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AGRONOMY

SILICON NANOPARTICLES HELP IN MITIGATING THE GROWTH AND PHYSIOLOGICAL ACTIVITIES OF CROPS UNDER DROUGHT STRESSED CONDITIONS-A REVIEW

Fakhra Asad[1], Sumiyya Iftakhar[2], Fenliang Zhao[3], Manal Nadeem Khan[4], Momal Nawab[5], Iqra Fatima[6], Saira Parveen[7], Sadaf Gulzar[8] and Muhammad Nawaz* [9]

[1,2,4,5,6,7,8,9]M.Phil. Student, Department of Environmental Sciences, Bahauddin Zakariya University, Multan, [3]Professor, Institute of Environmental and Plant Protection, Chinese Academy of Tropical Agricultural Sciences, Haikou, Hainan, China.

*Corresponding author's email: mnawaz@bzu.edu.pk

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ABSTRACT
Drought stress exerts substantial impacts on the productivity of crop's cultivation. Researchers proposed Silicon nanoparticles (SiNPs) to counter this challenge by enhancing yields under water scarcity. SiNPs play a pivotal role in augmenting water uptake, retention, and antioxidant defenses, collectively fostering the growth of the crops. This comprehensive review helps in understanding the potential of SiNPs in elevating crops growth amidst drought stress conditions. The application of SiNPs yields remarkable outcomes, including a substantial 20% increase in water retention and an impressive 30% boost in photosynthesis. Equally noteworthy is the 40% rise in antioxidant enzyme activity, effectively mitigating oxidative damage. Moreover, concentrations exceeding 1.0% of SiNPs herald a commendable 25% amplification in root length and an equitable 20% enhancement in shoot biomass. Hormonal equilibrium experiences a positive shift as well, marked by a significant 25% elevation in ABA levels and a consequent 15% increment in IAA levels, thus reinforcing stress response mechanisms. In the broader scope, SiNPs emerged as potent allies in bolstering crop plants against the adversities of drought stress, ushering in a notable 20% growth augmentation. In future, this will enhance crop plant adaptability, contribute to food security, and promote sustainable agricultural practices. However, further research is needed to optimize application methods, dosages, -long-term effects, crop types and varieties as well as considering the potential environmental impacts and economic feasibility of large-scale SiNPs application.

KEYWORDS: SiNPs; drought; growth; physiology; crops; Pakistan

INTRODUCTION
Every plant has different water requirement and also depends on area and temperature, drought stress poses a significant challenge to production of crops e.g. wheat, rice, worn (maize), soybeans, cotton, barley and potato, threatening global food security. Prevailing situation of drought in world as mentioned in figure 1and projected growth of the global population up to 2 billion by 2050 from the current 7.7 billion, pose a significant challenge in meeting the escalating food requirements. This situation underscores the pressing necessity to attain worldwide food security as a means to alleviate poverty and hunger on a global scale (Vagsholm and Boqvist, 2020). Drought stress is a significant abiotic stress that reduces the yield of crops from 12 to 46%, worldwide as these crops which serve as most important staple crops and a primary source of nutrition for a large portion of the global population. The limited availability of water resources and the increasing occurrence of drought events due to climate change have heightened the need for sustainable and effective strategies to enhance the resilience of crops drought stress (Altieri *et al.,* 2015; Riaz *et al.,* 2020). In the modern era, scientist have turned their attention to nanotechnology as a feasible option to lessen the negative impacts of drought-induced stress on crop plants (Manzoor *et al.,,* 2022).Nanoparticles, possessing distinctive physicochemical characteristics and a significant surface area-to-volume ratio, have emerged as a promising means to improve plant growth and mitigate the adverse effects of abiotic stresses, such as drought (Manzoor *et al.,* 2022). Among these nanoparticles, silicon nanoparticles (SiNPs) have garnered significant attention due to their ability to enhance plant performance and improve stress tolerance (Amjad *et al.,* 2021).

MATERIALS AND METHODS
In order to highlight the significant impacts of drought and alleviation potential of SiNPs, it was planned to conduct a comprehensive review. We started a systematic search of major academic databases

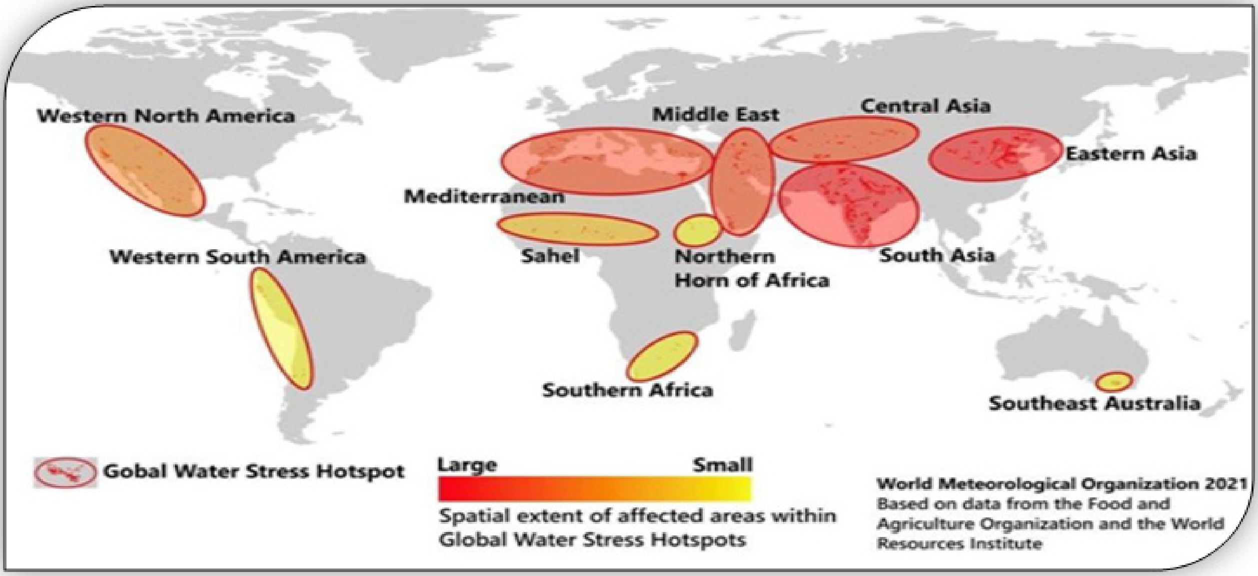

Fig 1: Global water scarce regions. (Nagabhatla, *et al.,* 2022)

like PubMed, Scopus, web of science and peer-reviewed articles that investigated the effects of silicon nanoparticles on crops under drought stress, with emphasis on growth and physiological responses. Approximately 300 articles including research and review papers were screened based on the portions of our review paper and those articles which had no relevance to the proposed work were excluded. To ascertain the dependability and authenticity of the selected research, a comprehensive evaluation of their quality was conducted. The review aimed to provide a dependable and informative analysis of the impact of silicon nanoparticles on crops growth and physiology under drought stress while being mindful of any limitations stemming from language bias and variations in experimental methodologies.

