lipids are absorbed through physisorption (61). Several studies have demonstrated that the application of NPs on leaf and stem surfaces does not interfere with key physiological processes such as photosynthesis or respiration in horticultural and crop plants. For instance, zinc oxide NPs applied to tomato plants showed no adverse effects on photosynthetic rate or stomatal conductance (62). Similarly, foliar application of TiO_2 NPs in maize did not significantly affect chlorophyll content or plant growth (63). In insect systems, gold NPs were found not to alter gene expression in tracheal epithelial cells, highlighting their potential as biocompatible nano biopesticides (64).The use of silica does not pose a health risk even as per the estimates made by the World Health Organization (65). When there was an introduction of nanotechnology in pesticides, a lot of emphasis was placed on the biodegradable polymer listed in Table 3. However, in this research, the exposure of the biodegradable polymer to sunlight and enzymatic reactions led to its degradation, demonstrating poor thermal and chemical stability (66). The combination of the fungicide metalaxyl with mesoporous silica nanospheres ensured sustained release whereby over a period of thirty days 11.5 % was released in soil and 47 % in water (67).

Nano-silica in enhancing plant resistance against pathogens

In the tropics and subtropics, crop losses are significant due to the contamination of food items by fungi (74). Plants of the monocot group have a specific requirement for remained in the leaf structure, called silica (SiO_2), which contributes to various forms of form resistance including biotic and abiotic stresses (75,76). It is believed that nano silica ($nSiO_2$) increases the resistance of plants by promoting the phytoalexins necessary for the attack against fungal pathogens (77). Elicitation in plants consists in the activation of phytoalexins and pathogenesis-

Table 2. Applications of nano silica in heavy metal removal from various water sources

S.No	Water type	Nanosilica Size (nm)	Mechanism	Heavy metal treated	Description	Reference
1.	Industrial wastewater	30-40 nm	Adsorption	Lead (Pb)	Nanosilica enhanced with iron oxides was effective for lead adsorption in contaminated water.	(55)
2.	Mining wastewater	40 nm	Surface complexation	Cadmium (Cd)	Functionalized nanosilica increased cadmium removal efficiency through surface interactions.	(56)
3.	River water	10-15 nm	Precipitation and adsorption	Mercury (Hg)	Nanosilica composites reduced mercury levels via adsorption and immobilization.	(57)
4.	Industrial wastewater	50-75 nm	Adsorption and reduction	Chromium (Cr VI)	Silica nanoparticles functionalized with amino groups enhanced chromium removal through adsorption and reduction.	(58)
5.	Groundwater	30-50 nm	Ion exchange	Arsenic (As)	Modified nanosilica improved arsenic adsorption under acidic conditions, reducing its concentration in water.	(59)
6.	Agricultural wastewater	70-102 nm	Ion exchange	Nickel (Ni)	Nanosilica particles were effective in removing nickel through ion-exchange mechanisms.	(60)

Table 3. Applications of nano-silica for enhanced pesticide delivery and pest control

S.No	Insect Name	Pesticide Treated	Mode of Action	Nanosilica Size (nm)	Description	Reference
1.	*Spodoptera litura*	Bifenthrin	Increased bioavailability	50-100	Nano-silica improves pesticide delivery, enhancing pest control and resistance management.	(68)
2.	*Aedes aegypti*	Azadirachtin	Sustained release	10-40	Controlled release system with nano-silica enhances insecticidal efficacy.	(69)
3.	*Diabrotica virgifera*	Imidacloprid	Bioavailability improvement	30-50	Enhanced bioavailability for more effective insect targeting and prolonged activity.	(70)
4.	*Musca domestica*	Pyrethroids	Controlled release	20-60	Nano-silica provides controlled release, minimizing environmental impact and toxicity.	(71)
5.	*Culex pipiens*	Deltamethrin	Enhanced degradation	280-300	Improves Deltamethrin efficacy in pest control through enhanced degradation resistance.	(72)
6.	*Helicoverpa armigera*	Carbofuran	Sustained efficacy	25-45	Nano-silica allows for controlled release, leading to improved control over pest infestations.	(73)

related proteins such as chitinase and glucanase which are responsible for the lysis of fungal cells (78,79). The defence mechanisms mounted by plants are facilitated by silica through inhibiting the growth of pathogens and helps in the removal of heavy metals (80-82). Cases of powdery mildew (caused by *Podosphaera fusca*) on cucumber (83), rice sheath blight (*Rhizoctonia solani*) (84) and blast disease (*Magnaporthe grisea*) (85) have shown that silica in plants provides the same resistance as that in cucumbers. *Podosphaera fusca* resistance was conferred on maize plants using silica (86,87). It has been suggested that the strong mechanical connection of silica with the cell wall of plants is the reason for their resistance against pathogenic fungi as it strengthens the cell wall at the site of infection (88). The bonding of the silica with the hydroxyl group of signal-transmitting proteins induces resistance (83). Additionally, the variation in the plants' resistance has been noted to be dependent in maize.

Greater emphasis should be placed on the utilization of nanoscale silica in soils over bulk forms, given its significant potential to influence agricultural practices. Adoption of recommended management strategies can enhance the efficiency of nano-silica applications in soil, ultimately contributing to improved agricultural productivity, as outlined in Table 4 (37).

Economic impacts of nano-silica in agriculture

Nano-silica is an innovative addition to agricultural technologies as it can be incorporated in various agricultural inputs such as fertilizers, pesticides, disease resistance formulations and sensors as well as in wastewater management. These inputs are also said to promote economic growth. Since nano-silica is on the nanoscale, it shows high adsorption, low amounts of inputs are required because of its large surface area. Thus, this reduces the total cost of inputs and maximizes agricultural output. The requirements of the increasing population are being met and in addition there is food security. In contrast to traditional fertilizers, nano fertilizers are considered environmentally friendly and are used in green agriculture. The number of chemical inputs is lessened, spores of toxic residues are minimized and crops are supplied with necessary nutrients alongside protection. In this way, nano-silica is assisting in improving agricultural productivity and conserving the environment (95). Silica has a significantly lower production cost, as it is obtained from plant waste rather than manufactured like other NPs illustrated in Fig. 3. By making silica out of waste materials, raw materials are preserved and such discarded waste is turned into a valuable material that provides stability to farmers economically.