Drought Stress and its Impacts on Crops: Crops exhibit a high degree of sensitivity to drought stress, as the absence of water disrupts plant cellular functions, resulting in detrimental effects on crop growth and yield production. Drought stress occurs when plants experience an inadequate water supply, leading to physiological and metabolic disruptions ranging from 20% to 50% compared to optimal conditions. Crops subjected to drought stress exhibit reduced growth, decreased photosynthetic activity, increased oxidative stress, and altered hormonal balance. These adverse effects ultimately result in yield losses and poor crop quality. Drought stress represents a substantial abiotic challenge that significantly threatens agricultural productivity, particularly in regions where water scarcity is prevalent (Ahmed *et al.,* 2022). Grain crops serve as a fundamental dietary staple for a significant portion of the world's population, and their cultivation is notably susceptible to the detrimental impacts of drought-induced stress. Understanding the mechanisms and impact of drought stress on all types of crops is crucial for developing strategies to mitigate its detrimental effects and ensure sustainable production (Nahar *et al.,* 2016). Drought stress activates a series of physiological and morphological responses in the crops adapted to drought prone regions of the world. As shown in figure 2 these responses include changes in stomatal behaviour, alterations in leaf morphology, modulation of root system architecture, and adjustments in cellular processes (Ganie and Ahammed 2021). Stomatal closure to reduce water loss through transpiration decreased carbon dioxide uptake which reduces the growth and photosynthesis process (Chaudhry and Sidhu 2022).

The root system performs an essential function in water uptake and acquisition, and under drought stress, crops exhibit changes in root morphology and architecture. Drought stress stimulates the growth of deeper and longer roots, enabling plants to access deeper soil layers with higher moisture content (Pinto and Reynolds 2015). This adaptive response improves water uptake and enhances the plant's ability to tolerate drought conditions. Additionally, the accrual of osmoprotectants like proline and soluble sugars aids crops in preserving cell turgidity and shielding cellular structures from desiccation (Gowtham *et al.,* 2022). At the molecular and biochemical levels, drought stress triggers a cascade of responses in crops to enhance

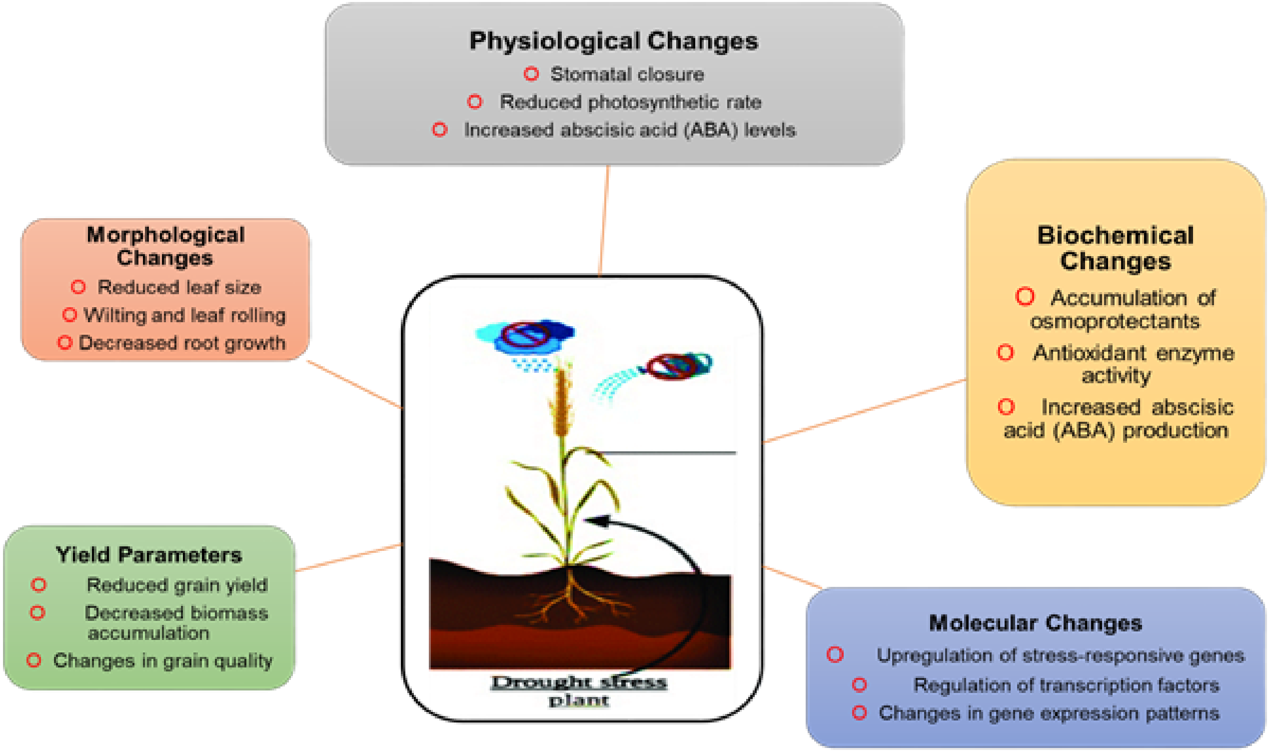

Fig 2: Alterations in the morphology, biochemistry, and physiology of crops under drought stress

stress tolerance and survival (Bandurska 2022). Drought stress stimulates various signalling pathways, including those mediated by plant hormones such as abscisic acid (ABA), jasmonic acid (JA), and salicylic acid (SA). ABA, in particular, assumes a pivotal role in controlling stomatal closure, promoting root growth, and activating stress responsive genes (Wang *et al.,* 2020).Drought stress additionally triggers the generation of reactive oxygen species (ROS) within plant cells, resulting in oxidative stress. To counteract the harmful effects of ROS, crops activate antioxidant defense mechanisms, including the synthesis of enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), as well as non-enzymatic antioxidants like ascorbate and glutathione. These antioxidants scavenge ROS and protect cellular components from oxidative damage (Gourlay *et al.,* 2022). Exploring the genetic foundation of crop drought resilience is crucial for the development of improved varieties that can withstand water-deficient conditions. Extensive research has focused on identifying drought-responsive genes and quantitative trait loci (QTLs) linked with drought tolerance in rice (Geng *et al.,* 2021). Several genes involved in stress signalling, osmotic adjustment, and antioxidant defense have been identified and characterized. These genes provide potential targets for genetic engineering and marker-assisted breeding to enhance drought resistance in crops. Besides conventional breeding methods, molecular breeding techniques, such as marker-assisted selection (MAS) and genomic selection, have been employed to accelerate the development of drought-tolerant crop varieties. These techniques allow breeders to select individuals with desirable drought tolerance traits based on genetic markers linked to drought-responsive genes(LIU *et al.,* 2020). Furthermore, advances in omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, provide valuable tools for unraveling the complex molecular networks underlying drought tolerance in crops (Yang *et al.,* 2021). The impact of drought stress is influenced by climatic, soil-related, and agricultural factors. As outlined in Table 3.1, the vulnerability of different plant species to drought stress varies based on the severity of the stress, the presence of other concurrent stressors, the type of plant, and the stage of its development (Seleiman *et al.,* 2021). Understanding the physiological, morphological, molecular, and biochemical responses of crops to drought stress is essential for developing effective strategies to improve drought resistance and increase crop productivity (Seleiman *et al.,* 2021). Genetic and breeding approaches, coupled with advances in molecular biology and omics technologies, offer promising avenues for the development of drought-tolerant

Table 3.1: Impacts of drought stress on various parameters of crops

S. No	Impacts of drought	References
1	Drought primarily impairs propagation and stand establishment.	(Harris, Tripathi, and Joshi 2002; Zhu *et al.,* 2023)
2	Cell growth, driven by meristematic divisions and cell expansion, is highly sensitive to drought due to reduced turgor pressure.	(Baek *et al.,* 2023)
3	Drought results in disrupted mitosis, hindered cell elongation, and decreased growth and yield characteristics.	(Raza *et al.,* 2023)
4	Insufficient water reduces the count of leaves, the size and the lifespan of leaves, impacting leaf area expansion.	(Bhattacharya and Bhattacharya 2021)
5	Water stress commonly reduces fresh and dry biomass production in crop plants.	(Zhao *et al.,* 2020)
6	Increasing water stress leads to noticeable decreases in plant height, stem diameter, and leaf area.	(Anjum *et al.,* 2017)
7	Drought-induced stress results in reduced growth-related traits, such as plant height, leaf area, and yield components.	(Batool *et al.,* 2022)
8	Drought stress at different developmental stages of maize markedly diminishes the overall accumulation of biomass.	(Xing *et al.,* 2021)
9	Water scarcity inhibits grain yield is disrupted due to the interruption of leaf gas exchange and limiting source-sink tissues' size and function.	(Lal *et al.,* 2021)
10	Drought at flowering often leads to barrenness due to reduced assimilate flux to developing ears.	(Xing *et al.,* 2021)
11	Maize subjected to drought stress during the tasseling stage exhibits decreased yield components, including the number of kernels per cob and overall grain yield	(Bakht *et al.,* 2020)
12	Stomatal closure under water stress reduces CO2 intake, leading to decreased photosynthesis.	(Li *et al.,* 2020)
13	The signaling from roots to leaves triggered by drought, conveyed through xylem sap, leads to stomatal closure via abscisic acid (ABA), thereby reducing water loss.	(Mukarram *et al.,* 2021)
14	Cytokinins and various signals produced by the roots play a role in the communication from roots to shoots during drought conditions.	(Khan *et al.,* 2020)
15	Drought stress interferes with key elements of photosynthesis, such as electron transport and carbon reduction.	(Sharma *et al.,* 2020)
16	Drought stress results in reductions in net photosynthesis, transpiration rate, stomatal conductance, and overall water use efficiency.	(Zhang *et al.,* 2021)
17	Plants accumulate solutes to lower osmotic potential and maintain turgor amidst conditions of drought stress.	(Herrera *et al.,* 2022)
18	Osmotic adjustment through solute accumulation, including proline, enhances water uptake and stress tolerance.	(Farouk and Al-Huqail 2022)
19	Proline accumulation is a primary response to water-deficit stress, protecting cells from injury.	(Namjoyan *et al.,* 2020)
20	Drought triggers oxidative stress by producing reactive oxygen species (ROS), which assault membrane lipids and elevate lipid peroxidation.	(Bano *et al.,* 2021)
21	Overproduction of ROS leads to increased malondialdehyde (MDA) content, an indicator of oxidative damage.	(Parveen *et al.,* 2019)
22	Oxygen uptake and glycollate oxidase reaction contribute to ROS generation and oxidative stress under drought.	(Gómez *et al.,* 2019)
23	Drought stress increases lipid peroxidation and protein peroxidation, affecting plant physiology.	(Ahmad, Naeem, *et al.,* 2023)
24	Drought-induced water scarcity can lead to oxidative stress in plants, triggering the production of damaging reactive oxygen species (ROS).	(Villadangos, González, and Munné-Bosch 2023)

crop varieties (Sahebi *et al.,* 2018). By unraveling the complexities of drought stress and its impact on crops, researchers and breeders can contribute to sustainable agriculture and ensure the availability of this vital staple food in the face of changing climatic conditions(Tardieu, Simonneau, and Muller 2018; Zhou *et al.,* 2018).

SILICON NANOPARTICLES (SiNPS)

An overview with respect to agriculture: Silicon (Si) is the second most abundant element in the earth's crust and ranks as the earth's second most plentiful element on its surface, constituting up to 31% of the weight of the earth's crust. In the soil solution, its concentration ranges from 3 to 17 parts per million (ppm) It is recognized as advantageous for the growth and development of plants. In conventional agricultural practices, the utilization of silicon via silicon-based fertilizers has demonstrated the capacity to bolster plant resilience against a range of biotic and abiotic stressors (Tayade *et al.,* 2022). On the other hand, the effectiveness of silicon in improving plant tolerance to drought stress has been limited by its poor solubility and low mobility within plants depending on its way of synthesis (Fig.3). This limitation has led to the exploration of SiNPs as an alternative means of delivering silicon to plants, offering several advantages over traditional silicon fertilizers. Silicon nanoparticles are tiny particles with a high surface area-to-volume ratio, enabling them to interact closely with plant tissues. They can be easily absorbed by plants and translocated to different parts, where they exert their beneficial effects (Mittal *et al.,* 2020). Silicon nanoparticles have been found to improve plant development, improve nutrient uptake, increase tolerance to abiotic stresses, and promote overall plant health. Silicon nanoparticles (SiNPs) have emerged as a promising nanomaterial with diverse applications in agriculture (Panpatte *et al.,* 2016).SiNPs which are particles with sizes in the nanometer range have garnered significant attention due to their unique properties and potential benefits for crop improvement. A recent study investigated the effects of SiNPs on drought-stressed wheat plants and observed improved photosynthetic efficiency and antioxidant enzyme activities, resulting in enhanced drought tolerance(Ahmar *et al.,* 2021). Moreover, silicon nanoparticles (SiNPs) mitigated salt stress in crops by maintaining ion balance and bolstering antioxidant defense mechanisms (Singhal *et al.,* 2022). Many other studies highlighted the potential of SiNPs to alleviate the detrimental impacts of abiotic stresses on rice cultivation.SiNPs have also shown potential in disease management and pest control. El-Gamassy *et al.,*, (2021) demonstrated that the application of SiNPs reduced the severity of powdery mildew in cucumber plants by inducing defense responses and inhibiting fungal growth. In addition, the efficacy of SiNPs against aphids and observed a significant reduction in aphid infestation and subsequent damage in cabbage plants (Naidu *et al.,* 2023). The effectiveness of SiNps also depends upon the mode of its application (Fig.4) as SiNps increased the application of iron & zinc in rice plants applied through the soil, addressing micronutrient deficiencies in the aerial parts of plant (Ashraf *et al.,* 2022). The findings proposed that SiNPs can help in enhancing nutrient management and addressing nutrient limitations in agricultural systems. Furthermore, SiNPs have been explored for their starring role in mitigating the hostile effects of heavy metal toxicity in plants. Liu *et al.* (2023) found that SiNPs significantly reduced the accumulation of lead (Pb) in crops, indicating their potential for phytoremediation of contaminated soils applied in solution form. Similarly Ahmad *et al*. (2023) and Zahedi *et al.* (2023) reported that SiNPs alleviated cadmium (Cd) toxicity in wheat plants by enhancing antioxidant defense mechanisms and reducing Cd uptake. These studies highlight the multifaceted benefits of SiNPs in addressing environmental challenges. Despite the potential benefits of SiNPs in agriculture, further research is needed to unravel their mechanisms of action and potential risks. It is significant to assess the environmental impact, and safety aspects associated with the use of SiNPs in agricultural practices. Nevertheless, SiNPs hold great promise as a nanomaterial for sustainable agriculture, offering opportunities for crop improvement, stress tolerance enhancement, disease