Table 4. Application of nano silica for enhancing plant resistance against pathogens

S.No	Crop Type	Pathogen Targeted	Mechanism	Description	Nanosilica Size (nm)	Reference
1	Tomato	*Fusarium oxysporum*	Physical barrier formation	Nanosilica enhances plant resistance by strengthening cell walls and inhibiting fungal growth.	15-20	(89)
2	Pepper	*Xanthomonas vesicatoria*	Induces plant immune response	Improves systemic resistance and minimizes bacterial spread in plants.	50-70	(90)
3	Grape	*Botrytis cinerea*	Reactive Oxygen Species (ROS)	Promotes antifungal properties through oxidative stress induction in fungi.	55-60	(91)
4	Apple	*Pseudomonas syringae*	Strengthens cell integrity	Nanosilica application reduces infection rates by supporting cellular defences.	15-40	(92)
5	Potato	*Phytophthora infestans*	Mechanical and chemical barrier	Acts as a defensive barrier against spore penetration and pathogen colonization.	25-45	(93)
6	Tomato	*Alternaria solani*	Enzymatic activation	Enhances cell wall stability and activates resistance-related enzymes in plants.	10-20	(94)

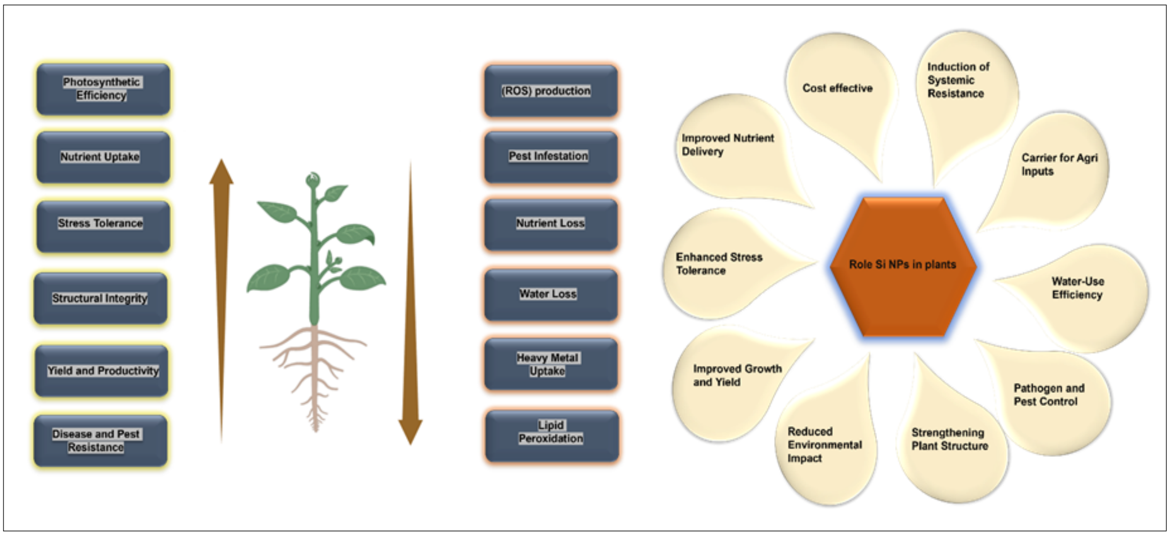

Fig. 3. Advantages of application of SiNPs in agricultural sector to promote economic growth.

Economic benefits of nano-silica in postharvest technology and food preservation

Nano-silica cannot be directly consumed by humans. Nano-silica can be used as a food additive. Postharvest treatment strategies have shown promising results in controlling microbial contamination in fresh produce. In strawberries, nano silica treatment led to a 2.5-fold reduction in microbial load, while tomatoes exhibited a 1.8-fold reduction. These outcomes emphasize the role of nano silica in improving microbial safety and extending the shelf life of perishable fruits and vegetables. Furthermore, composite materials containing nano-silica are also used for food packaging in order to inhibit food spoilage and limit the oxidation of fats and proteins. This improves the quality of rice, thereby increasing its worth, which results in an economic gain. The effectiveness of one percent nano-silica in postharvest technology has also been proven in the case of mango, where the fruit was enhanced during the cold storage period and after marketing (96). Chitosan and nano-silica film were applied onto mushrooms that affected the quality and oxidative activity of the mushrooms. The oxidative activity, respiration rates and reactive oxygen species levels are dampened during the cold storage of the fruits. Some fruits such as blueberries have also been coated with nano-silica, which has antifungal properties that inhibit bacterial growth on them. The storage life of loquat fruits is greatly improved as the fruits are able to withstand chilling temperatures during cold storage. Combining chitosan with nano-silica improves the physicochemical and physiological attributes of longan fruit, thereby increasing its value (97).

Nanomaterials as efficient storage pesticides

According to FAO, between 10-25 % of harvested food is destroyed by rodents, storage pests and insects. They estimated that the addition of nano-silica to diatomaceous earth increased insecticidal activity so that mortality was up to 86 %, *T. confusum* and 95 % *R. dominica*. The LD_{50} values were obtained after treating *O. surinamensis* adults with nano-silica (98). Higher doses of nano-silica enhanced mortality within the test subjects. A similar finding was observed when the time factor was introduced, postponing the time of exposure increased the percentage of deaths greatly. After 72 hr of exposure, 78.34 % of the test subjects died. Amorphous silica brings significant harm, especially to the midgut of the larva and as a result, the larva dies. Furthermore, *Tribolium confusum* and *Sarocladium oryzae* can be easily controlled with the mixtures of essential oil and silica gel (99). Silver NPs (20-60 nm) and SiNPs have been introduced as storage insecticides for cowpea seeds. An effective insecticide is obtained when the nanocomposites of silver and silica are combined as they are effective in killing adult and larval *Callosobruchus maculatus* (cowpea weevil). These silica and silver NPs have resulted in 100 % mortality at the adult stage and in 83 % of the cases in the larval stage (100). From these findings it may be considered that SiNPs are promising candidates to be used as efficient storage pesticides.

Safety measures and environmental impact

SiNPs have multiple applications, the industrial and cosmetic industries as well as the medical sector. There are several groups of people that deal with or consume products that contain silica NPs. These are individuals who work in the production of nano-silica or are employed by drug manufacturing companies, scientists working in the laboratories that have been set up for drug production, individuals who take drugs which contain nano-silica as an active ingredient and even individuals that use cosmetic products that have nano-silica in them. It is important to note that nano-silica is different from other forms of silica, for instance, bulk silica in terms of its physical and chemical characteristics which in turn alters how toxic it can be (101,102). The US Environmental Protection Agency (EPA) has not included silica under the Integrated Risk Information System (IRIS). This is because so far, no guidelines have been established under silica for minimum risk levels, maximum contaminant levels and reference doses. The use of vitreous silica, fumed silica and silica gel in pesticides is also considered safe hence the US EPA is not making plans to set any restrictions. As food additives both silica and diatomaceous earth have been approved by the Food and Drug Administration (FDA) (103). The most concerning method of exposure is inhalation which poses the bigger problem, both from an environmental point of view as well as an occupational point of view (104). Alveolar spaces are the correct location where SiNPs are expected to be deposited as they belong to the fractions that can be inhaled.