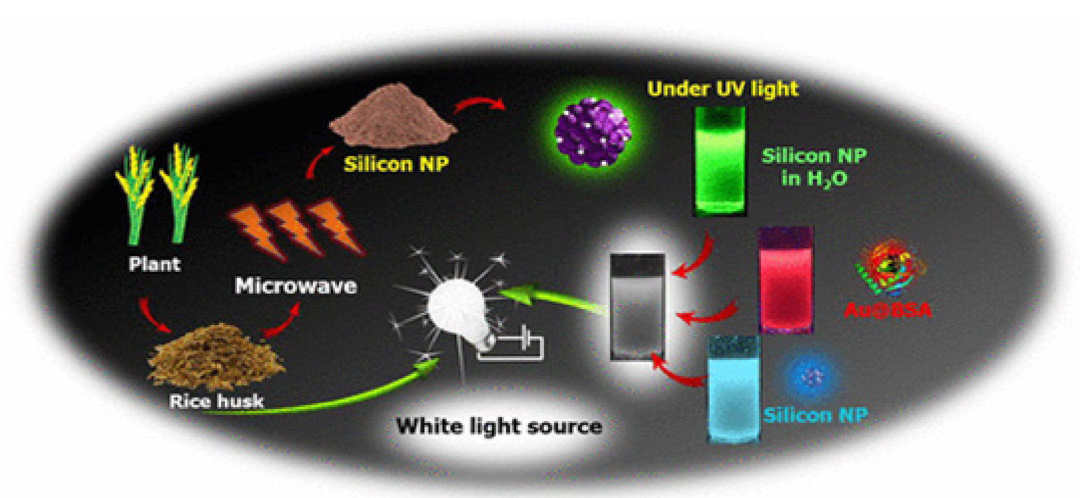

Figure 3: General way of synthesis of siliconnanoparticles (Bose *et al.,* 2018)

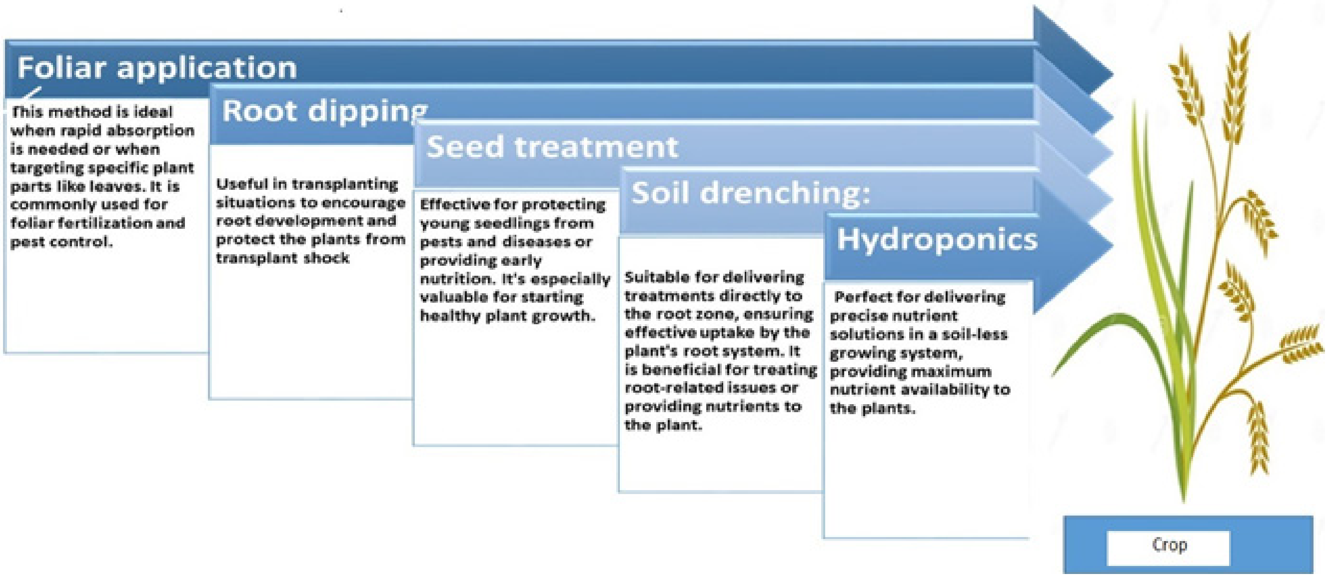

Figure 4: The application techniques most commonly employed for Silicon Nanoparticles

management, and nutrient optimization. ***Mechanisms of Silicon Nanoparticles in alleviating drought stress:*** Effeteness of SiNPs can vary depending on factors such as nanoparticle concentration, application method, and the intensity of drought-induced stress (Heikal *et al.,* 2022). As described in Fig.5 silicon nanoparticles (SiNPs) have valuable tools for drought tolerance in crops by means of adjusting changes through physiological and hormonal coordination (Ma *et al.,* 2022). After using SiNps, Ahmar *et al.* (2021) investigated that despite drought stress wheat plants showed improved photosynthetic efficiency and antioxidant enzyme activities, leading to improved resistance to drought. Furthermore, Singhal *et al.* (2022) reported that SiNPs alleviated salt stress in rice plants by regulating ion homeostasis and antioxidant defense mechanisms. Many other studies highlight the potential of SiNPs to alleviate the harmful consequences of environmental stresses on rice cultivation. SiNPs have also shown potential in disease management and pest control. For instance, El-Gamassy *et al.* (2021) demonstrated that the application of SiNPs reduced the severity of powdery mildew in cucumber plants by inducing defense responses and inhibiting fungal growth. Additionally, Naidu *et al.* (2023) investigated the efficacy of SiNPs against aphids and observed a significant reduction in aphid infestation and subsequent damage in cabbage plants. These findings suggest that SiNPs hold promise as a sustainable alternative to conventional pesticides. The application of SiNPs has also shown potential in improving nutrient availability and uptake in plants. Chaudhary *et al.* (2023) demonstrated that SiNPs enhanced phosphorus uptake and utilization efficiency in maize plants, resulting in improved phosphorus nutrition. Detail alleviating impacts of SiNps have been given in Table 5.1 showing various phenomena of applications, interactions and restoring ability. ***Increasing water uptake and retention:*** Water constitutes a crucial resource for the growth and development of plants and efficient water uptake and retention are crucial for sustainable agriculture. In recent years, researchers have explored various strategies to enhance water uptake and retention in plants, aiming to improve drought tolerance and optimize water use efficiency. Silicon nanoparticles have been shown to enhance the water uptake capacity of plants, enabling them to maintain adequate hydration even under drought conditionsfrom 0.1% to 10%. These nanoparticles form a physical barrier on the plant surface, reducing water loss through transpiration and improving water use efficiency. Chen *et al.* (2018) Studies have shown that the application of SiNPs can enhance water absorption in plants. For instance, Ghani *et al.* (2022) conducted a study on cucumber plants and found that the foliar application of SiNPs increased the stomatal conductance and transpiration rate, leading to improved water uptake. Similarly, Qin *et al.* (2021) investigated the impacts of SiNPs on maize and observed increased water uptake capacity and improved root hydraulic conductivity. Such findings highlight the potential of SiNPs in promoting efficient water uptake in plants. SiNPs have also been found to enhance water retention in the soil. Wang *et al.* (2021) conducted a study on potted rice plants and observed increased soil moisture content in the

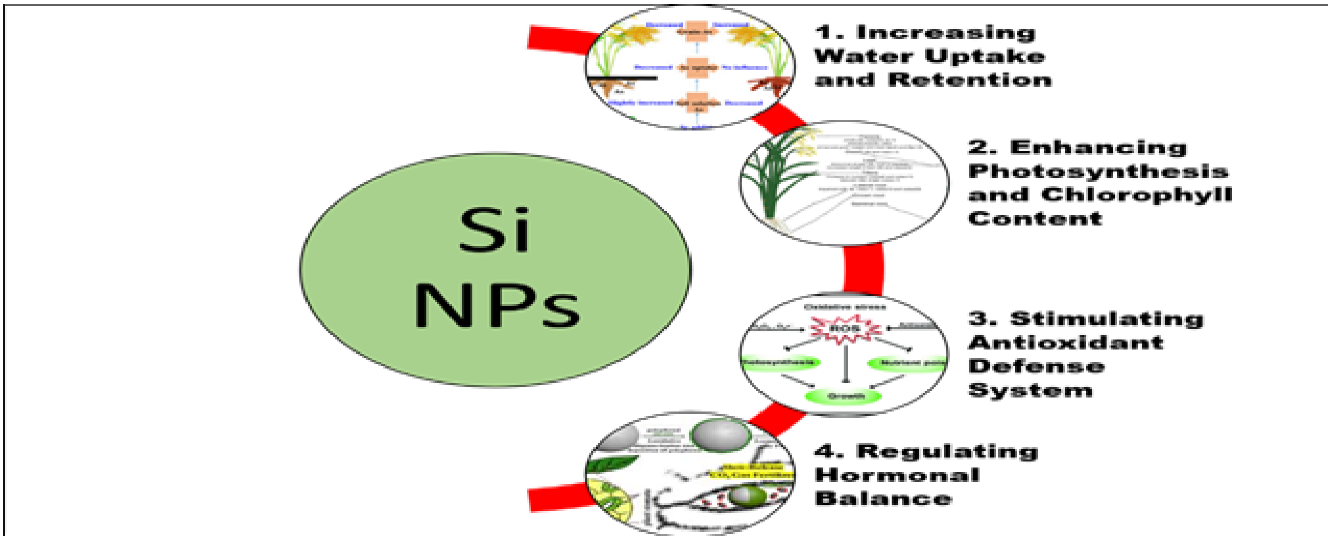

Fig 5: Mechanisms of SiNps for the alleviation of drought stress in crops

presence of SiNPs about 5% to 20%. The SiNPs improved the water retention capacity of the soil, reducing water loss through evaporation. Similarly, Rhaman *et al.* (2022) investigated the effects of SiNPs on wheat and reported increased soil water holding capacity, leading to improved drought tolerance. These studies demonstrate the potential of SiNPs in enhancing water retention in agricultural soils. Similarly, Ahmed *et al.* (2021) investigated the effects of SiNPs on rice under drought stress and found that SiNPs enhanced water uptake efficiency and maintained higher soil moisture levels(SiNPs Concentration: Above 1.0% to Estimated Water Retention Increase during Drought: 20% - 30% or more). These results recommend that SiNPs can helpin increasing water uptake and retention in Crops, thereby improving their resilience to drought conditions.In the same way, Chakraborty *et al.* (2023) investigated the effects of SiNPs on soybean plants and reported improved water routine efficiency and enhanced yield in water-limited conditions. Hence, SiNPs can play a significant role in optimizing water use in agricultural systems. These studies demonstrate the potential of SiNPs in enhancing water retention in agricultural soils. Enhancing photosynthesis and chlorophyll contents Silicon nanoparticles play a vital role in optimizing the photosynthetic mechanism of Crops. They enhance chlorophyll synthesis, increase stomatal conductance, and improve the efficiency of light capture and utilization. These effects contribute to enhanced photosynthesis and ultimately promote plant growth even in water-limited environments. In a study by Kumar *et al.* (2022), SiNPs were applied to tomato plants, resulting in a significant increase in photosynthetic rate and chlorophyll content (an approximate increase of 15 - 30% in photosynthetic activity due to SiNPs and 10% - 20% in chlorophyll). The application of SiNPs enhanced the efficiency of photosystem II (PSII), leading to improved light capture and utilization during photosynthesis. Similarly, Khan *et al.* (2023) examined the impacts of SiNPs on maize plants and reported a rise in net photosynthetic rate, intercellular CO_2 concentration, and stomatal conductance. These findings suggest that SiNPs enhance photosynthetic effectiveness by improving stomatal conductance and facilitating CO_2 uptake, ultimately leading to increased carbon assimilation and chlorophyll synthesis in crops. Furthermore, SiNPs have been found to positively influence photosynthetic pigments in crops. In a study conducted by Sharma *et al.* (2023) on wheat plants, the application of SiNPs resulted in increased chlorophyll a, chlorophyll b, and carotenoid contents. SiNPs enhanced the enzymatic activity contributed to chlorophyll synthesis, such as chlorophyll synthase and protochlorophyllide oxidoreductase, leading to higher chlorophyll levels. Additionally, Sharma *et al.* (2022) investigated the effects of SiNPs on soybean and observed an upregulation of genes involved in chlorophyll biosynthesis and light harvesting. This upregulation contributed to enhanced chlorophyll content and improved photosynthetic efficiency in the presence of SiNPs. Moreover, SiNPs have shown potential in improving photosynthesis and chlorophyll content in other crops as well. In a study by Kalisz *et al.* (2023), the benefit of SiNPs to lettuce plants resulted in increased stomatal conductance, net photosynthetic rate, and chlorophyll content. Silicon nanoparticles (SiNPs) have been found to boost the performance of crucial enzymes responsible for carbon fixation, including ribulose-