Once these NPs reach the air-liquid interface, they come into contact with pulmonary surfactant which is essential for lung functioning and defence (105). SiNPs which are not eliminated by the alveolar macrophages will cause negative effects on lung tissues or will be absorbed into circulation and affect other body parts. The inhalation of SiNPs has also been implicated in a range of well-known diseases including silicosis (106,107). Employees are usually prone to dangers of silica dust silicosis exposure is said to be high in occupational lifestyle. It is for this those major laws on this matter in regions like the US and the European Union are of work-related concerns listed in Table 5. Silo tuberculosis is the prime area of disease affecting most of the people as a result of sharp focus by the researchers, but unfortunately there are no effective treatments for the disease at the moment. This disturbing vacuum has been the objective of recent researches which look for viable and effectual alternatives (108). NPs are known to pose threats after being deposited in lithosphere and hydrosphere. While gene therapy is gaining greater acceptance, these NPs have often been tested for toxicity using EC_{20} or EC_{50} values. These two figures relate to specific concentrations of a given test material which produce such effects as 20 % or more reverse effects on the organism involved (109). Hydraulic fracturing operations can minimize silica dust exposure through process enclosures and localized exhaust ventilation. During sand pumping, stilling curtains, tents, or enclosed chutes reduce dust from drop points. Enclosed hoppers and covered systems control proppant handling emissions. Vehicle movement on dry sites generates airborne dust, which is mitigated by spraying water mixed with chlorides or polymers. Rubber mats beneath equipment prevent ground disturbance dust. Gravity-fed conveyor belts further reduce airborne silica by limiting direct sand handling (101).

Another source of silica exposure which is not as obvious but is still significant is the dust released from workers' clothes which can if not washed completely or availed from the worker, transfer silica containing particles to the home and respective families. Workers usually depend on air, brushes or their hands

Table 5. Nanosilica toxicity and biocompatibility in humans (*in vitro* and *in vivo*)

S.No	Parameter	Study Design	Concentration/Exposure	Duration	Observed Effects	References
1.	Cytotoxicity	*In vitro* (lung epithelial cells)	10-100 µg/mL	24-48 hr	Dose-dependent mild cytotoxicity	(111-113)
2.	Genotoxicity	*In vitro* (human lymphocytes)	50 µg/mL	48 hr	DNA damage observed at higher concentrations	(114-116)
3.	Oxidative Stress	*In vitro* (human skin cells)	20-40 µg/mL	6 hr	Elevated ROS production	(117,118)
4.	Immune Response	*In vivo* (human clinical trial)	1 mg/kg orally	7 days	No significant inflammatory markers	(119,120)
5.	Biodistribution	*In vivo* (human clinical trial)	5 mg/kg orally	14 days	Minimal accumulation in blood and tissues	(121,122)
6.	Biocompatibility	*In vivo* (topical application)	50 µg/mL	4 weeks	No adverse skin reactions	(123-125)
7.	Hemocompatibility	*In vitro* (human blood cells)	10-100 µg/mL	24 hr	No haemolysis or platelet aggregation	(126,127)

to get rid of dust from clothes, so in this case they actually inhale silica dust increasing exposure. Moreover, cleaning the body with blasts of air brings about additional hazards. An additional measure of controlling the problem is the use of HEPA vacuum systems which do help in removal of dust with clothing but do not allow particles to be dispersed in air. As for workers, it is also reasonable to use wet methods of cleaning to wash the dust from the hands and face (109,110).

Future prospects and innovation in agri- tech

Agricultural practices can be improved by utilizing SiNPs to ensure sustainable farming, efficient use of resources, as well as conservation of the environment. SiNPs possess some remarkable characteristics such as high surface area, porosity and biocompatibility which, if effectively put to use in agriculture, can usher a revolution in the now-SI NPs can be used as smart carriers for fertilizers and agro-chemicals wherein nutrients may be delivered 'on-target' in a controlled manner So, Nano-silica-based carriers serve their purpose by preventing premature loss of constitutive active ingredients, which is at an enzymatic and freely active form and providing a sustained and ordered release of nutrients preventing environmental degradation through nutrient loss. Such developments can leverage the nutrition of crops and enhance the amount harvested. Drought, salinity and heavy metals are limiting factors interfering with global hunger relief programs. The administration of Silo increases the capability of plants by increasing the antioxidant and the tolerance towards global climate 'change' versus 'stressor' at cellular levels. These alterations may aid in creating climate resilient crops in the future. Silica particles can alternatively be installed along the microprocessor blocking bacteria growth or limiting insects from mounting attacks or becoming a microbiological ecosystem. They can also be used as fillers for biopesticides and antifungal agents to provide safe alternatives of synthetical pesticides.

The use of SiNPs in soil amendments encourages improvement of soil structure, water holding capacity and the development of a soil microbial population. They have also proven useful in the immobilization of heavy metals and other pollutants, which can help in the bioremediation of degraded soils, thus, fostering agricultural sustainability. Sensors and imaging technologies integrated with SiNPs make it possible to monitor soil moisture, nutrients and pest activities in real-time. To take full advantage of this integration, data-driven and precision farming practices can be adopted by farmers, thereby lowering costs while increasing productivity. New findings should concentrate on creating silica nanocomposites such as Pickering emulsions for diverse applications. These advancements should be able to integrate nutrient application, stress elimination and pest control onto one platform. Furthermore, the use of plant extracts and agricultural waste in green synthesis approaches for SiNPs appears promising as it makes these technologies cheaper and more environmentally friendly.

Conclusion

Nano-silica from *Equisetum* has the potential to convert the agricultural sector into a more ecologically sustainable and efficient system. It promotes the growth of crops, improves their tolerance to stresses such as pests or droughts and optimizes the use of nutrients. More importantly, it can be produced in ways that are environmentally friendly, lessening the application of harmful chemicals and protecting soil and water systems in the future, as *Equisetum* holds all these advantages.

Nano-silica holds great potential for future agriculture, especially in precision farming and urban systems like vertical farming. It could be integrated into smart sensors for real-time monitoring of soil and plant health, optimizing water and fertilizer use. Advancements like breeding high-silica *Equisetum* could enhance sustainable nano-silica production. To address the current research gaps, more studies are needed on the long-term safety of nano silica for plants, soil and the environment. This includes understanding how nano-silica behaves in different ecosystems and whether there are any unintended side effects. Developing cost-effective, large-scale production methods is another key challenge. This also entails the evaluation of the interacting activities of nano-silica within various biological communities and anticipating negative consequences that might arise as a result. Approaches may include modified green synthesis methods or optimisation of nano-silica retrieval from poor-grade soil and from sources of agricultural waste. With these approaches and future reforms, nano silica made from *Equisetum,* which is the silica as well as carbon source, can be a paradigm shift in the agriculture domain. It serves many purposes in effectively addressing problems faced by humankind such as food, climate change and even the scarcity of resources.

Acknowledgements

We sincerely thank everyone who helped make this review possible, both individuals and organizations, for their valuable contributions.