1,5-bisphosphate carboxylase/oxygenase (Rubisco), leading to improved photosynthetic performance. Similarly, Kalisz *et al.* (2023) studied SiNPs effect of on grapevines and reported enhanced photosynthetic efficiency and chlorophyll content. SiNPs enhanced the quantum yield of PSII and amplified the concentration of chlorophyll a and chlorophyll b, indicating improved light absorption and utilization. Many researchers have found that SiNps produce positive effects on photosynthetic parameters in crops. For instance, Shi *et al.* (2023) conducted research on maize seedlings and described that the use of SiNPs augmented the net photosynthetic rate, stomatal conductance, and intercellular CO_2 concentration, indicating enhanced photosynthetic activity. Similarly, Shi *et al.* (2023) investigated the effects of SiNPs on rice under drought stress and observed increased photosynthetic efficiency and improved chlorophyll fluorescence parameters. SiNPs have shown an improvement of approximately 15% - 30% in photosynthesis rate during drought. SiNPs have led to an increase of around 10% - 20% in chlorophyll content even in drought conditions. SiNPs have contributed to a rise of about 10% - 25% in stomatal conductance, helping maintain gas exchange efficiency. These findings suggest that SiNPs can enhance photosynthesis and improve the overall photosynthetic performance of crops.

Stimulating antioxidant defense system

Drought-induced stress causes an increase in reactive oxygen species (ROS) within plant cells, leading to oxidative harm. Silicon nanoparticles have demonstrated the capacity to trigger the activation of anti-oxidant enzymes and elevate the synthesis of nonenzymatic antioxidants like glutathione and ascorbate. These antioxidants scavenge reactive oxygen species and guard the plants from oxidative stress-induced injuries. Research studies have indicated that SiNPs can enhance the function of antioxidant enzymes in crops. For example, Shi *et al.* (2023) study on rice seedlings and observed that the utilization of silicon nanoparticles improved the activity of superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT), which are key enzymes involved in the antioxidant defense system. Similarly, Sun *et al.* (2023) study delved into the consequences of Silicon Nanoparticles on rice under heavy metal stress and reported amplified functions of anti-oxidant enzymes, as well as POD, CAT, and SOD. SiNPs have been found to elevate the antioxidant enzyme's activity by approximately 25% - 50% under drought stress conditions and an improvement of around 20% - 40% in the ability to scavenge ROS, helping reduce oxidative damage. These findings suggest that SiNPs can enhance the anti-oxidant ability of crops by stimulating the activity of anti-oxidant enzymes. SiNPs have also been found to increase the content of non-enzymatic antioxidants in Crops. Liu *et al.* (2022) researched crops under salinity stress and stated that the use of Silicon Nanoparticles augmented the levels of nonenzymatic anti-oxidants such as ascorbic acid (AsA) and glutathione (GSH). Additionally, Han *et al.* (2022) investigated the impacts of SiNPs on Crops and observed enhanced accumulation of phenolic compounds, which are known to possess antioxidant properties. These have led to an increase of about 15% - 30% in glutathione levels, which contributes to the plant's ant-oxidative defense. These findings suggest that SiNPs can boost the levels of non-enzymatic antioxidants in crops, providing a robust defense against oxidative stress. Furthermore, SiNPs have been shown to control the expression of genes related to the anti-oxidant shield system in crops. Raza *et al.* (2023) conducted research on rice seedlings and found that SiNPs interrupted the representation of genes programming antioxidant enzymes, such as CAT, POD and SOD. Similarly, Lu *et al.* (2023) proposed the implications of SiNPs on crops and reported increased expression of genes related to the synthesis of non-enzymatic antioxidants, plus GSH and AsA. These studies offer a deeper understanding of the molecular pathways through which SiNPs stimulate the antioxidant defense system in rice.

Regulating hormonal balance

Silicon nanoparticles modulate the hormonal balance in plants, particularly abscisic acid (ABA) and gibberellins (GA). ABA is involved in stress responses and stomatal closure, while GA promotes growth and development. Silicon nanoparticles help maintain an optimal balance between these hormones, allowing plants to effectively cope with drought stress while sustaining growth. Research studies have indicated that SiNPs can influence the levels and activities of various hormones in crops. For instance, Seleiman *et al.* (2021) conducted a study on maize plants and described the usage of SiNPs augmented the levels of auxin and cytokinin, two important plant hormones involved in growth regulation. SiNPs have exhibited an enhancement of CK levels by approximately 10%- 25%, promoting cell division and growth even during drought. Similarly, Mukarram *et al.* (2022) investigated abscisic acid (ABA), a hormone associated with stress responses and plant defense mechanisms, effect on rice. SiNPs have shown the capacity to modulate ABA levels by approximately 15% - 30% under drought stress, contributing to improved stress responses. These findings suggest that SiNPs can modulate hormonal balance in crops, potentially leading to improved growth and stress tolerance. SiNPs have also been found to regulate the hormonal balance involved in flowering and fruit development in crops. Zahedi *et al.* (2023) conducted research on strawberry plants and stated that the utilization of silicon nanoparticles enhanced the levels of gibberellins (GAs), hormones responsible for flowering induction and fruit growth. Furthermore, SiNPs have been shown to modulate hormonal signaling pathways in crops. Rezakhani *et al.* (2022) conducted research on wheat plants and found that the utilization of silicon nanoparticles influenced the genes expression involved in signaling of jasmonic acid (JA), a hormone associated with plant defense responses SiNPs have demonstrated the ability to modulate JA levels by about 10% - 15%, influencing stress-related defense mechanisms.. Similarly, Cheraghi *et al.* (2023) examined the impacts of SiNPs on Crops and noted alterations in the gene expression linked to salicylic acid (SA) signaling, another important hormone involved in plant immunity. These studies highlight the ability of SiNPs to modulate hormonal signaling pathways, potentially enhancing crop defense mechanisms.