Authors' contributions

KR conceptualized the review and developed the initial framework. JSSD conducted the comprehensive literature search, data collection and writing the original draft. GV critically analysed the synthesis part. AJ contributed to the sections on tables and pictures. SV and RP reviewed the manuscript for scientific accuracy and provided valuable insights on sustainability implications. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Khatoon Z, Huang S, Rafique M, Fakhar A, Kamran MA, Santoyo G. Unlocking the potential of plant growth-promoting rhizobacteria on soil health and the sustainability of agricultural systems. J Environ Manage. 2020;273:111118. https://doi.org/10.1016/j.jenvman.2020.111118
2. Hatti V, Raghavendra M, Singh Y, Sharma S, Halli HM, Goud B. Application of nano technology in crop production to enhance resource use efficiency with special reference to soil and water conservation: A review. J Soil Water Conserv. 2020;19(4):375-81. https://doi.org/10.5958/2455-7145.2020.00050.8
3. Carneiro ME, Magalhães WLE, Bolzon de Muñiz GIB, Nisgoski S, Satyanarayana KG. Preparation and characterization of nano silica from *Equisetum arvenses*. J Bioprocess Biotechniques. 2015;5(2):205. https://doi.org/10.4172/2155-9821.1000205
4. Kaufman PB, Bigelow WC, Schmid R, Ghosheh NS. Electron microprobe analysis of silica in epidermal cells of *Equisetum*. Am J Bot. 1971;58(4):309-16. https://doi.org/10.1002/j.1537-2197.1971.tb14468.x
5. Sola-Rabada A, Rinck J, Belton DJ, Powell AK, Perry CC. Isolation of a wide range of minerals from a thermally treated plant: *Equisetum arvense*, a mare's tale. J Biol Inorg Chem. 2016;21:101-12. https://doi.org/10.1007/s00775-015-1309-6
6. Mathur P, Roy S. Nanosilica facilitates silica uptake, growth and stress tolerance in plants. Plant Physiol Biochem. 2020;157:114-27. https://doi.org/10.1016/j.plaphy.2020.08.004
7. Bayoumi Y, Shalaby T, Taha N, El-Ramady H. Nano-silicon for plant biotic stress: A short communication. Environ Biodivers Soil Secur. 2021;5:267-74. https://doi.org/10.1007/978-981-15-7616-9_26
8. Grewal S, Boora R, Kumari S, Thakur R, Goel S. Fascinating aspects of nanosilicon enabled plant stress tolerance-A comprehensive review. Plant Nano Biol. 2024;8:100077. https://doi.org/10.1016/j.plnbio.2024.100077
9. Kong X-P, Zhang B-H, Wang J. Multiple roles of mesoporous silica in safe pesticide application by nanotechnology: A review. J Agric Food Chem. 2021;69(24):6735-54. https://doi.org/10.1021/acs.jafc.1c01724
10. Singh SP, Endley N. Fabrication of nano-silica from agricultural residue and their application. In: Nanomaterials for agriculture and forestry applications. Elsevier; 2020. p. 107-34 https://doi.org/10.1016/B978-0-12-818896-6.00006-2
11. Kouadri I, Ben Seghir B, Hemmami H, Zeghoud S, Allag N, Rebiai A, et al. Extraction of silica from different sources of agricultural waste. Asian J Res Chem. 2023;16(1):97-101. https://doi.org/10.52711/0974-4150.2023.00016
12. Shahbaz A, Ayaz M, Bin Khalid U, Liaqat L. Sustainable synthesis of silica nanoparticles from agricultural waste and its utilization in modern technology: A review. Energy Sources A. 2023;45(1):1464-84. https://doi.org/10.1080/15567036.2023.2189487
13. Goswami P, Mathur J, Srivastava N. Silica nanoparticles as novel sustainable approach for plant growth and crop protection. Heliyon. 2022;8(7):e09934. https://doi.org/10.1016/j.heliyon.2022.e09934
14. Awad-Allah EF. Effectiveness of silica nanoparticle application as plant nano-nutrition: a review. J Plant Nutr. 2023;46(11):2763-76. https://doi.org/10.1080/01904167.2023.2162234
15. Setyawan N, Hoerudin, Yuliani S. Synthesis of silica from rice husk by sol-gel method. In: Proceedings of the 1st International Conference on Agriculture and Bioindustry; 2021 Oct 27-28; Bogor, Indonesia. Bristol (UK): IOP Publishing; 2021. p. 012149. https://doi.org/10.1088/1755-1315/733/1/012149
16. Azat S, Korobeinyk A, Moustakas K, Inglezakis V. Sustainable production of pure silica from rice husk waste in Kazakhstan. J Clean Prod. 2019;217:352-9. https://doi.org/10.1016/j.jclepro.2019.01.142
17. Liu W, Zhang X, Ren H, Hu X, Yang X, Liu H. Co-production of spirosiloxane and biochar adsorbent from wheat straw by a low-cost and environment-friendly method. J Environ Manage. 2023;338:117851. https://doi.org/10.1016/j.jenvman.2023.117851
18. Terzioğlu P, Yücel S, Kuş Ç. Review on a novel biosilica source for production of advanced silica-based materials: Wheat husk. Asia Pac J Chem Eng. 2019;14(1):e2262. https://doi.org/10.1002/apj.2262
19. Seroka NS, Taziwa R, Khotseng L. Green synthesis of crystalline silica from sugarcane bagasse ash: physico-chemical properties. Nanomaterials. 2022;12(13):2184. https://doi.org/10.3390/nano12132184
20. September LA, Kheswa N, Seroka NS, Khotseng L. Green synthesis of silica and silicon from agricultural residue sugarcane bagasse ash–a mini review. RSC Advances. 2023;13(2):1370-80. https://doi.org/10.1039/D2RA07490G
21. Farirai F, Mupa M, Daramola MO. An improved method for the production of high purity silica from sugarcane bagasse ash obtained from a bioethanol plant boiler. Particulate Sci Technol. 2021;39(2):252-9. https://doi.org/10.1080/02726351.2020.1734700
22. Manigandan P. Experimental investigations of epoxy biocomposites developed using alkali-silane treated cellulosic corn husk fiber and corn cob biosilica. Silicon. 2023;15(6):2941-51.
23. Harun Z, Azhar FH, Hussin R, Ibrahim SA, Hubadillah SK, Sazali N, et al. The extraction of organic silica from agricultural waste: a mini review. Emerg Adv Integr Technol. 2024;5(1):65-74. https://doi.org/10.30880/emait.2024.05.01.009
24. Adediran AA, Alaneme KK, Oladele IO, Akinlabi ET. Processing and structural characterization of Si-based carbothermal derivatives of bamboo leaf. Procedia Manufacturing. 2019;35:389-94. https://doi.org/10.1016/j.promfg.2019.05.057
25. Silviana S, Bayu WJ. Silicon conversion from bamboo leaf silica by magnesiothermic reduction for development of Li-ion battery anode. In: Proceedings of the 24th Regional Symposium on Chemical Engineering; 2017 Nov 15–16; Semarang, Indonesia. Les Ulis (FR): EDP Sciences; 2018. p. 05021. https://doi.org/10.1051/matecconf/201815605021.
26. Peerzada JG, Chidambaram R. A statistical approach for biogenic synthesis of nano-silica from different agro-wastes. Silicon. 2021;13:2089-101. https://doi.org/10.1007/s12633-020-00439-5
27. Anuar MF, Fen YW, Zaid MHM, Matori KA, Khaidir REM. The

physical and optical studies of crystalline silica derived from the green synthesis of coconut husk ash. Applied Sciences. 2020;10 (6):2128. https://doi.org/10.3390/app10062128

28. Razak NAA, Othman NH, Shayuti MSM, Jumahat A, Sapiai N, Lau WJ. Agricultural and industrial waste-derived mesoporous silica nanoparticles: a review on chemical synthesis route. J Environ Chem Eng. 2022;10(2):107322. https://doi.org/10.1016/j.jece.2022.107322

29. Chung I-M, Park I, Seung-Hyun K, Thiruvengadam M, Rajakumar G. Plant-mediated synthesis of silver nanoparticles: their characteristic properties and therapeutic applications. Nanoscale Research Letters. 2016;11:40. https://doi.org/10.1186/s11671-016-1257-4

30. Huang R-a, Hu X, Guo Y, Wang J, Yang B. Highly hierarchical fibrillar biogenic silica with mesoporous structure derived from the perennial plant *Equisetum fluviatile*. ACS Appl Mater Interfaces. 2020;12(31):35259-65. https://doi.org/10.1021/acsami.0c09567

31. Hosseini Mohtasham N, Gholizadeh M. Nano silica extracted from *Equisetum arvense* as a natural silica support for the synthesis of $H_3PW_{12}O_{40}$ immobilized on aminated magnetic nanoparticles (Fe_3O_4@SiO_2-EP-NH-HPA): a novel and efficient heterogeneous nanocatalyst for the green one-pot synthesis of pyrano[2,3-c] pyrazole derivatives. Res Chem Intermed. 2020;46:3037-66. https://doi.org/10.1007/s11164-020-04161-0

32. Mattos BD, Gomes GR, de Matos M, Ramos LP, Magalhães WL. Consecutive production of hydroalcoholic extracts, carbohydrate derivatives and silica nanoparticles from *Equisetum arvense*. Waste and Biomass Valorization. 2018;9:1993-2002. https://doi.org/10.1007/s12649-018-0292-7

33. Adach K, Kroisova D, Fijalkowski M. Biogenic silicon dioxide nanoparticles processed from natural sources. Particulate Sci Technol. 2021;39(4):481-9. https://doi.org/10.1080/02726351.2020.1828638

34. Tayebee R, Pejhan A, Ramshini H, Maleki B, Erfaninia N, Tabatabaie Z, et al. *Equisetum arvense* as an abundant source of silica nanoparticles. $SiO_2/H_3PW_{12}O_{40}$ nanohybrid material as an efficient and environmental benign catalyst in the synthesis of 2-amino-4H-chromenes under solvent-free conditions. Appl Organomet Chem. 2018;32(1):e3924. https://doi.org/10.1002/aoc.3924

35. Rahimzadeh CY, Barzinjy AA, Mohammed AS, Hamad SM. Green synthesis of SiO_2 nanoparticles from *Rhus coriaria* L. extract: comparison with chemically synthesized SiO_2 nanoparticles. PLoS One. 2022;17(8):e0268184. https://doi.org/10.1371/journal.pone.0268184

36. Roychoudhury A. Silicon-nanoparticles in crop improvement and agriculture. Int J Recent Adv Biotechnol Nanotechnol. 2020;3 (1):2582-1571.

37. Suriyaprabha R, Karunakaran G, Kavitha K, Yuvakkumar R, Rajendran V, Kannan N. Application of silica nanoparticles in maize to enhance fungal resistance. IET Nanobiotechnology. 2014;8(3):133-7. https://doi.org/10.1049/iet-nbt.2013.0155

38. Grégoire C, Rémus-Borel W, Vivancos J, Labbé C, Belzile F, Bélanger RR. Discovery of a multigene family of aquaporin silicon transporters in the primitive plant *Equisetum arvense.* Plant J. 2012;72(2):320-30. https://doi.org/10.1111/j.1365-313X.2012.05045.x

39. Snehal S, Lohani P. Silica nanoparticles: its green synthesis and importance in agriculture. J Pharmacogn Phytochem. 2018;7 (5):3383-93.

40. Banerjee K, Pramanik P, Maity A, Joshi DC, Wani SH, Krishnan P. Methods of using nanomaterials to plant systems and their delivery to plants (mode of entry, uptake, translocation, accumulation, biotransformation and barriers). In: Ghorbanpour M, Wani SH, editors. Advances in phytonanotechnology. Amsterdam: Elsevier; 2019. p. 123-52

41. Mukarram M, Petrik P, Mushtaq Z, Khan MMA, Gulfishan M, Lux A. Silicon nanoparticles in higher plants: uptake, action, stress tolerance and crosstalk with phytohormones, antioxidants and other signalling molecules. Environ Pollut. 2022;310:119855. https://doi.org/10.1016/j.envpol.2022.119855

42. Vass A. Over half the world will face water shortages by 2032. British Medical Journal Publishing Group; 2002. https://doi.org/10.1136/bmj.324.7349.1293

43. Goswami P, Mathur J. Positive and negative effects of nanoparticles on plants and their applications in agriculture. Plant Science Today. 2019;6(2):232-42. https://doi.org/10.14719/pst.6.2.433

44. Huang M, Yao Q, Feng G, Zou H, Lu Z-H. Nickel–ceria nanowires embedded in microporous silica: controllable synthesis, formation mechanism and catalytic applications. Inorg Chem. 2020;59(8):5781-90. https://doi.org/10.1021/acs.inorgchem.9b03673

45. Chiappini C, De Rosa E, Martinez J, Liu X, Steele J, Stevens M, et al. Biodegradable silicon nanoneedles delivering nucleic acids intracellularly induce localized *in vivo* neovascularization. Nat Mater. 2015;14(5):532-9. https://doi.org/10.1038/nmat4249

46. Park J-H, Gu L, von Maltzahn G, Ruoslahti E, Bhatia SN, Sailor MJ. Biodegradable luminescent porous silicon nanoparticles for *in vivo* applications. Nat Mater. 2009;8(4):331–6. https://doi.org/10.1038/nmat2398

47. Phillips E, Penate-Medina O, Zanzonico PB, Carvajal RD, Mohan P, Ye Y, et al. Clinical translation of an ultrasmall inorganic optical-PET imaging nanoparticle probe. Sci Transl Med. 2014;6 (260):260ra149. https://doi.org/10.1126/scitranslmed.3009524

48. Sheikhzadeh E, Beni V, Zourob M. Nanomaterial application in bio/sensors for the detection of infectious diseases. Talanta. 2021;230:122026. https://doi.org/10.1016/j.talanta.2020.122026

49. Mathew FP, Alocilja EC. Porous silicon-based biosensor for pathogen detection. Biosens Bioelectron. 2005;20(8):1656–61. https://doi.org/10.1016/j.bios.2004.08.006

50. Sastry RK, Rashmi H, Rao N, Ilyas S. Integrating nanotechnology into agri-food systems research in India: a conceptual framework. Technol Forecast Soc Change. 2010;77(4):639–48. https://doi.org/10.1016/j.techfore.2009.11.008

51. Guerra FD, Attia MF, Whitehead DC, Alexis F. Nanotechnology for environmental remediation: materials and applications. Molecules. 2018;23(7):1760. https://doi.org/10.3390/molecules23071760