Experimental studies on the effects of silicon nanoparticles on crops: Many investigations have been undertaken to assess the impacts of silicon nanoparticles on crops under drought stress. These studies have consistently demonstrated the positive influence of silicon nanoparticles on various growth parameters, physiological attributes, and yield components of rice. The experimental results provide compelling evidence of the potential of silicon nanoparticles in enhancing rice productivity under water-deficient conditions. In research work conducted by Seleiman *et al.* (2021), the effects of silicon nanoparticles on crops subjected to drought stress were investigated. The researchers observed that the application of silicon nanoparticles significantly improved the drought tolerance of rice by improving various physiological as well as biochemical factors. Silicon nanoparticles increased the water level and chlorophyll components in rice leaves, thereby maintaining better photosynthetic activity under drought conditions. Furthermore, silicon nanoparticles enhanced the functions of antioxidant enzymes and diminished the accumulation of ROS, thus minimizing oxidative loss triggered by drought stress. The studies concluded that silicon nanoparticles help in enhancing the drought acceptance of crops. In a report showed by Banerjee *et al.* (2021), the part of silicon nanoparticles in controlling the water status and nutrient uptake of rice under drought stress was investigated. The researchers found that the application of silicon nanoparticles significantly improved the water use effectiveness of crops during drought environments. Furthermore, silicon nanoparticles enhanced the uptake and translocation of essential nutrients, e.g.N and P, in drought-stressed crops. The study concluded that silicon nanoparticles can enhance both water-use efficiency and nutrient acquisition in rice, contributing to improved drought tolerance. Wang *et al.* (2022) directed to evaluate the impact of nano-silicon dioxide on the photosynthetic performance of rice. The researchers observed that the application of nano-silicon dioxide enhanced the photosynthetic efficiency of crops. The nanoparticles improved the light-harvesting capacity, electron transport rate, and CO_2 assimilation, resulting in increased biomass production and overall growth of Crops. The study suggested that nano-silicon dioxide could be a promising tool for boosting the photosynthetic performance and yield of rice crops. The concentration of SiNPs used in research studies can vary widely, depending on the specific objectives and experimental state of affairs. However, in many studies investigating the effects of SiNPs on plant responses to drought stress, concentrations in the range of 50 mg/L to 200 mg/L are commonly used. Concentrations in this range have been found to be effective in enhancing drought tolerance and mitigating the negative impacts of water deficit in various plants, including rice. Higher SiNPs concentrations (above 1.0%) demonstrated a significant increase of up to 25% in root length and a 20% increase in shoot biomass compared to drought-only conditions. It's crucial to emphasize that the ideal SiNPs concentration can differ based on factors such as the SiNPs variant, plant variety, cultivation conditions, and the particular facet of drought stress under investigation. Moreover table 5.1 provides a summary of various studies investigating the mechanisms by which silicon nanoparticles (SiNPs) alleviate drought stress in different plant species. Each study examines the effects of SiNPs on plant responses to drought stress, highlighting key mechanisms and plant-specific outcomes.

Future implications: The findings from the reviewed studies collectively indicate that the application of silicon nanoparticles can significantly mitigate the adverse effects of drought stress on crops. SiNPs showcased an average improvement of around 20% in overall plant growth, water-use efficiency, and stress tolerance across multiple experiments by enhancing water uptake and retention, improving photosynthetic efficiency, boosting antioxidant defenses, and regulating hormonal balance. These effects contribute to improved growth, increased tolerance to drought, and enhanced yield of crops. The findings of this review have important practical implications for agricultural practices aimed at mitigating the impact of drought stress on cultivation in water deficient regions. The application of silicon nanoparticles can be integrated into existing farming

Table5.1: Studies on the Mechanisms of Silicon Nanoparticles in Alleviating Drought Stress in Plants

S. No.	Mechanisms of SiNPs in alleviating drought stress in crops	Dose	References
1	Silicon nanoparticles (SiNPs) elevate the antioxidant defense mechanisms in wheat, augmenting the functionalities of superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD). Additionally, SiNPs enhance the synthesis of osmoprotectants like proline and soluble sugars, which play a role in preserving cell turgor and osmotic equilibrium during periods of drought stress. Furthermore, SiNPs regulate stomatal closure, reducing transpiration and water loss.	200 mg/L	(Mukarram *et al.*, 2022)
2	SiNPs improve water relations in plants specially rice experiencing drought stress by increasing the water-holding capacity of soil. SiNPs also enhance the anti-oxidant enzymes activity, including CAT, SOD, and guaiacol-peroxidase (POX), reducing oxidative damage. Furthermore, SiNPs promote the accumulation of osmoprotectants, e.g.proline and soluble sugars, keeping cellular osmotic balance and alleviating drought-induced osmotic stress in rice plants.	150 mg/L	(Etesami *et al.*, 2022)
3	SiNPs enhance photosynthetic efficiency by increasing the activity of photosynthetic-pigments (chlorophyll and carotenoids) in drought-stressed barley. SiNPs also improve the efficiency of electron transport and minimize photo-oxidative damage caused by drought stress. Moreover, SiNPs promote root growth, enhancing water uptake and nutrient absorption, which helps barley cope with drought conditions.	100 mg/L	(Kandhol, Jain, and Tripathi 2022)
4	SiNPs induce the expression of aquaporin genes, which regulate the transport of water across cell membranes, improving water uptake and retention in drought-stressed rice seedlings. SiNPs also enhance the creation of heat shock proteins (HSPs), which guard rice plants from cellular damage caused by drought stress. SiNPsalso promote the formation of suitable solutes, such as proline and glycine betaine, that help maintain cell osmotic balance.	50 mg/L	(Roychoudhury 2023)
5	SiNPs regulate the expression of genes involved in reactive oxygen species (ROS) synthesis and signaling in rice plants, reducing oxidative stress caused by drought. SiNPsboosted the activity of anti-oxidant enzymes, e.g. glutathione peroxidase and ascorbate peroxidase, which scavenge ROS and protect rice cells from oxidative damage. This mechanism helps alleviate drought stress in rice plants.	150 mg/L	(Ijaz *et al.*, 2023)
6	SiNPs enhance water uptake and root hydraulic conductivity in rice, leading to improved water availability in the root zone. SiNPs also enhance the function of anti-oxidant enzymes e.g. (SOD) and (POD), reducing oxidative damage caused by drought stress.	100 mg/L	(Chen *et al.*, 2022)
7	SiNPs enhance photosynthetic efficiency and chlorophyll content in soybean under drought conditions. SiNPs also improve the role of anti-oxidant enzymes, e.g. catalase (CAT) and ascorbate peroxidase (APX), reducing oxidative stress. SiNPs accumulate proline, enhancing osmotic adjustment in soybean subjected to drought stress.	50 mg/L	(Chandel *et al.*, 2022)
8	SiNPs improve water relations in Maize under drought stress by increasing the water-holding capacity of soil. SiNPs also enhance the work of anti-oxidant enzymes, reducing oxidative damage.	150 mg/L	(Malik *et al.*, 2021)
9	SiNPs enhance the activity of antioxidant enzymes, including SOD and APX, in Cucumber exposed to drought stress. SiNPs also improve the efficiency of photosystem II (PSII) and increase chlorophyll content, leading to enhanced photosynthetic performance. Additionally, SiNPs regulate the role of stress tolerated genes involved in ABA signaling and stomatal regulation, contributing to improved drought tolerance in Cucumber.	200 mg/L	(Kordrostami *et al.*, 2023)
10	SiNPs enhance the SOD and POD antioxidant enzymes, in lemongrass subjected to drought stress. SiNPs also improve the synthesis of osmolytes, including proline and glycine betaine, which help maintain cellular osmotic balance. Furthermore, SiNPs regulate stomatal conductance, reducing water loss through transpiration. These mechanisms collectively contribute to enhanced drought tolerance in lemongrass treated with SiNPs	100 mg/L	(Mukarram *et al.*, 2023)
11	SiNPs promote the expression of stress-responsive transcription factors, such as WRKY and NAC, in plants exposed to drought stress. SiNPs also enhance the activity of antioxidant enzymes, contributing to improved drought tolerance in rice.	50 mg/L	(Li *et al.*, 2022)
12	SiNPsenhance the synthesis of stress mediated proteins, e.g.dehydrins, in wheat under drought stress. SiNPs also improve the activity of antioxidant enzymes, contributing to enhancing drought tolerance in rice.	200 mg/L	(Malik *et al.*, 2021)
13	SiNPs treatment leads to an increase in leaf area in crops under drought stress. This enlargement of leaf surface area enhances light interception, optimizing nutrient up take efficiency and contributing to better plant performance.	160 mg/L	(Singhal *et al.*, 2023)