52. Meng L, Ren Y, Zhou Z, Li C, Wang C, Fu S. Monodisperse silica nanoparticle suspension for developing latent blood fingermarks. Forensic Sci Res. 2020;5 (1):38–46. https://doi.org/10.1080/20961790.2018.1446721

53. Kiruba UP, Kumar PS, Prabhakaran C, Aditya V. Characteristics of thermodynamic, isotherm, kinetic, mechanism and design equations for the analysis of adsorption in Cd (II) ions-surface modified *Eucalyptus* seeds system. J Taiwan Inst Chem Eng. 2014;45(6):2957–68. https://doi.org/10.1016/j.jtice.2014.08.016

54. Sorour M, Helmy M, El Mahrouky AS, Ahmed II. Using activated and nano silica as adsorbent materials for filtration of industrial wastewater. Food Technol Res J. 2023;2(3):68–72. https://doi.org/10.21608/ftrj.2023.329291

55. Manyangadze M, Chikuruwo NM, Narsaiah TB, Chakra CS, Charis G, Danha G, et al. Adsorption of lead ions from wastewater using nano silica spheres synthesized on calcium carbonate templates. Heliyon. 2020;6(11). https://doi.org/10.1016/j.heliyon.2020.e05309

56. Foroutan R, Mohammadi R, Peighambardoust SJ, Jalali S, Ramavandi B. Application of nano-silica particles generated from offshore white sandstone for cadmium ions elimination from aqueous media. Environ Technol Innov. 2020;19:101031. https://doi.org/10.1016/j.eti.2020.101031

57. Xiong C, Wang S, Zhang L, Li Y, Srinivasakannan C, Peng J. Preparation and application of phosphinic acid functionalized nanosilica for the effective removal of mercury (II) in aqueous solutions. J Sol-Gel Sci Technol. 2018;87:442–54. https://doi.org/10.1007/s10971-018-4723-x

58. Meky N, Salama E, Soliman MF, Naeem SG, Ossman M, Elsayed M. Synthesis of nano-silica oxide for heavy metal decontamination from aqueous solutions. Water Air Soil Pollut. 2024;235(2):154. https://doi.org/10.1007/s11270-024-06944-6

59. Alnasra O, Khalili F. Synthesis and characterization of a nanosilica -cysteine composite for arsenic (III) ion removal. Acta Chim Slov. 2023;70(4). https://doi.org/10.17344/acsi.2023.8160

60. Akhayere E, Essien EA, Kavaz D. Effective and reusable nano-silica synthesized from barley and wheat grass for the removal of nickel from agricultural wastewater. Environ Sci Pollut Res. 2019;26(25):25802–13. https://doi.org/10.1007/s11356-019-05759-x

61. Saw G, Nagdev P, Jeer M, Murali-Baskaran R. Silica nanoparticles mediated insect pest management. Pestic Biochem Physiol. 2023:105524. https://doi.org/10.1016/j.pestbp.2023.105524

62. Wang Q, Ma X, Zhang W, Pei H, Chen Y. The impact of cerium oxide nanoparticles on tomato (*Solanum lycopersicum* L.) and its implications for food safety. Metallomics. 2012;4(10):1105–12. https://doi.org/10.1039/c2mt20149f

63. Nair R, Varghese SH, Nair BG, Maekawa T, Yoshida Y, Kumar DS. Nanoparticulate material delivery to plants. Plant Sci. 2010;179(3):154–63. https://doi.org/10.1016/j.plantsci.2010.04.012

64. Goodman CM, McCusker CD, Yilmaz T, Rotello VM. Toxicity of gold nanoparticles functionalized with cationic and anionic side chains. Bioconjugate Chem. 2004;15(4):897–900. https://doi.org/10.1021/bc049951i

65. Barik T, Sahu B, Swain V. Nanosilica-from medicine to pest control. Parasitology Res. 2008;103:253–8. https://doi.org/10.1007/s00436-008-0975-7

66. Nuruzzaman M, Rahman MM, Liu Y, Naidu R. Nanoencapsulation, nano-guard for pesticides: a new window for safe application. J Agric Food Chem. 2016;64(7):1447–83. https://doi.org/10.1021/acs.jafc.5b05214

67. Wanyika H. Sustained release of fungicide metalaxyl by mesoporous silica nanospheres. In: Nanotechnology for sustainable development. Springer; 2014. p. 137–48

68. Khandelwal N, Barbole RS, Banerjee SS, Chate GP, Biradar AV, Khandare JJ, et al. Budding trends in integrated pest management using advanced micro- and nano-materials: Challenges and perspectives. J Environ Manage. 2016;184:157–69. https://doi.org/10.1016/j.jenvman.2016.09.005

69. Shah MA, Wani SH, Khan AA. Nanotechnology and insecticidal formulations. J Food Bioeng Nanoprocessing. 2016;1(3):285–310.

70. Oirdi ME, Yaseen M, Farwa U, Raza MA, Farhan M, Sandhu ZA, et al. Crops and people: the dangers and potential benefits of pesticides. Cogent Food Agric. 2024;10(1):2334096. https://doi.org/10.1080/23311932.2024.2334096

71. Ibrahim SS, Elbehery HH, Samy A. The efficacy of green silica nanoparticles synthesized from rice straw in the management of *Callosobruchus maculatus* (Col., Bruchidae). Sci Rep. 2024;14(1):8834. https://doi.org/10.1038/s41598-024-58856-4

72. Khalifa A, Moselhy W, Mohammed H, Nabil T, Shaban M, Aboelhadid S, et al. Toxicological evaluations of chitosan and silica nanoparticles loaded with deltamethrin with improved efficiency against *Culex pipiens* larvae. Int J Environ Sci Technol. 2022;19(12):11809–28. https://doi.org/10.1007/s13762-022-03921-6

73. Balamurugan S, Priyadharshini V, Venkatesh G. A review on nano-pesticides in pest management. Mater Today Proc. 2023;73:3309–14. https://doi.org/10.1016/j.matpr.2023.02.354

74. Tamburic-Ilincic L, Schaafsma A. The prevalence of *Fusarium* spp. colonizing seed corn stalks in southwestern Ontario, Canada. Can J Plant Sci. 2009;89(1):103–6. https://doi.org/10.4141/CJPS08083

75. Epstein E. Silicon in plants: facts vs. concepts. In: Studies in plant science. Elsevier; 2001. p. 1–15 https://doi.org/10.1016/S0928-3420(01)80005-7

76. Rains D, Epstein E, Zasoski R, Aslam M. Active silicon uptake by wheat. Plant Soil. 2006;280:223–8. https://doi.org/10.1007/s11104-005-3082-x

77. Yin H, Zhao X, Du Y. Oligochitosan: a plant diseases vaccine-a review. Carbohydr Polym. 2010;82(1):1–8. https://doi.org/10.1016/j.carbpol.2010.03.066

78. Das SN, Madhuprakash J, Sarma P, Purushotham P, Suma K, Manjeet K, et al. Biotechnological approaches for field applications of chitooligosaccharides (COS) to induce innate immunity in plants. Crit Rev Biotechnol. 2015;35(1):29–43. https://doi.org/10.3109/07388551.2013.798255

79. Thakur M, Sohal BS. Role of elicitors in inducing resistance in plants against pathogen infection: a review. Int Scholarly Res Notices. 2013;2013(1):762412. https://doi.org/10.1155/2013/762412

80. Iwasaki K, Maier P, Fecht M, Horst WJ. Leaf apoplastic silicon enhances manganese tolerance of cowpea (*Vigna unguiculata*). J Plant Physiol. 2002;159(2):167–73. https://doi.org/10.1078/0176-1617-00691

81. Liang Y, Wong J, Wei L. Silicon-mediated enhancement of cadmium tolerance in maize (*Zea mays* L.) grown in cadmium-contaminated soil. Chemosphere. 2005;58(4):475–83. https://doi.org/10.1016/j.chemosphere.2004.09.034

82. Ma JF. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. Soil Sci Plant Nutr. 2004;50(1):11–8. https://doi.org/10.1080/00380768.2004.10408447

83. Fauteux F, Rémus-Borel W, Menzies JG, Bélanger RR. Silicon and plant disease resistance against pathogenic fungi. FEMS Microbiol Lett. 2005;249(1):1–6. https://doi.org/10.1016/j.femsle.2005.06.034

84. Kim S-G, Kim K-W, Park E-W. Increase in resistance to leaf blast as accumulation of silicon in rice leaf tissues. Plant Pathol J. 2001;17(6):374–1.

85. Urbi ZR. Development of resistance system in rice plant against blast disease caused by *Magnaporthe oryzae* using selected novel chemicals. MS [thesis]. Dhaka: Sher-e-Bangla Agricultural University; 2021.

86. Rodrigues F, Datnoff L, Korndörfer G, Seebold K, Rush M. Effect of silicon and host resistance on sheath blight development in rice. Plant Dis. 2001;85(8):827–32. https://doi.org/10.1094/PDIS.2001.85.8.827

87. Seebold K, Kucharek T, Datnoff LA, Correa-Victoria FJ, Marchetti M. The influence of silicon on components of resistance to blast in susceptible, partially resistant and resistant cultivars of rice. Phytopathology. 2001;91(1):63–9. https://doi.org/10.1094/PHYTO.2001.91.1.63

88. Kim SG, Kim KW, Park EW, Choi D. Silicon-induced cell wall fortification of rice leaves: a possible cellular mechanism of enhanced host resistance to blast. Phytopathology. 2002;92(10):1095–103. https://doi.org/10.1094/PHYTO.2002.92.10.1095

89. Madany MM, Saleh AM, Habeeb TH, Hozzein WN, AbdElgawad H. Silicon dioxide nanoparticles alleviate the threats of broomrape infection in tomato by inducing cell wall fortification and modulating ROS homeostasis. Environ Sci Nano. 2020;7(5):1415–30. https://doi.org/10.1039/D0EN00157B

90. Awad-Allah EF, Shams AH, Helaly AA. Suppression of bacterial leaf spot by green synthesized silica nanoparticles and antagonistic yeast improves growth, productivity and quality of sweet pepper. Plants. 2021;10(8):1689. https://doi.org/10.3390/plants10081689

91. Youssef K, de Oliveira AG, Tischer CA, Hussain I, Roberto SR. Synergistic effect of a novel chitosan/silica nanocomposites-based formulation against gray mold of table grapes and its possible mode of action. Int J Biol Macromol. 2019;141:247–58. https://doi.org/10.1016/j.ijbiomac.2019.08.024

92. dos Santos OAL, dos Santos MS, Antunes Filho S, Backx BP. Nanotechnology for the control of plant pathogens and pests. Plant Nano Biol. 2024:100080. https://doi.org/10.1016/

j.plgene.2023.100080

93. Chen S, Guo X, Zhang B, Nie D, Rao W, Zhang D, et al. Mesoporous silica nanoparticles induce intracellular peroxidation damage of *Phytophthora infestans*: a new type of green fungicide for late blight control. Environ Sci Technol. 2023;57(9):3980–9. https://doi.org/10.1021/acs.est.2c08198

94. Albalawi MA, Abdelaziz AM, Attia MS, Saied E, Elganzory HH, Hashem AH. Mycosynthesis of silica nanoparticles using *Aspergillus niger*: control of *Alternaria solani* causing early blight disease, induction of innate immunity and reducing of oxidative stress in eggplant. Antioxidants. 2022;11(12):2323. https://doi.org/10.3390/antiox11122323

95. Xin X, Judy JD, Sumerlin BB, He Z. Nano-enabled agriculture: from nanoparticles to smart nanodelivery systems. Environ Chem. 2020;17(6):413–25. https://doi.org/10.1071/EN20043

96. Neme K, Nafady A, Uddin S, Tola YB. Application of nanotechnology in agriculture, postharvest loss reduction and food processing: food security implication and challenges. Heliyon. 2021;7(12). https://doi.org/10.1016/j.heliyon.2021.e08516

97. Kassem HS, Tarabih ME, Ismail H, Eleryan EE. Influence of nano-silica/chitosan film coating on the quality of 'Tommy Atkins' mango. Processes. 2022;10(2):279. https://doi.org/10.3390/pr10020279

98. Zahran N, Sayed R. Protective effect of nanosilica on irradiated dates against saw toothed grain beetle, *Oryzaephilus surinamensis* (Coleoptera: Silvanidae) adults. J Stored Prod Res. 2021;92:101799. https://doi.org/10.1016/j.jspr.2021.101799

99. Idris I, Naddaf M, Harmalani H, Alshater R, Alsafadi R. Effects of nano-silica extracted from two different plant sources on survival and development of *Phthorimaea operculella* (Zeller.) larvae. Hellenic Plant Protection Journal. 2023;16(2):59-66. https://doi.org/10.2478/hppj-2023-0008

100. Wazid SN, Prabhuraj A, Naik RH, Shakuntala N, Sharanagouda H. The persistence of residual toxicity of zinc, copper and silica green nanoparticles against important storage pests. J Entomol Zool Stud. 2020;8:1207–11.