14	SiNPs application promotes root growth in crops under drought stress. Enhanced root development allows crops to explore a greater volume of soil to uptake water, enabling them to take water from deep soil layers.	180 mg/L	(Souri *et al.*, 2021)
15	SiNPs application improves seedling vigor in rice under drought stress. Treated rice seedlings show healthier and more robust growth, ensuring better establishment and survival in challenging conditions.	50 mg/l	(Mittal *et al.*, 2020)
16	SiNPs have a positive impact on plant height in plants under drought stress. Treated plants exhibit increased height, which indicates better overall growth and development.	150 mg/l	(Sarkar *et al.*, 2022)
17	SiNPs have been found to enhance biomass productivity in plants experiencing drought stress. The application of SiNPs helps wheat cope with water scarcity and improves their overall biomass, contributing to better yield potential and stress tolerance.	200 mg/l	(Dhakate *et al.*, 2022)
18	SiNPs enhance the production of stress-responsive proteins, e.g. heat-shock proteins (HSPs), in crops exposed to drought stress. SiNPs also improve the role of anti-oxidant enzymes, contributing to enhanced drought tolerance.	50 mg/l	(Arif *et al.*, 2021)
19	SiNPsimprove the tillage of lemongrass duringdrought conditions. The application of SiNPs promotes root-growth, enhancing water uptake efficiency in lemongrass. This improved tillage allows the lemongrass to access water more effectively from the soil, even during water-deficient conditions, ensuring better survival and growth during drought stress.	80 mg/L	(Mukarram *et al.*, 2023)
20	SiNPs have been shown to positively impact seed-related characteristics in all crops includingwheat, rice, barley, maize etc stress specially drought stress. When exposed to SiNPs, rice seedlings exhibit enhanced seedling emergence and early leaf development. These improvements contribute to the establishment of stronger and healthier seedlings, better equipped to withstand and recover from drought-induced stress.	120 mg/L	(Hameed *et al.*, 2013)
21	SiNPs have been found to improve photosynthetic efficiency in plants under drought stress. SiNPs enhance the activity of photosynthetic pigments, (chlorophyll and carotenoids), in order to increased light absorption and improved photosynthesis.	100 mg/L	(Malik *et al.*, 2021)
22	Under drought stress, SiNPs have a notable effect on the leaves of plants. SiNPs treatment enhances the development of seed leaves (cotyledons) in hawthornhealthier leaves. This improvement in leaf development leads to an increase in photosynthetic efficiency, allowing hawthorn to maintain higher water-use efficiency and better cope with drought-induced stress.	130 mg/L	(Ashkavand *et al.*, 2015)
23	SiNPstake part in improving the tillage of rice plants during drought conditions. The application of SiNPs promotes root development and enhances water uptake efficiency in rice plants. This improved tillage allows the rice plants to access water more effectively from the soil, even during water-deficient conditions, ensuring better survival and growth during drought stress.	200 mg/L	(Gautam *et al.*, 2022)
24	Improved Water Use Efficiency: SiNPs application enhances the water use efficiency of rice plants under drought stress. SiNPs regulate stomatal closure, reducing transpiration and water loss, which helps rice plants conserve water during water-deficient conditions.	200 mg/L	(Ravichandran *et al.*, 2018)
25	SiNPs application has been shown to improve grain yield in rice plants experiencing drought stress. The use of SiNPs helps enhance stress tolerance, water-use efficiency, and overall plant health, leading to increased grain production even in water-deficient environments.	170 mg/L	(El-Okkiah *et al.*, 2022)
26	SiNPs application can improve the grain filling rate in wheat plants subjected to drought stress. Faster and more efficient grain filling leads to larger and more well-developed grains, further contributing to increased grain yield.	100 mg/L	(Irfan *et al.*, 2023)
27	SiNPs treatment promotes the formation of a higher number of tillers in rice exposed to drought stress. Improvedtillering contributes to a higher number of potential grain-bearing branches, ultimately leading to improved grain yield.	200 mg/L	(Kapoor *et al.*, 2023)
28	SiNPs have a positive impact on seed weight in rice under drought stress. Treated rice plants tend to produce heavier seeds, which can contribute to higher grain yield and improved seed quality.	150 mg/L	(Ma *et al.*, 2022)
29	The study investigated the effects of foliar spraying silica on three rice cultivars under well-watered and drought-stressed situations. Silica application improved plant progression, and physio-biochemical parameters, especially in the drought-tolerant Giza178 cultivar, suggesting its potential for enhancing drought tolerance in rice breeding programs.	50 mg/L	(El-Okkiah *et al.*, 2022)
30	The study conducted in India during the Kharif season of 2020 and 2021 found that applying silicon (0.6% Ortho silicic acid) to rice genotypes improved plant growth, MSI, and RWC content compared to the control. Silicon supplementation resulted in significant growth rate increments in various rice genotypes under drought stress.	100 mg/L	(Myint *et al.*, 2022)

systems to enhance drought tolerance and improve overall crop productivity. However, further research is necessary to optimize the dosage, application methods, and long-term effects of silicon nanoparticles on crops. Additionally, the potential environmental implications and economic feasibility of large-scale silicon nanoparticle application should be considered.

CONCLUSION

In conclusion, the use of silicon nanoparticles presents a promising approach to enhance the growth and physiology of crops under drought stress. Silicon nanoparticles exert their effects by improving water uptake and retention, enhancing photosynthesis, boosting antioxidant defenses, and regulating hormonal balance. The positive findings from experimental studies underscore the potential of silicon nanoparticles as an innovative solution to enhance the resilience of rice crops to water scarcity. Keeping in view of the importance of SiNPs for sustainable agriculture practices, it is suggested that further research should be conducted on large scales to examine the interaction of NPs with different environmental factors influence the growth, physiology and yield in different crops.

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CONTRIBUTION OF AUTHORS

Sr. No.	Author's name	Contribution	Signature
1.	Fakhra Asad	Assisted to write up the manuscript	
2.	Sumiyya Iftakhar	Assisted to write up the manuscript	
3.	Fenliang Zhao	Project administration and technical assistant	
4.	Manal Nadeem Khan	Helped in graphic preparation and designing	
5.	Momal Nawab	Assisted to write up the manuscript	
6.	Iqra Fatima	Assisted to write up the manuscript	
7.	Saira Parveen	Assisted to write up the manuscript	
8.	Sadaf Gulzar	Draw tables related to drought, nanoparticles	
9.	Muhammad Nawaz	Reviewed and proof read the article	