101. Croissant JG, Butler KS, Zink JI, Brinker CJ. Synthetic amorphous silica nanoparticles: toxicity, biomedical and environmental implications. Nat Rev Mater. 2020;5(12):886–909. https://doi.org/10.1038/s41578-020-0213-7

102. Mohammadi P, Abbasinia M, Assari MJ, Oliaei M. The toxicology of silica nanoparticles: a review. Toxicol Environ Chem. 2018;100(3):285–316. https://doi.org/10.1080/02772248.2018.1432307

103. Thomas RS, Bahadori T, Buckley TJ, Cowden J, Deisenroth C, Dionisio KL, et al. The next generation blueprint of computational toxicology at the US Environmental Protection Agency. Toxicol Sci. 2019;169(2):317–32. https://doi.org/10.1093/toxsci/kfz044

104. Kavlock RJ, Daston GP, DeRosa C, Fenner-Crisp P, Gray LE, Kaattari S, et al. Research needs for the risk assessment of health and environmental effects of endocrine disruptors: a report of the US EPA-sponsored workshop. Environ Health Perspect. 1996;104(suppl 4):715–40. https://doi.org/10.1289/ehp.96104s4715

105. Garcia-Mouton C, Hidalgo A, Cruz A, Pérez-Gil J. The Lord of the lungs: the essential role of pulmonary surfactant upon inhalation of nanoparticles. Eur J Pharm Biopharm. 2019;144:230–43. https://doi.org/10.1016/j.ejpb.2019.07.012

106. Greenberg MI, Waksman J, Curtis J. Silicosis: a review. Dis Mon. 2007;53(8):394–416. https://doi.org/10.1016/j.disamonth.2007.04.001`

107. Leung CC, Yu ITS, Chen W. Silicosis. Lancet. 2012;379(9830):2008–18. https://doi.org/10.1016/S0140-6736(12)60235-9

108. Boccuni F, Ferrante R, Tombolini F, Natale C, Gordiani A, Sabella S, et al. Occupational exposure to graphene and silica nanoparticles. Part I: workplace measurements and samplings. Nanotoxicology. 2020;14(9):1280–300. https://doi.org/10.1080/17435390.2020.1834634

109. Vareda JP, García-González CA, Valente AJ, Simón-Vázquez R, Stipetic M, Durães L. Insights on toxicity, safe handling and disposal of silica aerogels and amorphous nanoparticles. Environ Sci Nano. 2021;8(5):1177–95. https://doi.org/10.1039/D0EN01019J

110. Heidel D, Carson K, Baker J, editors. Safety and health management aspects for handling silica-based products and engineered nanoparticles in sequences of shale reservoir stimulations operations. In: Proceedings of SPE International Conference and Exhibition on Health, Safety, Environment and Sustainability; 2014 Mar 17–19; Long Beach, CA. Richardson, TX: Society of Petroleum Engineers; 2014.

111. Li J, Yang H, Sha S, Li J, Zhou Z, Cao Y. Evaluation of *in vitro* toxicity of silica nanoparticles (NPs) to lung cells: influence of cell types and pulmonary surfactant component DPPC. Ecotoxicol Environ Saf. 2019;186:109770. https://doi.org/10.1016/j.ecoenv.2019.109770

112. Karimi T, Najmoddin N, Menhaje-Bena R. Evaluation of silica nanoparticles cytotoxicity (20–40 nm) on cancerous epithelial cell (A549) and fibroblasts cells of human normal lung fibroblast (MRC5). Occup Med. 2021. https://doi.org/10.1093/occmed/kqab153

113. Akhtar MJ, Ahamed M, Kumar S, Siddiqui H, Patil G, Ashquin M, et al. Nanotoxicity of pure silica mediated through oxidant generation rather than glutathione depletion in human lung epithelial cells. Toxicology. 2010;276(2):95–102. https://doi.org/10.1016/j.tox.2010.07.002

114. Lankoff A, Arabski M, Wegierek-Ciuk A, Kruszewski M, Lisowska H, Banasik-Nowak A, et al. Effect of surface modification of silica nanoparticles on toxicity and cellular uptake by human peripheral blood lymphocytes *in vitro*. Nanotoxicology. 2013;7(3):235–50. https://doi.org/10.3109/17435390.2012.657580

115. Rajiv S, Jerobin J, Saranya V, Nainawat M, Sharma A, Makwana P, et al. Comparative cytotoxicity and genotoxicity of cobalt (II, III) oxide, iron (III) oxide, silicon dioxide and aluminum oxide nanoparticles on human lymphocytes *in vitro*. Hum Exp Toxicol. 2016;35(2):170–83. https://doi.org/10.1177/0960327115599108

116. Battal D, Celik A, Güler G, Aktaş A, Yildirimcan S, Ocakoglu K, et al. SiO2 nanoparticle-induced size-dependent genotoxicity–an *in vitro* study using sister chromatid exchange, micronucleus and comet assay. Drug Chem Toxicol. 2015;38(2):196–204. https://doi.org/10.3109/01480545.2014.944683

117. Napierska D, Rabolli V, Thomassen LC, Dinsdale D, Princen C, Gonzalez L, et al. Oxidative stress induced by pure and iron-doped amorphous silica nanoparticles in subtoxic conditions. Chem Res Toxicol. 2012;25(4):828–37. https://doi.org/10.1021/tx200500j

118. Ahamed M. Silica nanoparticles-induced cytotoxicity, oxidative stress and apoptosis in cultured A431 and A549 cells. Hum Exp Toxicol. 2013;32(2):186–95. https://doi.org/10.1177/0960327112452119

119. Gómez DM, Urcuqui-Inchima S, Hernandez JC. Silica nanoparticles induce NLRP3 inflammasome activation in human primary immune cells. Innate Immun. 2017;23(8):697–708. https://doi.org/10.1177/1753425917709144

120. Chen L, Liu J, Zhang Y, Zhang G, Kang Y, Chen A, et al. The toxicity of silica nanoparticles to the immune system. Nanomedicine. 2018;13(15):1939–62. https://doi.org/10.2217/nnm-2018-0113

121. Malfatti MA, Palko HA, Kuhn EA, Turteltaub KW. Determining the pharmacokinetics and long-term biodistribution of SiO2 nanoparticles *in vivo* using accelerator mass spectrometry. Nano letters. 2012;12(11):5532-8. https://doi.org/10.1021/nl302801x

122. Kumar R, Roy I, Ohulchanskky TY, Vathy LA, Bergey EJ, Sajjad M, et al. *In vivo* biodistribution and clearance studies using multimodal organically modified silica nanoparticles. ACS nano. 2010;4(2):699-708. https://doi.org/10.1021/nn901186v

123. Kim M, Park J-H, Jeong H, Hong J, Choi WS, Lee B-H, et al. An evaluation of the *in vivo* safety of nonporous silica nanoparticles:

ocular topical administration versus oral administration. Scientific reports. 2017;7(1):8238. https://doi.org/10.1038/s41598-017-08664-7

124. Rancan F, Gao Q, Graf C, Troppens S, Hadam S, Hackbarth S, et al. Skin penetration and cellular uptake of amorphous silica nanoparticles with variable size, surface functionalization and colloidal stability. ACS nano. 2012;6(8):6829-42. https://doi.org/10.1021/nn301502z

125. Huang Y, Li P, Zhao R, Zhao L, Liu J, Peng S, et al. Silica nanoparticles: biomedical applications and toxicity. Biomed Pharmacother. 2022;151:113053. https://doi.org/10.1016/j.biopha.2022.113053

126. Kim J, Heo Y-J, Shin S. Haemocompatibility evaluation of silica nanomaterials using hemorheological measurements. Clin Hemorheol Microcirc. 2016;62(2):99-107. https://doi.org/10.3233/CH-151924

127. Giovannini G, Warncke P, Fischer D, Stranik O, Hall AJ, Gubala V. Improving colloidal stability of silica nanoparticles when stored in responsive gel: application and toxicity study. Nanotoxicology. 2018;12(5):407-22. https://doi.org/10.1080/17435390.2018.1457881

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.